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TRANSMISSION OVERHEAD LINE DESIGN & EXTREME EVENT MITIGATION (TODEM) INTEREST GROUP

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GUIDE FOR TRANSMISSION LINE FOUNDATIONS WITH LEAST IMPACT TO ENVIRONMENT

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ABSTRACT

This report is a best practices guideline for the evaluation and selection of appropriate transmission line foundations with the least environmental impact. The methodology focuses on the review of published case studies supplemented with selected utility and consultant surveys along with the writer's personal files on transmission line foundations susceptible to various sensitive and difficult environments conditions. Difficult environments can be classified as wetlands/waterways, mountainous/rough terrain, permafrost/frozen ground, woodlands, conservation/wilderness areas, and desert/rangeland. Utilities often use traditional foundations in sensitive conditions, controlling impacts with construction mitigation measures such as improved access or modular matted paths. Environmental impacts can be mitigated by a combination of good planning, design and construction practices (i.e. avoiding sensitive environments, minimizing activity in these conditions, etc.), or using foundation installation practices that limit construction time. Gaining access for geotechnical investigations in these conditions can be costly, but offers great potential to reduce overall foundation construction cost due to reduced uncertainty. This report details the advantages and disadvantages of both traditional foundation systems (driven piles, drilled shafts, direct embedment poles, steel grillages, spread footings and anchored structures) and alternate foundation systems (helical anchors/piles, vibratory caissons, micropiles, rock socketed anchors and auger cast piles). Local practices, economy, available equipment, and site access generally control the selection of foundation alternatives for projects in sensitive environments.

This guideline presents a great deal of information, options, and alternatives that must be assessed to select the optimal foundation alternative in sensitive environments. Organizing this information is critical to performing logical assessments that arrive at the best foundation alternative for a project. A rational step-by-step model is presented where information is organized, and numerical values are assigned to criteria for each foundation option.

Keywords:
Foundations, Transmission, Sensitive, Environment, Design, Mitigation

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EXECUTIVE SUMMARY

This report is a best practices guideline for evaluating and selecting appropriate transmission line foundations with the least impact to the environment. The scope incorporates decision making processes that aid in the selection of foundation alternatives which best meet the economic, engineering, and environmental needs of the project. This work includes a review of the literature and a case history summary to identify the standard of practice, the range of alternative design solutions, and the real-world remediation techniques for various environmental conditions.

Case studies illustrate industry trends and highlight types of foundations installed in difficult environments. Twenty-six documented case studies were reviewed for this report, representing sensitive environments classified as wetlands/waterways, mountainous/rough terrain, permafrost/frozen ground, woodlands, conservation/wilderness areas, and desert/rangeland. Traditional foundations are used to support transmission structures in just under 40 percent of cases, with access controls used to mitigate construction environmental impacts. Most studies demonstrate the use of alternate foundation designs (e.g. micropiles, vibratory caissons, and helical piles) along with minimally invasive access methods (helicopters, barges, boats, marsh buggies, light/small equipment, etc.). Of the nineteen unpublished cases received through solicited surveys, nearly 85 percent of respondents indicated a preference for construction mitigation measures over the use of alternative foundation types (improved access or modular matted paths). Alternative access methods such as hauling in equipment by hand, improving the ground with stabilizers, and the use of helicopters are less common.

Wet environments can result in foundation construction access restrictions, due to the presence of both near surface water and open water. Since these environments are home to many plant and animal species, construction will likely be seasonally limited, and include pre- and post-construction mitigation. Foundation construction may include constraints or mitigations for drilling debris, machinery fuel, and sediment turbidity. Access will likely need to be improved to compensate for weak surfaces; otherwise equipment will need to be delivered to sites by boat, air, or crane.

The environmental conditions of rough terrain regularly include highly variable topography (often deeply incised with steep slopes). Mountainous regions pose unique access considerations due to their remoteness and climatic extremes. Mountain forests tend to be classified as conservation areas and often have access restrictions related to the seasonality of flora, fauna and fire risk. Subsurface conditions tend to be dense or hard, and require special tooling/equipment for foundation installation. If roads cannot be built, few options exist for foundation construction in rough terrain. Small diameter (micropile) foundation drilling equipment is often mobilized to sites by helicopter. Otherwise, foundations may need to be constructed by hand with small-size portable equipment using low volumes of materials moved near structure sites via 4-wheeled vehicles, ATVs or carried to sites by construction workers.

Over half the land in the Northern Hemisphere seasonally freezes and thaws. Non-seasonal frozen ground, regions of permafrost, and permanently frozen tundra encompasses the extremely high latitudes and high altitudes of the world. Frozen ground is seasonally dependent, and affects scheduling, access, and construction. In areas of discontinuous permafrost, access may be limited to frozen periods, as the locations may become wetlands or bogs during the warmer seasons. The major environmental impact to installing foundations in frozen ground environments is land disturbance caused by accessing sites. During periods of thaw, the subsurface is weak and

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susceptible to inundation, making access with heavy machinery difficult. In extreme cases, snow and water are used to build "ice roads" or "winter roads" to support machinery. Transmission line tower types located in frozen ground regions are designed to reduce foundation size and limit ground disturbance. These tower structure foundations typically include down guys as a means to reduce the foundation footprint and environmental impact.

Most projects include a carefully thought out construction access plan to minimize impacts in all environments, with special emphasis on sensitive environments and steep/rocky terrain. Foundation construction equipment must be able to access transmission line structure sites, and operate within a sufficient footprint to safely accommodate drill rigs, erection cranes, and workers. It should also allow for the delivery of foundation materials. These plans should be specific to the final selected structure and foundation design alternatives.

Foundation construction environmental impact mitigation allows for the assessment of practices resulting in the most desirable combination of available options. These options include avoidance, activity minimization, and selective protection at sensitive sites. During project planning, various types of environmental evaluations are prepared, including accepted best practices for reducing impacts. Access practices commonly used as mitigation include ungraded paths, matted drives, spur road construction, and frozen ground. More costly mitigation strategies include temporary geotextile drives, the creation of temporary ice roads, and manual construction. In areas where ground access is not permitted, alternative access to structure sites by air or water may require the use of helicopeters, marsh buggies, or barges.

The type of foundation selected for a project can positively influence construction schedules and environmental impacts by providing alternative methods for construction in less than desirable situations, or negatively affect these same elements due to the nature of the equipment, placement, or materials. Some foundation types require a more extended schedule to account for the design and fabrication of the material elements, while other options can be readily purchased and constructed. To help mitigate environmental impacts, foundation construction schedules must account for the time needed to design, fabricate and build foundation elements. Rapid and efficient foundation construction reduces environmental exposure and the scope of mitigation.

Engineers have a wide array of tools and techniques for founding transmission line structures. Conditions, economy, available equipment, and site access drive construction means and methods. The most common foundations (traditional), along with less frequently used (alternate) foundation systems, are presented in terms of the advantages and disadvantages inherent to each system. These systems are then considered in relation to design and construction processes in sensitive environments. Traditional foundation systems discussed include driven piles, drilled shafts, direct embedment poles, steel grillages, spread footings, and anchored structures. Alternate foundation systems presented include helical anchors/piles, vibratory caissons, micropiles, rock sockets with anchors, and auger cast piles. A brief discussion of underground installation via horizontal directional drilling is given as this method is an alternative to foundations (in addition to structures).

Descriptions of foundation systems, along with design methodologies and models, are given in general form to provide an understanding of the information needed to design and construct. Equations for foundation design are reported without safety or resistance factors, in order to illustrate model relationships. Depending on design approach (reliability-based or allowable stress), resistances must be reduced as appropriate. ***The engineer's final design must include these***

factors to ensure proper foundation performance. This report should not be considered as a design manual, as details of design are intentionally omitted, guiding the reader to more comprehensive texts. Its purpose is to present foundation options and models for various transmission structure types and their use in sensitive environments. Direction is provided for selecting the most advantageous option(s) for a particular situation.

For any given site, environment, and condition, multiple foundation options can be used to either support transmission line structures or span a sensitive or difficult environment. The project owner and its engineers, therefore, have the challenge of selecting one or more feasible and economical option for further consideration and design. Organizing this information is critical to performing a logical assessment that arrives at an economical foundation alternative for a project producing the least environmental impact. A rational model is presented in the form of flow charts and decision matrices via a step-by-step process in which criteria is ranked. Predicted outcomes allow the designer to select one or more option with the highest likelihood of successfully meeting project goals.

There is an element of subjectivity in evaluating foundation options via the use of flowcharts and tables. Flowcharts provide defined values for ranking each factor and criteria, but must be used in conjunction with comparative summary foundation information regarding each foundation option discussed herein. For a particular project the designer may decide that a given criterion has more importance in the final decision process. Many codes include importance factors as a way to mitigate higher risks or protect lives and property. Similarly, importance factors are provided to customize the foundation selection process for a given situation. When used together, these tools provide an excellent base for making good decisions for selecting foundation system that least impacts a particular environment.

This process is best used on a project-by-project basis to take into account unique regional or local variations in the availability of equipment, contractors/constructors, materials, transportation and economics for difficult environments. Examples are given to demonstrate the decision making process for various environments. Once foundation options are narrowed to those that are feasible and produce the least environmental impact, the designer can either perform more detailed cost and scheduling (risk) estimates to compare feasible methods or bid to contractors.

NOTATION

This guide document deals with the technical aspects of multiple, often independent, bodies of knowledge, including: geology, geophysics, civil engineering, geotechnical engineering, structure engineering, electrical engineering and other specialized scientific, engineering, and construction disciplines. As such, it is inevitable that the accompanying equations will have overlapping variable definitions. For example, in several cited references, the letter N might refer to blow count, bearing capacity factor, number of samples, etc.

Ideally, new variables or subscripts will be introduced to remove the overlap. However, this approach presents challenges, as these individual variable names are standard in a particular specialty; and renaming them makes conducting outside research challenging for the reader. Hence, when it seems to make sense, the variables of the equations within are changed to prevent overlap. Otherwise, they are left in industry standard form. Regardless of the final decision, every variable used is defined with associated units just before or after every equation is presented and indicated in the following notation section.

REFERENCES

In the interest of providing useful information, some liberties are taken when it comes to citing literature. Thus, when cited materials are better-known by their title than by their author (such as the Standard 691), the title is used as opposed to the authoring institution (i.e., IEEE 2001). Unless otherwise noted, the latest version of these standards is used. Regardless of the citation method adopted, the works cited included at the end of each section contains the full reference.

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GLOSSARY

Term	Definition
Alternative Foundations	Less common foundation types used to support transmission line foundations: vibratory steel caissons, auger cast piles, helical anchors/piles, micropiles, rock sockets/anchors, underground transmission lines.
Anchored Structures	Structures primarily supported by guy wires to provide required lateral stability.
Construction Controls	Installation processes including schedule, expertise, machinery, materials, and mitigation methods.
Cost and Risk	Uncertainty in foundation design, construction, and reliability that affect scheduling.
Criteria	The environment dependent factors and impacts of a foundation alternative, including design considerations, site access, and construction controls.
Design Considerations	Includes line design, structure location, subsurface investigation, avoidance, logistics, and foundation design.
Drilled Shaft	A round shaft excavated into the subgrade. The shaft is later filled with either reinforced concrete, or receives the base section of a steel, wood or concrete pole (with the annulus spaced then backfilled).
Environment	Includes the geographic area of a transmission line including both right of way and access requirements that may impact flora/fauna, geology, water resources, cultural sites and aesthetic setting.
Embedment	The portion of a foundation that extends below the ground surface that transfers structural loads to the surrounding soil.
Foundation	A subsurface structure used to support transmission structures.
Geotechnical Investigation	An assessment of subsurface conditions including geological, physical, and structural considerations by a certified geotechnical engineer or engineering geologist.
Grillage	Steel beams provided in single or double crossing tiers and connected to lattice tower legs as a foundation support.
Load	Forces exerted on a structure of foundation, including vertical dead load, wire tension load, wind loads, hydraulic loads and ice loads.
Load Factors	The load and strength factors multiplied with nominal loads to account for uncertainties in load and load analysis models. These factors may or may not be related to a probability of event occurrence.
Mitigation	Construction practices that minimize and reduce environmental impacts.
Frost Heave	During a freeze cycle, ice pressure causes swelling of overlying soil; During a thaw cycle, overburden soil can collapse.
Frozen Ground	Soil at or below the freezing point of water on a seasonal basis.
Permafrost	Soil at or below the freezing point of water for two or more years.
Pier	A relatively short foundation element in comparison to its width with a design-specific shape & size which provides lateral and axial load resistance.
Pile	A relatively long foundation element, slender column & a design-specific shape & size providing load resistance primarily by side friction and/or end bearing.

Term	Definition
Rank	The result of the decision matrix calculations, indicating the feasibility of foundation alternatives for a given environment.
Reveal	The portion of a foundation that extends above the ground surface and connects to the structure base to meet various operational and maintenance conditions (stick up).
Right of Way (ROW)	Public land authorized to be used or occupied pursuant to a right of way grant. A right of way grant authorizes the use of land for construction, operation, maintenance and the termination of a project.
Rough Terrain	Encompasses areas of variable ground elevation such as mountains, steep slopes, and uneven ground surfaces including woodland and open range regions.
Sensitive Environments	Environments that are evaluated during environmental impact statements or environmental assessments as having negative impacts associated with foundation accessibility, construction, and serviceability.
Shallow Foundation	A pier or abutment footing that transfers load vertically to the earth.
Site Access	Access requirements imposed on sensitive environments that limit pathways, transportation methods, and construction practices to get to a foundation site.
Traditional Foundations	Commonly used foundation types to support transmission line foundations: driven piles, drilled shafts, direct embedment, grillage foundations, spread footings, guy anchored structures.
Transmission Lines	Power lines used to conduct electricity between two or more substations.
Wet Environment	Encompasses areas inundated with water (seasonally or continuously) such as wetlands, estuaries, waterways, coastal areas, and flood plains.

SYMBOLS

Variable	Definition	Unit
a, b	coefficients from best fit regression curves (dimensionless)	-
A_1	Area of the conical failure surface of the half truncate cone	m^2
A_2	Area of the vertical failure plane at the center of the footing	m^2
A_3	Area of the horizontal plane at the bottom of the anchor bars	m^2
A_{bar}	Cross sectional area of steel reinforcing bar	m^2
A_{Base}	Area of the grillage base	m^2
A_{casing}	Cross sectional are of steel casing	m^2
A_{cone}	Area of the conical failure surface of the truncate cone	m^2
A_g	Area of grout in micropile cross section	m^2
A_h	Area of helix plate	m^2
A_l	Area of the bottom helix	m^2
A_T	Area of the top helix	m^2
$(A_{lat})_i$	Lateral bearing area of the i^{th} member	m^2
B	Pile or shaft diameter	m
B_A	Width of loaded area	m
B_f	Base width of footing pad/mat	m
B_h	Diameter of helix plate	m
c	Cohesion of soil	N/m^2
c'	Effective cohesion	kPa
c_h	Cohesion at helix depth	N/m^2
c_u	Undrained shear strength	kPa
C	Instant pile top displacement	m
CL	Center line (dimensionless)	-
C_c	Compression index of clay (dimensionless)	-
d	diameter of a circle circumscribed around the shaft	m
d_b	Diameter of anchor bar	m
d_{eff}	Effective shaft diameter	mm
d_h	Diameter of drilled hole	m
D	Pole diameter	m
D_{AVG}	Average diameter of helical bearing plates on a given pile	m
D_b	Diameter of the drill hole	m
e_d	Eccentric distance	m
e	group efficiency (dimensionless)	-
e_o	Initial void ratio of clay stratum (dimensionless)	-
e_h	Hammer efficiency	%
E	Foundation Modulus of Elasticity	N/m^2
Ep	Pressuremeter Modulus	MPa
f_{bu}	Ultimate bond strength between tendon and grout	N/m^2
f'_{cg}	Unconfined compressive strength of grout	N/m^2
F_a	Allowable axial stress that would be permitted if axial force alone existed	N/m^2

Variable	Definition	Unit
F_b	Allowable bending stress that would be permitted if bending moment alone existed	N/m^2
F_b	Area under the micropile base	m^2
F_y	Yield stress of steel	N/m^2
F'_e	Euler buckling stress	N/m^2
h	Height of fall of ram	m
H	Length of shaft above the top helix	m
I_w	Shape factor (dimensionless)	-
K_H	At-rest earth pressure coefficient (dimensionless)	-
K_t	Empirical torque correlation factor	m^{-1}
L	Length of pile or shaft	m
L_a	Lever arm for the force-couple	m
L_{AB}	Anchor bar bonded length	m
L_B	Pile embedment depth into the bearing stratum	m
L_b	Bond length	m
L_f	Base length of footing pad/mat	m
L_P	Total length of pole	m
L_S	Length of pile developing side shear	m
M	Applied moment at groundline	kN-m
n	Coefficient of restitution (dimensionless)	-
$(n-1)_s$	Length of soil between the helices	m
N	Normal force at the grillage	N
N	Criteria factor modifier	-
N'	Average corrected SPT resistance value along the embedded pile length	Blows/m
N'_B	Average corrected SPT resistance value of the bearing stratum	Blows/m
N'_o	Average corrected SPT resistance value for the stratum overlying the bearing stratum	Blows/m
N_c	Cohesion factor (dimensionless)	-
N_γ	Weight factor (dimensionless)	-
N_γ, N_q	Average of bearing factor N_γ and N_q (dimensionless)	-
N_q	Surcharge factor (dimensionless)	-
p_U	Ultimate unit stress under the micropile base	N/m^2
P_B	Bearing resistance force	kN
P_b	Ultimate bearing capacity	N
P_c	Applied vertical load at footing base	N
$P_{c\text{-allowable}}$	Allowable compression load	N
P_G	Ultimate geotechnical bond capacity	N
P_T	Applied vertical load	kN
$P_{t\text{-allowable}}$	Allowable uplift load	N
q	Surcharge pressure	N/m^2
q'	Effective vertical overburden stress at helix depth	N/m^2
q_b	Nominal end bearing	kN
q_{bn}	Nominal bearing pressure of grillage	N/m^2
$q_{c,\,max}$	Maximum applied unit bearing pressure	N/m^2

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Variable	Definition	Unit
$q_{c,\ min}$	Minimum applied unit bearing pressure	N/m^2
q_{pu}	Unit end bearing resistance value	kPa
q_s	Nominal unit side resistance	kN
q_{si}	Unit skin resistance value	kPa
q_{ult}	Unit bearing pressure	N/m^2
q_{ult}	Unit bearing pressure	N/m^2
q_c	Ultimate unit bearing resistance capacity	N/m^2
q_o	Average effective overburden pressure	N/m^2
Δq	Average change in pressure in stratum due to applied load from the footing	N/m^2
Q_c	Ultimate compressive capacity	kN
Q_u	Ultimate uplift capacity	kN
Q_b	Ultimate end-bearing resistance, capacity	kN
Q_s	Ultimate side shear resistance	kN
$Q_{lat,uD}$	Lateral bearing capacity under uplift forces	N
$Q_{lat,cD}$	Lateral bearing capacity under compression forces	N
$(q_{lat,n})_i$	Nominal lateral bearing pressure of the backfill material for the i^{th} member	N/m^2
S	Total settlement	m
S_2	Mobilized unit shear resistance on the conical failure surface	N/m^2
S_1	Mobilized unit shear resistance at vertical and horizontal force shear planes	N/m^2
S_c	Long term settlement due to consolidation settlement	m
S_i	Immediate (elastic) settlement due to elastic deformation	m
$s_{u,\ base}$	Undrained shear strength of the base material	N/m^2
T	Final installation torque	m-N
T_i	Ultimate load by an untensioned individual anchor or design load for a tensioned individual anchor	N
T_A	Anchor tensile force from overturning applied to the anchor group	N
T_R	Uplift resistance of the rock anchor group	N
V_{ss}	Total side shear force	N
V_T	Applied shear load at groundline	kN
W	Foundation weight	N
W'_{bf}	Effective weight of the backfill material	N
W_{cone}	Weight of the truncated rock anchor group mass uplifted	N
W_p	Weight of pile including weight of pile cap, driving shoe, and capblock	N
W_r	Weight of ram	N
W_R	Weight of uplifted rock	N
Y	Displacement at groundline	m
z	Design embedment depth	m

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Variable	Definition	Unit
α	Empirical side shear reduction factor (dimensionless)	-
α_c, α_ϕ	Cohesion and friction reduction factors	kPa
α_s	Adhesion between the soil and the shaft	N/m^2
α_{bond}	Grout to ground ultimate bond strength	N/m^2
λ_k	Fitting factor	$mm^{0.92}/m$
ϕ	Soil friction angle	Degrees
ϕ'	Effective friction angle	Degrees
f_a	Axial stress	N/m^2
f_b	Bending stress	N/m^2
γ	Unit weight of soil	N/m^2
γ_t	total unit weight of soil/rock	g/cm^3
γ'	Effective unit weight	kN/m^3
σ'	Average vertical effective stress	kPa
T	Soil shear strength	N/m^2
τ_{allow}	Ultimate bond strength between grout and rock, or c, whichever is less	N/m^2
λ_k	Fitting factor	1/m
μ	Poisson's ratio for soil (dimensionless)	-

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Electric power transmission lines are often located in remote regions and environmentally sensitive areas that place accessibility, construction, and serviceability constraints on the work. Utilities worldwide have identified the environmental impacts of the construction of transmission line foundations, but the evaluation of various traditional and unique foundation design alternatives is not straightforward or directly cost comparable, due to local differences in environment, equipment and material availability, and subsurface conditions. Proprietary methods for alternate foundations also create difficulties in design and contracting work, limiting competitive bidding, and resulting in reduced use of more appropriate and cost effective methods in sensitive environments.

This report seeks to identify transmission line foundation technologies used in sensitive environmental conditions, and makes recommendations for best practices regarding both design and selection practices that minimize impacts. This report intends to act as a useful guide, helping utilities to:

(a) Identify factors and processes related to transmission line foundation design and construction in environmentally sensitive areas;

(b) Assess the environmental impacts of various transmission line foundation designs and other factors involved in foundation construction in sensitive environments;

(c) Understand the application and use of various traditional and alternate transmission line foundation technologies;

(d) Compare the environmental effects, remediation needs, and costs of various transmission line foundation options; and

(e) Apply information to select, specify, and contract various alternative transmission line foundation design alternatives located in environmentally sensitive areas.

Geotechnical investigations are performed as part of the foundation design process to determine in-situ material properties of the subgrade, and to allow efficient and economical design. Drilling and sampling is often performed in advance of reasonable access to remote sites and prior to environmental clearances in sensitive areas. Many times these areas are excluded from the investigation process, lending to increased uncertainty and time spent during construction. This guide presents methods used by utilities to obtain geotechnical data, using low impact and non-intrusive methods in evaluating foundation design. Best practice recommendations are provided.

To better guide engineers and designers in the use of this report, flow charts and decision matrices are presented to address specific design scenarios, directing the user to the appropriate section of the document where detailed analysis is shown. Additionally, example cases are provided which guide the user through the selection processes within the report.

1.1 Methodology

1.1.1 Study Approach

The study approach focused on the review of literature related to transmission line and related foundation design and construction in sensitive and difficult environments. There is a sufficiently large body of published literature, allowing the authors to be selective in their identification of better case histories that provide more comprehensive information. The published case histories have been supplemented with survey results from those in the transmission line design community with personal file case information.

Work was divided into five general tasks:

1. Review of published and unpublished case histories to ascertain the state of the practice;
2. Review of environmental factors, impacts, and mitigations associated with foundations;
3. Review alternatives related to constructing foundations in sensitive environments;
4. Review of traditional and alternative foundation design practices and methods;
5. Compare and contrast all relevant information to aid in the selection of optimal foundation alternatives.

This task work was primarily performed via a thorough review of the literature, along with extracting data in company files of examples of alternative foundation design and construction. The literature reviewed examined a wide range of sources, both domestic and international, on information related to transmission line foundation construction in sensitive and difficult environments. Team members principally used electronic databases, supplemented with an extensive network of specialty foundation contractors, transmission line structure vendors, and other design firms. Other sources researched included technical reports, national and regional foundation design and electrical system standards, and publications created by governmental organizations.

The initial literature review resulted in the development of an annotated bibliography (**Appendix A**) used to understand the breadth and depth of published case histories, and give direction to continued report development. The annotated bibliography is divided into the following sections (number of articles in each section noted in parentheses): Regulatory Constraints (7); Mitigation and Remediation Methodology (10); Site Access and Alternatives (12); Alternative Foundations (18); and Foundation Design and Contracting (12). As the research work continued, more than 90 additional reference documents, technical publications, and related articles were reviewed for inclusion in this report.

To supplement published literature, the research team surveyed selected utilities and utility consultants to gather unpublished case history information regarding transmission line foundations susceptible to various environmental conditions. In addition to the CEATI affiliated utilities, 86 individuals were contacted to receive survey forms via email. 19 responses were received over a four-month period. 18 of the responses included relevant case history information. The survey request forms are shown in **Appendix B**.

1.1.2 Information Analyzed & Analysis

Information from the literature review and industry surveys conducted was evaluated with an applied research approach in mind. The goal of the report is to produce a practical, best practice guide. Case history review includes both large and small-scale projects, including foundation design and construction from designer, owner and contractor perspectives. The research team recognizes low survey response in that only 19 of 86 potential participants responded to the request. 27 additional published case histories help supplement unpublished data from designer files and provide a substantial archive of projects for analysis. The selected published and unpublished case studies illustrate industry trends, and highlight details in relation to foundation impacts in difficult or sensitive environments.

The team reviewed literature and case histories recognizing the variety of climate conditions and geographical situations of CEATI utility members, as well as an understanding of where transmission lines are constructed. It should be recognized that the archived information has a definite North American flavor, with only 2 case histories and 1 survey from outside of the continent. Although the data tends to be concentrated in one region of the world, the climates and environments represent a broad cross-section of conditions expected in sensitive environments.

The case history review is utilized to group sensitive environments into three general categories: wet, rough and frozen. This importantly enables a comparative ranking of the various criteria that can be used to evaluate traditional and alternative foundations in several conditions, thus facilitating the selection process. Supplemental categories are addressed in discussions regarding other sensitive environments, encountered outside of the three general categories. **Section 7** of this report recognizes this variation and accommodates by adding a generic category to capture difficult environments that are not controlled by wet, rough or frozen conditions.

Lastly, the criteria used to assess foundation types are divided into three major groupings: site access, construction considerations, and design considerations. Review of the case histories and past practices by others indicate that these categories are either intuitively or intentionally used in the foundation selection process. The report sections evaluate the factors and impacts of the elements that comprise each criterion.

1.1.3 Report Organization

The report is divided into the following major sections:

- Case Histories (**Section 2**)
- Environmental Impacts of Foundations (**Section 3**)
- Mitigations (**Section 4**)
- Access Alternatives (**Section 5**)
- Foundation Alternatives (**Section 6**)
- Foundation Selection (**Section 7**)
- Examples (**Section 8**)
- Conclusions and Recommendations (**Section 9**)

This format is organized to build on lessons gained through previous experience, and concludes with recommendations for the evaluation process. **Section 2** provides an exploratory tool to identify the standard of practice, the range of alternative design solutions, and real-world remediation techniques. Presented is the breadth of environmental conditions encountered and solutions used by the transmission line industry for design and construction of transmission line foundations in environmentally sensitive areas. **Section 3** categorizes the sensitive environments found worldwide relating to transmission line siting. The discussion details environmental factors and impacts affecting transmission line foundation construction in wet environments, rough terrain, and frozen ground. **Section 4** identifies the various environmental strategies, studies, and planning involved in the design and construction of foundations for electric power transmission lines, which result in the

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most desirable combination of available options. Mitigation options in relation to foundation design and construction are presented. **Section 5** discusses construction considerations related to site access for foundations in sensitive environments. Plans must be developed to bring equipment, materials and workers to the line and structure locations that heavily influence foundation design alternatives. Access alternatives range from standard roads to more exotic air and water transports. Foundation design alternatives are summarized in **Section 6**. The most common foundation methods are presented along with the most widely available alternate foundation systems. Foundation types are presented in terms of advantages and disadvantages inherent to each system, and in relation to design and construction difficulties in sensitive environments and contexts. This section of the report should be considered a design primer and not a design manual, as necessary details of design are intentionally omitted and the reader is guided to more comprehensive texts.

Section 7 synthesizes information developed in the previous sections, and offers a decision-making framework for selecting economical foundation systems that have the least impact upon the environment. A rational model is presented in the form of flow charts and decision matrices. The flow charts are intended to be read as road maps which guide the designer through processes, referencing back to report sections for more detailed information. The decision matrices are a specific component of these charts that provide a quantitative aspect in the assessment process. **Section 8** applies the model to examples that illustrate the evaluation and decision making process. These examples are meant to aid in guiding the designer through best practices for selecting foundations with the least impact upon the environment.

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2.0 CASE HISTORIES – LESSONS LEARNED

Case studies provide an exploratory tool to identify the standard of practice, the range of alternative design solutions, and the real-world remediation techniques. This report reviews the published literature and presents industry survey results to identify the breadth of environmental conditions encountered, and the solutions used by the transmission line industry for the design and construction of transmission line foundations in environmentally sensitive areas.

2.1 Literature Review

The intent of the literature review is to offer a thorough examination of published case histories within the power utility sector. Case studies are selected based on their completeness, illustrating industry trends and highlighting details in relation to foundations installed in difficult environments. **Table 2-1** gives a summary of published case history scope, in terms types of difficult environments, line structures, and foundations included in this report

Twenty-seven documented case studies were reviewed (**Table 2-1**). The majority of case studies represent sensitive environments classified as wetlands/waterways (60 percent). Of the documented case studies, the majority consisted of lattice tower (38 percent) and monopole (40 percent) transmission line structures. Only a few published cases indicate the use of traditional foundation design (e.g. drilled shaft, grillage, direct embed) (38 percent). The majority of cases illustrate the use of alternative foundation design (e.g. micropiles, vibratory caissons, and helical piles) (83 percent). Most cases present only one foundation type per transmission line, though a few indicate different structure types and foundations across the same transmission line project (23 percent).

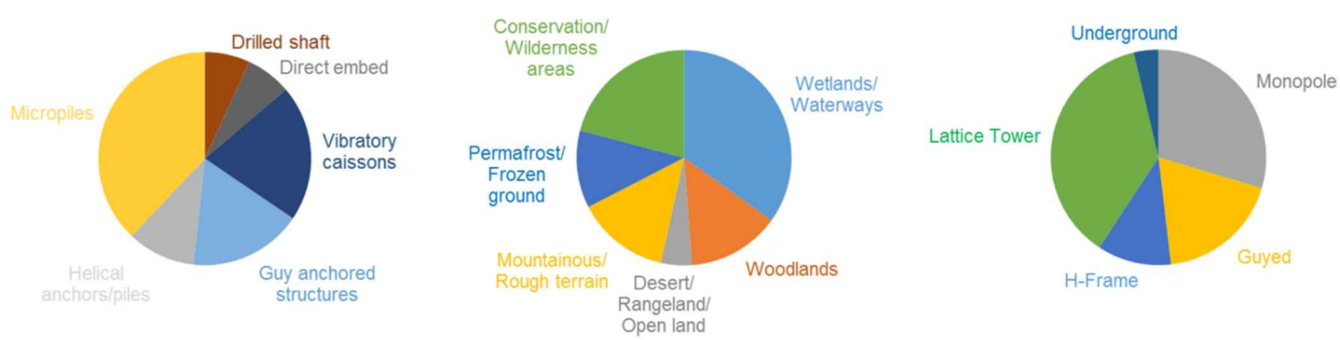

Figure 2-1: Distribution of Environments, Structures, and Foundations in Published Case Studies.

Table 2-1: Summary of Published Case Histories.

Case	Location	Environment	Line Voltage	Structure Type	Foundation Type	Access	Issues Encountered	Source
1	Angeles National Forest, California	Conservation area; Mountainous terrain	500 kV	Lattice tower	Micropiles	Access roads not permitted, Helicopter only	High winds, fog affected visibility, fire risk, variable depth to bedrock, workable days limited due to heat	(Chen & Salisbury, 2012)
2	Middletown, Connecticut	Rough terrain; Wetlands; Conservation area	345 kV 115 kV	Monopole	Drilled shaft; rock socketed drilled shafts	Restricted access	Schedule, drilling into rock, structure relocation during final design, permitting, amount of spoils, wetland disturbance, mobilization issues, foundation redesign for as-drilled rock conditions, alternative designs considered including anchored mats, crane mounted drilling equipment; minimized disturbance in wetlands	(McCall, et al, 2009)
3	Snohomish County, Washington	Wetlands; Waterways; Industrial area	115kV	unknown	Vibratory Caisson	Helicopter only	Cost-effectiveness and schedule, access, multiple sensitive environments including a superfund site, wetland areas, tribal land, river crossings. Traffic control was needed near highways, alternative fuel used for caisson hammer; barge crane used for water installs	(White, & Eisinger 1997)
4	Alaska	Permafrost/frozen ground	230kV	guyed X-towers; self-supporting Y-towers; Swing-set towers	Driven piles, Rock anchored guys	Vehicle/helicopter, limited to frozen ground for ice roads	Cost-effectiveness and schedule, access, various temperature, distinct geographic areas, pile damaged during installation, limited alternative foundation knowledge of contractor; subarctic conditions.	(Wyman, 2009)
5	Port Arthur, TX	Wetlands; Industrial area	230 kV double circuit	Steel single pole	Driven steel caisson	Helicopter only	Wildlife restrictions; requirement for hurricane loadings; restricted access; Coastal salt marsh conservation area	(Williamson, & Rowland 2009)
6	Berwick, Pennsylvania	Wetlands	230 kV 500 kV	lattice towers, monopoles	Micropiles	Helicopter only; restricted seasons	Priority wetland of Troy Meadows a freshwater marsh; project initially designed for drilled shaft foundations; variable and unknown depth to bedrock; access restrictions due to endangered wildlife	(Davidow, 2015)
7	San Diego, California	Rough terrain; Conservation area	500 kV 230 kV	lattice tower	Micropiles	Helicopter only; restricted season; remote location	scheduling delayed due to permitting; speed of construction; carbon footprint of helicopter use; variable depth to bedrock; variable elevations, national forest,	(Salisbury & Davidow, 2014)

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Table 2-1: Summary of Published Case Histories (continued).

Case	Location	Environment	Line Voltage	Structure Type	Foundation Type	Access	Issues Encountered	Source
8	Southern California	Conservation area; Rough terrain	500 kV 220 kV	Y-structure	Drilled shaft	Restricted access	Remote rough terrain, high wind issue for helicopters, sensitive plant and animal species, safety considerations for remote locations; National forest	(Johnson & Gerling, 2011)
9	Maryland	Wetlands; Conservation area	138 kV	Steel monopole	Caisson/ anchor bolt	Within existing ROW	identify impacts to wetlands, species, forests, green infrastructure, vegetation management; National forest	(Gill, 2014)
10	St. Andrew Bay, Florida	Wetland/waterway	115 kV double circuit; 4 kV	Steel single pole and H-frame/ Lattice tower/ underground	Vibratory caisson	Barge only	Span and clearance for barge traffic; shoreline stabilization; Height restriction from Federal Aviation; sea life restrictions to work; nesting season restrictions; erosion prevention; considered different structure types with different foundations;	(Shanmugasundaram, 2009)
11	Lake Fork, Texas	Waterway	138 kV	Concrete monopole	Vibratory caissons with concrete fill	Barge/boat	Working in deep lake; clear channels for boating traffic; limiting number of structures; fish habitat preservation; cultural restrictions for construction period; evaluated jetting and vibratory caissons	(Norman, 2009)
12	San Jose, Costa Rica	Conservation area; Wetland	230 kV	Lattice tower	Helical pile system	Restricted access	Poor soil would result in large floating found; not permitted to cut any trees; long span required to minimize disturbance, wet soggy soil	(CHANCE, 2014)
13	Ontario, Canada	Permafrost/frozen ground; Wetland	500 kV	"V" Towers with guys	Helical pile system replaced grillage	Restricted access	Used helical piles to retrofit existing grillage foundations, which reduced access issues for earthmoving equipment. Left grillage in place and added new foundation attachment to structure. Frozen marsh land.	(Hudspeth, 2008)
14	Roanoke, VA	Wetland	500 kV	Lattice tower	Helical pile system with anchors	Restricted access	Peat marsh; environmental regulations in estuary, peat and organic marsh result in highly compressible soil, limited equipment	(Rodgers, 1987)
15	Bismarck, North Dakota	Frozen ground	230 kV 115 kV	Substation	Piers	Restricted access	Restricted outages, frost heave, frozen ground	(Milbradt & Vasbinder, 2011)

Table 2-1: Summary of Published Case Histories (continued).

Case	Location	Environment	Line Voltage	Structure Type	Foundation Type	Access	Issues Encountered	Source
16	Morristown, New Jersey	Wetlands	500 kV	Steel monopoles	Micropiles	Restricted access	Deep bedrock with wetland and saturated conditions in Troy Meadows	(Davidow, 2015)
17	NW Transm. Line, British Columbia, Canada	Wetland; Frozen ground	287 kV	Lattice towers, guyed towers	Micropiles	Helicopter only	variable depth to bedrock; variable rock quality in field; unexpected field conditions; frozen ground	(Davidow, 2015)
18	Spokane, Washington	Conservation area	500 kV	Lattice tower	Micropiles	Minimal land disturbance required	limited geological analysis, design in field; National forest	(Chen & Salisbury, 2012)
19	Seattle, Washington	Conservation area; Waterway	500 kV	Lattice tower	Micropiles		First major implementation of micropiles; protected watershed	(Thompson et al., 2009)
20	Southeast Alaska	Frozen ground	138 kV	Y, H, guyed 3-pole, guyed A frame	Micropiles	Helicopter only, limited seasonal window	limited foundation construction schedule, soft ground	(Thompson et al., 2009)
21	San Diego, California	Rough terrain	230 kV	Steel monopole	Micropiles	Restricted access	restricted access, environmental restrictions, noise control	(Thompson et al., 2009)
22	Marysville, Washington	Wetland	230 kV	Steel monopole	Micropiles	Restricted access	Estuary; limited access required specialized transport equipment	(Thompson et al., 2009)
23	Los Angeles, California	Conservation area	500 kV	Lattice tower	Micropiles	No roads permitted, limited work season	limited access by workable days controlled by temperature, humidity, wind and fire danger, national forest	(Thompson et al., 2009)
24	Hanford, Washington	Industrial area	N/A	Underground	Horizontal drill	Restricted access	alluvial soils with large cobbles/boulders, containment berm	(DTD, Inc., 2009)
25	St. George Island, Florida	Waterway; Conservation area	115 kV	Concrete monopole, h-frames, pyramid structures	Steel vibratory caissons with temporary protection	Matting, barges, helicopter	Regulatory permitting; shellfish disease; hurricane season, marine, intercostal waterway, natural resources, endangered animals, salt marsh	(Richardson & Bennett, 2012)
26	Amazonas, Brazil	Wetland; Conservation area	500 kV	Lattice towers	Driven piles	Barge only	Difficult, remote access in rainforest; limited access window during rainy season, different geology in field	(Beim, et al, 2014)
27	Phoenix, Arizona	Desert; Rough terrain; Conservation area	230 kV	Lattice tower replacements	Micropile	Restricted access; Helicopter sites	Limited access along alignment; tourism and recreation area; environmental restrictions; dust issues; limited subsurface investigation	(DGA, 2016)

2.1.1 Standards of Practice

The published case studies represent transmission line projects constructed in sensitive environmental settings. The research pinpointed several transmission line environmental assessments, in which avoidance was identified as the primary option for mitigating sensitive environmental impact, via: rerouting rights of way (ROW), increasing span lengths, or implementing other avoidance procedures. A brief sampling of published environmental assessments and permit reports indicate that rerouting transmission lines away from sensitive environments is the primary worldwide design choice (AEP, 2006; CEB, 2010; Chau, Pugh, & Kennedy, 2009; CL&P, 2013; Duncan, 2010; MEG, 2011; PSCW, 2013; ERM, 2005). However, in these reports, alternate foundation design options are not considered.

Issues identified in the published case histories include logistical challenges, access limitations, and construction difficulties (**Table 2-2**). Aspects outside typical construction considerations include impacts to the local economy, aesthetic considerations, carbon footprint, traffic control, "green" infrastructure, and population resettlement.

Table 2-2: Types of Issues Encountered in Published Case Studies.

Access	Design Considerations	Construction Controls
• Weather/climate limits to working days	• Mobilization for specialized materials	• Redesign for actual geologic conditions
• Plant and animal disturbance	• Safety considerations for remote locations	• Contractor qualification
• Regulatory constraints and permitting	• Specialized equipment	• Alternative structures and foundations
• Helicopter-only access	• Schedule	• Limited geologic information
• No roads/Remote sites		• Alternative fuels
		• Noise limitations
		• Restricted outages

The published case studies demonstrate that a balancing of cost, schedule, safety and environmental impacts is required. Published best management plans are difficult to obtain and often copyrighted (i.e. Salisbury & Davidow, 2014). Avoidance practices are often incorporated within standards (i.e. Cibulka, 2012; CL&P, 2013; PSCW, 2013; Williams, 2003). Williams (2003) outlines international best practices, focusing on ROW rerouting to avoid environmentally sensitive areas, highlighting the need to integrate detailed environmental data with project design.

Requirements for construction in environmentally sensitive areas is typically driven by local, regional or national regulatory agencies (no standard industry practices were evident in the review). Published case histories identify general industry trends. Regardless of environmental setting, foundation construction cost and installation time are controlling factors for foundation type, selection, and construction technique. The allowable time for construction is affected by outage scheduling (Wyman, 2009), workable days (Thompson et al., 2009), material availability (McCall, et al, 2009), and permitting (Johnson & Gerling, 2011). The cost of a project is strongly linked to the accessibility of structure locations, as access is a factor in selecting the foundation type, arranging for construction material transport, selecting vehicles to be used and, the scheduling of the work. Even small scale projects (less than 20 structures) can incur large costs due to accessibility limitations arising from environmental conditions, for example, the Snohomish County project in the state of Washington (White & Eisinger, 1997), and an unpublished single pole case history in Pinal County, Arizona from the author's files.

Williams' (2003) survey of international standards highlights the need to integrate detailed environmental data with project planning and bidding. Multiple case histories indicate delays in construction due to improper permitting and compliance with regularity constraints. Environmental issues associated with foundation construction are typically not identified or included in the bidding stage of a project. The case studies illustrate that the majority of transmission lines are designed with a fixed set of foundation alternatives. Contractors who bid upon this work typically specialize in the foundation types identified in the design documents (i.e. McCall, et al, 2009; Chen & Salisbury, 2012). Common construction bid practices typically exclude an evaluation of alternative foundations not part of the original design package. The case studies suggest that the risk associated with bidding alternative foundations and working in challenging environments needs to be balanced with cost and schedule (i.e. Wyman, 2009).

2.1.2 Mitigation

Outside of complete avoidance, the mitigation strategies identified in the included case studies are highly variable and dependent upon environmental setting. Multiple publications indicated that there are increasing logistical challenges to meeting the requirements of rising environmental stipulations. In wetland environments, mitigation options included matting, construction platforms, cofferdams, lightweight portable cranes, modular barges, marsh buggies, and helicopter installation (CHANCE, 2014; Davidow, 2015; McCall, et al, 2009; Norman, et al, 2009; Rodgers, 1987; Salisbury & Davidow, 2014; Shanmugasundaram, 2009; Thompson et al., 2009; White, 1997; Williamson & Rowland, 2009). Outside wetland environmental settings, mitigation techniques reported were largely related to poor access, due to bog conditions or rough terrain. Mitigation includes limiting workable days, the use of ice roads, and helicopter construction (Chen & Salisbury, 2012; Johnson & Gerling, 2011; Milbradt & Vasbinder, 2011; Thompson et al., 2009; Wyman, 2009). With poor access due to terrain issues, multiple case studies indicated the need for flexible foundation design to meet field conditions. Suggested solutions include variable foundation embedment, pre-design of alternative foundations, and real-time foundation design.

2.2 Industry Survey

The research team performed an industry survey (as shown in **Appendix B**) to identify the numerous unpublished cases of foundations located in environmentally sensitive environments. Eighty-six individuals were selected to receive the survey form via email.

Nineteen responses were received via the survey, fourteen of which have designed or constructed foundations in environmentally sensitive areas. The survey participants represent a variety of utilities (17) and consultants (2). Eighteen respondents represent utilities located in North America; one respondent located in Europe. The respondents report transmission lines installed in a wide variety of sensitive and/or difficult environmental conditions (**Figure 2-2**).

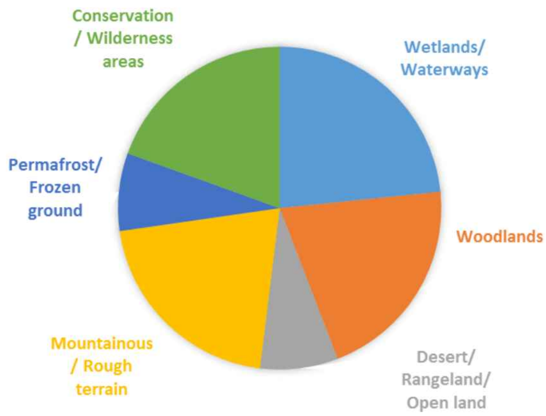

Figure 2-2: Distribution of Foundations Installed in Sensitive Environments from Survey Results.

Environmentally sensitive areas are typically identified in the planning process (100 percent of respondents). Avoidance practices tend to be preferred. One respondent reported that their utility did not install foundations in environmentally sensitive areas. However, ROW and ground clearance limitations often dictate foundation locations in environmentally sensitive areas.

All respondents indicate that they require geotechnical testing as part of the design and/or construction process. Geotechnical testing, however, is largely conducted as part of line design activities (represented by 10 respondents), with few conduct-testing prior to line design (6 respondents). Some respondents indicate the use of low/no impact geophysical testing methodologies for site investigation where access with drill rigs is limited (10 respondents).

Respondents indicate a preference for construction mitigation measures over foundation modifications/alternatives where installation of foundations in environmentally sensitive areas is unavoidable (84 percent of respondents). When access is restricted, roughly half of the respondents opt to improve existing access roads, and roughly half install modular matted paths. Alternative access methods, such as hauling in equipment by hand, improving ground with stabilizers, and the use of helicopters are less common.

All respondents indicate that they allow the use of alternative foundations such as auger cast piles, helical anchors, micropiles, rock sockets, vibratory caissons, and spread footings. About half of the respondents use staff to design transmission line foundations in lieu of contractors or consultants. Respondents who design in-house often use internal standards/methods for analyzing foundation alternatives. Respondents' report that the cost and time associated with constructing an alternative foundation outweighs the risk and reliability considerations of traditional foundation methods. A lack of regional contractor familiarity with alternative foundation installation is reported as another limiting factor preventing their use.

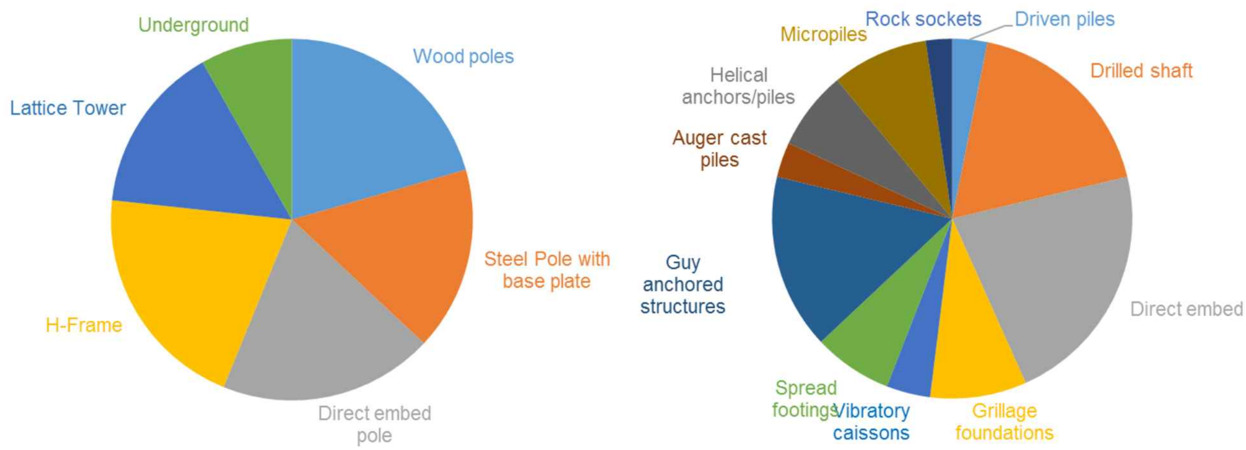

Figure 2-3: Structure Types and Foundation Types used by Survey Respondents.

The respondents report the installation of wood poles, steel poles, H-frames, and lattice towers in environmentally sensitive areas (**Figure 2-3**). The foundations constructed to support these structures vary by geographic region as illustrated in **Figure 2-4**. Drilled shaft and direct embedment foundations are used across all environments, as are guy anchored structures. Additionally, rock sockets with anchors are commonly installed in mountainous terrain. Grillages are installed in frozen ground conditions, with rock socketed foundations used where bedrock is present.

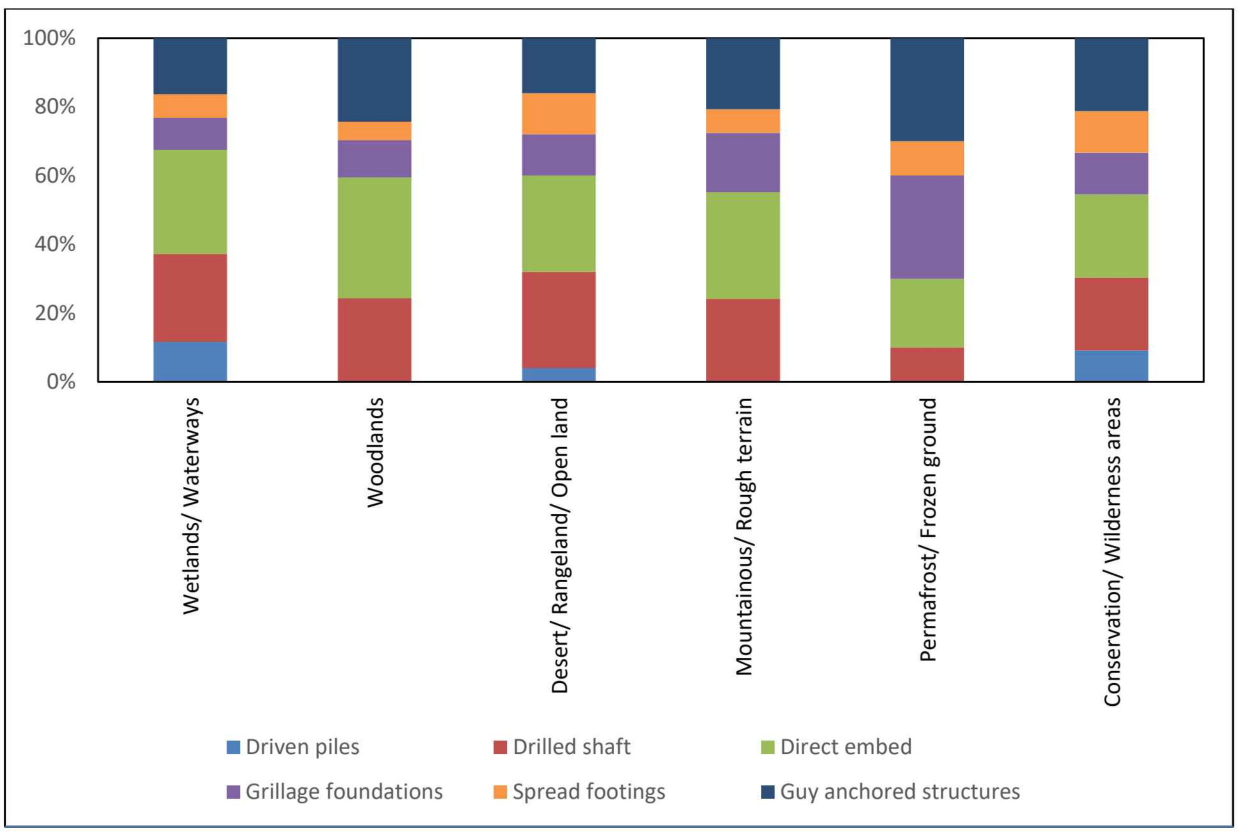

Figure 2-4: Variability in Traditional Foundation Type by Geographic Region.

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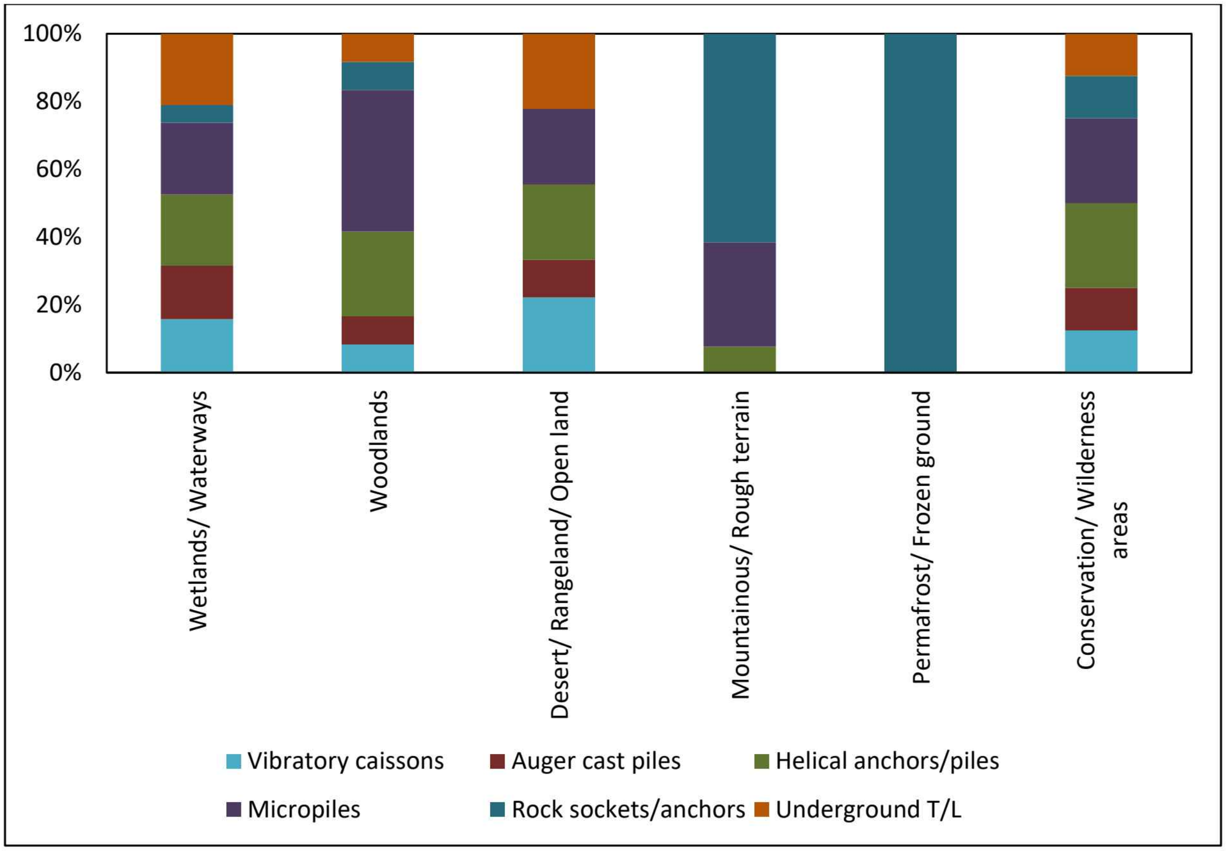

Figure 2-5: Variability in Alternative Foundation Type by Geographic Region.

The most common challenges encountered during foundation installation include access roads, as well as constructability and the related cost of access road construction and maintenance. The cost of alternative foundations is sometimes reported as a project challenge. More often, deadlines and regulation constraints are more significant issues. Almost all respondents indicate performing post-construction processes that include site restoration, the removal of spoils and ground restoration (disking/loosening). Almost all of the utility respondents indicate the use of ATVs, helicopters, boats, or walking trails to maintain structure access after construction.

2.3 Case History Synopsis

Relevant issues gleaned from published case histories and unpublished case studies are listed as follows:

- Case studies identify and classify sensitive environments as wetlands/waterways, mountainous/rough terrain, permafrost/frozen ground, woodlands, conservation/wilderness areas and desert/rangeland. These represent the most common locations for alternative foundation design.
- Environmental assessment in the planning stages primarily focuses on routing of ROW, and does not include the impacts of foundation design or alternatives.
- Geotechnical testing that seeks to identify properties for foundation construction is rarely done in advance of determining the foundation type.

- Of interest, traditional foundations were used to support transmission lines in just under 40 percent of the cases, with access controls used to mitigate construction environmental impacts.
- The majority of published case studies illustrate the use of alternate foundation designs (e.g. micropiles, vibratory caissons, and helical piles), along with minimally invasive access methods (helicopters, barges, boats, marsh buggies, light/small equipment, etc.).
- Alternately, nearly 85 percent of survey respondents indicate a preference for construction mitigation measures over the use of alternative foundation types (improved access, modular matted paths etc.).
- In terms of alternative foundations, micropiles, helical anchors, and vibratory caissons are the most commonly used in the industry (published and survey data).
- Alternative access methods, such as hauling in equipment by hand, improving ground with stabilizers, or the use of helicopters are less common.

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3.0 ENVIRONMENTAL IMPACTS OF FOUNDATIONS

3.1 Environments

Transmission lines are long linear features that can cross multiple geologic, geographic and environmental settings world-wide (Lakhapati, 2009). As part of the design process, great effort is put forth to minimize the placement of new structures in sensitive environments. If this is not feasible, final locations are often adjusted to mitigate impacts, improve access, and to accommodate environmental permitting requirements. Invariably, portions of the line route or selected structure sites must be constructed in less than desirable environmental conditions. The engineer must then opt for structure, foundation, and access alternatives that minimize impacts, while balancing economic, safety, operation, maintenance, and construction needs.

Sensitive setting included the evaluation of environmental, cultural, and aesthetic considerations. Environmental and culturally sensitive areas are predominately identified by local, state, and federal entities, as illustrated by the National Historic Preservation Act (NHPA, 1966), the Native American Graves Protection and Repatriation Act (NAGPRA, 1990), the Clean Water Act (CWA, 1972), and the Endangered Species Act (ESA, 1973). Aesthetic considerations tend to be incorporated within various regulatory or zoning requirements enforced by state, provincial and local agencies (such as public utility commissions), and are evaluated during the siting process.

Based on the case history review, sensitive environments can be categorized as follows: wet environments (wetland, waterway, coast, estuary), rough terrain (mountainous, desert), and frozen ground (seasonal frozen ground, permafrost). The case histories' distribution of sensitive environments can be found in **Figure 3-1**. The review also notes projects in other sensitive environments, such as woodlands, conservation areas, archeological sites and wilderness lands as typically included as part of these three settings. The following discussions detail the environmental factors and impacts effecting transmission line foundation construction in wet environments, rough terrain, and frozen ground.

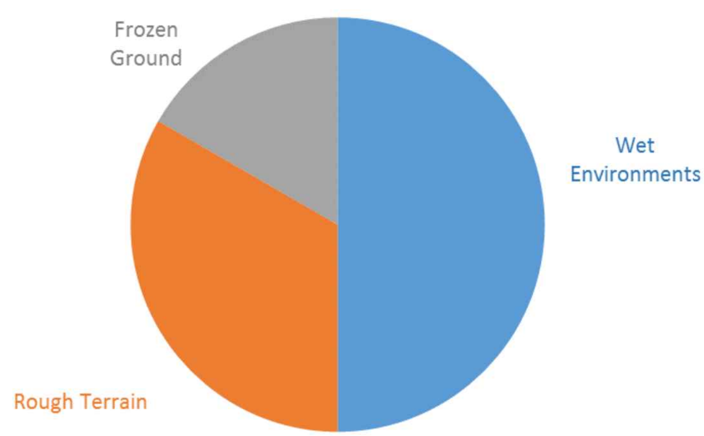

Figure 3-1: Environment Distribution of Case Studies.

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3.2 Wet environments

Wet environments encompass areas inundated with water, such as wetlands, estuaries, waterways, coastal areas, and flood plains (**Figure 3-2**). These wet environments have similar mitigation considerations for managing water inundation, saturated soils, and equipment impacts, in terms of line design, access, and construction. An example is provided in **Section 8.2**.

North American Wetlands

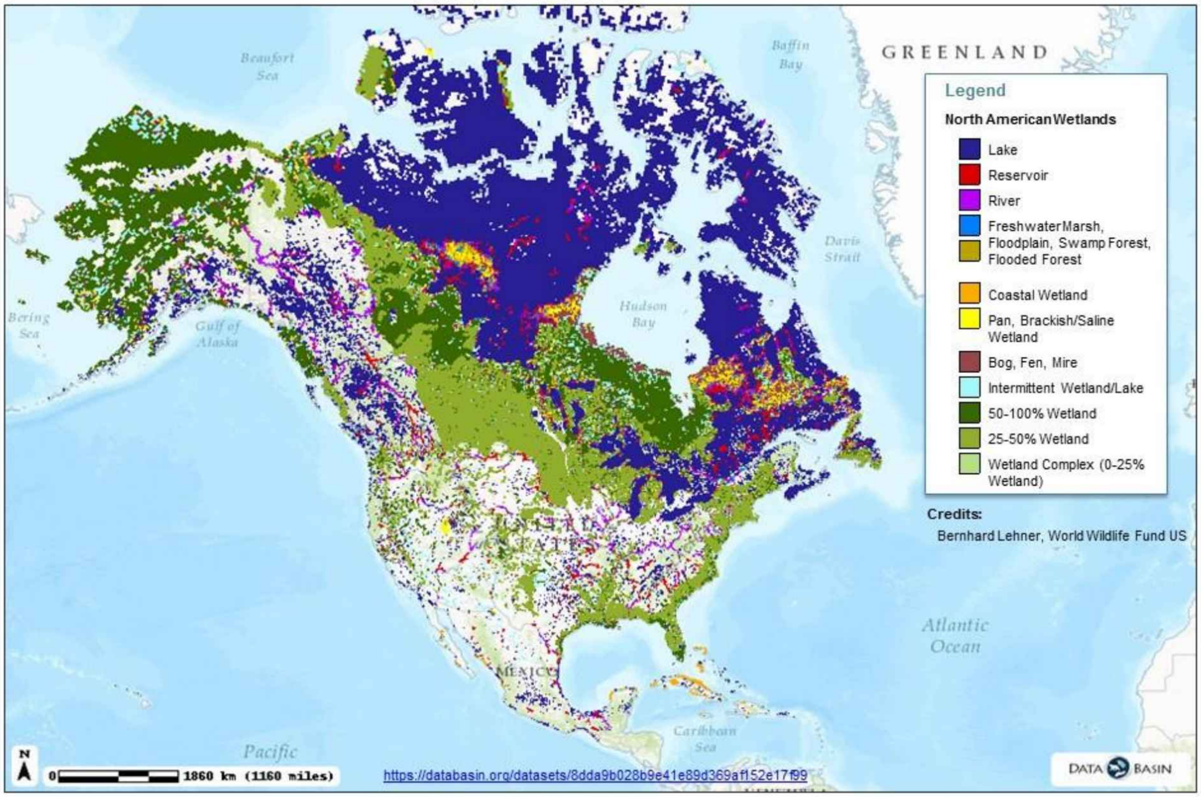

Figure 3-2: Distribution of Wetlands – North America (Data Basin, 2017).
(Note: Worldwide distribution of wetlands map available from USDA-NRCS: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054021)

3.2.1 Factors

By nature, wet environments can result in line construction and maintenance restrictions, due to the presence of both near surface water and open water. Where existing roads and trails do not exist, new access must be constructed, mitigations must be installed, and/or equipment and materials may need to be delivered via crane, helicopter, or floating vessel. Since these environments are home to many plant and animal species, construction is likely to be seasonally limited, with rules and restrictions set by one or more governmental agency. Foundation construction factors may include constraints for drilling debris, machinery fuel, and sediment turbidity. The costs of foundation construction are generally higher in wet environments, mainly due to efforts required to both provide equipment access and to protect sensitive environmental conditions. Additionally, costs for foundations installed in saturated conditions are generally higher, due to high water tables where drilled shafts must be stabilized by various methods (casings, slurries, etc.).

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Foundation construction access typically requires ground improvement that bridges or compensates for weak surface conditions. A floodplain may not be inundated during construction, but compressible ground may still require mitigation (Hudspeth, 2008; Thompson et al., 2009). Where feasible, foundation construction in wet environments may require waiting until the ground is frozen, allowing for access. In extreme cases where active waterways must be traversed to reach foundation construction sites, access may require the transportation of equipment, materials and workers via crane, barge, boat, or helicopter (Beim et al, 2014; Norman, et al, 2009; Shanmugasundaram, 2009).

Soft subsurface conditions are typically encountered in wet environments (**Figure 3-3**). These soils are often highly organic and highly compressible (i.e. constitution in the Great Dismal swamp as described by Rodgers, 1987). As such, these soils provide limited lateral and vertical strength for supporting foundations, and provide limited bearing for construction equipment (Davidow, 2015; Hudspeth, 2008; Rodgers, 1987; Shanmugasundaram, 2009; Wedell, et al, 2015). These conditions typically result in the need to design larger foundations, mobilize bigger construction equipment, and use greater quantities of foundation material.

Figure 3-3: Future Foundation Location in an Inundated Wet Environment
(Stake in Photo).

Foundations in wet environments may require additional reveals to account for future flooding, inundation, and splash zones (**Figure 3-4**) (Richardson & Bennett, 2012). Likewise, high groundwater tables may affect the construction technique and size of foundation (Williamson & Rowland, 2009). The placement of concrete will inevitably require stabilization and tremie placement methods. Wet environment conditions can also limit foundation options. For example, the economic value of helical anchors becomes questionable in very soft soils. Foundation design in wet environments must also consider additional factors, such as higher potential for ground loss due to erosion and scour.

Figure 3-4: Transmission Line located in a Wet Environment (Note high reveal in flood zone).

Wet environments have specific constraints that can limit workable days and structure locations, such as seasonal hurricanes, recreation & fishing, and waterfowl nesting & animal mating. As wetland environments are often major nesting locations for migratory birds, these conservation areas typically impose seasonal limitations on construction to limit the impact of migration and nesting periods (Williams, 2003). One case history notes seasonal wildlife safety and breading restrictions on working times and access, including prohibiting work within 15 meters of manatees, and no work days during osprey nesting season (Shanmugasundaram, 2009).

3.2.2 Impacts

Wet environments present unique conditions, where line construction can adversely impact water quality, water resources, and endangered plant and animal species, and cause damage to sensitive surface soils. Even minor disturbances have long-lasting effects, due to high erosion rates typical in wet environments. The contamination caused by fuels and lubricants used to operate and maintain equipment is also of concern. Disturbances and pollution occur as a result equipment requiring site-access, along with foundation-focused construction activities.

Williams (2003) describes the impacts of line construction, which "compact[s] soil, remove[s] plant cover, and alter[s] existing drainages, or create[s] new ones. Altered hydrology can affect aquatic, wetland, and riparian habitats and species, [as well as] soil moisture and surface water availability in other kinds of ecosystems." The compaction of soft soils can increase runoff, block flows, and reduce water holding capacity, resulting in degraded site conditions (PSCW, 2013).

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Transmission line construction has the potential to damage plant and animal habitats, and to introduce invasive species via equipment traveling through sensitive wetland environments to foundation sites. In addition to soil compaction, the transportation of equipment and workers can result in soil erosion, altered hydrology, polluted surface and groundwater, and changed the timing and water and nutrient flow magnitude essential to ecosystem functions (Williams, 2003). Water quality can be affected by erosion of overburden during line foundation construction, and by contamination triggered by construction materials and machinery fuel type's spillage (White & Eisinger, 1997). Environmental considerations also include preventing the introduction of invasive species tracked out by equipment (PSCW, 2013).

Transmission line construction methods must be adapted to mitigate water resource impacts, protecting agriculture, potable water, recreation, and wildlife. As such, there are strict environmental regulations of water resources that work to maintain water quality at the international, national, state, and local levels (i.e. United Nations Guiding Principles on the Human Environment; U.S. Clean Water Act; Canada Water Act; state, city and local regulations). Even a short transmission line (under 16 km) that crosses a waterway can be impacted by water regulations (Richardson & Bennet, 2012).

Estuaries act as reservoirs of biodiversity for both endangered and economically valuable species. The construction process can increase water turbidity and sediment content which disturb wildlife (PSCW, 2013; Richardson & Bennett, 2012). The case studies herein identify numerous protected plant and animal species encountered along transmission lines in wet environments, including seagrasses, salt marshes, California condor, manatees, micro-flora and micro-fauna (Shanmugasundaram, 2009; TCN, 2012; White & Eisinger, 1997; Williamson & Rowland, 2009). For example, Norman et al (2009) contended with local economic and tourism constraints while constructing foundations in a lake , as they endeavored to prevent the loss of fish habitat while removing submerged stumps at sites.

3.3 Rough terrain

Rough terrain encompasses regions of variable ground elevation, such as mountains, steep slopes, and uneven ground surfaces. Rough terrain is characterized by highly variable topography, and it is found throughout the world in both woodland and open-range regions (indicated by much of the forested, cordillera, sierra and highland regions in **Figure 3-5**; a detailed map from the same source can be found at:

ftp://newftp.epa.gov/EPADataCommons/ORD/Ecoregions/cec_na/NA_LEVEL_III.pdf).

These conditions are located in a variety of climates and often in sparsely populated, remote regions.

3.3.1 Factors

The environmental conditions of rough terrain include variable ground elevation and variable depth to bedrock. Mountainous regions pose unique access considerations for structure locations, due to their remoteness and climatic extremes. To meet clearance needs, transmission structures in rough terrain tend to be located on high ground at hilltops, on hillsides, and along ridge lines, thus creating access challenges. Mountain forests (noted in the survey as 'woodlands') tend to be classified as conservation areas, and often have access restrictions related to the seasonality of flora and fauna. The case studies indicate that rough terrain environments make up a third of the sensitive environments encountered (**Figure 3-1**). Further, the cost of construction for foundations in rough terrain is most dependent upon available or permitted access and the drillability of bedrock.

As defined, rough terrain consists of variable topography, which is generally a product of mountain-forming geologic process such as faulting, volcanic activity, and orogeny. Highly variable topography is often deeply incised with steep slopes related to fluvial or mass wasting processes. The mountainous gorge region of Afghanistan is an extreme example, at which a 230kV transmission line was installed between the steep valley walls (Lakhapati, 2009). This site posed difficult access for workers and materials, and required manual labor to complete foundation installation.

Figure 3-5: North American Map of Rough Terrain by Eco-Regions (after CEC, 2017).
(Note: Worldwide distribution of land quality map available via USDA-NRCS: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054011**)**

The subsurface in rough terrain typically consists of near surface bedrock ranging in strength depending on the geologic formation processes. Due to the limited accessibility in rough terrain, subsurface conditions encountered during construction often differ from assumed design conditions (indicated by numerous case studies). Depth-to-bedrock tends to be highly variable across the topography. For example, a 115kV line foundation upgrade project located in the rugged

Superstition Mountains of Arizona fluctuated from zero to 15 meters of overburden across the route, in very different geologic conditions. Access to all sites was not granted during design investigations due to permitting restrictions. Existing access roads were mostly lost due to erosion, and only 20 of the 75 sites could be visited prior to issuing the project for construction (author's unpublished files, see example in **Section 8.3**).

Foundation installation considerations in rough terrain are largely present mobilization challenges for equipment, materials, and workers. Equipment selection is a function of rock drillability, available access, and structure type. When construction access is either unavailable or prohibited, small diameter foundation drill rig equipment is often mobilized to sites via helicopter (**Figure 3-6**) (Johnson, 2009). Helicopters are heavily relied upon in rough terrain environments, whereas new road construction is not permissible. But their use is limited by low visibility, restricted load capacity, high altitude, and warm air temperature. If air transport is found to be unfeasible due to economics, line outage needs, or climate conditions, foundations may require construction by hand, and small-size portable equipment that uses low volumes of materials. These are then moved near structure sites via 4-wheeled vehicles, ATVs, and/or by helicopter, then carried to sites by construction workers (**Figure 3-7**) (author's unpublished files). Few options exist for foundation construction in rough terrain if roads cannot be built.

All of the case histories in rough terrain note climate restrictions for workable days. Climatic concerns include both hot and cold temperature extremes that pose limitations for manual labor, as well as hazards due to wind, terrain, and wildfire. In the California mountains, the risk of forest fires and high winds has posed a unique challenge for transmission line foundation construction (Chen & Salisbury, 2013; Johnson & Gerling, 2011; Salisbury & Davidow, 2014; Thompson et al., 2009). High wind and high elevations limit both manual labor and helicopter access. Risks of extreme weather events at high elevations also cause safety concerns, and require special safety plans for medical resource access. For example, the Tehachapi Renewable Transmission Project had to account for daily changes in wind, in order to enable worker mobility between foundation sites with provisions and survival training for possible overnight stays (Johnson & Gerling, 2011).

Figure 3-6: Example of Rough Terrain Foundation Installation
(**Photo courtesy of CRUX Subsurface**).

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Figure 3-7: Location of Transmission Tower in Rough Terrain.

3.3.2 Impacts

Rough, remote locations tend to be within conservation areas, and require extensive environmental permitting. Conservation areas are protected regions defined at federal, state, provincial, tribal, and local governmental levels, such as national parks, forests, and monuments in the U.S. and Canada. They may also include city parks and recreation areas. Nationally designated and protected areas comprise 14.3% of the world's mountain areas (Wyman 2009), and are generally concentrated in the developed world. For instance, the permitting of a recent 500kV transmission line project in California's mountainous Angeles National Forest took nearly two years to complete, and included mitigation, monitoring, and compliance plans for sensitive plant species, protected California condor, and migratory birds (Johnson & Gerling, 2011). Likewise, plans typically include the consideration of invasive plants, vegetation removal, and vegetation alternation (PSCW, 2013; Williams, 2003).

Mountainous areas and other rough terrain are often regulated to minimize disturbance and development. Rapid changes in elevation can result in more severe water-related erosion, resulting in disturbance restrictions caused by construction and maintenance of access roads for transmission line structure sites. Impacts also include foundation drilling spoils erosion, hydraulic fluid spills and machinery emissions (Chen & Salisbury, 2013). As such, access via new roads is often restricted or not permitted in rough terrain locations (Chen & Salisbury, 2013; Johnson & Gerling, 2011; Salisbury & Davidow, 2014). Although helicopters provide minimum ground disturbance, issues of migratory bird flight paths, air space restrictions, and emissions must be weighed with the use of alternate foundation designs.

Aesthetic impacts can also pose significant issues in rough terrain conditions, in cases where the line is visible to the public. Minimal disruptions to the natural scenery during and after construction are often required for permitting (PSCW, 2013). Current best practices focus on mitigation via route development, structure design, topographically-sensitive siting methods, off-site mitigation, visual simulations, structure and conductor finishes, and other inputs (Cibulka, 2012; Chau, et al, 2009).

Also, since improper disposal of foundation rock spoils on rock outcrops can result in a site's un-natural appearance, mitigation must be performed.

3.4 Frozen ground

More than half of the land in the Northern Hemisphere freezes and thaws seasonally. Non-seasonal frozen ground, regions of permafrost, and permanently frozen tundra, encompass the extremely high latitudes and high altitudes of North America (**Figure 3-8**). Permafrost (cryotic or cryic) is defined as soil at or below the freezing point of water. In regions with air temperature above the freezing point of water, permafrost may be discontinuous and localized to sheltered areas (i.e. forests). Shaped by past glacial activity, the subsurface topography of frozen ground is characterized by highly variable depth to bedrock.

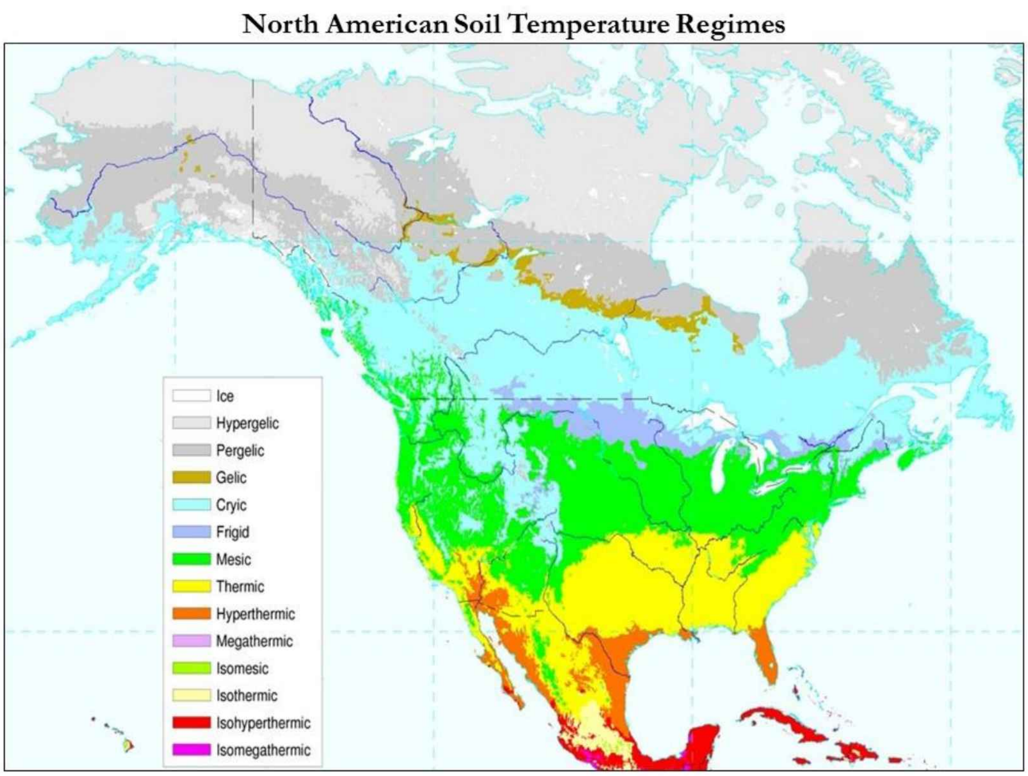

Figure 3-8: North American Soil Temperature Regimes (Adapted from USDA-NRCS, 1997).

(Note: Worldwide distribution of soil temperature regimes map available via USDA-NRCS: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/worldsoils/?cid=nrcs142p2_054019**)**

3.4.1 Factors

The case studies indicate that challenges for foundation construction on frozen ground (predominately located in the northern hemisphere); include access limitations due seasonal and daily climatic changes. Frozen ground in northern latitudes coincides with extreme climatic conditions, in which daylight persists in the summer period or not at all in the winter period. A case history in Alaska noted temperature fluctuations from 32°C to -45°C during construction (Wyman, 2009). For this reason, foundation design must consider both the frozen and unfrozen conditions that a structure may encounter. Seasonal and daily changes in temperature can affect foundation stability and become problematic for construction (Wen et al., 2015; Wyman, 2009).

Cycles of freeze and thaw can drastically change subsurface strength and result in frost heave (Grigor'ev, et al, 2012; Wyman, 2009). Frost heave is the condition where ice pressure causes the swelling of overlying soil (**Figure 3-9**). Thawing of permafrost can result in overburden collapse. This action can incite extreme ground movements and possibly uproot foundations from the ground (i.e. frost jacking). Design must take these forces into account, extending foundation embedment as needed.

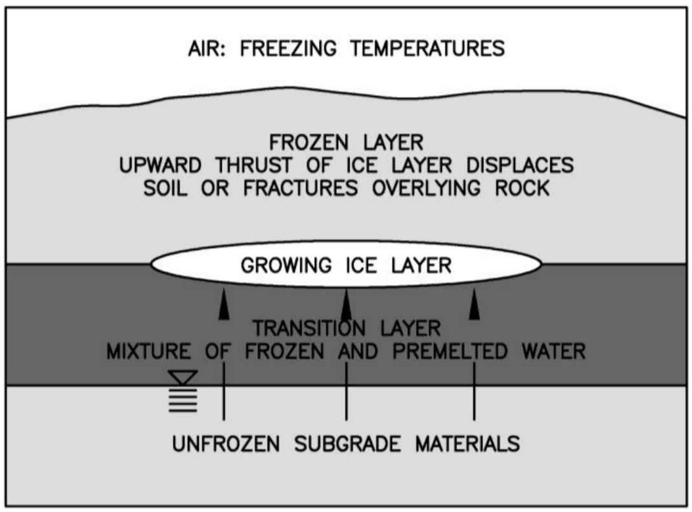

Figure 3-9: Frost Heave (after Rempel, 2007).

Shallow foundations have been previously used to support transmission lines due to difficult conditions caused by frozen ground. The literature and surveys note lattice tower spread footings and single pedestal guyed structures as the dominant foundation types in frozen ground conditions. The typical foundation failure mechanism was due to frost heave where temperature fluctuations at the base of the foundation drastically changed the bearing and uplift capacity (Wen et al., 2015). Case studies indicate that the replacement of these aging structure foundations with deep foundation elements, such as micropile, helical, and driven pile foundations, are not reliant on the bearing capacity of frozen layers, and account for uplift in design.

Access to foundation locations in frozen ground is seasonally dependent. In areas of discontinuous permafrost, access may be limited to frozen periods, as the locations may become wetlands or bogs during the warmer seasons. Frozen ground conditions are unique geotechnical cases that affect scheduling, access, and construction. Frozen ground regions tend to be sparsely populated and require special mobilization for safe working conditions and access to emergency services. Planning and scheduling is critical for construction in frozen ground regions, which also require methods to reduce field construction time. Precast concrete and steel foundation materials are typically used instead of cast-in-place concrete (Lakhapati, 2009). An example is provided in **Section 8.1**.

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3.4.2 Impacts

Frozen ground occurs due to the highly porous structure allowing for capillary action of water to spread ice formations. At high latitudes, ground ice is massive, with ice content exceeding 250 percent of soil weight. In areas where frozen ground is discontinuous, overburden may consist of high organics and high water contents, creating a soft soil condition during un-frozen periods. This soft soil is largely maintained structurally by the root systems of tundra vegetation. Any disturbance of the vegetation will decrease the structural integratory of the subsurface. As a result, construction activities and site access is minimized to reduce vegetation damage. For example, one case study illustrated the construction of large cribbing around a drilling site (Wyman, 2009).

Transmission line tower types located in frozen ground regions are designed to reduce foundation size and limit ground disturbance, including guyed X-towers, Y-towers, and “swingset” towers. Design for these tower structure foundations typically includes down guys as a means to reduce the foundation footprint in permafrost. The reduced foundations have a minimal environmental impact in frozen ground environments. Unfortunately, these foundations are particularly susceptible to frost heave action, and deep foundation elements must be included in the design of anchors and pedestals.

The major environmental impact to installing foundations in frozen ground environments is land disturbance caused by site access. During periods of thaw, the subsurface is weak and susceptible to inundation, causing access with heavy machinery to be difficult. To minimize impact to the ground in sensitive environments, frozen ground access is preferred. In extreme cases, contractors have been required to make their own snow to build an “ice road” or “winter road” to support machinery (Wyman, 2009).

Transmission line construction in frozen environments has the potential to damage plant and animal habitats and introduce invasive species. As frozen ground environments are generally located in remote areas, any disruption to migratory spices and native flora must be considered. For example, Canada consists of vast expanses of intact natural areas and has strict conservation laws to protect biodiversity. Over 10% of Canada consists of protected areas for migratory bird and wildlife, such as caribou.

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4.0 MITIGATIONS

The mitigation of environmental impacts associated with the construction of foundations for electric power transmission lines allows for assessment practices that result in the most desirable combination of available options. These options include avoidance, activity minimization, and protection at sensitive sites. As a starting point, various types of environmental evaluations are prepared, and include accepted best practices for reducing environmental impacts. The purpose of this section of the report is to discuss mitigation options in relation to transmission line foundation design and construction.

4.1 Assessing Environmental Effects

Identification of sensitive environments is commonly conducted as part of the project's environmental assessment process. Although there are several variations in detail according to country and locality regarding environmental assessments, commonalities suggest similar activities and best practices (Williams, 2003). In the United States and Canada, evaluations are most commonly performed as part of either environmental impact statements (EIS), or during environmental assessments (EA). Worldwide, requirements for assessments are particular to the national regulating agency, or may be done for project funding agencies, such as the World Bank (TCN, 2012), Asian Development Bank (Williams, 2003), and European Bank (ERM, 2005).

Environmental evaluations are the process by which anticipated environmental effects are identified and measured for a proposed project, and environmental data is integrated with project design. As such, these assessments delineate the "relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity" (Commonwealth Associates Inc., 1982).

A brief summary of thirteen international transmission line project environmental assessments or impact statements are presented in **Table 4-1**. In general terms, these documents should include an assessment of social impacts, public input, mitigation plans, and monitoring (Williams, 2003). As part of the planning phase, evaluations are largely conducted as desktop studies. Foundation design factors are often generalized or excluded from the process, because locations and types of transmission line structures are only approximated. Subsurface and site investigations are minimal or non-existent prior to permitting. As indicated by the case studies, all evaluations include water, geology, wildlife and cultural/historical site assessments. Plans developed as part of these studies for the purposes of site mitigation, monitoring and compliance are often incorporated into construction activities (Johnson & Gerling, 2011).

4.2 Avoidance

Avoidance is the primary design strategy deployed to limit transmission line impacts upon sensitive environments. Transmission line planners select routes that strategically avoid numerous factors, such as existing structures, residential areas, schools, cultural resources/landmarks, historical sites, recreational areas, scenic views, natural resources, geologic barriers, waterways (including lakes and ponds), springs, wetlands/riparian ecosystems, un-fragmented and old-growth forests, and sensitive species habitats. When siting in such areas cannot be avoided, the area of disruption ought to be minimized in order to mitigate impacts (Williams, 2003).

Table 4-1: Summary of Environmental Study Elements (published).

Location	China	Ukraine	Georgia	Sir Lanka	Africa	WA, USA	SC, USA	WI, USA	CN, USA	WVA-NJ, USA	AK, USA	NL, Canada
Reference	**Williams (2003)**	**ERM (2005)**	**Gabechava, et al (2009)**	**CEB (2010)**	**TCN (2012)**	**Duncan (2010)**	**MEG (2011)**	**PSCW (2013)**	**CL&P (2013)**	**RG&E (2011)**	**CAI (1982)**	**Nalcor (2016)**
Soil/geology	x	x	x	x	x	x	x	x	x	x	x	x
geologic hazards			x			x						x
Land use	x	x	x	x			x	x		x	x	x
Land rights			x		x		x	x			x	x
Ground/ surface water	x	x	x	x	x	x	x	x	x	x	x	x
water pollution	x		x		x	x			x			x
Wildlife	x	x	x	x	x	x	x	x	x	x	x	x
forest	x		x	x								x
biodiversity	x		x		x							x
vegetation management			x			x						x
invasive species			x					x				x
Climate/air quality		x	x	x	x				x		x	x
protected environment			x	x								x
environmental justice							x					
open space/parks						x			x			x
recreation/tourism			x				x	x				x
Noise/light	x		x		x	x		x	x	x		
Economic	x		x	x	x		x	x		x	x	x
transportation			x	x			x	x	x			x
Safety/ health	x		x	x	x		x	x				x
emergency			x			x						
Aesthetic/ landscape	x	x	x				x	x	x	x	x	x
Cultural/historic sites	x	x	x	x	x	x	x	x	x	x	x	x
Indigenous peoples	x		x								x	x
resettlement	x		x	x							x	
Education			x	x	x							x

Avoidance strategies can include: the rerouting of transmission lines around sensitive environments, increased span lengths, and/or the selection of lower impact route(s). The ability to avoid sensitive environments becomes increasingly more difficult as growth encroaches upon remote locations. Environmental protection policies at all levels of government have been steadily increasing since the early 1970's, following the creation of the United Nations Environment Program. These policies have imposed further limitations upon siting transmission lines in sensitive environments.

4.3 Design Considerations

As part of transmission line design, the engineer must consider location, structure, foundation, and access alternatives that minimize impacts while economics, safety, construction, operations and maintenance needs must also be balanced. Design choices can be made to minimize impacts. Alternatives that work to avoid sensitive environments include increased structure spacing, increased structure height, and the use of angle structures to reroute around sensitive areas. Shorter spans can be used to reduce structure size and loads, resulting in lower weight structures. Shorter and lighter structures reduce construction equipment physical needs, thus minimizing size and load carrying requirements. This strategy may allow for the use of helicopters to assist with foundation installation and structure erection (PSCW, 2013).

The placement of large structures within sensitive environments (such as water crossings and seasonal wetlands), is sometimes unavoidable. Therefore, the selection of structure may be focused toward low impact access locations (near developed roads and drive paths), on high ground, away from drainage features, and away from slopes. The performance of a comprehensive desktop geologic study provides excellent advanced knowledge of the site that proves invaluable during line siting and structure locating.

Geotechnical investigations are required to provide cost-effective and structurally sound foundation designs. However, access to environmentally sensitive or difficult access areas is generally minimal in the early phases of the line siting and design process, as mitigation measures for foundation construction are typically not yet in place. The lack of driving access precludes the use of standard downhole subsurface investigation techniques. The case histories indicate the variability in conducting geotechnical investigations in sensitive environments (**Section 2**). Alternatives range from a prohibition of investigations at sensitive site environments, to the installation of mitigation measures (matting) for minimizing drill rig impacts. Other alternative methods used by geotechnical professionals include remote sensing methods (geophysics), transported via small 4-wheel drive all-terrain vehicles or backpacked into sites. In some regions, geotechnical sampling firms use low impact, all-terrain, track-mounted drill rigs that can traverse sensitive areas, or modular drill equipment that can be disassembled, transported by helicopter, boat, or marsh buggy to sites and reassembled for the investigation (PSCW, 2013). The cost of low impact investigation and equipment can be significantly greater than standard methods.

Even when good access allows for the performance of soil borings via drill rigs at a proposed structure location, final locations can change prior to construction. Normal geologic variability remains a concern, which is particularly problematic when depth to competent bedrock, or depth of organic material, varies across a transmission line. One case history noted variable rock depths limiting the use of anchored drilled shaft foundations, and requiring re-design of drilled shaft foundations during construction (McCall, et al, 2009).

Once right-of-way and structure locations are finalized, the design process considers various mitigation techniques that can help reduce the impact of the project on environmentally sensitive sites that cannot be avoided. Best practice mitigation methods incorporate low impact access to sites, alternative foundation types, protective countermeasures, compact construction techniques/equipment, light-weight or low volume foundation materials, and site vegetation management and restoration.

By default, transmission line structures require foundations. Design options, though, can vary even for the same structure type. It is incumbent upon the engineer to select a foundation alternative that is economical, constructible, and compatible with the site environment. Therefore, structure selection should consider foundation design as well as line design requirements in sensitive environments. In one case study examining a wetlands environment, design minimized foundation dimensions by using directional loading components that accommodated individual load combinations (Davidow & Carr, 2015). Alternate foundations can be chosen that: limit (or eliminate) the need for concrete, avoid foundation dewatering, generate little to no spoils, and/or help to minimize excavation. With thoughtful design, foundations can be viewed of as part of the environmental mitigation process.

4.4 Site Access Alternatives

Construction access challenges are commonalities that occur on a global scale, ranging from the narrow gorges in Afghanistan to the frozen tundra of Kazakhstan, and the river crossings in India (Lakhapati, 2009). In the included case histories (**Section 2**), site access is shown to be restricted based on outages, climatic conditions, footprint area, and wildlife constraints. Mitigation strategies vary based on the degree of environmental disturbance permitted at the site. Common mitigation practices include ungraded access, matted drives, spur road construction, and frozen ground access. More costly and less common mitigation strategies include temporary geotextile drives, the creation of temporary ice roads, and manual construction. In areas where ground access is not permitted, alternative access to structure sites by air or water may require the use of helicopeters, marsh buggies, or barges. Details regarding mitigiation alternatives are covered in **Section 5**.

Access restrictions can be transitory in nature. Access and workable days may change throughout the course of a construction period due to climate factors, including temperature, precipitation, and daylight. Construction periods can also be limited by seasonal weather patterns, such as hurricane seasons (Richardson & Bennett, 2012); workable weather times of day or year during very hot and very cold conditions (Chen & Salisbury, 2013; Wyman, 2009); and equipment/material use restrictions (concrete use in hot or cold weather, or helicopter travel in high winds). Numerous case study examples further note construction restrictions based on animal migration and breeding seasons (Chen & Salisbury, 2012; Johnson & Gerling, 2011; Richardson & Bennett, 2012; Salisbury & Davidow, 2014; Thompson et al., 2009; White & Eisinger, 1997; Williamson & Rowland, 2009). Access may also be limited seasonally due to other factors. For example, construction was held to the rainy season in the Amazon of Brazil. Site access was authorized only when the water levels were high enough for barges to move without disturbing riverbeds and vegetation (Beim et al., 2014). Frozen ground is often used to access sensitive sites in northern climes during cold weather periods.

Case histories note situations where heavy machinery transit is prohibited. Structure relocation is potentially the only feasible alternative for the prevention of ground disturbance (CHANCE, 2014). In situations where limited access is permitted, manual labor may be the only feasible option for bringing in equipment, materials and workers to rough terrain. In cases where new roads cannot be built, access via helicopter, barge, and boat are often the most feasible alternatives. However, these alternatives likely will have additional environmental and cost constraints. In the Golden Pass case study, helicopters were used to access the site, but their use included evaluating flight crew requirements for scheduling, helicopter weight limitations for foundation design, fuel costs for travel, flight path restrictions, and carbon footprint considerations (Williamson & Rowland, 2009).

Regardless of line length, multiple sensitive environments with specific restrictions may be encountered. For example, a short 5.5 km transmission line crossed wetlands, a river, a Superfund landfill site, Native American land, an active shipping channel and a major interstate highway in the Snohomish River delta in the state of Washington (White & Eisinger, 1997). Multiple access methods were used to accommodate the various environmental restrictions, including barges, helicopters, and existing access roads.

4.5 Construction Controls

Foundation selection can positively influence construction schedules via the provision of alternative methods for construction in less than desirable situations. However, they can also negatively affect construction schedules, due to the nature of the placement or materials. Transmission line projects are highly influenced by scheduling, with firm energization dates and outage restrictions. During the construction phase, scheduling and cost are impacted by installation, material, and mitigation constraints.

At a basic level, some foundation options simply require a more extended schedule to account for the design and fabrication of the material elements, while other options can be readily obtained and constructed. Construction schedules for transmission lines must account for time required to design, fabricate and construct foundations.

Construction schedule constraints are highly dependent upon the expertise of field crews, site, subsurface variability, and equipment availability. Foundation construction schedules and costs are negatively impacted when field conditions differ from those assumed in design. Alternatively, foundation construction risks and costs are well managed when the field conditions encountered reflect predictions made at the time of construction. Foundation installation is also dependent on construction equipment, as the sheer size of certain equipment is unsuitable in sensitive environments. Foundation construction equipment also varies in availability, versatility/adaptability, capability, weight, and support equipment needs.

Each foundation design option requires variable amounts of concrete, steel, grout, and backfill to transfer the pole load to the subsurface. Each material has temperature and climatic limitations required to maintain acceptable performance. Likewise, foundation material durability varies in terms of corrosion protection needs. Generally, this consideration is somewhat climate dependent, and susceptible to corrosion and other long-term durability factors.

Environmental site controls and mitigation are integral foundation construction activities. The foundation installation method selected can negatively impact the surrounding environment, as shown in **Section 3**. The aspects of the environment influence include: dust and noise generation, the potential for oil/grease spills, the disposal of waste concrete and spoils, the handling of drilling fluids, and noise or vibration impacts to the surrounding community. Rules are outlined by Spill Prevention, Control, and Countermeasure (SPCC) regulations in the U.S., and by Spill Prevention Preparedness and Response plans (SRP) in Canada. Pollution that must be mitigated during foundation construction includes machinery fuel, emissions, sediment erosion from excavations and access roads, leakage from material stockpiles, material slurries, metal corrosion, hydraulic lubricants, vibration, and noise.

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4.6 Post-Construction Monitoring & Restoration

Typical construction monitoring focuses on the evaluation of material and installation requirements specified for foundation design. Environmental monitoring must also be integrated into the process, including: the minimization of disturbance to historic and cultural artifacts via ground survey, continuous monitoring for animal crossings, water quality checks, equipment cleaning preventing the introduction of invasive species, and surveys that identify the proximity of work to endangered flora or animal habitats. The monitoring of many endangered species requires highly trained experts. An unpublished case study conducted in Arizona noted the need for a trained botanist to identify the endangered hedgehog cactus (*Echinocereus triglochidiatus var. arizonicus*) prior to foundation construction. A pre-construction site survey had to be performed and cactus physically marked on the ground before the local regulatory agency would allow foundation construction to proceed (author's files). Archaeological and historical sites similarly require initial site monitoring, and may require continued monitoring throughout the construction process depending on the type of excavation. The environmental studies noted in **Table 4-1** have requirements for cultural and historic preservation. In some cases, the transmission line structure itself may fall under historic preservation protection (JRP, 2000).

The goal of site restoration is to minimize aesthetic impacts and to mitigate long-term environmental consequences caused by construction activities (Chau et al., 2009). Although aesthetic aspects of transmission lines are largely a product of the line route and vegetation management, foundation materials and construction activities can influence site restoration. Existing foundations were reused in one case history to minimize ground disturbance in a marine environment (Richardson & Bennett, 2012). In mountainous terrain, rock spoils from drilling were necessarily removed from the site to match the exposed ground tones and texture to surrounding exposed bedrock (author's files). In cases where temporary matting is used for site access, vegetation restoration, disking, and re-seeding may be necessary. Permanent access often requires some form of revegetation and grading to inhibit long-term erosion.

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5.0 ACCESS ALTERNATIVES

Foundation construction equipment must be able to access transmission line structure sites, and operate within a sufficient footprint (generally 30 meters by 30 meters) to safely facilitate drill rigs, erection cranes, and workers. It must also allow for the delivery of foundation materials (concrete, steel, etc.). Most projects include a carefully thought-out construction access plan to minimize impacts in all environments, with special emphasis on sensitive environments and steep/rocky terrain locations. These plans should be specific to final selected structure and foundation design alternatives.

Access alternatives are generally categorized as follows:

- Permanent and temporary paved, surfaced, graded, & un-graded access roads or spur roads,
- Temporary seasonal roads, ice roads, or frozen ground,
- Temporary matted or geotextile drives to protect underlying surfaces,
- Air access via helicopter,
- Water access via boats, barges, or marsh buggies,
- Manual labor – all equipment and materials carried to sites by workers alone (this approach may be augmented via cranes or long-reach pump trucks to reach locally remote sites).

The following list of best management practices has been excerpted from various projects and guide documents for the assessment of access alternatives:

1. Prepare maps showing the most relevant structures, residential areas, schools, cultural resources/landmarks, historical sites, recreational areas, scenic views, natural resources, geologic features, hydrologic features, wetlands/riparian ecosystems, un-fragmented and old-growth forests, and sensitive species habitats, along and within reasonable proximity to the transmission line route.
2. Determine whether access is to be temporary or used for future construction or maintenance activities.
3. Locate existing linear disturbances (roads, transmission lines, pipelines, trails, etc.) within the project area, and attempt to align with new access. Use spur roads as feasible to eliminate new roads along the transmission line route.
4. Evaluate existing liner disturbances to determine whether use could cause or intensify erosion problems.
5. Minimize the number of new access roads to the project site through comprehensive road planning.
6. Place new access within or adjacent to existing developments to minimize impacts and reduce the project footprint.
7. Determine the minimum standard dimensions of access and site footprint to accommodate specific foundation and structure construction needs.
8. Determine whether sufficient time is available in the project schedule to obtain all permits and permissions necessary to construct new access in sensitive areas.
9. Minimize the number of stream crossings within the project area. If additional new access is required, choose stable stream crossing locations, preferably not in areas identified as having critical or important fish habitats. Alternatively, select design crossing structures that do not impede stream flows.

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10. Consider constructing foundations that optimize seasonal conditions: (a) when the ground is frozen and vegetation is dormant to minimize wetlands impacts, (b) delaying construction in agricultural areas until after harvest to minimize crop damage, and (c) delaying construction in forested areas outside of high-risk fire danger periods.
11. Compare alternative access methods compatible with the proposed construction, in order to evaluate impacts to sensitive areas and associated costs.
12. Use wide-track vehicles and matting to reduce soil compaction and rutting in sensitive soils and natural areas.
13. Consider the use of foundation alternatives that do not require access road construction (transport equipment, materials, and workers to sites via helicopter, boat, barge, or marsh buggy).
14. Determine supplemental best management practices (BMPs) needed to mitigate impacts from selected access alternatives (such as silt fences, containments, dust suppression, buffer zones, mulching, nets/blankets, drainage culverts, straw wattles, geotextiles, berms, stabilized construction entrances, etc.).
15. Devise monitoring to occur during and after construction for the assessment of the effectiveness of access road mitigation measures.
16. Establish a reclamation plan for temporary access roads.

5.1 Access Roads

Use of existing or construction of new roads is the most common approach taken for accessing transmission structure sites for all facets of line construction. Access roads are temporary or permanent travel ways (typically 4 to 10 meters wide), that provide safe, fixed routes of travel for moving equipment, workers, and materials along the line route. It is important to first determine if access roads are able to provide a permanent channel for the construction, operation, and maintenance of the line, and whether they are available for emergencies. Permanent roads are typically designed for long-term operations, and generally include vegetation removal, grading, drainage installation, and gravel surfacing. Temporary roads are constructed to a much lesser standard, and are either abandoned or restored to the original land use condition after the completion of construction.

Ungraded access trails are often required under terrain conditions which make the construction of a road impractical or unnecessary. Minimal vegetation clearing is performed so that soils are protected by plant root systems (mowing may be done in lieu of clearing). Minimal grading may be done to provide a safe drive surface, or to redirect storm water and to mitigate local erosion. This practice is also done in croplands where permanent access is not compatible with long-term land use. Restoration and BMPs may or may not be required, depending upon the environment and permit requirements.

In lieu of new access roads that fall under or directly adjacent to lines, many projects will construct temporary or permanent access via the construction of short paths that branch from existing roads. These spur roads are used to limit disturbance, to avoid sensitive areas, or to provide better access in rough terrain (**Figure 5-1**).

Figure 5-1: Spur Access Roads to Tower Sites.

Review of the literature suggests the following common practices for access roads:

- Restricting all vehicle movement outside the power-line right of way to designated access roads or public roads.
- Limiting practices that widen or upgrade existing access roads, except in cases of repairs, so as to make them passable in areas with sensitive soils, vegetation, and archaeological sites.
- Opting not to blade new roads at perennial streams, designated recreational trails, and irrigation channels.

Additional considerations need to be taken for the abandonment of temporary access roads:

- Restoration should be sufficient to prevent long-term erosion of the former drive path,
- Road access should be blocked to prevent use by unauthorized off-road vehicles.

5.2 Ice Roads and Frozen Ground

Temporary access to transmission line structure sites can be accomplished via winter access roads, including either frozen ground or those built across ice (both natural and man-made). Access to structures in shallow standing water and saturated or otherwise unstable soils is more feasible during frozen conditions. The development of frozen ground and ice roads can begin as soon as freezing conditions are sustained and there is sufficient frost or snow to support lightweight or low ground pressure equipment.

Frozen ground provides bearing support for equipment that otherwise would not be available in unfrozen periods. Frozen conditions can also make environmentally sensitive areas less susceptible to damage by reducing soil degradation and soil structure damage. Frozen ground does not inhibit foundation construction, as augers and excavators are sufficient capable of breaking through the hard upper layer. A pre-augured pilot hole may be needed for helical auger and driven pile construction.

The use of frost roads can be a less expensive alternative to other equipment access options (such as timber mats). However, the development of frozen ground requires sustained freezing weather conditions that provide sufficient time for the construction of foundations. These conditions are limited to northern and Rocky Mountain states in the U.S., many parts of Canada, and other high altitude/latitude climes around the world that experience frozen conditions for shorter periods of time.

To expedite freezing, snow should be removed from the ground surface, or packed along the access road route to reduce insulating properties. Regular snow removal and plowing with earthmoving equipment helps maintain the ground's frozen state. This action also smooths the access road for driving and working along the line. Continued travel with heavy equipment also drives frost deeper in the subsurface, as soil moisture is squeezed closer to the surface and exposed to freezing temperatures. Water trucks may also be used to spray the road and build the frozen layer.

Surface and subsurface conditions can influence the feasibility of frozen ground development. Deep organic soils that generate heat through natural decomposition can increase the difficulty of frost development. Thick vegetation can also act as an insulating blanket, preventing or slowing frost development. Sometimes it is necessary to maintain a thin layer of snow on frozen ground to reflect radiant solar energy, and to minimize thawing as the day warms. Exposed dark soils can also absorb heat and accelerate thawing.

It is important to understand that soil temperatures can change during cold weather months. A thawing of the frost road could result in limited access and a reduced ability to avoid impacts upon sensitive resources. Construction mats or timbers should be kept available and used as needed to proceed with foundation construction.

A case history offers an example of the usefulness of ice roads and frozen ground for transmission line foundation installation. A 96-km segment of a project in Alaska required driven piles installed for each of lattice transmission tower footings. Pile diameters ranged from 250 to 760 cm, with embedment from 12 to 21 meters below grade. Subsurface conditions encountered included permafrost comprised of dense to loose silts and gravels. Access required frozen ground conditions. The contractor reported that almost 90 percent of the pilings were installed before the company was forced to stop in early spring, when they lost their ice road permits for the season. The remainder of the foundation work was complete within a few weeks once the ice roads were available the next winter (Wyman, 2009).

5.3 Mats and Geotextiles

Wood timbers, composite wood laminate mats, and high-density polyethylene (HDPE) mats are frequently used to create temporary access and spur roads for transmission line construction projects. These mats are used primarily in wetlands, farm fields, and other environmentally sensitive areas to protect underlying soils and vegetation. Various line projects have used mats as spur roads to access individual structure sites, or contributed to the creation of right-of-way access roads for the full length of the line. There are many vendors across North America that provide mats regionally. Matting is often viewed as a low cost alternative to graded and surfaced access roads.

Matting enables contractors to access sensitive areas safely, and minimizes their environmental impacts. Linings are typically incorporated into mattings to prevent contamination. Wood mats risk possible cross-contamination transport of undesirable plant species, so caution must be taken to properly clean prior to removal from the site. Once removed, vegetation often self-restores in the previously covered areas. Disking may be needed in farmed fields to loosen compacted ground, and to enhance crop growth.

Mats of all types are used to cross fields, access farmlands, and to bridge small creeks (**Figures 5-2 through 5-4**). Due to low cost and the ease of material procurement, mattings are extensively used in wet environments. Interlocking composite wood and HDPE mats tend to have better performance in swampy soils than timber mats, due their need to move under traveling loads. Interlocking mats also distribute equipment weights across a large surface area. HDPE mats incorporate a tread pattern for the improvement of traction and safety. Timbers (typically 200 cm thick or greater) placed lengthwise have been used as matting for decades, and are very effective with heavy traffic and high loads. The selection of a matting type must consider weight, durability, environmental cost, and transportation in relation to the work site location and conditions.

Figure 5-2: Typical Wood Matting for Transmission Line Access.

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Figure 5-3: HDPE Matting Crossing Farm Field.

Figure 5-4: Completed Wood Matting Access Road in a Wet Environment.

Typical difficulties encountered with matting include: floating during rain events, thickness not meeting bearing support requirements of construction vehicles, sinking due to ground freeze-thaw cycles, and short life cycles due to heavy use and frequent relocation.

Geotextiles are used for permanent access and reduce the need for thick aggregate base roads. Various geotextiles have been used to stabilize the ground along access roads, with geogrids most commonly applied. Thin layers of gridded HDPE fabric are laid both below and between gravel layers (**Figure 5-5**). When compacted, the system locks and bridges weak subsurface soils. Geogrid road and pad design thickness varies from 0.2 to 1.5 m, depending on the instability and moisture content of subgrade soils. These stabilized access roads are very resistant to erosion and washout due to their permeable nature.

Figure 5-5: Use of Geogrid in Wet Environments (Tensar UK, 2016).

5.4 Air (Helicopter) Access

Helicopters have been in use to support the utility industry since 1947 when the first civilian certified aircraft became available in the United States. Usage expanded as technology improved, and as more applications were found in the transmission line field. The first use of these aircrafts by a line contractor was in 1966 (Irby Construction, 2017). Helicopters can both provide a working platform to perform aerial construction, maintenance, and inspection, and they can also deliver equipment, materials, and workers to structure sites without the need for access roads.

A helicopter's use and success for transmission line construction is dependent on the power output of the engine and the lift produced by the rotors, whether it is the main rotor or the tail rotor. Helicopters can provide access to remote and sensitive environments, despite being limited by payload and climatic conditions. Any factor that affects engine and rotor efficiency affects performance. The three major factors that affect performance are: 1) density altitude, 2) weight, and 3) wind. Helicopter performance hinges upon whether or not the helicopter can be hovered. More power is required during the hover than in any other flight regime. The Erickson Aircrane has a rated lift capacity of up to 11,340 kilograms. Comparatively, Chinook (a civilian version) is capable of carrying similar loads, and both can tote complete tower structures and large poles. Many utilities own small capacity helicopters for maintenance reconnaissance use, which is likely not to meet requirements for foundation installation.

Helicopters transport items using a sling system. Generally, the sling system can be made from an appropriate length of non-twist steel cable for non-energized line work, or for new construction and ultra-high modulus, such as: polyester, spectra, technora and other synthetic lines, used when working near energized lines to maintain obstacle clearance.

Helicopters are frequently used to transport micropile foundation rigs to remote and sensitive areas. Vibratory caisson foundations have been installed using helicopters to place the caisson and to hold the vibratory hammer in place while in operation. These operations are not without cost, but may be the optimal situation if access is not feasible, or permits the construction of traditional access outside of project timelines.

Industry guidelines have been developed for helicopter use with utility activities. The Utilities, Patrol, and Construction Committee (UPAC) of the Helicopter Association International, maintains the UPAC Safety Guide for Helicopter Operators. The purpose of these guidelines is to offer general information and recommendations for the mitigation of associated risks: (a) for those individuals and companies involved in utility (power line or pipeline) patrol and inspection (routine or detailed); (b) for those involved in power line construction and related maintenance operations; and (c) to aid in the selection of qualified contractors for these operations. Section 6 of this document offers safety guidelines, intends to give utilities guidance when selecting helicopter contractors for the performance of energized and non-energized Line Work, as well as Patrol, Construction, Maintenance, Inspection, and other helicopter-related support functions.

5.5 Water Access

The installation of foundations along coastlines, on islands, in marshes, or within open bodies of water, limits available options for investigations, foundation materials, construction methods, and access. Designers often favor underwater or underground high voltage cables when crossing open water. Yet, cost, maintenance, environmental impact, and reliability factors may drive the project to the selection of overhead construction methods. Construction access in these conditions must rely on amphibious systems. Where water is shallow, mats or sand bags can be used to extend driving from the shoreline. Otherwise, foundation sites must be reached by the use of barges, buoyant pontoon carriers, or specially designed vehicles knows as "marsh buggies." These transportation methods are used for both geotechnical investigations as well as for foundation construction.

Barges offer the opportunity to both transport and work from a dry floating surface (**Figure 5-6**). The construction process includes building an accessible barge ramp or dock to load and unload equipment and materials. Case history research demonstrates several transmission line projects in which barges were used to provide foundation construction access (Shanmugasundaram, 2009; Norman, et al, 2009; Carlson & Huffman, 2011; Richardson & Bennett, 2012; Xcel, 2014a).
Marsh buggies are lightweight amphibious tracked vehicles designed to have less impact on wetlands than conventional vehicles, and to help minimize impacts on the surrounding environment.

Sometimes known as swamp buggies, these vehicles are designed to move foundation construction equipment on dry land, and also to traverse boggy terrain, shallow mud, sand shallow water, and sometimes deep mud. Vehicles have raised bodies and are typically track-mounted, with some models designed with an amphibious undercarriage, giving the craft the ability to float in and propel itself through water.

Figure 5-6: Barge in (Stake in Photo) Position to Drive Caisson (Norman et al. 2009).

Since marsh buggies come in variable sizes and capacities, they are used both for access during geotechnical investigations, and for foundation construction. American Transmission Company utilized a 7.6 m long by 4.3 m wide marsh buggy to perform investigative soils borings, and hauling equipment for 10 structure sites of a 32-mile 345kV transmission line (ATC, 2010). This equipment was used to minimize disturbances within the environmentally sensitive Yahara Wetlands. A similar ATV-like vehicle was used to transport the geotechnical crew and supplies to the rig on a daily basis, while an oversized version supported a 36,000 kg trackhoe. Case histories using marsh buggies for transmission line foundation construction include:

- Micropile foundations were constructed for 11 steel pole structures located within the Ebey Slough Basin via the use of marsh buggies and buoyant tracked pontoon carriers for the transportation of equipment, materials, and personnel to foundation locations. Booms on the marsh buggies were also utilized to set sheet pile rings, which were used as containment basins during drilling, and as forms for the concrete caps (PSE, 2008).
- Portions of a 45-km long new 500kV transmission line were constructed within Florida's wetlands using five specially designed amphibious marsh buggies. The vehicles were constructed according to the following dimensions: 9.1 m long by 1.5 m wide by 1.5 m high double pontoons, with a cargo capacity of 13,608 kg, weighing up to 22,680 kg. The vehicles could crawl through mud on tracks, and were self-propelled when floating in water. Drilled shaft foundations within permanent casing were constructed with depths up to 18.3 m from the vehicles. Cranes mounted on the marsh buggies lifted anchor bolt cages, pump hoses, and other equipment (Givens, et al, 1996).

- 500kV guyed anchor tower transmission line foundations in Minnesota peat bogs required restoration. Custom manufactured marsh buggies traversed muddy ground and peat, transporting excavators and trucks (weighing up to 30,000 kg). They were also used as platforms to install foundation anchors. Upon completion of the project, the utility kept two vehicles for use in emergency-response situations (Xcel, 2014b).

5.6 Manual Labor

In cases where access is prohibited, and when the construction of roads and the use of helicopters is not feasible or cost effective, manual labor is sometimes relied on to transport equipment, excavate foundations, and place materials (**Figure 5-7**). Distances to foundation sites are generally short (a few hundred meters at most). Helicopters may be used to place workers near the foundation. Examples of this type of access are provided in the examined literature (Lakhapati, 2009; Porter and Hynchuck, 2009; author's files).

Frequently, these foundation types are installed in bedrock conditions. Manual jackhammers or small track-mounted drills run by gas-powered air compressors are often used to excavate the subgrade. These methods can be supplemented by the use of expansive grouts, which work to fracture rock and improve the rate of removal. Rock is often removed from foundation excavations by hand. Anchor or reinforcement bars are either grouted in place, or formed for future concrete placement. If in close proximity, concrete is transported to the site by pipe or pumper truck. Otherwise, a helicopter is typically used to deliver concrete.

Manual labor is also commonly used to install rock or soil anchors for guyed structures, especially those with lower voltage line structures.

Figure 5-7: Access to Foundation Site feasible only via Travel by Foot.

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6.0 FOUNDATION ALTERNATIVES

6.1 Introduction

Foundation design methods for transmission line structures have developed over the past century as either by-products of construction methods used by other industries (such as highway and railroad bridges), or from the unique nature of overhead line support structures (such as practices for direct embedment wood poles deriving from commercial telegraphy). Foundation systems were adapted to accommodate the uniqueness of transmission line structure loads, given that loading tends to create large eccentricities. The inclusion of elements such as concrete, buried wood beams and grillages, and guy wires with steel anchors, became necessary to relieve large lateral loading on pole structures, especially in weak soil conditions. Gravity foundations and simple pole embedment were no longer sufficient, as weights and heights increased, and as materials advanced to make structures stronger and more resilient.

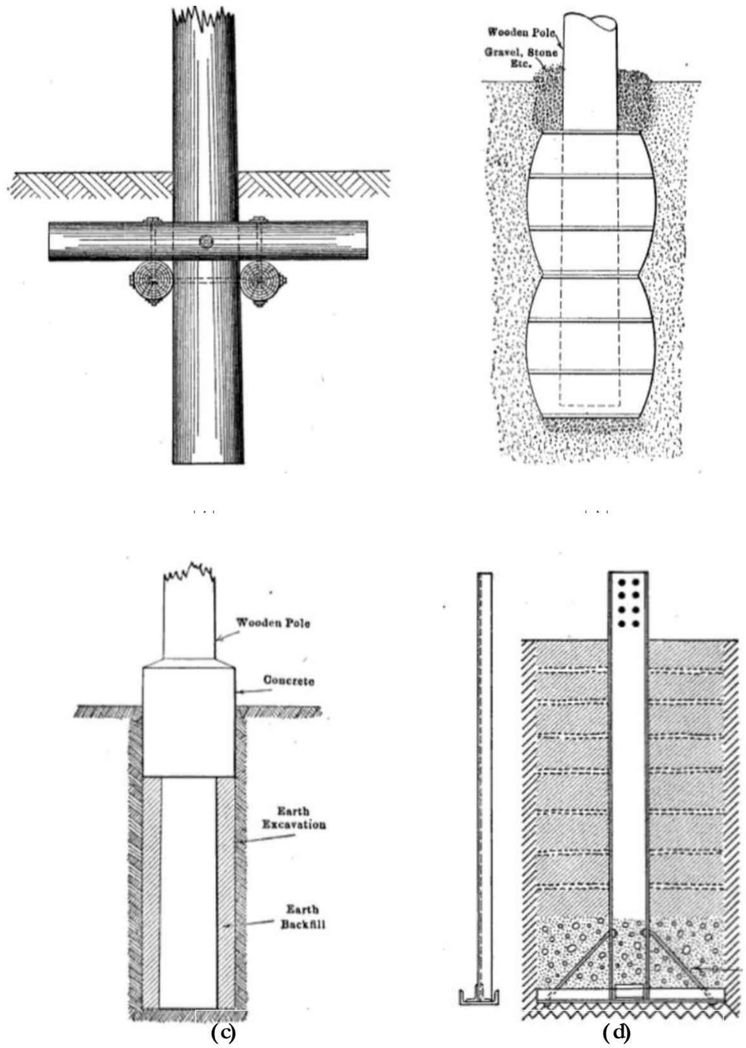

Figure 6-1: Various Foundation Supports in Weak Soils (Coombs, 1916).
(a) Bog Shoe; (b) Barrel Foundation; (c) Ground Line Concrete Envelope
(d) A-frame foundation

Coombs' (1916) text on the design of overhead pole and tower lines describes a trial-and-error approach taken to founding support structures, and the need to standardize design. This text provides one of the first recommendations for minimum wood pole embedment depths (the rule of thumb method), and an early recognition of the necessity to adapt design for "bad ground" conditions (**Figure 6.1**). Most significantly, the author recognizes the need to adapt foundation design in a manner that accommodates the environmental conditions found at site. For example, conceptual design recommendations are provided for foundations in peat bogs, where hand-carried equipment (wooden barrels and sand) could be buried with the embedded pole to better distribute lateral pressure against weak soil (as seen in (b) of **Figure 6.1**).

Today the engineer has a wide array of tools and techniques available for founding transmission line structures when compared to the past century. However, just as it was over a century ago, conditions, economy, available equipment, and site access still drive how these methods are used for design and construction. This section discusses the most common foundation design and installation methods in present use, and available alternate foundation systems.

The foundation types described herein are presented in terms of advantages and disadvantages inherent to each system, in relation to design and construction in sensitive environments, or in cases where construction difficulties are expected. Descriptions of foundation systems, along with design methodologies and models, are given in general form to provide an understanding of the information needed to design and construct. Equations for foundation design are reported without safety or resistance factors to illustrate model relationships. Depending on design approach (reliability-based or allowable stress), resistances ought to be reduced as appropriate.

The engineer's final design must include these factors to ensure proper foundation performance. This report should not be considered a design manual, as details of design are intentionally omitted, with the reader accordingly guided to more comprehensive texts. The purpose of this section is to present foundation options and models for various transmission structure types and their use in sensitive environments. Directions are given to the reader for selecting the most advantageous option or options for their particular situation.

Traditional foundations are delineated as those most commonly in use or used in the recent past. These include driven piles, drilled shafts, direct embedment poles, steel grillages, spread footings and steel anchored structures. Foundation types listed as traditional are identified in the IEEE foundation design guide document 691 (IEEE, 2001).

Alternate foundations and methods are examined and uncovered during the literature review, and the industry survey examines alternative foundations in active use, though these are not considered traditional by most practitioners. These include helical anchor piles, vibratory caissons, micropiles, rock anchor/sockets, and auger cast piles. In addition, a short discussion is given on horizontal directional drilling for underground line installation, as this technology is used primarily in sensitive environments as a substitute for overhead lines and structure foundations. Tabular comparative summaries are presented at the end of the section to allow direct comparison of traditional and alternate foundation types.

6.2 Traditional Foundations

6.2.1 Driven piles

Driven piles are deep foundational elements constructed by impact driving prefabricated structural members made of concrete, steel or timber to create a foundation that will support anticipated loads. These foundation elements are relatively long, slender columns (depth-to-diameter ratios in excess of 10:1) with a design-specific shape and size, which provides load resistance primarily by side friction and/or end bearing (PDCA, 2015). Driven piles can be classified by the different shapes and materials, such as steel pipe piles, steel H-piles, concrete piles, timber piles, cylinder concrete piles, and composite piles (note: steel H-piles and closed end round steel piles are common options for supporting steel lattice towers for transmission systems).

Driven piles are typically embedded into the ground and structurally tied together with a steel or reinforced concrete cap (**Figure 6-2**). Piles can be installed vertically or with a batter if required. Reinforced tips are often welded to the end of piles, to prevent damage to the pile caused by driving into underground obstructions or hard strata (EPRI, 2012). Single or multiple large diameter piles (greater than 300 mm) may be used to support individual poles or towers via the use of above grade steel structural members. These piles are frequently modified with fins to improve uplift capacity.

Figure 6-2: Driven Pile Foundation: ATCO Electric Hanna Region Transmission Development Project. (ATCO Electric, 2012)

Axial compression and uplift loads are resisted by the side friction, while end bearing supports compression resistance. Except for large diameter piles, lateral shear loads are resisted by the use of battered pile groups. It should be noted that most piles provide resistance via a combination of skin friction and end-bearing, even though they are often classified as friction piles or end-bearing piles. Even though a pile driven in clay has small end-bearing capacity, it is primarily resisted by friction. However, the vast majority of the piles that are driven into granular soil have combined skin friction and end-bearing capacity (NYSDOT, 2015). Driven pile foundations are typically characterized by low displacement and high bearing capacity (ODOT, 2016).

6.2.1.1 Pile Design

Driven pile design is performed by the use of one or more of the following methods:

1. Static analysis using soil strength parameters;
2. Empirical correlations with field data such as SPT-N values, known empirical factors, or cone penetrometer results;
3. Dynamic analyses estimated prior to installation and determined during installation via wave equations.

The pile capacity analytical methods listed only provide an estimate of capacity. Load testing is needed to determine with certainty the actual uplift or compression resistance. Due to high costs and the time-consuming nature of the operation, load testing is rarely performed for transmission line driven pile foundations.

6.2.1.2 Static Analysis

Static pile capacity analysis methods use the strength and deformation properties of soil layers (such as the angle of internal friction or the cohesion), to estimate pile ultimate capacity and performance. Soil parameters may be determined from laboratory tests on undisturbed samples or estimated from correlations to field test data. Static capacity is defined as the sum of side shear resistance of the pile-soil/rock interface and the available end-bearing resistance to the applied load. It can be computed using the following general equation:

$$Q_c = Q_b + Q_s$$ Equation 6.2-1

Where,

Q_c = Ultimate compressive capacity (kN);
Q_b = Ultimate end-bearing resistance (kN);
Q_s = Ultimate side shear resistance (kN);

End-bearing resistance can be obtained once the base area of pile and bearing resistance per unit area is known. If a cylindrical pile is assumed, bearing resistance can be described as:

In cohesive soil: $$Q_b = 9c' \frac{\pi}{4} B^2$$ Equation 6.2-2

In cohesionless soil: $$Q_b = N_{\gamma,q} \gamma' \left(\frac{B}{2} + L\right) \frac{\pi}{4} B^2$$ Equation 6.2-3

Where,
c' = Effective soil cohesion (kPa);
γ' = Effective soil unit weight (kN/m^3);
B = Pile diameter (m);
L =Length of pile (m);
$N_{\gamma,q}$ = Average of bearing factor N_γ and N_q (dimensionless);

For uniform soils and a cylindrical pile of diameter *B* and length *L*, the simplified equations for side shear resistance are as follows:

In cohesive soil: $$Q_s = \pi B L_s \alpha_c c'$$ Equation 6.2-4

In cohesionless soil: $$Q_s = \frac{\pi}{2} B \alpha_\phi L^2 \gamma' tan\phi'$$ Equation 6.2-5

Where,

c' = Effective soil cohesion (kPa);
γ' = Average effective unit weight of the soil for the length of the pile (kN/m^3);
ϕ' = Effective angle of internal friction (°);
B = Pile diameter (m);
L_s = Length of pile developing side shear (m);
α_c, α_ϕ = Cohesion and friction reduction factors (kPa).

See Spangler and Handy Chapter 22 and 23 of *Foundation Analysis and Design* for a detailed discussion of pile design (Spangler & Handy, 1982).

6.2.1.3 Empirical Methods

Empirical methods are typically used to provide a preliminary estimate of driven pile length. A number of empirical correlations exist with cohesion-less soils between Standard Penetration Test (SPT) results and static pile load tests. The most common (as developed by Meyerhof, 1976) are as follows:

q_{si} = 2N' ≤ 100 kPa (closed end pipe and concrete displacement piles) Equation 6.2-6

q_{si} = N' ≤ 100 kPa (non-displacement piles such as H-piles) Equation 6.2-7

$q_{pu} = 400N'_o + (40\ N'_B - 40\ N'_o)L_B/B \leq 400\ N'_B$ (kPa) Equation 6.2-8

Where
q_{si} = Unit skin resistance value (kPa);
q_{pu} = Unit end bearing resistance value (kPa);
N' = Average corrected SPT resistance value along the embedded pile length;
N'_o = Average corrected SPT resistance value for the stratum overlying the bearing stratum;
N'_B = Average corrected SPT resistance value of the bearing stratum;
L_B = Pile embedment depth into the bearing stratum (m);
B = Pile diameter (m).

For piles in cohesive soil, consistency in terms of Cone Penetrometer Testing (CPT) unit cone tip resistance (q_C) can be correlated to SPT N-values to estimate unit side resistance, as provided in the previous equations. The relationship between N and q_C is represented as follows (Yenumula, 1997):

q_C = 200 N (kPa) Equation 6.2-9

For piles in clay, total stress analysis is often used to determine ultimate capacity, assuming that shaft resistance is independent of effective overburden pressure. Unit shaft resistance is expressed in terms of an empirical adhesion reduction factor multiplied by the undrained shear strength:

$$q_{si} = \alpha\, c_u \qquad \text{Equation 6.2-10}$$

Where

q_{si} = Unit skin resistance value (kPa);
α = Empirical side shear reduction factor;
c_u = Undrained shear strength (kPa).

The "alpha" method is commonly referred to as the Tomlinson Method (1977). Various researchers have derived alpha values for driven piles based on pile geometry, pile material composition, strata overlying the clay layer, and clay layer undrained shear strength.

CPT is often described as a "model pile," since the test applies axial loading to a static cone that acts as a single pile. Cone penetration resistance generally correlates well with that of a driven full-size pile under static load conditions. Details of the various CPT methods along with other empirical SPT methods can be found in the FHWA Design and Construction of Driven Pile Foundations Manual (Hannigan, et al, 2006).

6.2.1.4 *Dynamic Analysis*

Numerous equations have been developed to estimate the ultimate capacity of driven piles. However, none of the equations are consistently reliable. Therefore, the best approach for predicting capacity involves driving a pile, recording the driving history, and measuring the load on the pile using field tests. Dynamic formulas have been widely used to estimate pile capacity in lieu of driving the pile to a predetermined depth. Predictions tend to improve when a load test in conjunction with the equation is used to adjust the input variables. The basic dynamic pile capacity formula is derived from and dependent upon impulse-momentum principles:

$$Q_c = \frac{e_h W_r h\left(W_r + n^2 W_p\right)}{C\left(W_r + W_p\right)} \qquad \text{Equation 6.2-11}$$

Where,
Q_c = Ultimate compressive capacity (kN);
e_h = Hammer efficiency (%);
W_r = Weight of ram (for double-acting hammers include weight of casing) (N);
W_p = Weight of pile including weight of pile cap, driving shoe, and capblock (also includes anvil for double-acting steam hammers) (N);
c = Height of fall of ram (m);
n = Coefficient of restitution (dimensionless);
C = Instant pile top displacement (m).

Dynamic formula have been developed by other researchers based on similar assumptions (See Bowles, 1996, Chapter 17, *Foundation Analysis and Design* for the details of dynamic analysis).

6.2.1.5 Driven Piles Construction

Driven pile foundations are transported and held by crane or track-vehicle, while mounted pile drivers install foundations via impact hammering, vibrating, or pushing into the earth. This equipment requires paved roads, stoned and graveled roads, matted access drives, or barges on waterways to access construction sites. Piles are prefabricated and transported to the site, and construction is accordingly rapid. Group installations are common, and piles can be placed vertically or at a batter.

Driven piles are best suited in soil with end bearing in dense cohesion-less soil or on rock, and are typically used to penetrate soft/loose upper strata where bearing or uplift is questionable. Piles can be damaged, and drift or refuse can occur early in very dense soils, cemented soils, and strata with boulders or manmade obstructions (debris). These foundations may conveniently be used in locations with ground water, over open water, or along coasts, as no casing or open shaft drilling is required (Builder's Engineer, 2016). Steel pile caps or formed reinforced concrete pile caps are needed to transfer loads from the structure to the foundation.

Improper arrangement or installation may cause adjacent finished driven piles to lift during the driving of a new pile nearby. Driven piles result in minimal ground disturbance and backfill is not required for their installation. Noise and vibration during installation ranges from moderate to severe, and dust levels are moderate. Caution must be exercised when driving piles adjacent to existing structures, as they are likely to be affected by the vibrations generated during installation operations. Special hauling permits are typically not required, due to the short length and small diameter of most transmission line pile foundations. Methods protecting steel against material loss (coatings or sacrificial) and corrosion require further consideration.

6.2.2 Drilled shaft

A drilled shaft foundation is a large diameter, poured in-place reinforced concrete cylinder (shaft), constructed vertically into the ground (**Figure 6-3**). A stabilized circular hole is excavated into subsurface soil and/or rock to allow for the controlled placement of reinforced concrete. Pole-type transmission line structures are most often fixed to foundations via steel anchor bolts, which can be partially or fully extended within the drilled shaft. It can also be made part of the reinforcement cage or contained within (and separate from) reinforcement. Lattice tower structures attach to drilled shaft foundations by a steel stub angle embedded into the center of the shaft. Most often, a separate steel reinforcement cage is incorporated into the design. The shaft is formed above grade and then filled with concrete. Drilled shaft foundations are typically uniformly cylindrical, but they can also be drilled with tapers, uniformly variable shaft sections, or with belled bottoms.

Reinforced concrete drilled shaft foundations are used to support a wide variety of transmission system structures, including lattice towers, single shaft steel pole structures, and multi-pole structures. Foundation lateral loading is most significant for single pole and multi-pole structures, while uplift and compression axial forces control the design of drilled shaft foundations with lattice towers. Large diameter drilled shaft foundations are capable of providing substantial resistance to lateral forces and overturning moments. Axial forces are resisted by a combination of side shear and end bearing. With high voltage transmission line structures, typical diameters range from 0.7 m to 4 m with depths up to 30 m. The foundations are typically considered short piers with depth-to-diameter ratios from 2 to 10.

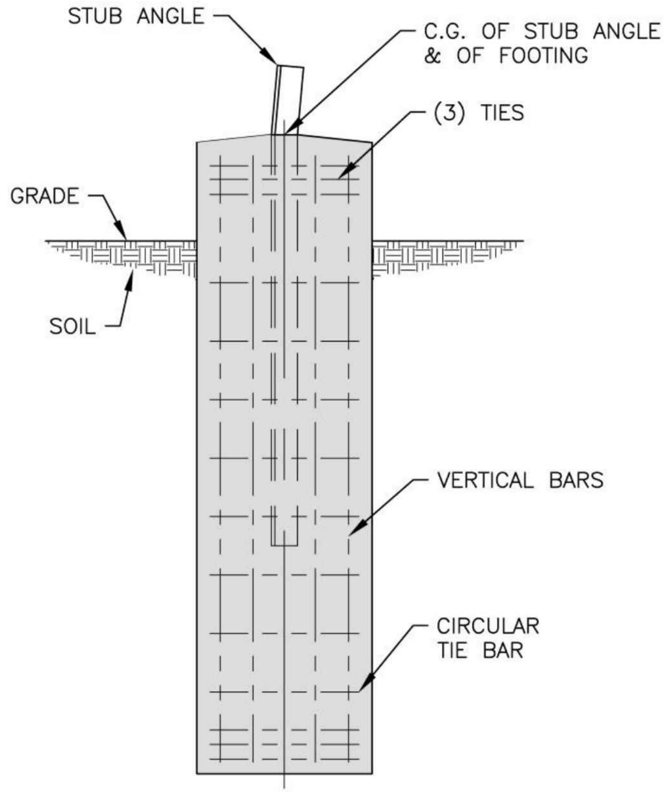

Figure 6-3: Drilled Shaft with Stub Angle.

6.2.2.1 *Drilled Shaft Design - Axial Loading*

The design of drilled shafts for axial loading requires the analysis of strength and service limit states for compression and uplift forces. Resistances consist of combined side shear and base capacity, as shown in **Figure 6-4**. Generally, side and base resistance developed as a function of shaft displacement, and the mobilized resistance of each occur at different displacement points (Kulhawy, 1991). Therefore, the differences in side and base resistance mobilization, as functions of axial displacement, should be considered in design (Brown, et al, 2015).

The general form of axial drilled shaft design capacity in relation to a transmission line foundation is identical to that of a driven pile, and is shown as follows:

In compression:

$$Q_C = Q_S + Q_b - W \qquad \text{Equation 6.2-12}$$

In uplift:

$$Q_U = Q_S + W \qquad \text{Equation 6.2-13}$$

Where,
Q_b = Ultimate end-bearing resistance (kN);
Q_s = Ultimate side shear resistance (kN);
W = Foundation weight (N).

Side shear and end-bearing resistance can be calculated by using the general equation forms:

$$Q_s = \pi B L q_s \qquad \text{Equation 6.2-14}$$

$$Q_b = \frac{\pi B^2}{4} q_b \qquad \text{Equation 6.2-15}$$

Where,
B = Shaft diameter (m);
L = Shaft length (m);
q_s = Unit side resistance (N);
q_b = Unit base resistance (N).

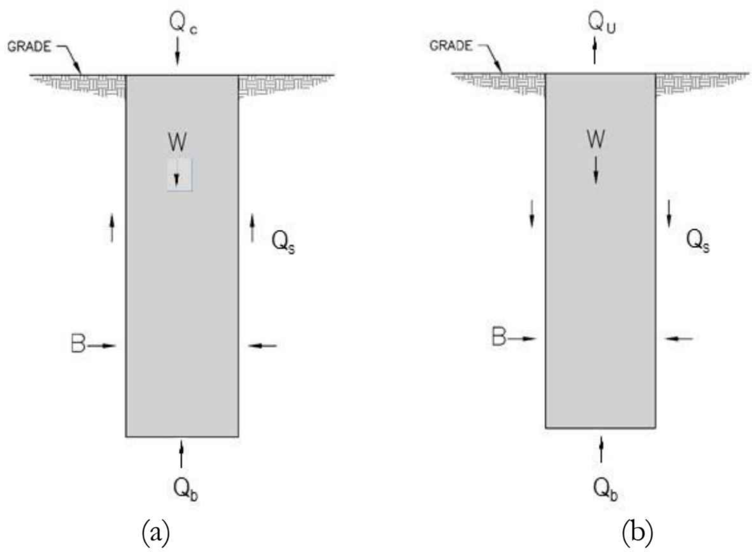

Figure 6-4: Axially Loaded Drilled Shaft Models (a) Compression; (b) Uplift.

With drilled shafts, side shear is determined using a cylindrical shear model. Nominal unit side resistance is dependent upon the soil strength parameters of friction, and undrained shear strength (cohesion):

$$q_s = \sigma' \, K_H tan\phi + c' \qquad \text{Equation 6.2-16}$$

Where,
σ' = Average vertical effective stress (kPa);
K_H = At-rest earth pressure coefficient (dimensionless);
ϕ' = Effective friction angle (degree);
c' = Effective undrained shear strength (kPa).

Only one of the strength parameters (undrained shear strength or friction angle) should be used to determine side shear, unless in cemented or over-consolidated unsaturated soil (or rock). Nominal unit side resistance in rock is primarily a concrete-rock bond capacity evaluation, typically correlated to uniaxial compressive strength.

End bearing is evaluated based on a derivation of Terzaghi's bearing capacity theory for continuous round foundations:

$$q_b = c'N_c + \gamma L N_q + 0.3\gamma N_\gamma \qquad \text{Equation 6.2-17}$$

Where,
c' = Effective undrained shear strength (kPa).
γ' = Effective unit weight (kN/m^3);
L = Shaft length (m);
N_c = Cohesion factor (dimensionless);
N_q = Surcharge factor (dimensionless);
N_γ = Weight factor (dimensionless);

Detailed design methods for determining axial load capacity for drilled shafts can be found in several design manuals (Brown et al., 2015; EPRI, 2012).

6.2.2.2 Drilled Shaft Design – Lateral Loading

Over the past sixty years, numerous analysis methods for predicting the soil-structure interaction of laterally loaded drilled shaft foundations have been developed. These methods attempt to model the load-deflection and/or load-resistance relationship (foundation capacity) of piers, with primarily lateral load applied at or near the ground line.

Most classical methods calculate a state of static equilibrium assuming ultimate lateral capacity is based on the passive resistance of soil along the vertical pier face (**Figure 6-5.a**). The theory assumes that there is a uniform mobilization of strength from top to bottom of the pier. For clays, the principle soil property that resists the load is undrained shear strength; for sands, the angle of shearing resistance. The theory also assumes purely elastic soil behavior. Most classical methods assume that deflection is independent of footing width (Broms, 1964, 1965; Czerniak, 1957; Hansen, 1961).

Rational solutions attempt to predict lateral soil resistance along the foundation as a function of pier deflection. It is necessary that conditions of both static equilibrium and compatibility of deformation are achieved simultaneously for all parts of the system. Based on the model, the foundation can be treated as either a linear elastic or non-linear elastic component, while the soil may provide linear or non-linear resistance. The load-deflection and load-rotation relationship for a laterally loaded drilled shaft foundation are highly non-linear. Classical methods tend to under-predict capacity, and to provide limited evaluations of movement only. Non-linear methods can include limits to lateral soil pressure resistance in relation to movement, commonly referred to as "p-y" analysis (**Figure 6-5.b**).

The "p-y" analysis involves the idealization of soil resistance via a series of relationships between local lateral pressure (p) and local lateral deflection (y) at various locations along the shaft. The shaft itself is modeled as an elastic beam supported by non-linear springs, whose characteristics are represented by the p-y curves. The bending of the shaft under lateral loading can be carried out by either finite differences or finite element analyses, which allows the relationship between lateral loading and deflection to be obtained.

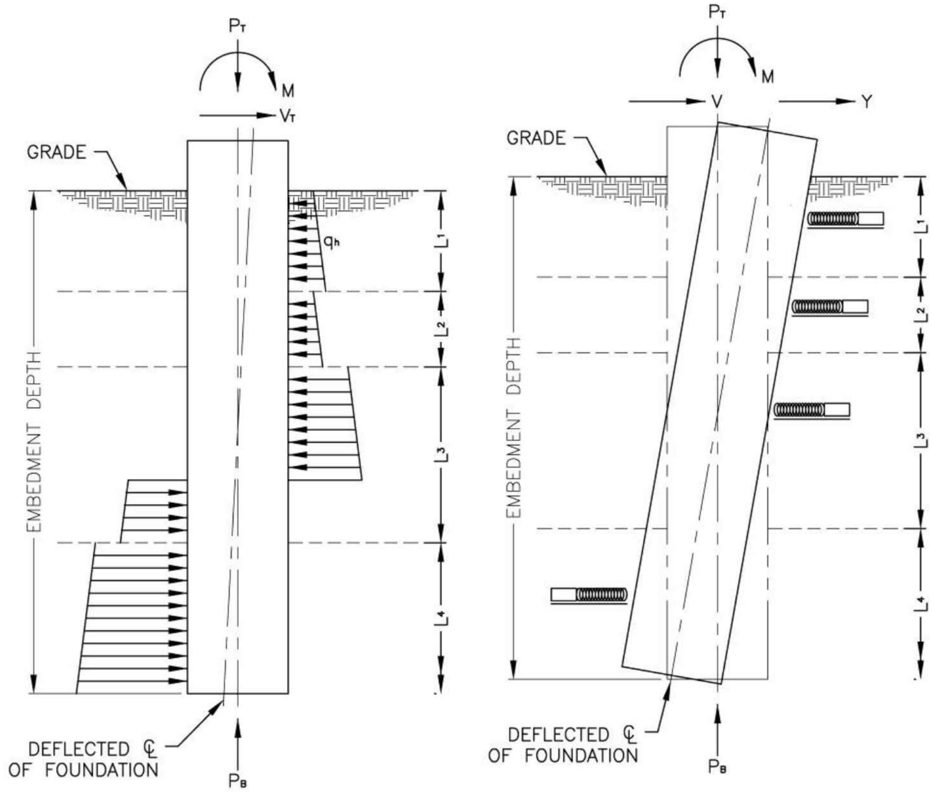

Figure 6-5: Laterally Loaded Drilled Shaft Models.
(a) Static Equilibrium Model; (b) Non-linear Elastic Model

Detailed design methods for determining drilled shaft lateral load capacity can be found in a number of federal, state, and electric utility research institute design manuals. The most comprehensive guides include the FHWA's Geotechnical Engineering Circular No. 10 (Brown et al., 2015), and the Electric Power Research Institute's (EPRI) Transmission Structure Foundation Design Guide (EPRI, 2012).

6.2.2.3 Drilled Shaft Construction

Rotary drilling equipment varies in size and design, as well as by the type of vehicle upon which the drill is mounted. For typical transmission line foundations, most must be driven to sites on developed access roads (paved, graveled, matted or graded). Additionally, concrete ready-mix transit trucks, along with cranes and other support vehicles required to lift and install steel reinforcement and/or anchor bolt cages, must also be driven to sites, and roads of similar quality are needed (see **Figure 6-6**).

Drilled shaft foundations can be installed in nearly any subsurface condition. However, boulders and very hard rock can significantly slow down construction. Casing or slurry stabilization is typically needed in weak or loose soil conditions, and in cases where high groundwater is present (i.e. tremie methods used to place concrete). Large quantities of concrete and heavy steel reinforcing cages are often required. Concrete can be placed during hot and cold weather conditions, but must follow good practices for mixing, transport, and placement in extreme weather conditions. Installation is done by either specialty or general contractors with experience in foundation construction.

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(a) (b) (c) (d)

Figure 6-6: Drilled Shaft Construction – Terrains.
(a) Access Road in Rough Terrain; (b) Concrete Placement Equipment in Floodplain;
(c) Drilling in Saturated Soil Conditions; (d) Construction in Cold Weather Conditions.

Ground disturbance ranges from moderate to extensive depending on shaft diameter, shaft depth, and the degree of caving or shaft raveling. Drilled cuttings need to be removed from the site, or (if allowed), distributed around the foundation site. Special hauling permits are not typically required for foundation materials, as drilled piers are built on-site. Noise, vibration, and dust are moderate with the use of drilled shafts. Reinforcement and anchor bolt cages along with formwork must be fabricated by experienced workers, but these can be either fabricated and hauled to the site or built in place (**Figure 6-7**). Concrete is vulnerable to accelerated deterioration when in contact with aggressive soils, chemicals, and groundwater. Sulfate resistant cement can be used in the concrete to increase concrete durability.

Figure 6-7: Drilled Shaft Construction.
(a) Monopole Reinforcement Cage; (b) Lattice Tower Pier Footing Formwork and Jig.

6.2.3 Direct Embedment Pole Foundations

Lower voltage transmission line structures with lighter loading conditions are frequently embedded directly into the ground without a secondary foundation system. Monopoles, either alone or as part of a multi-pole structure, made of steel, concrete, or wood, are embedded directly into the ground. The foundation is constructed by first auguring a shaft into the subgrade of sufficient diameter to fit the pole base, and to have adequate annular space for placing backfill between the outside of the pole and the shaft walls. The pole or base section of the pole is lowered into the excavation and held plumb, while the annulus around the pole is backfilled with concrete, cementitious slurry, compacted granular aggregate, or compacted native soil. Steel poles typically have backfill placed at the base of the drilled shaft, in order to create a level bearing surface for the pole (**Figure 6-8**).

Direct embedded foundations are widely used in transmission line systems, especially for single poles and H-frame structures. The embedded pole resists moderate overturning moments with good uplift capacity. With very stiff backfills, these foundations perform similarly to reinforced concrete drilled shaft foundations. The strength and stiffness of a direct embedment foundation is strongly influenced by the quality, method of placement, and the degree of compaction of the backfill (if native soil or aggregates are used), and usually result in performance variation.

Since poles are tapered, the drilled shaft diameter is a function of the butt diameter of the embedded portion of the pole. Drilled shaft holes (typically ranging from 0.4 m to 1.8 m in diameter) are oversized, creating an annulus between the embedded pole and the ground. Pole performance functions best when the annular space ranges from 150 mm to 300 mm in width. Permanent steel casing may be used to stabilize the drilled shaft where groundwater is present.

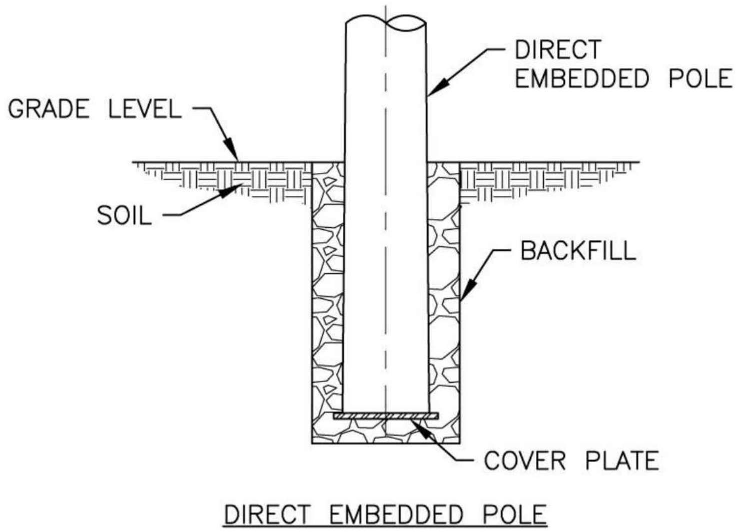


Figure 6-8: Direct Embedment Pole Foundation.

6.2.3.1 Traditional Embedment Design

Direct embedment pole foundations have traditionally been designed based on prescriptive methods (referred to as "rule of thumb"), where the embedment depth is based on some percentage of the pole length, plus a pre-defined additional length. This process has been sufficiently successful to prevent significant foundational failures for wood poles supporting distribution-level voltages. But for higher voltage lines, and in cases where steel or concrete poles are used, studies show that these methods significantly underestimate or overestimate required embedment depths, depending on soil conditions (Gajan & McNames, 2010; McNames & Gajan, 2009). This empirical approach is devoid of load condition assessment (uplift, compression, & lateral), and assumed to meet needs of all load modes.

Although direct embedment foundations and drilled shaft foundations respond similarly to axial and lateral loads, the principle difference lies in the interaction between structure and backfill, particularly in terms of load transfer and deformation. The pole must transfer loads to the backfill, and then to the supporting strata.

6.2.3.2 Axial Load Design

Backfill will significantly influence the uplift and compression capacity of a direct embedment pole. A weaker response is to be expected for compacted native soils (particularly clays), than what is typically seen with concrete annulus-fill. If the combined adhesion and friction resistance of backfill against the foundation is greater than the shear strength of the native soil, failure is likely to result in the native soil or at its interface. Alternately, if the backfill shear strength is less than the native soil, failure could occur in the backfill (IEEE Std 691, 2001). In the case where cementitious slurry or concrete is used as the annulus backfill, axially loaded direct embedment foundations may reasonably be modeled as drilled shafts (see **Section 6.2.2**).

EPRI studies developed a computer-based analytical model for direct embedment foundations, as part of the work done for drilled shaft analysis. The HFAD model uses a cylindrical shear for uplift and compression loads to compute nominal axial capacity, at both the pole/backfill interface and at the backfill/soil (or rock) interface. Pole embedment section weight is assumed to be included in the applied loads, and not in the computation of axial capacity. The model neglects end-bearing resistance, due to the variation in utility practices for bedding direct embedment foundations.

6.2.3.3 Lateral Load Design

EPRI computer programs can be used to calculate the lateral capacity of direct embedded poles. The MFAD model includes a subroutine to account for the annulus backfill surrounding a direct embedment foundation. The analytical expressions used in the model (**Figure 6-9**) include translational and side shear moment springs, to account for the differences in stiffness and shear strength between the in-place soil and the annulus backfill**.** The detailed design process is described in the original EPRI research report for direct embedment foundations (Bragg et al., 1989).

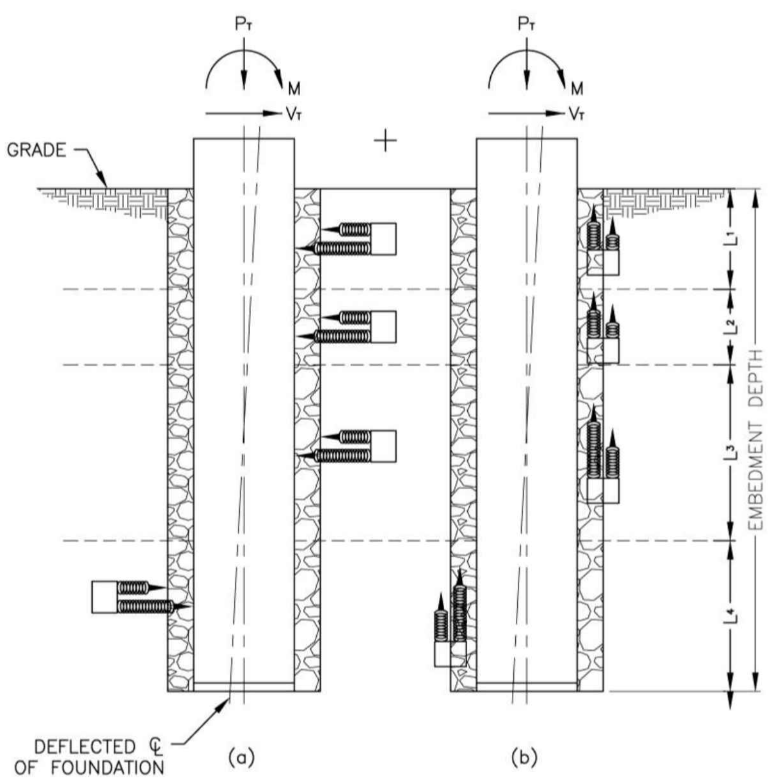


Figure 6-9: MFAD Direct Embedment Design Model.

Other methods have been adopted to determine proper pole embedment depths, exclusive of annulus backfill material and properties. The Southern Company developed both a nondestructive testing method to quantify soil stiffness, and a limit equilibrium analysis to determine the pole embedment depth. The nondestructive testing method involves a stress-wave based testing technique, coupled with a rational design methodology (Ong, et al, 2006). Another predictive methodology for wood poles assumes traditional static short rigid pile resistance in rotation, and evaluates lateral soil pressure distribution along the depth of embedment (Gajan & McNames, 2010; McNames & Gajan, 2009). Normalized relationships are developed to determine self-supporting wood pole embedment:

Cohesive soil (Gajan & McNames, 2010):

$$\frac{z}{L_P} = a\left[\frac{c_u D L_P^2}{M}\right]^b \qquad \text{Equation 6.2-18}$$

Cohesionless soil (Gajan & McNames, 2010):

$$\frac{z}{L_P} = a\left[\frac{D L_P^3 \gamma (\tan\phi)^{1.5}}{M}\right]^b \qquad \text{Equation 6.2-19}$$

Where,
z = design embedment depth (m);
L_P = total length of pole (m);
D = pole diameter (m);
c_u = undrained shear strength of soil (kPa);
ϕ = friction angle of soil (degree);
M = ground line moment reaction (N-m);
a, b = dimensionless coefficients from best fit regression curves
(cohesive soils: "a" ranges from 0.73 to 0.80, "b" ranges from -0.48 to -0.46)
(cohesionless soils: "a" ranges from 0.73 to 0.86, "b" ranges from -0.38 to -0.34)

6.2.3.4 Direct Embed Construction

Equipment similar to that required for drilled shaft foundations is used for the installation of direct embedment foundations. Paved, graveled, or graded roads, or matted access drives, are required to access construction sites for drilling and pole delivery equipment. Embedded pole segments are prefabricated and transported to the site, reducing the time required for installation. Placing concrete backfill via the tremie method is required in situations where high groundwater is encountered. Alternatively, compacting granular backfill is difficult under these conditions, and may be placed using gravity methods. Typically, these foundations are not practical for areas with open water. Concrete may be required for backfill.

These foundations can be installed in very hard to very weak soil conditions. and casing is also typically required in weak soil conditions. Running sands and soft cohesive material may cause excavation to collapse or squeeze, thus casing may be needed for this situation. Boulders and very hard rock can significantly slow the construction process. Installation may require casing or drilling mud in loose granular soils, as well as in soft cohesive soils. Due to groundwater, boulders, hard rock, and/or weak soils, direct embedment shafts do not always remain uniform (**Figure 6-10**). Backfill materials significantly influence pole capacity. Select materials, lean concrete, or flowable backfill materials should be used as backfill to limit deformation, and to ensure good performance (Haldar, et al, 2000).

Drilled cutting needs to be removed from the site or distributed around the foundation site (if allowed). Noise, vibration, and dust generation is moderate with these foundations. For one-piece poles, no connection between steel pole and foundation is required. However, multi-piece poles are connected to base embedment sections, and installed using either slip-fit or flanged connections. Galvanization, sacrificial steel, and/or coatings are required for protecting steel poles from corrosion.

Figure 6-10: Non-uniform Direct Embedment Excavation.

6.2.4 Steel Grillage Foundation

Steel grillage foundations are comprised of structural members, and used to support steel lattice tower structures. The grillage base consists of a grid of steel members or rows of I-shaped beams, laid at right angles to form a mat bearing on the subsurface at the base of an excavation. A single vertical beam or lattice steel frame pyramid pedestal extends up from the mat and connects to the stub angle of the tower leg. **Figure 6-11** shows an example of steel grillage foundation with a pyramid pedestal. Sometimes the mat, pyramid and/or beam are encased in mass concrete. However, compacted backfill is typically placed above the grillage mat and around the pedestal to the ground surface (EPRI, 2012). The grillage base can be square, rectangular, or any shape necessary to efficiently transfer the reaction forces to the soil.

Steel grillage foundations are typically used when structure loads are extremely heavy, and bearing capacity of the soil is poor (Maity, 2016). These foundations function as spread footing. Bearing pressures are developed at the mat base, through the application of axial compression loads and overturning moments via structure at the ground line. Uplift loads are resisted by the grillage foundation system weight, and by shear forces that develop along the sides of a prism, ranging from the ground surface to the top of the grillage mat around the footprint of the foundation. Lateral shear loads are resisted by lateral bearing pressures on the sides of the foundation, and by frictional forces on the base of the mat (if the footing is in compression). A steel grillage with a single beam pedestal may utilize horizontal shear struts.

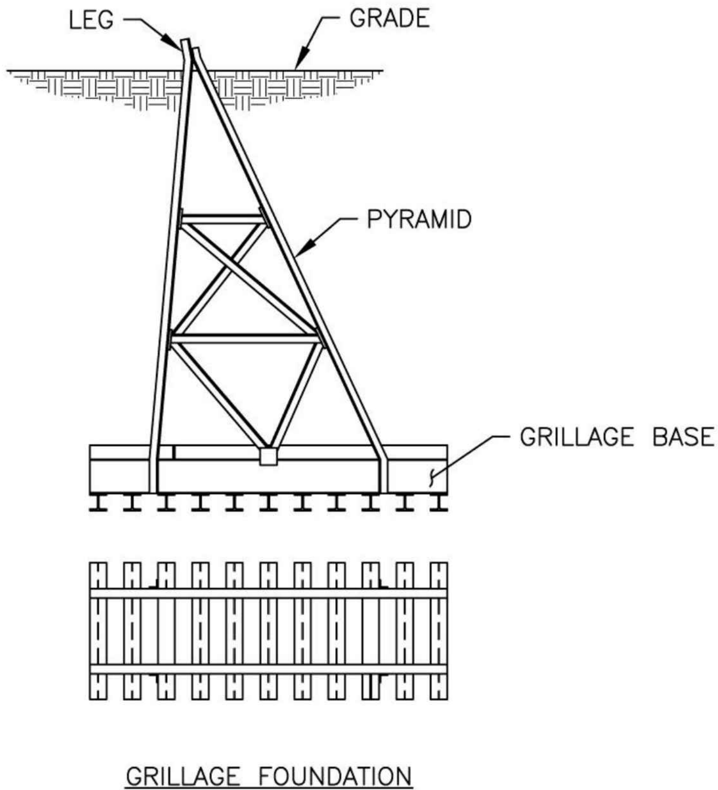


Figure 6-11: Steel Grillage Foundation.

6.2.4.1 Steel Grillage Foundation Design

Uplift capacity, compression capacity, lateral capacity under uplift, and lateral capacity under compression, must be determined as part of grillage foundation design. Four basic design models were evaluated or checked:

- Side shear under maximum uplift loads;
- Bearing capacity under maximum compression loads;
- Passive soil pressure from lateral loads under maximum uplift; and
- Sliding friction from lateral loads under maximum compression.

The uplift capacity (Q_u) of a steel grillage foundation is affected by the type of in-situ soil, the type of backfill material, the size of the grillage excavation, the location of the water table, plan dimensions of the grillage, and by the depth of the grillage. The general forms of the design uplift capacity models for granular backfill and cohesive soil are provided by the following equations (EPRI, 2012):

For granular backfill:

$$Q_u = 0.9\, W'_{bf} + V_{SS}$$ Equation 6.2-20

For cohesive soil:

$$Q_u = W'_{bf}$$ Equation 6.2-21

Where,
W'_{bf} = Effective weight of the backfill material (N);
V_{ss}=Total side shear force (N).

The bearing capacity of steel grillage foundations is affected by vertical load and overturning moments, the type of soil below the grillage base, the location of the water table, plan dimensions of the grillage, embedment depth, the inclination of the load and grillage base, stiffness of the soil below the base, and whether the grillage is located on or near sloping ground.

The basic bearing capacity model assumes that the soil beneath the grillage base resists the applied loads via a uniform bearing pressure. The general form of the design bearing capacity model can be calculated by using **Equation 6.2-22** (EPRI, 2012).

$$Q_b = q_{bn} A_{Base}$$ Equation 6.2-22

Where,
q_{bn} = Nominal bearing pressure (N/m^2);
A_{Base}=Area of the grillage base (m^2).

The lateral capacity is affected by the type of soil below the grillage base, the type of soil used as backfill, the location of the water table, plan dimensions, the location and depth of structural members used for lateral bearing, and the embedment depth. The lateral capacity of a steel grillage foundation must be calculated using separate methods depending on whether the grillage is under uplift or compression forces, as shown by the general forms in **Equation 6.2-23** and **Equation 6.2-24.**

Ultimate lateral bearing capacity under uplift forces:

$$Q_{lat,uD} = \sum_{i=1}^{N} \left(q_{lat,n}\right)_i (A_{lat})_i$$ Equation 6.2-23

Ultimate lateral bearing capacity under compression forces:

$$Q_{lat,cD} = \left(s_{u,base} BL + N tan\phi_{base}\right)$$ Equation 6.2-24

Where,
$Q_{lat,uD}$ = Lateral bearing capacity under uplift forces (N);
$Q_{lat,cD}$ = Lateral bearing capacity under compression forces (N);
$\left(q_{lat,n}\right)_i$ = Nominal lateral bearing pressure of the backfill material for the i^{th} member (N/m^2);
$(A_{lat})_i$ = Lateral bearing area of the i^{th} member (m^2);

$s_{u,base}$ = Undrained shear strength of the base material (N/m^2);
B = Width of grillage (m);
L = Length of grillage (m);
N = Normal force at the grillage (N).

The details of design and the analysis of steel grillage foundations, along with shear capacity equations, bearing stress equations, and strength reduction factors, can be found in Chapter 8 of EPRI Transmission Structure Foundation Design (EPRI, 2012). Commercial design software is available for geotechnical sizing of the footing (SFOOTING™, Power Line Systems, Inc.).

6.2.4.2 Steel Grillage Foundation Construction

The tower fabricator can install grillage foundations using the same equipment needed for the construction of the tower (**Figure 6-12**). Steel grillage foundations may require large amounts of concrete depending on the type of installation. If this is the case, paved or stoned and graded roads are needed to deliver ready-mix concrete. Otherwise, foundation members can be assembled in the field, and delivered with conventional construction equipment, similar to that needed for the steel tower. These foundations can be placed during both hot and cold weather conditions. Temporary shoring may be needed during installation. Compacted backfill is also required. Since most grillage foundations rely on compacted backfill, there is no cure time needed prior to loading structures.

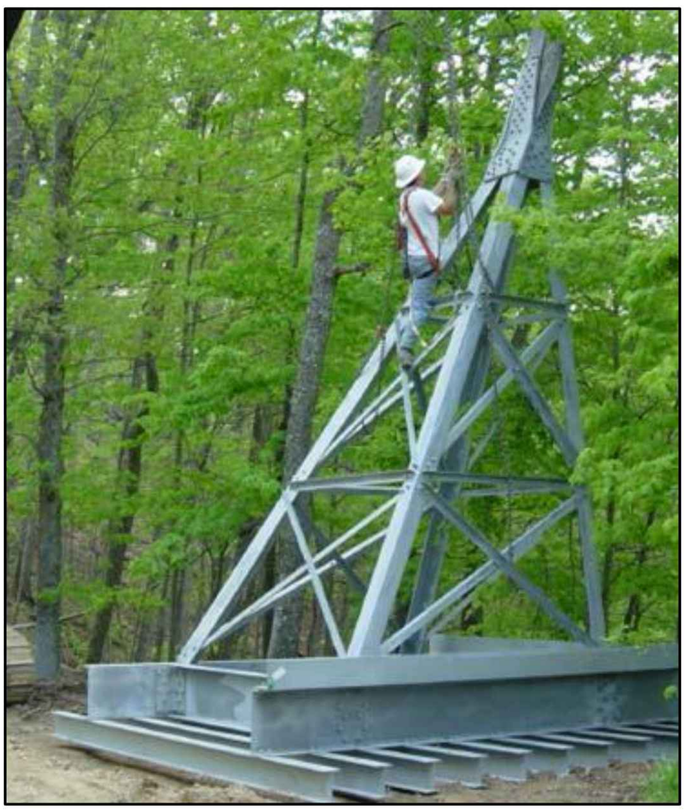


Figure 6-12: Steel Grillage Foundation Supporting Lattice Tower (EPRI, 2012).

Grillage foundations are best suited in areas where excavation is not difficult, though they can be installed in any soil or rock type. Adequate bearing capacity and settlement need to be confirmed if bearing on soil takes place. Hoe ramming or blasting may be required if excavation is needed in bedrock. These foundations are not suitable for sites with open water, and they are difficult to install where high ground water is present. Excavation dewatering would be needed in this condition for the excavation and placement of concrete/backfill.

Construction ground disturbance is considered moderate depending upon terrain and adjacent slopes. Noise and vibration during installation tends to range from minimal to moderate. However, the generation of dust will vary depending upon subsurface strata type. Steel is subject to corrosion when in contact with aggressive soil chemicals and fluctuating groundwater levels. Some methods that can help protect against corrosion include: galvanization, cathodic protection, a corrosion sleeve, and a polyurethane coating.

6.2.5 Spread Footings

A typical spread footing (also called a "pad and chimney" foundation), is a partially or completely buried reinforced concrete pad or mat (square, rectangular, or round), which either attaches directly to the supporting structure, or includes a reinforced concrete pedestal that attaches to the supporting structure (see **Figure 6-13**). Spread footings are used to support the legs of steel lattice tower structures, or act as center pads for anchored steel structures. Concrete is almost universally used for footings for its durability and economic value. A spread footing is constructed using conventional construction equipment, and via practices used for cast-in-place formed concrete (EPRI, 2012).

Figure 6-13: Spread Footing Foundation (EPRI, 2012).

Spread footings provide basic resistance to axial forces (uplift and compression), while also taking into consideration the load orientation (inclination and eccentricity) of the applied loads (Grigsby, 2012). Axial compression loads of a tower leg are resisted by bearing pressures on the base, while uplift loads are resisted by the weight of the concrete, the weight of the backfill (if present), and by shear forces that develop along the sides of a prism, extending from the ground surface to the top of the concrete mat around the footprint of the foundation. The uplift capacity is also dependent on the degree of backfill compaction. Lateral shear loads are resisted by lateral soil bearing pressure on the sides of the foundation, and by frictional forces at the base of the concrete mat (when the footing is in compression).

6.2.5.1 Sizing of Spread Footings

Three load cases should be considered during the design of spread footings:

- Foundation subjected to compressive load and some moment/shear;
- Foundation subjected to compression load only; and
- Foundation subjected to load uplift only.

The dimensions of spread footing can be determined by calculating the size required to resist each load case (**Figure 6-14**). In general, the size of the footing must be sufficient for the allowable bearing capacity. This is determined by the first two load cases being greater than the applied compressive load, in addition to having sufficient weight/uplift resistance to be greater than the applied uplift load in the third load case (see Bowles, 1996, Chapter 8 for design details).

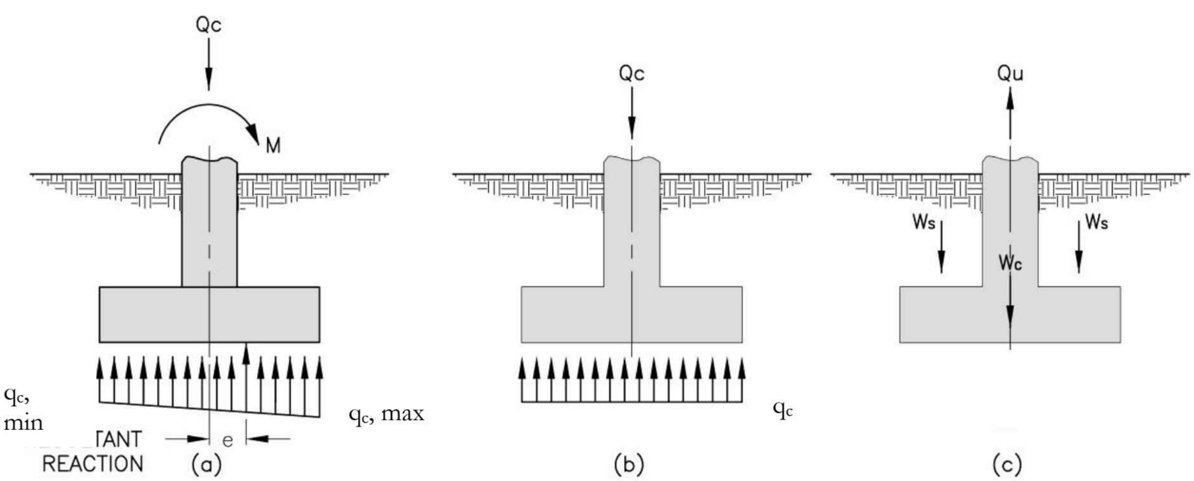


Figure 6-14: Spread Footing Models.
(a) Compression, Eccentrically Loaded; (b) Compression; (c) Uplift

The eccentricity of the footing under the applied (factored) moment load must be computed for the first load case (**Figure 6-14 (a)**):

$$e = \frac{M}{P_c}$$ Equation 6.2-25

Where,
M = Applied moment (N-m);

$P_c = Q_C + W_C$; Applied vertical load at footing base (includes footing weight) (N);
e = Eccentric distance (m).

If the load is eccentric and acts within the middle 1/3 of the footing (e ≤ L/6), bearing stresses are distributed over the full footing contact area. The maximum and minimum applied bearing pressures at the base of the foundation can be calculated as follows:

$$q_{c,max} = \frac{P_c}{B_f L_f}\left(1 + \frac{6e}{L_f}\right) \quad \text{Equation 6.2-26}$$

$$q_{c,min} = \frac{P_c}{B_f L_f}\left(1 - \frac{6e}{L_f}\right) \quad \text{Equation 6.2-27}$$

Where,
$q_{c,\,max}$ = Maximum applied unit bearing pressure (N/m^2);
$q_{c,\,min}$ = Minimum applied unit bearing pressure (N/m^2);
B_f = Base width of footing pad/mat (m);
L_f = Base length of footing pad/mat (m).

Otherwise, minimum bearing pressure is zero, and maximum applied bearing pressures for eccentrically loaded footings (with the reaction load acting outside the middle third), are determined as follows:

$$q_{c,max} = \frac{2P_c}{3B_f a} \quad \text{Equation 6.2-28}$$

Where,

$$a = \frac{L_f}{2} - e \quad \text{Equation 6.2-29}$$

The location of zero bearing pressure is a 3a distance from the footing end, where the pressure is at the maximum level. If possible, eccentrically-loaded footings are ideally designed with the reaction acting within the middle third. Bearing pressures must be evaluated in both directions.

For non-eccentric compressive loading (**Figure 6-14(b)**), the bearing pressure can be calculated as follows:

$$q_c = \frac{P_c}{B_f L_f} \quad \text{Equation 6.2-30}$$

Where,
q_c = Applied unit bearing pressure (N/m^2);

For uplift loading (**Figure 6-14(c)**), the weight of soil and concrete need to be sufficiently able to resist uplift loads, and the following check is to be performed:

$$Q_u \leq W_c + W_s$$ Equation 6.2-31

Where,
W_c = Total weight of footing concrete (N);
W_s = Total weight of soil backfill above pad/mat (N);

Depending upon the compaction of the backfill above the footing, additional uplift resistance can develop along the sides of a prism, extending from the ground surface to the top of the concrete mat around the footprint of the foundation. Further design considerations are discussed in Bowles (1996).

6.2.5.2 Geotechnical Design of Spread Footings

A footing is assumed to be shallow when the distance from the base of footing to the ground surface is not greater than its width. Base soil conditions and footing rigidity determine the actual stress distribution, with the understanding that the stress distribution beneath symmetrically loaded footings is not uniform. Bearing capacity is determined in terms of both soil strength and deformation. Each is evaluated independently.

The geotechnical consultant or engineer will typically provide an allowable value for bearing resistance capacity. Alternately, the bearing resistance capacity of footing based on underlying soil strength can be obtained by using the Buisman-Terzaghi equation (Terzaghi, 1943; Winterkorn, 1975) as shown in **Equation 6.2-32** (See Teng & Manuel, 1977 for details of design process):

$$q_c = cN_c + qN_q + 0.5\gamma BN_\gamma$$ Equation 6.2-32

Where,
q_c = Ultimate unit bearing resistance capacity (N/m^2);
c = Cohesion of soil (N/m^2);
q = Surcharge pressure (N/m^2);
γ = Unit weight of soil (N/m^3);
N_c, N_q, N_γ = Bearing capacity factors (dimensionless);
B = Width of the footing (m).

For transmission line structures, the allowable spread footing bearing capacity is rarely controlled by strength parameters. The allowable settlement typically dictates the maximum allowable bearing resistance capacity. The total settlement of a spread footing is determined as follows:

$$S = S_i + S_c$$ Equation 6.2-33

Where,
S_i = immediate (elastic) settlement due to elastic deformation (m);
S_c = Long term settlement due to consolidation settlement (cohesive soils only) (m);

Elastic settlement may be determined using Schleicher's equation (Winterkorn, 1975) as follows:

$$S_i = I_w q_c B(1-\mu^2)/E$$ Equation 6.2-34

Where,
I_w = Shape factor (0.95 for a square loaded area, 0.85 for circularly loaded area)
B_A = Width of loaded area (m);
μ = Poisson's ratio for soil (dimensionless);
E = Foundation Modulus of Elasticity (N/m^2).

Long-term settlement is assumed to be negligible for cohesionless soils. For a footing on or above a clay stratum with thickness H, settlement due to consolidation (S_C) can be calculated as follows (Terzaghi, 1943):

$$S_c = \{HC_c/(1+e_o)\}\{\log_{10}\{(q_o+\Delta q)/q_o\}\}$$ Equation 6.2-35

Where,
C_c = Compression index of clay (dimensionless);
e_o= Initial void ratio of clay stratum (dimensionless);
q_o = Average effective overburden pressure (N/m^2);
Δq = Average change in pressure in stratum due to applied load from the footing (N/m^2).

Generally, bearing capacity can be predicted from immediate settlement calculation, by assuming a maximum settlement of spread footing foundation. The IEEE/ASCE foundation design guide (IEEE 1985) offers a number of models for spread footings using traditional design methods. Commercial design software is available for the geotechnical sizing of spread footings (SFOOTING™, Power Line Systems, Inc.). AASHTO LRFD Bridge Design Specifications (AASHTO, 2010, Section 10.6) also provide detailed reliability-based design methods for spread footings. The methods presented are for installations in soil. Refer to the Bowles (1996) report for further information regarding the design of spread footings on rock.

6.2.5.3 Spread Footing Construction

Spread footings are constructed with conventional equipment, and are generally used when deep foundations are not feasible due to restricted site access. Paved, graveled, or graded roads are recommended for equipment and concrete deliveries. Good access, though, is not required, since their construction utilizes common materials. Spread footings can be constructed via readily available labor, simple and small equipment, and can be done without specialty contractors. The installation of spread footings requires a relatively large amount of concrete, since the weight of the footing generally resists uplift loads. When the footing mat is buried below grade, compacted backfill is needed. Special hauling permits are not typically required

Spread footing foundations can be designed with simplicity and flexibility, and these foundations are appropriate for the situations in which deep foundations or grillages are not recommended. Spread footings are best suited to areas where excavation is not difficult, but can be installed in any soil or rock type. Adequate bearing capacity and settlement needs to be confirmed if the bearing is on soil. Pneumatic hamming or blasting may be required if excavation is needed into bedrock. These foundations are not suitable for sites with open water, and they are difficult to install where high ground water is present, due to the necessity of dewatering for excavation, and the placement of concrete/backfill. Temporary shoring may be required during installation and backfill work.

Concrete can be placed during hot and cold weather conditions, but must follow best practices for mixing, transportation, and placement in extreme weather conditions.

Construction ground disturbance is considered moderate, depending upon the terrain and adjacent slopes. Noise and vibration during installation typically ranges from minimal to moderate. However, the generation of dust will vary depending upon subsurface strata type. Concrete is subject to accelerated deterioration when in contact with aggressive soils, chemicals, and groundwater. Sulfate resistant cement can be used in the concrete to increase concrete durability.

6.2.6 Anchored Structures

In lieu of embedded foundations, anchored structures are primarily supported by guy wires to provide the required lateral stability. These structures are often constructed at angle and dead end locations, where additional load capacities are often needed. They tend to be simple structures, considered lightweight, easy to erect, and able to be pre-assembled (Peyrot, 1997). Though there are a wide variety of structure types, this report will focus upon large rigid frame steel latticed or tubular structures with guys splayed longitudinally, which transverse to provide support in all directions. Uplift and horizontal loads are transferred from guy wires to ground guy anchors, providing resistance in tension, while the pole or tower transfers large compression loads to the base. Here, a spread footing, drilled shaft, or direct embedment of the pole provides bearing resistance.

The anchor provides resistance to upward forces. This element may include a buried steel plate or a concrete slab (deadman type), a helical screw pile, or a deformed/threaded steel bar grouted into a hole drilled into either soil or rock. Anchor selection depends on guy load, guy angle, subsurface strata, location, equipment access, and topography.

Plate anchors consist of a steel rod, a steel plate and compacted backfill as shown in **Figure 6-15**. Typical plates are comprised of rectangular plates crossed at 90 degree angles, expanding steel blades, and round steel plates. The load is applied through the anchor rod to the anchor, causing the anchor to bear upon relatively undisturbed earth. The holding capacity of a plate is usually limited by the strength of the connecting device, as well as the soil type which the plate bears against (IEEE, 1985). Helical screw anchors and grouted anchors are components of other transmission line foundation systems, described in **Section 6.2.1** and **Section 6.2.4**, respectively.

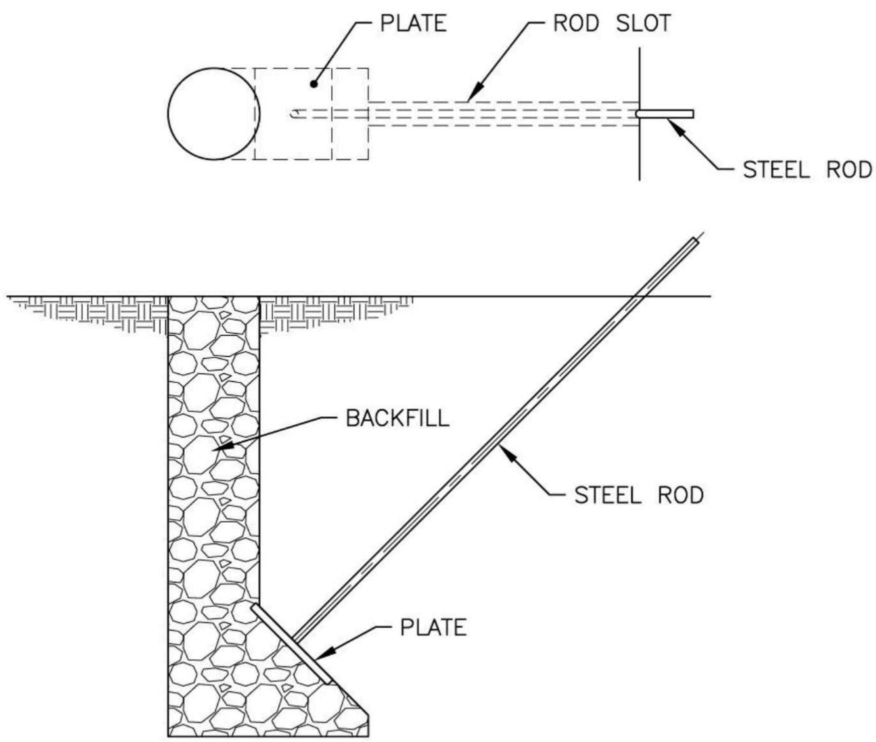


Figure 6-15: Plate Anchors.

6.2.6.1 Design and Selection of Anchors

With deadman-type installations, anchor capacity is based on the bearing area of the plate, and the shear strength of the soil. For expansion anchors, the capacity is also a function of the degree and adequacy of compacted backfill (Peyrot, 1997). Soil uplift resistance, tendon strength, and tendon-to-plate connection strength are important considerations in terms of the design of plate anchors (Hanna & Carr, 1971; Martin & Cochard, 1973). However, the load resistance of an installed anchor is difficult to accurately predict at times when information on the soil condition is lacking.

Subsurface data is rarely obtained for installation at individual anchors (investigations may be conducted regarding the structure location of high voltage lines). Geotechnical classification is typically determined in the field at the time of anchor installation. Anchor manufacturers rate anchor systems capacity on the basis of soil classifications – general descriptions categorizing soil or rock strata. As an example, Chance/Hubble provides a classification from zero (sound, hard rock) to 8 (peat, organic silt, etc.), and its correlation to proprietary soil probe values or SPT "N" blow counts. This classification system is demonstrated in **Table 6-1**. Vendors commonly provide ultimate holding capacity charts and graphs for various plate, helical, and grouted anchor systems in their product catalog (Hubbell, 2014).

Table 6-1: Chance/Hubble Soil Classification Table for Anchors.

Class	Common Subsurface Description	Geological Subsurface Classification	Probe Values (N-M)	Typical Blow Count "N" per ASTM-D1586
0	Sound hard rock, unweathered (bedrock)	Granite, Basalt, Massive Limestone	N.A.	N.A.
1	Very dense and/or cemented sands; coarse gravel and cobbles	Caliche, (Nitrate-bearing gravel/rock)	85-181	60-100+
2	Dense fine sands; very hard silts and clays (may be preloaded)	Basal till; boulder clay; caliche; weathered laminated rock	68-85	45-60
3	Dense sands and gravel; hard silts and clays	Glacial till; weathered shales, schist, gneiss and siltstone	56-68	35-50
4	Medium dense sand and gravel; very stiff to hard silts and clays	Glacial till; hardpan; marls	45-56	24-40
5	Medium dense coarse sands and sandy gravels; stiff to very stiff silts and clays	Saprolites, residual soils	34-45	14-25
6	loose to medium dense fine to coarse sands to stiff clays and silts	Dense hydraulic fill; compacted fill; residual soils	23-34	7-14
****7**	Loose fine sands; alluvium; loess; medium-stiff and varied clays; fill	Flood plain soils; lake clays; adobe; gumbo, fill	11-23	4-8
****8**	Peat, organic silts; inundated silts, fly ash very loose sands, very soft to soft clays	Miscellaneous fill, swamp marsh	0-11	0-5

Class 1 soils are difficult to probe consistently and the ASTM blow count may be of questionable value.

**** It is advisable to install anchors deep enough, by the use of extensions, to penetrate a class 5 or 6, underlying the Class 7 or 8 Soils.**

Helical anchor capacity can be determined by either vendor catalog charts/graphs, or by the methods described in **Section 6.3.1**. Similarly, rock anchor capacity can be determined via the description given in **Section 6.3.4**. Designs of reinforced concrete compression foundations that function to support the structure are provided in **Section 6.2.2** for drilled shafts, and in **Section 6.2.5** for spread footings.

6.2.6.2 Anchored Structure Foundation Construction

Plate anchors (**Figure 6-16**) are usually constructed via the excavation of a trench or hole, into which an anchor is inserted and backfilled with compacted soil or concrete (normally installed with a power digger) (Peyrot, 1997). Anchor excavations can be dug by the same auger used to dig pole embedment holes on transmission projects, since the size does not affect holding capacity. Plate anchors are installed in a diagonal bored hole, which is then undercut to situate the anchor at a right angle to the guy (**Figure 6-15**). A rod trench is either cut using a trenching tool, or drilled with a small power anchor (Hubbell, 2014). Excavation may need to be performed by hand in restricted access areas, or where there are safety considerations. Construction practices for rock anchor installation are discussed in **Section 6.3.4**, and helical anchors are examined in **Section 6.3.1**. Similarly, the construction of spread footing foundations is discussed in **Section 6.2.5**.

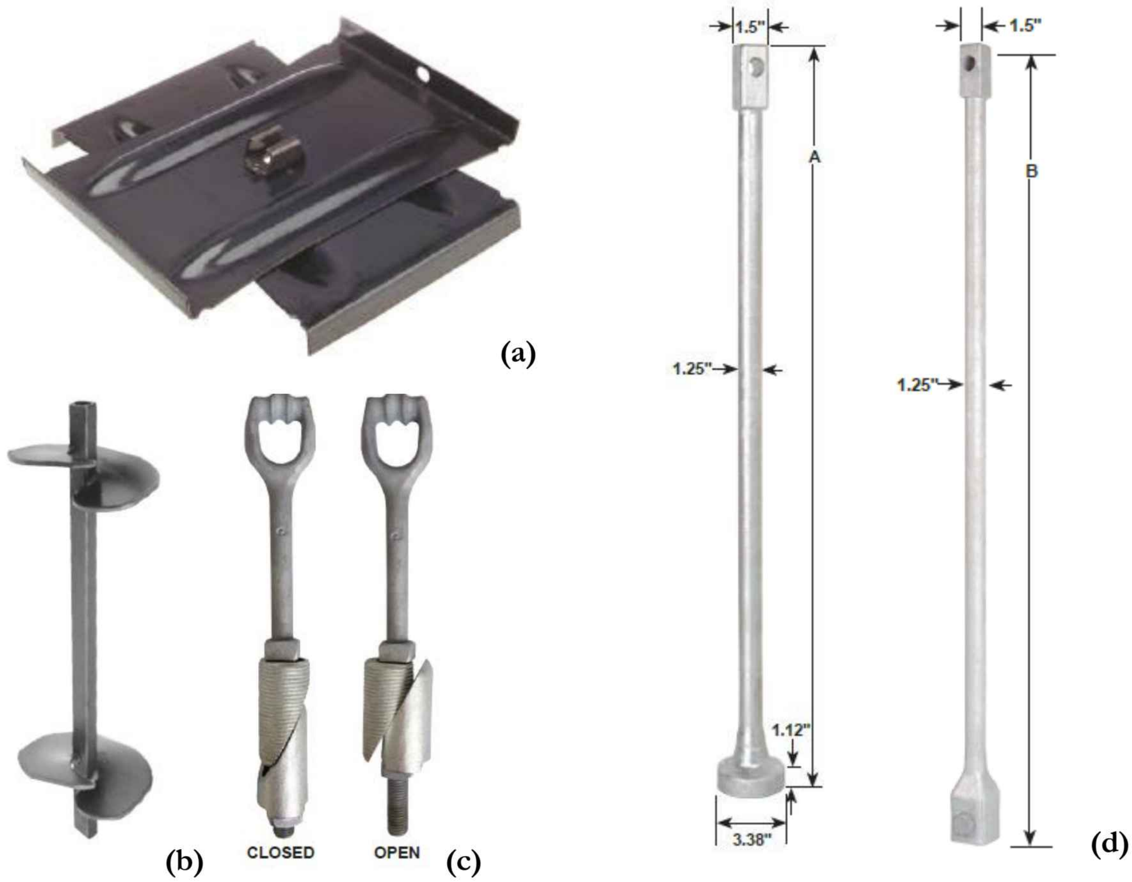


Figure 6-16: Anchor types (CHANCE, n.d.). (a) Cross-steel Plate; (b) Helix Anchors; (c) Expanding Rock Anchors; (d) Grouted Rock Anchors.

Anchors and spread footings are suitable for nearly any subsurface material, ranging from hard rock to soft soil. The center bearing foundation type will vary based on the condition of the soil (see sections on drilled piers, spread footing, and direct embedment foundations regarding the optimal subsurface conditions for each system). The anchor type varies based on subsurface strata.

As previously noted, anchored structures provide an advantage in terms of their economic value and flexibility for a large range of line voltages, and in highly variable terrain. Structure erection and foundation construction tends to be relatively simple and rapid. These systems, however, require substantially larger rights-of-way, as guys must be splayed at angles to achieve needed support. Therefore, their use in transmission systems is typically limited to undeveloped areas with open space (being less desirable in urban areas and in actively cultivated fields). Additionally, leads for anchors may be prohibitively long on steep slopes. The disturbed footprint and equipment used for installation also tend to be relatively small for each foundation element (guys and center footing). If needed, foundation construction equipment can be brought to sites via helicopter (**Figure 6-17**).

Noise and vibration during construction are minimal. Anchors are cost-effective foundation elements in comparison to other foundation types, since they require less labor and installation time than nearly all other foundation systems. Anchors are light-weight and easily transported, making these systems a favorable option for sites with limited access. However, the potential corrosion of anchors at the ground line must be considered and controlled. Galvanization, corrosion sleeves, or coating may require application to protect the steel. Corrosion analysis and control can also be involved in soil and material assessment. Field evaluation methods have been developed by the EPRI (Ostendorp, 2003), and certain solutions may require a good understanding of subsurface resistivity (Byrd, 1982).

Figure 6-17: Guy Anchor Installation in a Difficult Environment.

6.3 Alternative Foundations

The industry survey results (**Section 2.2**) show that 25% of the respondents use alternate foundations for the support of transmission line structures in sensitive environments. These alternates include helical anchors/piles, micropiles, vibratory caissons, auger cast piles, and rock sockets/anchors. A recent study significantly noted that 77 percent of utilities and utility consultants surveyed allow for the use of alternate deep foundations for the support of transmission lines (Kandaris & Davidow, 2015). However, only 45.4% indicate specifications readily available for non-traditional foundations. The types of alternate foundations mentioned in the survey include micropiles, helical piles, and auger cast piles (in this survey, driven piles were also considered alternate foundations). In many circumstances, these alternatives are necessary for the provision of economic foundation solutions in sensitive environments.

6.3.1 Helical Anchors & Piles

Helical piles and anchors are manufactured steel foundations rotated into the ground, which serve to support transmission structures or structural elements. Helical piles (also known as helical/screw anchors), consist of one or several helical shaped circular plates (helices), affixed to a central hub (Hoyt & Clemence, 1989). The basic components of a helical pile include the lead, extensions, helical bearing plates, and the bracket/pile cap, as depicted in **Figure 6-18** (Perko, 2009)**.** The pile is directed toward the soil (either vertically or at an incline), and mechanically rotated with constant downward pressure, advancing the pile into the soil. Helix size and quantity depend upon the required resistance capacity, soil properties, and subsurface conditions (Helical Pier Systems, 2010). Pile shaft diameters can range from 79 mm to 900 mm, and helix diameters can range from 150 mm to 1200 mm (O'Donoghue, 2012).

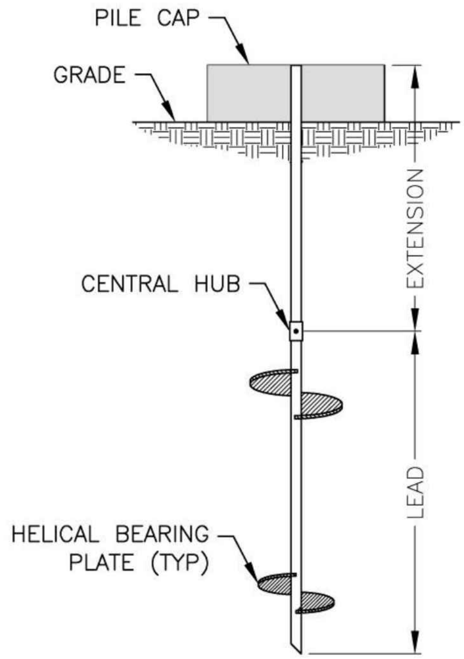


Figure 6-18: Helical Piles System.

Helical piles and anchors are used in various applications of transmission system applications, including the support of guy wires ("helical anchors"), foundations for transmission towers and poles, and as tie-downs for substation structures. The helical pile's resistance capacity for both uplift and downward bearing pressure, allows for use in cases where resistance to combined forces is required. Tension and compression loads are transferred from the structure to the subsurface stratum by the helices. Torque during installation and axial loads during use are transmitted to helical plates by the central shaft (O'Donoghue, 2012). The central shaft also provides a major component of the resistance to lateral loading. The plates provide both uplift and compression resistance.

Research indicates that large diameter helical piles (shafts ranging from 324 mm to 508 mm in diameter) can develop considerable resistance to lateral loads, in cases where this resistance is almost exclusively controlled by the shaft diameter (Sakr, 2010).

Case histories demonstrate the use of helical piles to support lattice tower and monopole structures. Typically, three to four inclined piles are installed for each lattice tower leg, and connected to the tower frame using an assortment of structural members. Similarly, multiple helical piles can be installed, either vertically or at a batter, and fastened to a steel grillage or concrete pile cap that bolts to a monopole base plate.

Three common analysis methods are used for predicting helical pile capacity, including: individual bearing, cylindrical shear, and torque correlation (Foundation Support Works, 2014). The first two methods are based on traditional geotechnical limit state analysis methodology (slightly modified with empirical data). They are generally used to calculate or estimate the pile capacity during the design phase. The individual bearing method relies on each helix plate to act independently, without overlap of significant stress influence between adjacent helices. The cylindrical shear method is applicable for multi-helix piles, and assumes that the top or bottom helix plate acts in bearing. A cylindrical shear surface then develops around the perimeter of the helices between the top and bottom helix. The torque correlation method is fully empirical, and it is generally used to confirm or verify capacity during field installation (Foundation Support Works, 2014). The torque correlation method uses a linear relationship between installation torque and capacity, and it is typically used on projects with insufficient soil information as the sole determination of pile capacity.

6.3.1.1 Individual Bearing Method

Adams and Klym (1972) conducted a series of helical anchor uplift tests to describe an individual bearing method. A summary of the design model developed is presented in Equation 6.3-1, in which ultimate pile bearing capacity (Q_b) is equal to the sum of the individual helix plate capacities:

$$Q_b = \sum A_h \left(c_h N_c + q'^{N_q} + 0.5 \gamma B_h N_\gamma \right) \qquad \text{Equation 6.3-1}$$

Where,
A_h = Area of helix plate (m^2);
c_h = Cohesion at helix depth (N/m^2);
q' = Effective vertical overburden stress at helix depth (N/m^2);
γ= Soil unit weight (N/m^3);
B_h = Diameter of helix plate (m);
N_c, N_q, N_Y = Dimensionless bearing capacity factors (dimensionless).

Helical pile end-bearing capacity is often ignored since the diameter of the pile is relatively small ($0.5\gamma BN_\gamma \rightarrow 0$).

Conservative N_c and N_q bearing capacity factors are calculated by the following equations:

$$N_c = (N_q - 1) cot\phi \qquad \text{Equation 6.3-2}$$

$$N_q = e^{\pi tan\phi} tan^2 \left(45 + \frac{\phi}{2} \right) \qquad \text{Equation 6.3-3}$$

Where,
ϕ = Soil friction angle (°).

The spacing between helix plates along the shaft is generally three times the diameter of the leading plate. The uppermost helix plate is embedded to a depth of at least five times the plate diameter. Skin friction along the shaft is generally ignored for shaft sizes less than 150 mm in the outside diameter. **Figure 6-19** shows the load transfer model for the individual bearing method in compression loading. A detailed discussion of individual bearing method design is given in Chapter 4 of Perko, 2009.

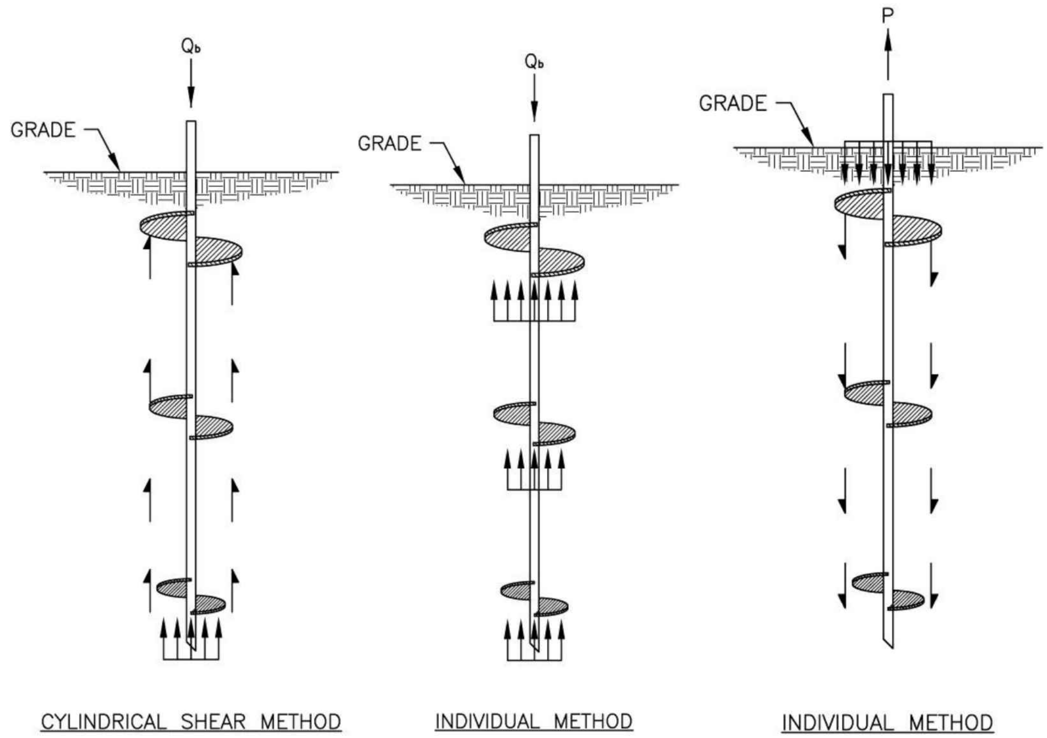


Figure 6-19: Helical Pier Models.
Cylindrical Shear Method (a), Individual Bearing Model (b), Cylindrical Shear Model, Bearing (c) Cylindrical Shear Model, Uplift

6.3.1.2 Cylindrical Shear Method

The cylindrical shear method, as applied to helical anchors, was originally developed by Mitsch and Clemence (1985), and later modified by other investigators for simplicity. The model assumes the development of a soil friction column (cylinder) between the upper and lower helix plates. Additional capacity is provided by the individual bearing of either the upper helix (pile in uplift), or via the lower helix (pile in compression), depending upon loading direction. The ultimate capacity is then determined by the summation of shear strength and bearing capacity.

Ultimate bearing capacity (Q_b) can be calculated as follows:

$$Q_b = q_{ult}A_l + T(n-1)s\pi D_{AVG} + \alpha_s H(\pi d)$$ Equation 6.3-4

Where,
q_{ult} = Unit bearing pressure (N/m^2);
A_l = Area of the bottom helix (m^2);
T = Soil shear strength (N/m^2);
H = Length of shaft above the top helix (m);
d = diameter of a circle circumscribed around the shaft (m);
a_s = Adhesion between the soil and the shaft (N/m^2);
(n-1)s = Length of soil between the helices (m);
D_{AVG} = Average diameter of helical bearing plates on a given pile (m).

Research demonstrates that the individual bearing method and cylindrical shear method provide similar results, specifically at helix spacings of 2.5 to 3.5 times the average diameter of the helical bearing plates (Foundation Support Works, 2014).

The pullout capacity of helical anchors follows the same general procedure used with bearing capacity, providing that anchors are embedded sufficiently to ensure a deep mode behavior (Perko, 2009). Pullout capacity (also interpreted as ultimate uplift capacity, Q_U), is found by a summation of the shear stress (adhesion) along the shaft and bearing on the upper helix:

$$Q_u = q_{ult}A_T + T(n-1)s\pi D_{AVG} + \alpha H(\pi d) \qquad \text{Equation 6.3-5}$$

Where,
A_T = Area of the top helix (m^2);
(remaining variables are described in Equation 6.3-4)

For more detailed discussions of cylindrical shear helical pile design and the development of associated parameters, see Section 4.3 of Perko (2009) for compression piles, and Chapter 5 of the same text for uplift piles.

6.3.1.3 Torque Correlation Method

The torque correlation method has become a well-documented and accepted technique for the estimation or verification of helical pile capacity during installation. Soil undrained shear strength can be predicted by the torsional resistance generated during helical pile installation, and the torque is also related to the ultimate bearing capacity (Q_b) of the pile with the following equation:

$$Q_b = K_t T \qquad \text{Equation 6.3-6}$$

Where,
K_t = Empirical torque correlation factor (m^{-1});
T = Final installation torque (m-N).

Due to the empirical nature of the method, the torque correlation method is a more precise predictor of capacity compared to limit state methods. The recommended torque correlation factor (K_t) for the shafts changes with different sizes and shapes. K_t can vary depending upon soil conditions, and is generally higher in sands, gravels, over-consolidated clays, and slits. Additionally, K_t is affected by the installation practices of the specialty contractor and the quality control approach of helical pile manufacturing. An exponential regression analysis applied to the load test data obtained at the site, via various technical papers by other investigators and/or companies, results in the following best-fit empirical equation:

$$K_t = \frac{\lambda_k}{{d_{eff}}^{0.92}} \qquad \text{Equation 6.3-7}$$

Where,
λ_k = Fitting factor equal to 1433 $mm^{0.92}/m$;
d_{eff} = Effective shaft diameter (mm).

See Chapter 6 of Perko (2009) for more details regarding compression pile design.

6.3.1.4 Buckling Under Compression Loads

Buckling can affect any long pile in soft or loose soils if the applied load exceeds the critical buckling capacity. These conditions are presumed to impact helical piles in bearing, but must be evaluated for long, slender piles. The resultant effect is generally referred to as "Euler buckling," in which the critical bearing force is a roughly calculated ratio of the section modulus and the effective length. The designer must determine if a pile is sufficiently braced by the soil, or if the combined soils and pile lengths are such that compensation for buckling must be undertaken. For an evaluation of simple buckling refer to Perko (2009) Section 4.8, and for the evaluation of advanced buckling, refer to Section 4.9. Ensoft LPILE® software has been used to perform advanced buckling analyses. Good references for approaching this analysis include Hoyt, et al (1995), and Perko (2009).

6.3.1.5 Helical Pile Construction

Helical piles are installed using minimal equipment, ranging from bobcats to large excavators, as shown in **Figure 6-20**. The pile shaft is turned into the ground by an application of torsion and down pressure, and via the use of a truck-mounted auger or hydraulic torque motor attached to a backhoe, fork lift, front-end loader, skid-steer loader, derrick truck, or other hydraulic machine (Perko, 2009). Helical pile foundation installation is executed using low impact equipment, which enables minimal vibration, noise, and dust levels (Winnipeg Screw Piles, 2013). Small equipment allows for piles to be installed in areas of limited access or low overhead clearance. In addition, helical pile foundations can be installed quickly with one piece of equipment, thus reducing the total foundation installation cost.

Figure 6-20: Helical Piles Construction (Courtesy Chance/Hubbell Power Systems).

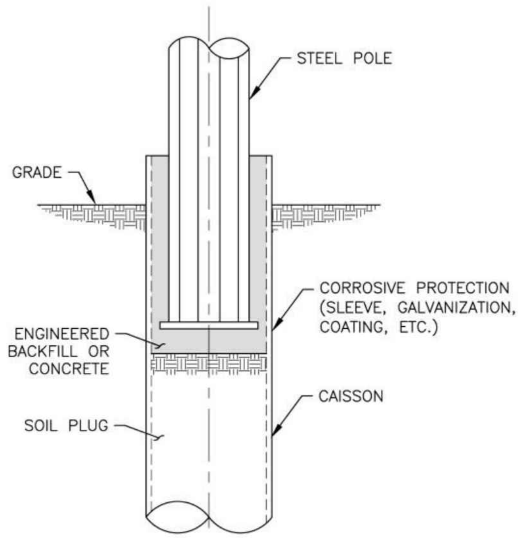
Helical anchors are best installed in soft soil conditions, or where expansive / collapsible soils are encountered. It is also best when they can be loaded immediately (no cure time), when they are not affected by high water tables, leave no spoil residue, and involve minimal ground disturbance. These foundations can be placed in cold weather and through frozen ground, but install equally well in all seasons. Predrilling may be needed to install piles in frozen ground or in cases where very hard layers are present. Under these conditions, the auger size should be limited to a minimum of 50 mm less than the size of the pile shaft (Sakr, 2010). Capacity can be economically verified during or after installation, via either direct in-line torque measurement or via pull-out tests.

Helical anchors are able to develop bearing and uplift capacity in nearly any soft soil, including wetlands, lacustrine deposits, marine clays, swamps, and lake sediments (Sakr, 2010; Winnipeg Screw Piles, 2013; Young, 2012), however, they may have questionable economy in very soft soils. These foundations (when using large center diameter rod shafts) can resist considerable lateral loads that are positioned vertically position, involving even greater lateral resistance when placed in a battered configuration. Helical piles are best used with structures that are fixed from translation or braced in some manner, preventing translation of the foundation (to the advantage of batter).

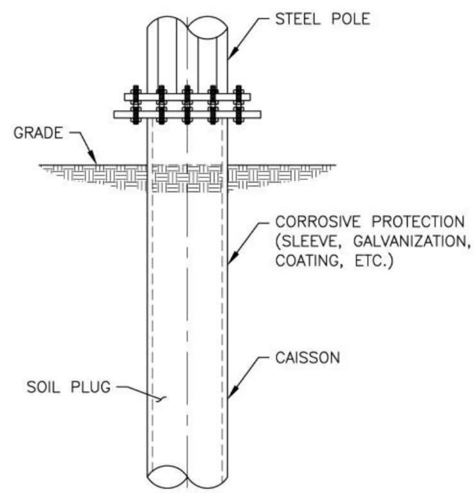
These foundations are generally not suitable for hard soil, hardpan, basal till, cobble, and rock conditions, as they are sensitive to damage or can fail due to high shaft torque. The anchors are generally limited to installation in soils that have a maximum granular size that is less than about 60% of the pitch of the helices (International Society for Helical Foundations, 2016). The length of the helical pile is generally limited to the available reach of the installation equipment, and depth is controlled by the available torque. Additional lengths can be welded or bolted on, and installed to increase the depth of a pile.

6.3.2 Vibratory Steel Caissons

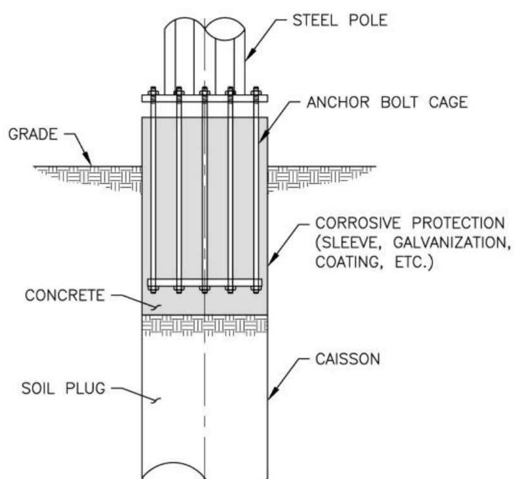
A vibratory steel caisson is a large diameter steel hollow tube or sheath that includes an open bottom end, which is embedded vertically into the subgrade (in a similar fashion to open-end driven piles). The steel caisson can have round or polygon tubular section. The foundation is typically constructed by advancing the embedded section into the ground, with a vibratory hammer operating at very high frequency suspended from a crane or helicopter (EPRI, 2012). The caisson is similar in material and shape to the supporting pole structure (the embedded portion is typically straight and un-tapered). Native soil is retained within the driven caisson that can be either partially or fully replaced with concrete. The supported steel pole is placed inside the caisson in a direct embedment mode as shown in **Figure 6-21(a)** (no backfill – typically concrete encased) or flange connected to the top of the caisson as shown in **Figure 6-21(b)** (note: the flange may be omitted in lieu of a slip-fit joint).



(a) Direct Embed



(b) Base Plate



(c) Anchor Bolt

Figure 6-21: Vibratory Steel Caisson with various Pole Installation Methods.

Alternatively, anchor bolts may be installed within the caisson and filled with concrete to connect a base plated pole to the foundation system. A soil plug subsequently remains inside the steel caisson below the depth of the pole and concrete (**Figure 6-21(c)**). A caisson diameter must be selected that physically allows for the desired above-ground structure attachment.

Vibratory steel caisson foundations are typically used in conjunction with transmission line monopole and H-Frame structures. These foundations can resist the large overturning moments, and provide reasonable uplift resistance in the same manner accomplished by drilled shaft elements. Lateral load analysis is performed in a similar fashion to drilled shaft or driven pile foundations. In bending, the foundation may not act as a rigid shaft, and the embedded portion should be considered a flexible steel pile (unless filled with concrete to depth).

6.3.2.1 Vibratory Steel Caisson Design

In most cases, lateral resistance controls design depth. Commercial software packages are available for the purpose of determining the load-deflection relation (p-y curves), which facilitates the design process of the buried steel pile (LPILE, for example). Axial resistance should be checked against applied loads. Skin resistance is the primary resisting force used to determine axial capacity (uplift and compression), and bearing resistance is generally considered minimal. The literature suggests the use of cylindrical shear methods to determine axial resistance (similar to drilled shafts), with a reduction that accounts for soil disturbance and pile material adhesion.

Vibratory hammers impart energy to the pile-soil system continuously rather than incrementally, as performed by drive pile systems (Warrington, 1992). Energy imparted by vibratory methods disturbs soils to the extent that axial capacity is difficult to predict. Soils are effectively liquefied or fatigued at the pile-soil interface to allow for caisson advancement, with either reduced capacity in dense sands (less in clays), or increased capacity via the densification of loose sands. There is a general lack of knowledge, experience, and well-documented case histories available to provide confidence in the dynamic soil stress/strain characteristics, particularly in the vicinity of the pile-soil interface. This condition has a minimal effect upon lateral load analysis, but is expected to significantly impact uplift capacity. Vibratory Driving Analysis (VDA) can be performed by specialty consultants for the assessment of caisson axial resistance.

Alternately, researchers have suggested the application of friction resistance reduction due to soil fatigue caused by cyclical loading via the Beta-Method (Jonker, 1987; Jonker & Middendorp, 1988; Middendorp & Verbeek, 2012). Since vibro hammers operate at high frequencies, shaft resistance has been found to rapidly drop from peak thresholds in approximately 4 to 8 minutes (Tara, Middendorp, & Verbeek, 2014). Typical vibro hammer soil fatigue beta values are presented in **Table 6-2**.

Primary variables for the selection of a steel caisson include caisson diameter, wall thickness, required length, and material strength (Trinity Meyer, 2015). The diameter is selected based on the requirements of the above-grade structure attachment dimensions. If the pole section or an anchor bolt cage is embedded within the caisson, the diameter of the steel caisson should be selected based on the needed annulus space between the caisson's internal walls and its supported structure/bolt cage (minimum 76 mm clearance). Otherwise, the use of a flanged connection (cap and base plate) requires sufficient diameter for bolt/nut connection placement, inside or outside the caisson without interference from the pile walls. The selection of steel caisson wall thickness depends on the loads transferred from supported structure, as well as corrosion protection needs. The length of the caisson is determined by the applied load and required projection above grade for the supported structure. Once diameter, wall thickness, and the length of the caisson are determined, the material strength can be easily calculated according to chosen design criteria.

Table 6-2: Typical friction fatigue β values. (Tara, Middendorp and Verbeek, 2014)

Type of Soil	Fatigue Factor β
Round Coarse Sand	0.10
Soft Loam/Marl, Soft Loess, Stiff Silt	0.12
Round Medium Sand, Round Gravel	0.15
Fine Angular Gravel, Angular Loam, Angular Loess	0.18
Round Fine Sand	0.20
Angular Sand, Coarse Gravel	0.25
Angular/Dry Fine Sand	0.35
Marl, Stiff/Very Stiff Clay	0.40

Steel caissons can be customized for design using different diameters and lengths, and according to variable foundation locations. However, steel is subject to corrosion when in contact with aggressive soils, chemicals, and groundwater. Corrosion is usually poorest at and just below the ground line. Protective methods against corrosion include galvanization, the use of a sacrificial steel corrosion sleeve, and/or the application of a protective polyurethane coating. A minimum wall thickness should be specified to prevent buckling or fatigue cracking during vibratory hammer installation. At this time, there is no commercial design software available for the structural design of the foundation-structure connection. Steel pole vendors can provide designs of the structure connection to the caisson (Trinity Meyer, 2015).

There are significant gaps in knowledge regarding the design of vibratory steel caissons. Very few standards or definitive guidelines exist for their design and installation, thus their use typically relies on local experience and expertise which is not always transferable, or applicable, to other locations or regions. This effectively makes vibratory caisson design, installation, and usage can be considered more of an art than a science at present. Insufficient field and laboratory testing has been executed by vibratory steel caissons to define an appropriate design practice. The following variables require investigation to better define design methodology:

- The effect of foundation flexibility on lateral capacity (existing rigid pile theories do not apply),
- The contribution of the inside soil plug to compression/uplift loads: a) the use of skin friction resistance inside and outside of the shaft, and b) end bearing on the soil plug,
- The impact of the concrete plug (if used) on installation and foundation performance,
- The impact of installation (i.e. soil disturbance/densification and its impact on skin friction),
- Straight shaft vs. the tapered vibratory caisson and its impact on skin friction,
- Proper corrosion protection methods,
- Proper structural thickness to avoid local buckling under installation loads,
- The impact of vibrations to nearby structures.

6.3.2.2 Vibratory Steel Caisson Construction

Conventional installation by crane requires paved roads, graded unsurfaced roads, matted access drives, or barges on waterways to deliver the steel caissons and vibratory hammer to construction sites. Additionally, concrete (when required for the connection between steel poles and foundations) is typically delivered via ready-mix transit trucks. Alternately, installation by the use of a helicopter has been performed successfully for a number of transmission line projects (Xcel, 2011; Piling Industry Canada, 2012; Pridmore, 2013; White & Eisinger, 1997). Subcontractors that specialize in the installation of transmission line structures by helicopter are typically employed for this type of work. Special jigs and attachments are required to support hammer equipment, and to hold caissons in place during the vibration process.

Vibratory steel caisson foundations are generally used in riverine environments, such as wetlands, streams, rivers, lakes, waterways, and bays, with subgrades having high water tables or open water. Subgrade conditions tend to consist of loose to medium dense granular sands or soft cohesive clays. These foundations are difficult to install in dense sands, soils composed of significant gravel or cobble contents, and/or medium-stiff clay conditions, since hard/dense subgrades can damage steel pipes, or prevent their penetration into subgrade. Steel caisson foundations cannot be installed into bedrock. Depending upon the pole connection method, minimal spoils are generated for removal from sites.

Installation noise and vibration ranges from moderate to severe, depending on the size of caissons. The vibratory installation process has the potential to cause ground disturbance, or damage to nearby structures, so caution (or structure vibration monitoring) must be exercised (Forbes & Camp, 2013). Dust generated from installation tends to be minimal (although moderate dust deriving from the hauling of equipment and materials to sites along unsurfaced roads is possible). Long shop-spliced and/or large diameter caissons may require special hauling permits. If anchor bolts are used for connections, cages are typically fabricated off-site and hauled to foundation locations.

6.3.3 Micropiles

A micropile (sometimes known as a pin pile or a mini pile) has a small diameter (typically less than 300 mm), high-capacity, and drilled and grouted deep pile consisting of these three main elements, as shown in **Figure 6-22:**

- A single strand of continuously threaded high-strength steel bar reinforcement, extending the full length of the micropile center,
- A design-specified length of steel tubing(casing) around the circumference that extends from the top of the micropile to a critical depth, and
- Neat cement grout encasing the bar and bonding the micropile components together, and to the geotechnical strata (Thompson, et al, 2009).
-

Micropiles are constructed by direct boring or casing driven through overburden material, and into a bearing stratum, placing reinforcement, and grouting (Davidow & Carr, 2015).

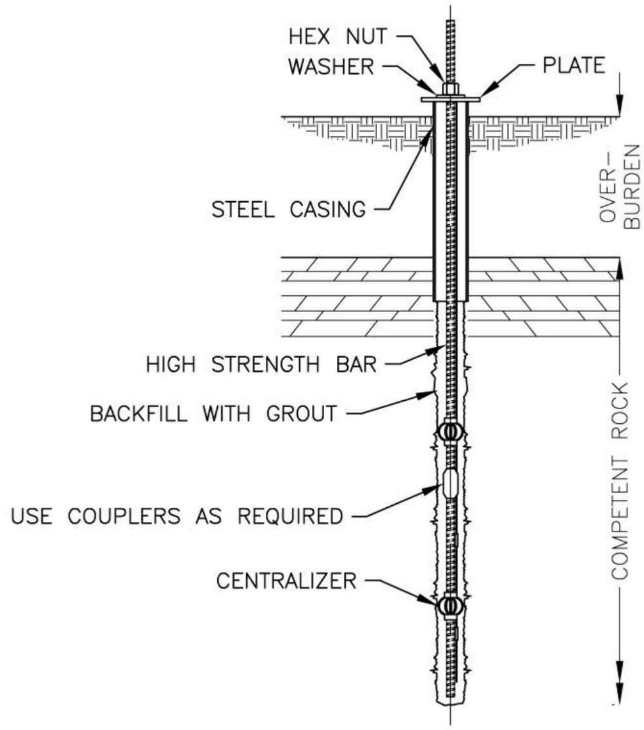


Figure 6-22: Single Micropile Section.

Micropile foundations are used to support lattice tower and tubular steel pole transmission structures in locations where access is difficult, at environmentally sensitive sites, or where challenging ground conditions exist (Chen & Salisbury, 2013; Ischebeck, 2008). Applied lateral loads are converted to and resisted by axial tension and compression in individual piles (Davidow & Carr, 2015). Steel reinforcement transfers axial force through friction with the grout and ground, while cased sections interact with the surrounding soil or rock to provide lateral capacity. Micropiles are used most often in groups (both vertical and battered configuration), which transfer loads from structures to the subsurface, using structural steel plates bolted to pile heads, or by encasing pile heads and structure members within reinforced concrete pile caps.

6.3.3.1 Micropile Design

Micropile design's basic concept differs little from that of a drilled shaft. The system must have the capacity for sustaining the anticipated loading conditions, with the micropile components operating at safe stress levels, and with resulting deflection within allowable limits (Sabatini, et al, 2005). Generally, the design of micropiles is controlled by structural considerations, due to a relatively small cross sectional area when compared with a typical drilled shaft foundation. A single micropile capacity can range from 100 kN to 2000 kN, with groups appropriately arranged supporting tremendous loads (Thompson et al., 2009). In terms of load conditions, monopole structures impart bending moment, torsion load, lateral shear load, and compression load to micropile foundations; H-Frame structures impart bending moment, lateral shear load, and axial uplift/compression loads to these foundations; and lattice tower structures impart lateral shear load and associated axial uplift/compression loads (EPRI, 2012). Bending moments are generally resolved into axial forces using group micropile foundations. Similarly, shear forces are both resisted through casing into soils where steel transfer plates are used, and though a pile cap where reinforced concrete encapsulates the above-grade micropile section.

The International Council on Large Electric Systems (CIGRE) identifies a design procedure for micropiles in their 2005 design and installation guide (CIGRE, 2005). The designer is directed to the consideration of the following objectives:

- Ground investigations;
- Selection of the configuration and inclination of the micropile as a part of the support foundation;
- Identification of the tendon type and size;
- Estimation of the length of the micropile on the basis of known soil characteristics;
- Checking the overall micropile – foundation stability;
- Selection of the corrosion protection system;
- Specification of a testing program;
- Specification of the inspection/investigation procedures during the construction of the micropile;
- Monitoring of the micropile foundation through the whole life of the support.

The FHWA Micropile Design and Construction Guidelines (Sabatini, et al, 2005) is a well-accepted industry micropile design manual. Along with the CIGRE guide, many utilities follow this document in combination with in-house standard specifications and practices for transmission line foundation micropile design. Applicable loading combinations require development depending on the required design approaches, such as Allowable Stress Design (ASD), or Load and Resistance Factor Design (LRFD). The preliminary design of micropiles includes the selection of micropile spacing, length, size of cross section, and micropile type. The CIGRE guide offers design methods using ASD, and includes recommendations for appropriate safety factors for transmission line foundations.

In general form, the allowable compression load and tension load for the cased length of a single micropile, is primarily a structural analysis that is calculated as follows:

$$P_{c-allowable} = \left[0.4f'_{cg}A_g + 0.47F_y\left(A_{bar} + A_{casing}\right)\right] \qquad \text{Equation 6.3-8}$$

$$P_{t-allowable} = 0.55F_y\left(A_{bar} + A_{casing}\right) \qquad \text{Equation 6.3-9}$$

Where,
$P_{c\text{-}allowable}$ = Allowable compression load (N);
f'_{cg} = Unconfined compressive strength of grout (typically a 28-day strength) (N/m^2);
A_g = Area of grout in micropile cross section (inside casing only, discount grout outside the casing) (m^2);
F_y = Yield stress of steel (N/m^2);
A_{bar} = Cross sectional area of steel reinforcing bar (if used) (m^2);
A_{casing} = Cross sectional are of steel casing (m^2).

Similarly, allowable compression load and tension load for uncased length are obtained by setting A_{casing} equal to zero in Equation 6.3-7 and Equation 6.3-8.

Micropiles are typically cased 3 to 6 meters into the subgrade to provide resistance to lateral loading, and the transference of axial load to the bond zone, with casing thickness variations that accommodate greater bending stress (EPRI, 2012). Alternatively, finite element analysis can be performed to accurately evaluate pile/ground interaction. For foundations set within weak soil layers, it is necessary to check the buckling in compression (CIGRE, 2005). Design practices should include checking combined stresses on the casing (reinforcing bar bending capacity is ignored), based on the methods given in Equation 5-3 of the FHWA design document (Sabatini, et al, 2005) for the structural steel section:

$$\frac{f_a}{F_a} + \frac{f_b}{\left(1-\frac{f_a}{F'_e}\right)F_b} \leq 1.0 \qquad \text{Equation 6.3-10}$$

Where,
f_a = Axial stress = P_c/A_{casing} (N/m²);
f_b = Bending stress = M_{max}/S (N/m²);
where S is the elastic section modulus of the steel casing;
F_a = Allowable axial stress that would be permitted if axial force alone existed = 0.47 $_{Fy\text{-}casing}$ (see AASHTO Table 10.32.1.A) (N/m²);
F_b = Allowable bending stress that would be permitted if bending moment alone existed = 0.55 $F_{y\text{-}casing}$ (see AASHTO Table 10.32.1.A) (N/m²);
F'_e = Euler buckling stress (N/m²).

The application of the lateral load and/or the overturning moment at the ground line due to the structure creates bending stresses in the micropile. These bending stresses cause additional compressive stresses in the micropile. Allowable stresses in the cased length of the micropile need to be evaluated using a combined stress evaluation. However, combined stress evaluation is not performed for the uncased length, since the steel casing is designed to be placed at a sufficient depth, so that bending moments below that depth are negligible.

Micropile cross sections should be modified if the allowable compression or tension-load for either the cased or uncased length is not sufficient to carry the compression or tension design loads. Possible design modifications, such as using more micropiles, deeper embedment, increasing the size of the drill hole, using a larger diameter reinforcing bar, replacing a single reinforcing bar with two bars, and/or increasing the steel area of the casing, may be required based on the design criteria discussed.

The design of micropile groups follows the methods described in the FHWA design guidelines (Sabatini, et al, 2005). Commercial software is available to perform group design (Ensoft GROUP). The spacing of micropiles, and the contact condition between the bottom of the micropile footing cap and the soil, can generally be considered primary factors for the determination of efficiency for a micropile group installed in cohesive soils. The capacity of a micropile group in cohesion-less soils can be calculated as the sum of the resistance of all of the individual micropiles in the group, so long as the center-to-center spacing of micropiles is greater than three times the diameter of the grouted body. Other design considerations of micropile groups include an estimation of micropile group settlement, and the design of footing connection.

6.3.3.2 Micropile Geotechnical Capacity - Bond Length

The FHWA design guide notes that maximum compression and tension loads applied at the top of the micropile must be resisted through a grout-to-ground bond over a specific length of the micropile. This length is referred to as the bond zone or bond length. Generally speaking, the ultimate geotechnical capacity of the bonded length is calculated as follows:

$$P_G = a_{bond}\pi D_b L_b \qquad \text{Equation 6.3-11}$$

Where,
P_G = Ultimate geotechnical bond capacity (N);
α_{bond} = Grout to ground ultimate bond strength (N/m^2);
D_b = Diameter of the drill hole (m);
L_b = Bond length (m).

The CIGRE guide (CIGRE, 2005) recommends the consideration of end bearing capacity as part of the load carrying capacity of a micropile in compression; this load component is defined in Equation 6.3-11. If used for support, vertical unit stress under the micropile base should be evaluated carefully to ensure that sufficient movement is achieved to allow for the full development of end bearing (stress-strain compatibility with side friction), and so that no extrusion of surrounding soil is possible.

$$P_b = F_b p_u \qquad \text{Equation 6.3-11}$$

Where,
P_b = Ultimate bearing capacity (N);
F_b = Area under the micropile base (m^2);
p_U = Ultimate unit stress under the micropile base (N/m^2);

Grout-to-ground bond capacity is influenced by the method of grouting used during the construction process. Accordingly, the mircopile can be classified by the method and pressure used for grout placement. Letter designations (A through E) are used in the classification based on construction practices, as shown in **Figure 6-23**, and are depicted as follows (EPRI, 2012):

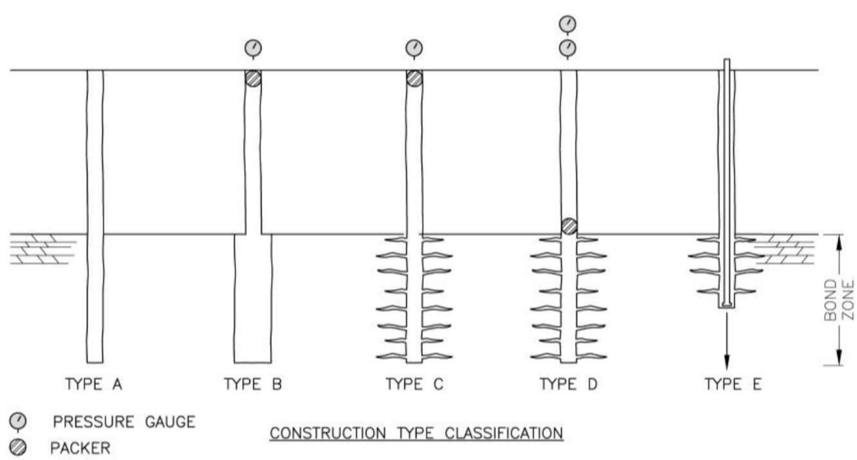


Figure 6-23: Classification of Micropiles according to Grouting Sequence.

- Type A – Neat cement or sand-cement grout placed under gravity head only;
- Type B - Neat cement grout placed under pressure (typically ranging from 0.5 to 1 MPa) as the temporary drill casing is withdrawn;
- Type C - Neat cement grout placed under gravity (Type A), with secondary pressure grouting (>1 MPa) applied through a sleeved grout pipe, without packer at the bond zone interface;
- Type D - Similar to Type C, but allows for full hardening of initial grout, with subsequent pressure grouting (2 -8 MPa) applied through a sleeved grout pipe including a packer inside the sleeved pipe;
- Type E – The drilling and injection of grout through a continuously threaded, hollow-core steel bar. Initial grout has a high water/cement ratio, which is replaced with thicker structural grout (lower water/cement ratio), near the completion of drilling.

6.3.3.3 Micropile Construction

Micropiles are particularly advantageous for projects with one or more significant geological, structural, logistical, environmental, access, or performance challenge. As represented in **Figure 6-24**, these foundations are an especially favorable option for hard soil/rock conditions and restricted access construction sites (Davidow & Carr, 2015). Corresponding materials and construction equipment are lightweight (rigs typically weigh from 65 kN to 180 kN), in comparison with conventional drilled shaft construction. The micropile installation process results in significantly reduced spoils, a small construction footprint, the elimination of drill fluids, and reduced emissions (Chen & Salisbury, 2013). Medium-lift helicopters are often used to transport specialized modular micropile rigs and support equipment to limited access sites (Chen & Salisbury, 2013; Davidow & Carr, 2015). These systems have an advantage over other rock anchor systems insofar as the equipment is packaged to allow for the rapid installation of individual piles to exact tolerances. However, while micropiles are not inexpensive foundation elements, they do become more economical (and less price sensitive than traditional transmission line foundations) when project limitations are imposed, due to access or other factors (Thompson et al., 2009).

Figure 6-24: Construction of Micropiles.
(Photo courtesy of CRUX Subsurface)

Micropile can be installed in virtually any geotechnical condition, including soft silts and clays, hard competent bedrock, and soil with boulders or debris. They can also be installed through existing foundations and in high groundwater tables (Davidow, 2015). Further, these foundations can be installed in ground with subsurface voids (karstic geology). Installation procedures and geometric configurations for micropiles are flexible and based upon variable conditions of foundation locations.

Figure 6-25: Micropile Foundations.

Micropiles have been used for founding transmission structures ranging from mountainous terrain to wetlands (Davidow, 2015; Davidow & Carr, 2015) (**Figure 6-25**). As the elements are relatively small, micropiles can be (and typically are) load tested after installation to validate their capacity, which reduces the need for additional conservatism and increased safety factors.

These foundations can also generally be installed with minimal noise, vibration, and dust generation, when compared to that of drilled shafts. Micropiles do have a high cost relative to traditional transmission line foundations however, and tend to lack wide application due to the lack of specialty contractors who perform micropile installations. Site requirements and construction workmanship protocol are provided in the CIGRE guide document, which includes quality control, corrosion protection, grouting, and equipment available in Europe.

Typically, single micropiles are limited in lateral capacity due to their high slenderness ratio. Consequently, these foundations may not be acceptable for conventional seismic retrofitting applications in areas where liquefaction may occur due to buckling concerns resulting from the loss of lateral support.

6.3.4 Rock Socket with Anchors

The main components of a rock socket/anchor system include a reinforced concrete shaft that is partially or fully embedded into the excavated rock mass, and steel rock anchor bar groups, where cement or resin is grouted into the rock mass below the shaft (see **Figure 6-26**). Tensile forces are transferred from the shaft to the anchor system, either in direct uplift mode or in rotational overturning via the moment couple. Rock anchor foundation are conceptually similar to a micropile group foundation, although shear capacity does not rely on the transfer of lateral loads to casing, and compression loads are resisted by concrete at the base of the shaft. Capacity is largely achieved through the anchor bonds between rock and grout.

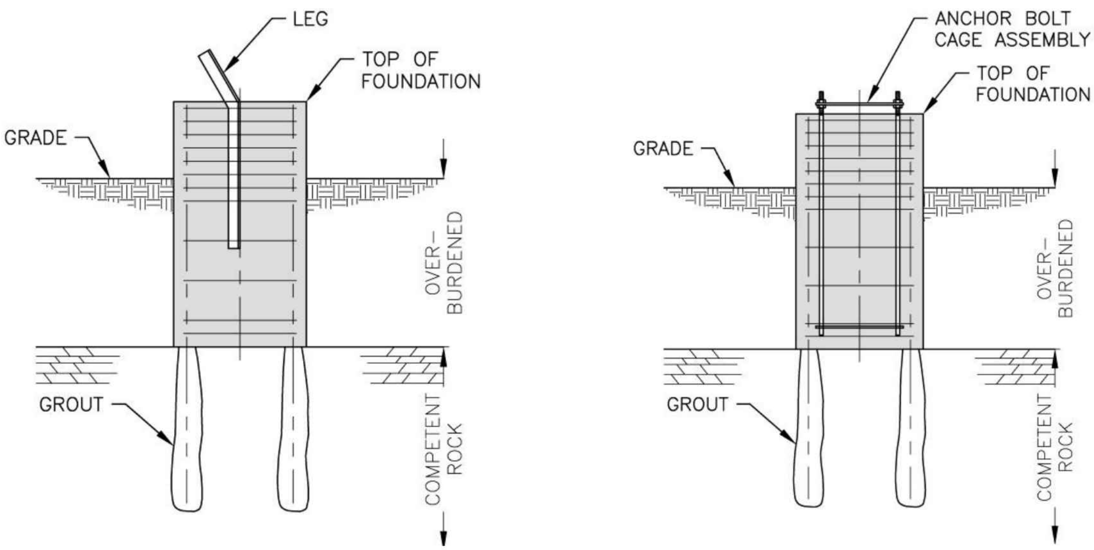


Figure 6-26: Rock Socket with Anchors.
(a) Supporting lattice tower; (b) Supporting single pole

Rock anchors are typically made of high-strength pre-stressed steel with sufficient ductility to meet elongation and reduced area requirements. Most commercial bars are continuously threaded, though deformed bars can be used. Grade 60, 75, 90 and 150 bars are commercially available in lengths up to 15 meters, and diameters ranging from 25 mm to 75 mm. Anchor drill holes range from 60 mm to 150 mm in diameter.

Rock socket/anchor foundation systems can support monopole, H-Frame, and lattice tower transmission line structures in lieu of drilled shaft foundations (Cricket Valley Energy, 2014; DiGioia & Rojas-Gonzalez, 1994). Conventionally shallow concrete spread footing foundations typically used for founding on rock must be very large to resist the applied moments and uplift forces transferred from transmission line structures that impart high overturning moments. Accordingly, a combined socket and anchorage foundation can minimize the footprint.

6.3.4.1 Capacity Evaluation –Overturning

Transverse shear and moment reactions at the top of the foundation are translated into tensile force mobilized in anchors, as well as through compressive force resisted by the bearing strength of concrete and rock (**Figure 6-27**). The behavior of the anchored footing can be analyzed based on the following four simplifying assumptions (Radhakrishna & Klym, 1980):

- The overturning moment (M) at the rock-concrete interface is resisted by a force-couple composed of tension (T) and compression (C);
- The load distribution between the anchors on the tension side is triangular;
- The rock failure surface in uplift is assumed to be in the form of a half truncated cone, formed by a vertical face at the center of footing, and a conical surface rising at an angle of 45° to the vertical from the tips of the anchor cluster;
- The unbalanced shear force is resisted partly by the friction between rock and concrete, and partly by the reinforcement steel anchored into the bedrock.

Anchor tensile force from overturning applied to the anchor group (T_A) can be calculated as:

$$T_A = M/L_a$$ Equation 6.3-12

Where,
M = Overturning moment at the bottom of the concrete pier (N- m);
L_a = Lever arm for the force-couple ≈ 2R/π (m);

The uplift resistance of the rock anchor group (T_R) to the overturning force is given by:

$$T_R = W_R + A_1 S + A_2 S_1 + A_3 S_1$$ Equation 6.3-5

Where
W_R = Weight of uplifted rock (N);
A_1 = Area of the conical failure surface of the half truncate cone (m^2);
A_2 = Area of the vertical failure plane at the center of the footing (m^2);
A_3 = Area of the horizontal plane at the bottom of the anchor bars (m^2);
S = Mobilized unit shear resistance on the conical failure surface (N/m^2);
S_1= Mobilized unit shear resistance at vertical and horizontal force shear planes (N/m^2);

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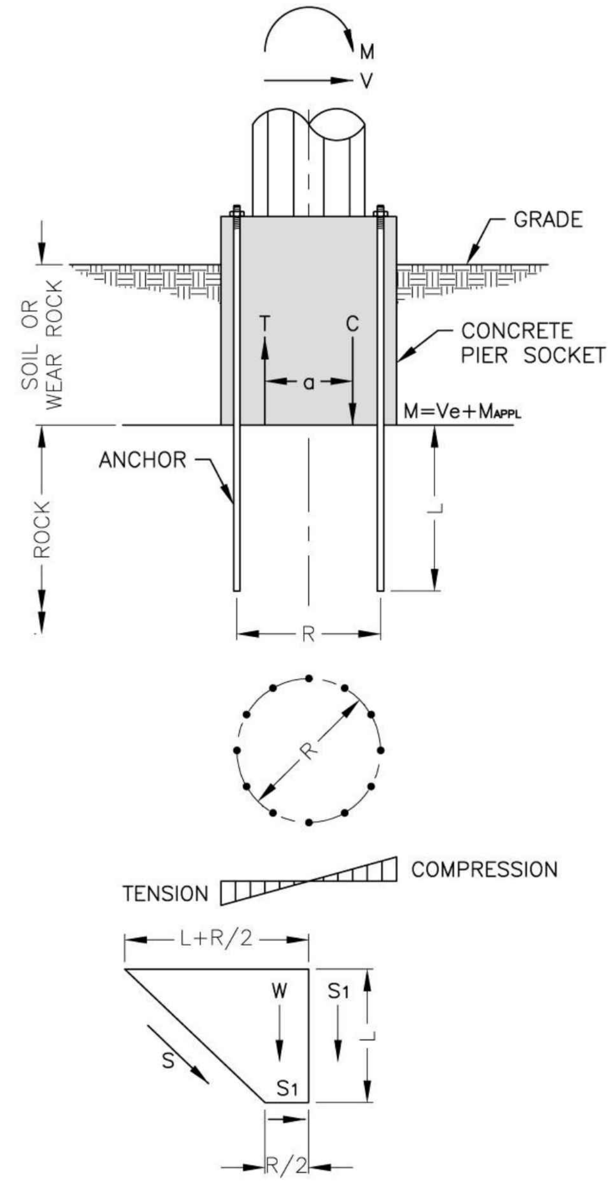

Figure 6-27: Rock Socket with Anchors Group Action.

Rock unit shear resistances *S* and S_1 are dependent upon the rock properties (values are the same for an isotropic rock mass). Tensile pull on each anchor in the group can be calculated from the rock anchor geometry, where total uplift resistance is the sum of the distributed tensions on each rock anchor. The depth of embedment then becomes an analysis of individual anchors in uplift, as described in **Section 6.3.5.2**. Bearing failure of the rock mass or concrete base must also be checked (though this is a very unlikely scenario, as anchor pullout is far more common). A detailed discussion of anchored foundation design subject to shear and moment reactions is provided by Radhakrishna & Klym (1980).

6.3.4.2 Capacity Evaluation – Anchors in Uplift

During the 1970's and 1980's, Ontario Hydro carried out several full scale tests on rock anchors and large rock anchor groups in various rock formations, to determine uplift capacity and required embedment depth (Ismael, et al, 1979). This work resulted in a good understanding of the failure mechanisms and design parameters needed for group anchor design. Four failure modes were identified for rock anchor groups in tension. Based on the load transfer ability of each component, failure can potentially occur as follows:

- Wedge type pull-out of the rock mass;
- Rock to grout bond failure;
- Anchor bar rod to group failure (rod-grout bond failure);
- Tensile failure of steel rock anchor bars.

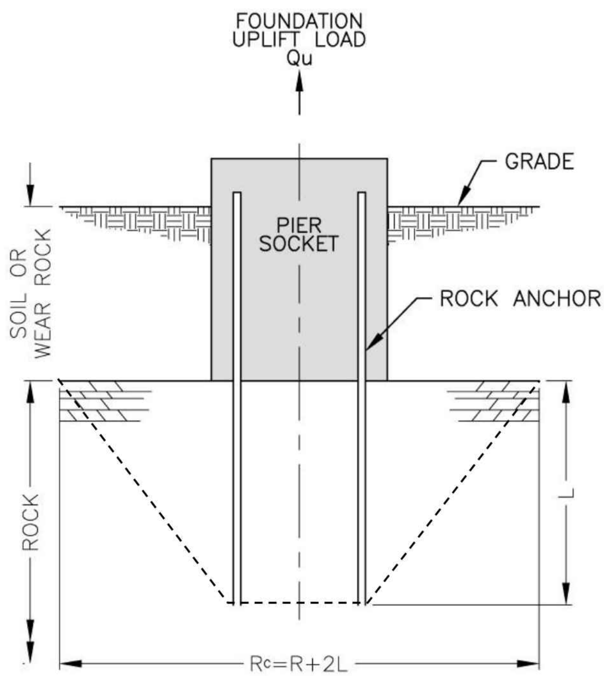

Figure 6-28: Uplift Rock Group Model.

In the case of a rock anchor group, the model assumes development of the shear at the face of a truncated cone (shear stresses along the base are ignored due to possible horizontal bedding planes) (see **Figure 6-28).** Rock anchor group uplift resistance (T_R) to the uplift load (Q_U) is determined via the calculation of the weight of the cone, plus the shearing stress on the conical surface (**Equation 6.3-14**). Resistance is modified according to varying rock anchor group embedment. Group effects must be considered and are dependent on anchor spacing.

$$T_R = (W_{cone} + A_{cone} S)e \qquad \text{Equation 6.3-14}$$

Where,
W_{cone} = Weight of the truncated rock anchor group mass uplifted (N);
A_{cone} = Area of the conical failure surface of the truncate cone (m^2);
S = Mobilized unit shear resistance on the conical failure surface (N/m^2);
e = group efficiency (dimensionless).

The geotechnical design of rock anchor systems is most often controlled by grout-to-rock bond resistance. The resistance along the anchorage length depends on rock-grout bond strength, anchor-grout bond strength, the diameters of the anchor, and the anchor drill hole. Said design procedure is documented within the Army Corps of Engineers manual EM 1110-2-2100 (USACE, 2005). The Ontario Hydro full scale test program showed high resistance, even with shallow embedment. In general, grout-to-rock capacity is determined for a single anchor (load distributed equally among all anchors in the group), with un-factored bond length determined as follows (USACE, 2005).

$$L_{AB} = T_i/(\pi d_h \tau_{allow})$$ Equation 6.3-6

Where,

L_{AB} = Anchor bar bonded length (m);

T_i = Ultimate load by an untensioned individual anchor or design load for a tensioned individual anchor (N);

d_h= Diameter of drilled hole (m);

τ_{allow}= Ultimate bond strength between grout and rock, or c, whichever is less (assuming rock mass failure in the direction of pull out) (N/m^2).

Anchor bar rod-to-group failure (rod-grout bond failure) is generally the least critical mode of failure. Un-factored anchor bar bonded length (L) can be calculated as follows (USACE, 2005):

$$L = T_i/(\pi d_b f_{bu})$$ Equation 6.3-7

Where,

T_i = Ultimate load by an un-tensioned individual anchor or design load for a tensioned individual anchor (N);

d_b= Diameter of anchor bar (m);

f_{bu}= Ultimate bond strength between tendon and grout (N/m^2) (for design, use f_{bu} equal to $6\sqrt{f_c'}$ where f_c' is the compressive strength of grout; f_{bu} must be verified by tests).

Bond strength is best determined by laboratory shear strength data or field pull-out tests. See EPRI, 2012, Chapter 10 or USACE, 2005, Chapter 8 for the details of design process.

The most predictable failure mode is tensile failure of the steel rock anchor bar, since the yield and the ultimate strength of the steel rods are usually known. Typically, rock-grout bond failure occurs well before the load needs to structurally fail the anchor rod (Ismael et al., 1979).

6.3.4.3 Rock Socket Design

Drilled shafts that are partially or fully embedded in rock are also called rock sockets when installed without underlying anchorage. In this case, rock strata that surrounds the foundation provides capacity in both lateral and uplift load modes (with some base resistance). These foundations are considered a specialty form of drilled shaft foundation, discussed further in **Section 6.2.2**. Alternatively with rock socket/anchor systems, the socket portion is assumed to provide no lateral resistance, but may be used to transfer shear to the surrounding rock.

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The rock socket/anchor model assumes that the reinforced concrete portion of the socket is designed similarly to an above-grade column. The shaft acts as a load transfer element that converts shear and overturning reactions, uplifting tensile forces within anchors and compression bearing forces at the base of the concrete.

6.3.4.4 Rock Socket / Anchor Construction

A rock socket/anchor system can significantly reduce excavation during foundation installation. Due to the high cost of rock anchor materials and the labor required to install them, their use is generally limited to difficult access locations where hand or small equipment installation is required, or in very hard drilling rock where excavation requires minimization (**Figure 6-29**). Helicopters are often used to haul both equipment and workers to these sites. Material volumes are small in relation to drilled shafts with comparable load capacity. Usually concrete for the rock socket portion must be flown to the site using portable buckets. If good access roads are within 40 to 50 meters and vertical distance is not beyond reach, concrete can be delivered to some remote sites via pump truck.

Figure 6-29: Construction of Rock Anchor Foundation.

Air-operated track-mounted rock drills are typically used to install rock anchors. Hand-operated rock drills are deployed in remote locations where equipment must be hand-carried or helicoptered. Sockets can be excavated using small rings with either augers (with rock teeth), or rock barrel bits. Most often, the socket is excavated into upper soils and weak rock, via the use of hand equipment. Expansive grouts have been used to break hard rock and to aid in socket excavation.

Minimal drilled cuttings are generated or need to be removed from site. Noise, vibration and dust are moderate to severe when using air-track drilling, or when installing the rock socket in hard subsurface strata.

Rock socket/anchor foundation systems have high axial resistance and moderate resistance to overturning, and can be a favorable option for hard and shallow rock conditions. These foundations are not used for typical soil subsurface conditions (except in strongly indurated or cemented formations). Caution should be exercised where bedding plane orientation is not favorable, or in places where fissures or other discontinuities exist. Research indicates that the presence of fractures and/or thin beds do not reduce the shear strength of bedrock in uplift when compared to the more massive or intact bedrock of some formations. However, the presence of a large void, clay seam or shale layers, tends to reduce the shear strength of the rock substantially (Ismael et al., 1979). Anchors can also be load tested prior to the placement of rock socket concrete to verify capacity (See **Figure 6-29**).

6.3.5 Auger Cast Piles

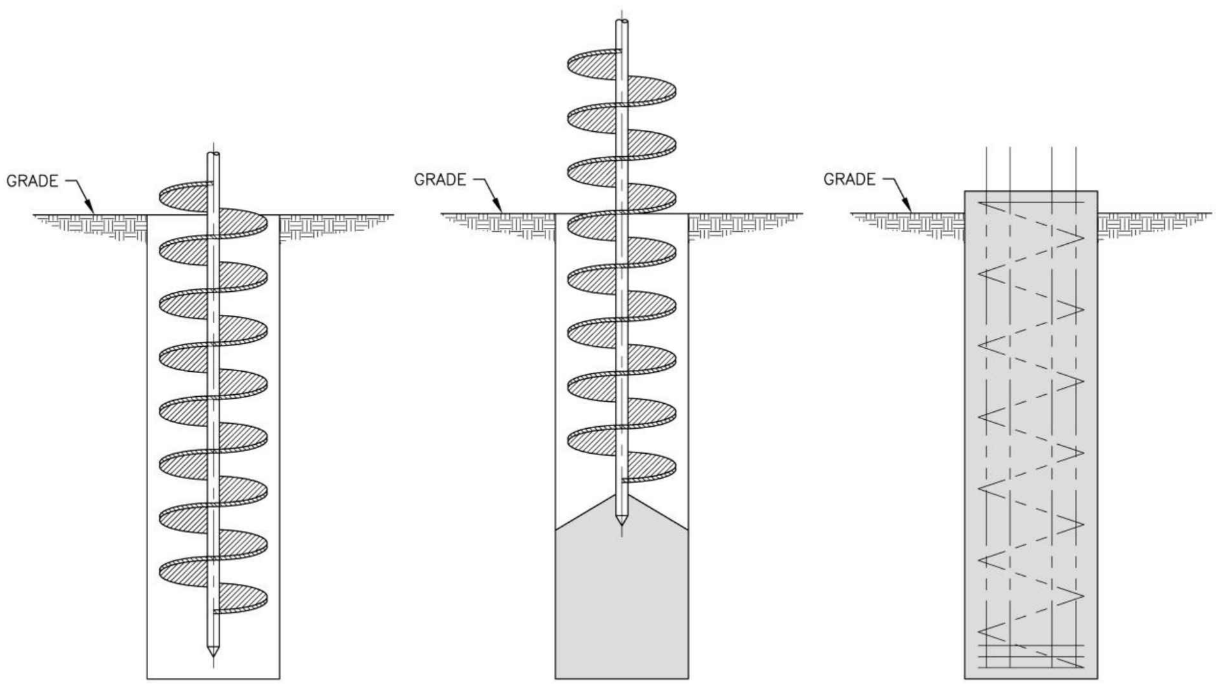

Figure 6-30: Auger Cast Pile Construction Sequence.
(a) Auger Drill into Subgrade; (b) Auger Extraction & Grout Fill; (c) Finished Pile with Rebar

Auger cast piles, also known as continuous flight augers, auger-pressure grout, and screw piles, are deep cast-in-place foundation elements that use a hollow stem auger with continuous flights. Auger cast piles in power delivery system construction generally deploy auger drilling into soil to a design-specific depth. They subsequently withdraw the auger from hole while simultaneously pumping concrete or grout through the hollow center of the auger pipe to the base of auger (note: the hollow stem is plugged during drilling to prevent soil entry). Continuous support of the hole is provided by both the auger and via simultaneous pumping of the grout or concrete at high pressure during auger withdrawal. Minimal lateral stress release and displacement occur. A steel reinforcement cage is placed immediately and rapidly into the shaft, and filled with fresh, highly fluid concrete or grout after the auger is fully withdrawn (**Figure 6-30**) (Brown, et al, 2007; O'Neill, et al, 1999).

Auger cast piles are rarely used for the foundation of transmission line structures, as base plate and stub angle supported structures must generally be installed prior to the placement of concrete. More commonly, auger cast piles are used to support substation foundations in unstable soil conditions or in cases where artesian water is encountered (AGRA, 2013). Piles are attached to the base section of steel structures or electrical equipment pads, using concrete pile caps or mat foundations in lieu of standard reinforced concrete drilled shaft foundations. Auger cast piles can be designed and sufficiently sized to resist compressive, uplift, and lateral loads from medium to low voltage line structures, and they do not require casing or other shaft sidewall support during excavation. Small diameter and depth auger cast piles have been used to provide additional capacity to existing lattice tower pier foundations in a manner similar to that of micropiles (author's files).

Pile diameters typically range from 0.4 to 0.6 meters (up to 1.2 meters with hydraulic auger rigs), with depths up to ten times of the pile diameter. Although high slump concrete can be used with limited size coarse aggregate (no greater than 9.5 mm), auger cast contractors typically employ special sand-cement-fly ash fluid grout mix designs that are adapted to their equipment. 28-day unconfined compressive grout strengths are normally at or below 27.5 MPa to improve pumping. Reinforcement cage lengths ranging between 10 to 15 meters are typical for placement in fresh grout or concrete.

6.3.5.1 Auger Cast Piles Design

An auger cast pile is essentially a reinforced concrete drilled shaft pier that uses a different installation practice. Refer to the drilled pier design methods discussed in **Section 6.2.2** for the design of auger cast piles.

6.3.5.2 Auger Cast Piles Construction

Paved, stoned, and graveled or matted access drives are required for equipment access, and for the delivery of concrete or grout from ready-mix trucks. A variety of rotary pile technologies may be used to auger piles depending on soil and access conditions, but typically these piles are installed using a crane-mounted drill rig with moderate torque (20 to 120 kN-m) and down-crowd (13 to 45 kN) capacities. Specialty hydraulic rigs (common in Europe with some North American availability) can have torque capacities ranging from 90 to 400 kN-m (**Figure 6-31**). When used as supplemental foundations for existing tower legs, auger drills are installed on tired or track-mounted excavators, as well as on dozers that do not require developed access roads. Torque capacity for this type of equipment is generally limited to less than 28 kN-m. In this case, piles (and grout quantities) are usually small in diameter and depth, with support equipment either hauled by similar transport, or flown in via helicopter.

Reinforcement cages can be fabricated at foundation sites or prefabricated and transported to the project. Detailed discussions of various equipment types and installation methods are given in FHWA Geotechnical Design Circular No. 8 (Brown, et al, 2007).

Auger cast pile foundations work well in medium to very stiff clay soils, cemented sands or weak limestone, residual soils, medium dense to dense silty sands, and in well-graded sands and rock overlain by stiff or cemented deposits. Installation can be problematic in very soft soils, loose sands or very clean uniformly graded sands under groundwater, geologic formations containing voids, pockets of water, lenses of very soft soils and/or flowing water, hard soils, or in rock overlain by

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soft soil or loose/granular soils, very hard strata, and where deep scour or liquefiable sand layers are present (Brown, et al, 2007). Soils can impact reinforcement cage installation, as free draining sand and/or dry soil tends to dewater concrete/grout, leading to placement difficulty. No casing is required and these foundations can be installed in high groundwater and artesian conditions.

Figure 6-31: Soilmec Hydraulic CFA Rig with Kelly-bar Extension (Brown et al., 2007).

Auger cast piles offer limited risk (depending upon subsurface strata) to adjacent structures, since minimal disturbance, caving, and vibration result from installation methods. Auger installation work results in low noise along with high productivity (Abdrabbo & Gaaver, 2012). Splices and cutoffs can be eliminated with auger cast pile foundations. Foundation diameters tend to closely match neat-line values, resulting in the lower generation of spoils, and in minimal drilled cuttings removed from sites.

As mentioned, the interconnection of auger cast piles to anchor bolted and stub angle structures is challenging, due to tight structure tolerances and the limited time available to install reinforcement and steel. Auger cast pile foundations are sensitive to down drag effects in settling soils, and are not suitable for bearing in highly compressible material (Hajduk, 2012). In these cases, special design is required to break side shear bonds, with piles founded on deeper, more stable ground.

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6.3.6 Horizontal Directional Drilling

Horizontal directional drilling (HDD) uses trenchless construction methods for the installation of new ducts and cables in situations where open trench excavation is not feasible or desirable. This technique is typically performed for the portion of underground transmission line projects crossing wetlands, waterways, rivers, railways, or congested urban areas. HDD is comprised of a directional drill rig, drill rods linked together to form a drill string, a transmitter for tracking and recording the location of the drill and product, a tank for mixing and holding drilling fluid, and a pump for circulating the drilling fluid (ISTT, 2016). Most often, a casing or carrier pipe made of steel, HDPE or thick-walled fiberglass is installed in advance of PVC conduit bundles (sometimes referenced as “slip lining”). Non-metallic casing is highly desirable for the improved ampacity of the cable system. Casing allows the annular space around conduits to be encapsulated within a thermal grout to better dissipate heat generated by line operation. Alternatively, bundled uncased PVC conduits can be directly installed using HDD methods. Electric underground cables are pulled into PVC conduits upon the completion of grouting.

Briefly, the process of horizontal directional drilling begins with boring a pilot bore into the ground at a specified angle, and, once the proper depth has been reached, the pilot bore is advanced horizontally to a destination point where the drill is redirected, exiting the ground (**Figure 6-32**). Once out of the ground, the drill head is removed and a back reamer or expander is attached along with the casing, carrier pipe, or conduit. The system is then pulled back through the pilot bore to the drilling unit (ISTT, 2016). Large diameter casings may be advanced via pneumatic hammer in lieu of drilling and reaming - typically used for short underground sections below roads.

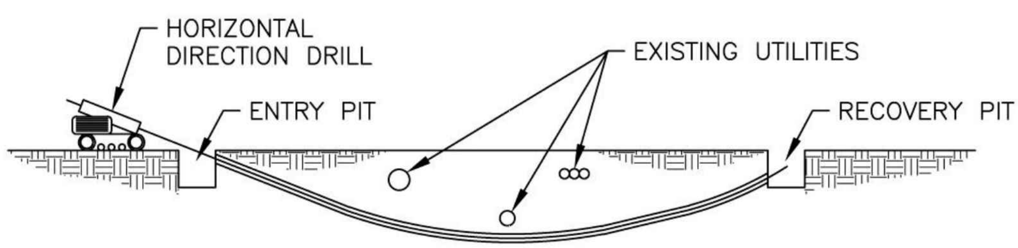

Figure 6-32: Horizontal Directional Drilling.

HDD techniques are a highly specialized and unique installation process for underground cable with high voltage transmission line systems. The drill path can be straight or gradually curved based on the terrain conditions. Obstacles can be steered by adjusting the direction of the drill head during bore (ASTT, 2010).

6.3.6.1 Design Considerations

Detailed design description for HDD is beyond the scope of this report, though specific design issues that need to be addressed for HDD installation include:

- The minimization of drill path curvature via the creation of as large a drill radius as possible, within the limits of the right-of-way. Curvature induces bending stresses, and affects the pullback load during the installation of the conduit and cable.

- A comprehensive geotechnical investigation should be deployed to aid boring practices. Specific geotechnical data is required based on the different soil conditions of sites. Thermal soil resistance must be understood by either in situ field or laboratory sample testing. Underground obstacles along the alignment should be identified, located, and mapped.
- Thermal dissipation analyses must be performed to assess ampacity. The use of thermal grouts should help to dissipate heat from underground electric cables into the surrounding subgrade. Often, thermal grouts are developed for the specific project based on available regional ready-mix materials.
- Calculations of pullback force, tensile stresses, and external pressure are required for the installation of carrier pipes and/or conduits.

See Chapter 12 of *Handbook of Polyethylene Pipe* for a more detailed discussion of design (PPI, 2016).

6.3.6.2 HDD Construction

The cost of underground installation via HDD methods is relatively high when compared to open-trench construction or overhead transmission lines under standard environmental conditions. These costs must be weighed against the need for shoring, utility relocation, traffic control, and street repairs in urban settings, or ground stabilization, seepage control and environmental remediation in wetlands. HDD methods can be competitive in difficult environments, and typically used where traditional open cut-and-cover methods are impractical or prohibited (**Figure 6-33**).

Drill rigs used for HDD installation should be evaluated and sized for rotation, forward thrust, and pullback capacity. Each step of HDD installation significantly affects the quality and function of the finished product, and needs to be carefully evaluated based on guided construction practices. This evaluation is typically performed by the HDD specialty contractor.

HDD can be performed in a wide range of subsurface conditions, and significantly minimizes surface disturbance in environmentally sensitive areas. Subsurface conditions that can adversely impact HDD installation include; a) transitions from soft/loose stratum to hard/dense layers, b) boring through extremely soft/loose soils, c) high gravel content stratum, d) lithified soils or hard rock, and e) reaming in weak cohesive, unconsolidated sediments, or boring/reaming through strong/impervious clays.

Figure 6-33: Construction of horizontal directional drilling (Curtis, 2009).

The noise and vibration of drilling equipment can become problematic when installation is performed near residential and commercial areas (Curtis, 2009). Crossing utilities pose problems for HDD, introducing requirements regarding installation depth. Heat dissipation becomes more challenging and costly when the new transmission line must be placed deeper below ground surface. When installed close to the ground surface, care must be taken to prevent ground heave or subsidence. The HDD process utilizes significant quantities of drilling lubricants (for example, muds such as bentonite), as well as other water-based drilling fluids during installation. Drill cuttings and fluids generated from this activity need to be properly managed and disposed. Additionally, measures should be taken to prevent drill fluids from entering waterbodies or wetlands near the job site (Ohio Division of Surface Water, 2013).

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7.0 FOUNDATION SELECTION

> "If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties."
> – *Francis Bacon, the Advancement of Learning*

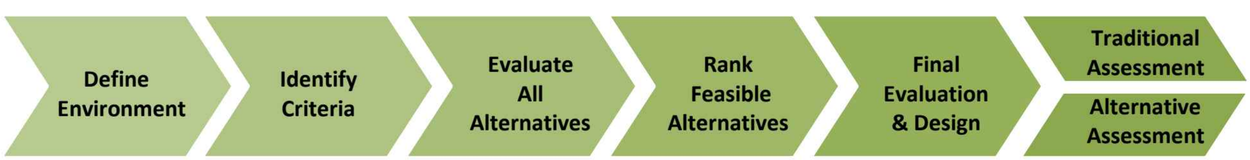
For any given sensitive environment and/or difficult site condition, multiple foundation options can be developed to support the transmission line structure. Alternatively, the designer can choose to span through or under a sensitive or difficult environment to avoid impacts. The project owner and its engineers, therefore, are faced by the challenge to select one or more feasible and economical foundation option for further consideration and design evaluation. This section aims to provide a methodology to aid in the foundation selection process.

Previous sections offered insight into foundation construction approaches taken in various challenging environments. Options are presented for improved construction access and the mitigation of impacts under these conditions (**Section 4** and **Section 5**). Various foundation design options (both traditional and alternative) are described, along with basic design methodologies (**Section 6**). The discussions provide general information on equipment and material needs, environmental and area impacts, and subsurface condition limitations for each of these foundation alternatives.

Table 7-1 (traditional foundations) and **Table 7-2** (alternate foundations) summarize the information presented in **Section 6** using a comparative format. Additionally, these tables note qualitative criteria in terms of the cost and risk involved for each foundation type. The objective of this section is to organize this information into a methodology for the direct comparison of the various foundation alternatives.

7.1 Rational Model

A great deal of information is presented within this guide for the assessment of transmission line foundation options in sensitive environments. The organization of this information is critical for performing a logical assessment that arrives at the optimal foundation alternative for a given project. A rational model can be utilized with a step-by-step process where information is organized and numerical values are assigned to criteria for each foundation option. The goal of the process is to yield a result where the best foundation options equate with the highest numerical rankings. Predicted outcomes, as identified in the case histories and studies (**Section 2**), allow for the designer to select one or more foundation option with the highest likelihood of successfully meeting project goals. The general framework is as follows:



This section presents a rational model in the form of flow charts and decision matrices. Flow charts presented herein are intended as road maps, guiding the designer through the processes and referencing back to report sections for more detailed information. **Figure 7-1** presents the decision making process as a whole, and refers to other flow charts with more detailed evaluations. Decision matrices (**Section 7.3**) are employed as specific components of the flow charts to provide a quantitative element to the assessment process. The following assessment methodology is developed as a general guide in the foundation selection process.

Table 7-1: Comparative Information Summary of Traditional Foundation Types.

		Driven Piles	Drilled Shaft	Direct Embedment	Steel Grillage Foundation	Spread Footing	Anchored Structures
Site Access	Access Requirements	Paved, graveled, graded or matted roads, constructed from barges in open water	Paved, graveled, graded or matted roads, constructed from barges in open water	Paved, graveled, graded or matted roads	Minimal road access needed, graded road typical	Minimal road access needed, graded road typical; good access not required	Small, can be installed with minimal access
Design Considerations	Subsurface Limitations/ Preferences	Typically used to penetrate soft/loose upper strata and bear in dense soil/rock Boulders, cemented soil or obstructions can damage or drift piles	Used in nearly any subsurface condition; Boulders /hard rock can slow drilling	Used in nearly any subsurface condition; Boulders /hard rock can slow drilling; must be cased in caving soils	Best suited where excavation is not difficult, but can be installed in any soil or rock type	Best suited where excavation is not difficult, but can be installed in any soil or rock type	Suitable in almost any subsurface material – capacity is based on soil type
	Geotechnical Investigation	Limited geotechnical info is acceptable; Flexibility in design depth during installation can account for subsurface variability.	Detailed geotechnical information required to determine foundation embedment.	Limited geotechnical info is acceptable; Generally overdesigned to account for subsurface variability.	Detailed geotechnical information very important for slope stability and foundation installation.	Detailed geotechnical information very important for bearing capacity and settlement determination.	Limited geotechnical info is acceptable; Capacity verified during installation; Anchor depths can be extended.
	Groundwater Considerations	Can be constructed through groundwater and within over open water	Casing or slurry stabilization required with groundwater	Not well suited with groundwater; casing required	Difficult to install in high groundwater table – required excavation dewatering	Difficult to install in high groundwater table – required excavation dewatering	Shallow installation generally not effected by groundwater
	Material Needs	Prefabricated steel/concrete/timber pile, steel pile cap	Concrete, rebar/anchor bolt cage, baseplate, casing, backfill	Prefabricated steel pole, backfill	Steel grillage, concrete, backfill	Concrete, steel reinforcement	Steel anchors and attachments
Construction Controls	Schedule Sensitivity	Rapid since piles are prefabricated; driving time minimal	Moderate to extended depending on size and stabilization needs	Rapid since pole and drilled shaft installed at same time	Moderate time required to assemble grillage structure; moderate time to excavate and backfill	Minimal, depending on size and subgrade condition	Rapid
	Installation Equipment	Cranes to support pile and impact or vibrating hammer	Rotary drilling equipment vary in size; cranes to hold reinforcing and anchor bolt cages	Rotary drilling equipment vary in size; cranes to hold pole embedded section or pole	Backhoe or excavator; hoe ram or blasting if rock excavation is needed	Backhoe or excavator; hoe ram or blasting if rock excavation is needed	Small excavator, hand augers, backhoes, track drills or jackhammers in rock
	Concrete Requirements	No below grade cast-in-place; can be used to form pile caps for groups to transfer load	Large concrete quantities; delivery via ready-mix truck or pump truck	Minimal concrete (if used as backfill)	May require large concrete quantities depending on the type of installation	Large concrete quantities; delivery via ready-mix truck or pump truck	Use of concrete is rare
	Backfill/ Grouting	Not applicable	Backfill required only when installing casing via drilled methods	Minimal backfill around annulus; typically compacted in place	Compacted backfill required	Compacted backfill only required if footing is formed	Compacted earth backfill or small quantities of grout in rock
	Corrosion	Steel pile susceptible to corrosion; coating and sacrificial steel suggested in fluctuating groundwater	Minor, deterioration controlled by sulfate-resistant concrete	Galvanization, sacrificial steel or coatings typically used for embedded pole portion	Galvanization, sacrificial steel or coatings are required for protecting steel from corrosion	Minor to moderate, deterioration controlled by sulfate-resistant concrete	Galvanization, sacrificial steel or coatings are required for protecting steel from corrosion
	Temperature	May need to auger a pilot hole in frozen ground	Concrete affected by both extreme hot and cold weather	Minimal – backfill generally not sensitive to temperature	Minimal – backfill generally not sensitive to temperature	Concrete effected by both extreme hot and cold weather	Minimal – materials fairly temperature insensitive
	Adjacent Ground Disturbance	Minimal; but use caution adjacent to other piles and structures	None to significant depending on soil type and installation method	None to significant depending on soil type and installation method	Moderate (depending upon terrain and adjacent slopes)	Moderate (depending upon terrain and adjacent slopes)	Minimal
	Noise/ Vibration/ Dust	Noise moderate to severe; dust minimal to moderate	Noise moderate to severe; dust minimal to moderate	Noise moderate to severe; dust minimal to moderate	Noise minimal; dust minimal to moderate	Noise minimal; dust minimal to moderate	Noise and dust minimal
	Environmental Mitigation	Minimal to average impact, restore access ways	Significant impact, restore access ways, concrete/slurry/backfill/steel stockpiles	Minimal to average impact, restore access ways	Significant impact, restore access ways, large footprint, concrete/backfill/steel stockpiles	Significant impact, restore access ways, large footprint, concrete/steel stockpiles	Minimal to some impact, restore access ways, medium footprint
Risk/Cost		Low cost, low uncertainty when field tested; fixed embedment is a limitation	Cost varies depending on access, stabilization; highly reliable, but not easily verified	Low cost of installation, higher cost of materials; undefined certainty - based on design method	Low to moderate cost of installation, higher cost of materials; low uncertainty	Moderate cost of installation and materials; low uncertainty	Low installation cost; capacity can be verified by simple pull tests
Comments		Group installations are common; piles can be placed vertically or on a batter; specialty contractors needed Can load very quickly (depending on pore water dissipation)	Reinforcement and anchor bolt cages required; depending on complexity, can be done by general contractors Must wait for concrete to cure before loading; highest load capacity	Not applicable for heavily loaded conditions since pole cross section controls capacity	Temporary shoring may be needed during installation; no cure time and can be loaded rapidly	Reinforcement required; can be done by general contractors; temporary shoring may be needed; must wait for concrete to cure before loading	Requires large ROW, may need multiple anchors for support; generally not used with large steel poles

Table 7-2: Comparative Information Summary of Alternative Foundation Types.

		Helical Anchors	Vibratory Steel Caisson	Micropiles	Rock Anchors	Auger Cast Piles	Horizontal Directional Drilling
Site Access	Access Requirements	Suitable for sites with limited access	Paved, graveled, graded or matted roads; constructed from barges in open water; can be installed by helicopter	Ideal for restricted access; can be delivered to site via helicopter, marsh buggy or barge	Ideal for restricted access; can be delivered to site via helicopter or by manual labor	Paved, graveled, graded or matted roads	Paved, graveled, graded or matted roads; but can be hauled to difficult access locations
Design Considerations	Subsurface Limitations/ Preferences	Best in soft soil conditions or where expansive/collapsible soils are found; predrilling may be needed in frozen ground; not suitable for gravels, hard soil, cobble and rock	Used in riverine environments with loose to medium dense granular sands and soft cohesive clays; difficult to install in dense sands, gravels, cobble, medium stiff clay; not suitable in rock	Favorable in hard soil / rock conditions but can be used to penetrate soft soils and reach deep rock; can be installed with subsurface voids	Favorable in hard and shallow cemented soil and rock conditions; Not used for typical soil subsurface conditions; bedding planes should be evaluated	Best in medium to very stiff clays, medium dense to dense or cemented sands, weak rock, residual soils; Difficult in loose or uniform sands/gravels, very soft soils, where voids are present, very hard strata or rock	Good in a wide range of subsurface conditions; difficult in very soft or loose soils, gravels, lithified soils and hard rock, strong, impervious clays; better where soils can readily dissipate heat from energized cables
	Geotechnical Investigation	Limited geotechnical info is acceptable; Capacity verified during installation; Anchor depths can be extended or helixes added	Detailed geotechnical information very important for installation feasibility; Embedment depth can be varied during installation	Limited geotechnical info is acceptable; Capacity verified during installation; Micropile depths can be extended or shortened	Limited geotechnical info is acceptable; Capacity verified during installation; Anchor depths can be extended or shortened	Detailed geotechnical information very important for installation feasibility; Pile depth can be varied during installation, with some difficulty	Detailed geotechnical information required to determine drilling conditions; thermal resistivity testing required
	Groundwater Considerations	Ideal in with high groundwater	Can be constructed through high groundwater or in areas with open water	Can be constructed through high groundwater	Not typically used where significant groundwater is present	Can be constructed in high groundwater, but not with flowing underground water	Can be constructed through high groundwater or under channels
	Material Needs	Helical anchors, steel casing, steel baseplate	Steel casing, concrete/steel baseplate	Pressure grout, concrete/steel baseplate	Steel anchor, concrete, pressure grout, steel baseplate	Concrete, steel rebar/anchor blots	Steel/HDPE/fiberglass/PVC casing, drill fluid, thermal grout
Construction Controls	Schedule Sensitivity	Rapid, except in frozen ground	Rapid; some additional time to connect to pole	Rapid	Time consuming if done by hand labor	Rapid	Significant setup time; rapid during boring and pulling operations
	Installation Equipment	Installed with truck-mounted auger or hydraulic torque motor on various equipment (bobcat to large excavator)	Crane or helicopter to support pile and vibrating hammer	Specialty hammer and track drill rigs; grout pumps	Helicopters; Air/Hand-operated track-mounted rock drills; grout and concrete pumps	Rotary drilling equipment vary in size; cranes to hold reinforcing and anchor bolt cages	Specialty directional drilling rigs
	Concrete Requirements	Not applicable	Small to no quantities, depends on load transfer method	Concrete can be used to form pile caps for groups to transfer load	Concrete used to form load transfer section; generally small quantities	Moderate to large concrete quantities; delivery via ready-mix truck; special flowable mix	Not applicable
	Backfill/ Grouting	Not applicable	Typically not needed	Pressure grouting common; amounts typically low	Pressure grouting common; amounts typically low	Not applicable	Uses specialty thermal grouts
	Corrosion	Galvanization, sacrificial steel or coatings are required for protecting steel from corrosion	Galvanization, sacrificial steel or coatings are required for protecting steel from corrosion	Steel reinforcement within grout; casings can be sacrificial	Steel anchors within grout; Minor, deterioration controlled by sulfate-resistant concrete	Minor, deterioration controlled by sulfate-resistant concrete	Cables in conduit or grouted conduit – not sensitive to corrosion
	Temperature	Not temperature sensitive	Not temperature sensitive, but rarely used in cold temperatures	Not temperature sensitive	Concrete load transfer component affected by both extreme hot and cold weather	Concrete affected by both extreme hot and cold weather	Wetlands, waterways, rivers, railways or congested urban areas
	Adjacent Ground Disturbance	Minimal	Minimal spoils/cuttings; but use caution adjacent structures	Minimal spoils /cuttings; disturbance very low	Minimal spoils /cuttings (more than micropiles)	Minimal ground disturbance	Minimal ground disturbance; caution with heave when close to surface
	Noise/ Vibration/ Dust	Minimal noise and dust	Noise moderate to severe; dust minimal	Noise moderate to severe; dust minimal to moderate	Noise moderate to severe; dust moderate to severe	Minimal noise and dust	Noise and vibration moderate; dust minimal
	Environmental Mitigation	Minimal to some impact depending on site access, small footprint	Average to significant impact depending on vibrator and access	Some to average impact depending on site access, small footprint	Minimal to some impact depending on site access, small footprint	Some to average impact depending on site access, medium footprint	Some to minimal impact, small footprint
Risk/Cost		Low cost, low uncertainty due to capacity correlations with torque	Cost is dependent on installation method; generally high since used in poor access areas; capacity uncertain as no field testing has ever been performed	High cost of materials and labor; generally used with difficult access; capacity can be verified with high degree of certainty	High cost of labor since typically used with difficult access; anchor capacity can be verified with high degree of certainty	Cost relatively low compared to drilled shafts; very reliable, but not easily verified	High cost relative to overhead construction (about 10x higher); very good reliability
Comments		Length of pile (and capacity) limited to the available reach of installation equipment and controlled by torque capacity	Specialty contractor required; special haul permits may be needed; components fabricated at shops	Specialty contractor required; limited lateral capacity – compensated with group application; not ideal for seismic retrofit	Can be done by a general contractor	Not commonly used for transmission line foundations; diameter limited by available auger diameters; mostly used to resist compression loads	Heat dissipation problematic and costly when line must be deep below ground; must manage drill fluids and cuttings

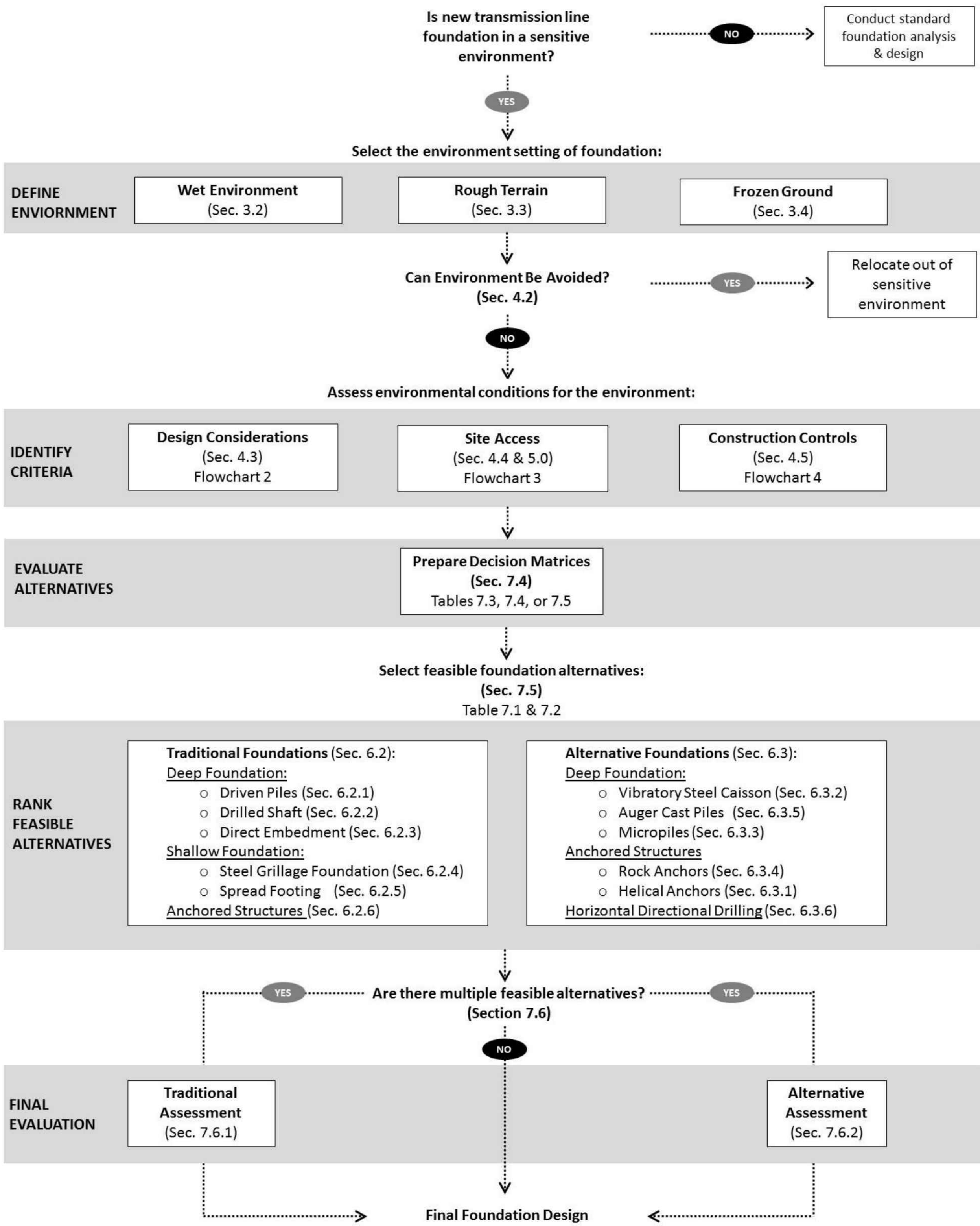


Figure 7-1: Decision Making Process.

7.2 Define Environment Setting

The environment sets the parameters for evaluating foundation alternatives, and dictates the first step of the assessment process. **Section 3** identifies the three major categories of sensitive environments: wet (wetlands, waterways, coats, estuaries, etc.), rough terrain (mountains, deserts, woodlands) and frozen ground (seasonal frozen ground, permafrost). Not all foundations along an alignment will be located in the same environment, so multiple analyses may need to be conducted or criteria redefined, to meet the needs of a particular project.

Avoidance should be a part of the initial assessment process, and is likely to be the preferred strategy. As mentioned in **Section 2**, industry surveys found a number of transmission line environmental assessments in which avoidance was the primary option selected to mitigate impacts via rerouting, increasing span lengths, and/or implementing other avoidance procedures.

7.3 Criteria

Each environment sets particular constraints on foundation design. Various advantages and disadvantages are associated with foundation alternatives. Each project will have specific criteria that the designer will be responsible to meet. As identified in the case histories, all projects will have criteria related to site access, design considerations, and construction controls (see **Figure 7-1** and **Section 4**).

Each of the three criteria identified involves a range of possible factors that make each foundation option more or less favorable for use in a given environment, and they are detailed in flowchart form (**Figure 7-2**, **7-3**, and **7-4**). The criteria and factors provided here are not all inclusive, but instead are intended to serve as a guide; each project may include these particular criteria or have additional criteria unique to the conditions. The designer should select the criteria and related factors that are relevant to the specific project prior to assessing foundation alternatives.

7.3.1 Design Considerations

Foundation design requires assessment of the foundation location, structure loadings, subsurface conditions, and material constraints (**Figure 7-2**). For each of these constraints, multiple factors affect the design decision-making-process, and the selection of the foundation alternative. In terms of design considerations, the most desirable foundation is located on high ground away from sensitive environments, covers only a small footprint, is embedded into well studied, strong, stable and easily excavated/penetrated subsurface material, and requires minimal materials for construction. In this situation, the foundation alternative would receive a high ranking. However, this ideal foundation is rarely the scenario encountered, as most foundations are required to meet particular project specifications.

7.3.2 Site Access

Available access for foundation construction is both dependent upon the environment, and the method used for foundation construction (**Figure 7-3**). Access options will vary based on both, and must be assessed for each alternative. Due to environmental regulations and specific site permitting requirements, the disturbance of a site may be restricted, and thus receive a low rank. Likewise, a climate and environment with limited workable days or seasons for access will receive a low rank. For each method of site access (land, water and air), there are factors that affect the degree of difficulty, environmental impacts, and support equipment/material needs.

7.3.3 Construction Controls

Construction schedules often influence the selection of foundation alternatives due to constraints related to outages, installation, materials, and mitigation (**Figure 7-4**). Foundation installation and construction is likely to require skilled workers to the operate machinery necessary to excavate and install foundation components. The materials used during construction are usually limited by the local availability. Each foundation alternative has specific mitigation and post-construction requirements. The highest ranked foundation construction condition includes a flexible schedule, simple and rapid installation, inexpensive materials that are locally available, and methods requiring minimal mitigation and restoration.

7.4 Evaluate Alternatives

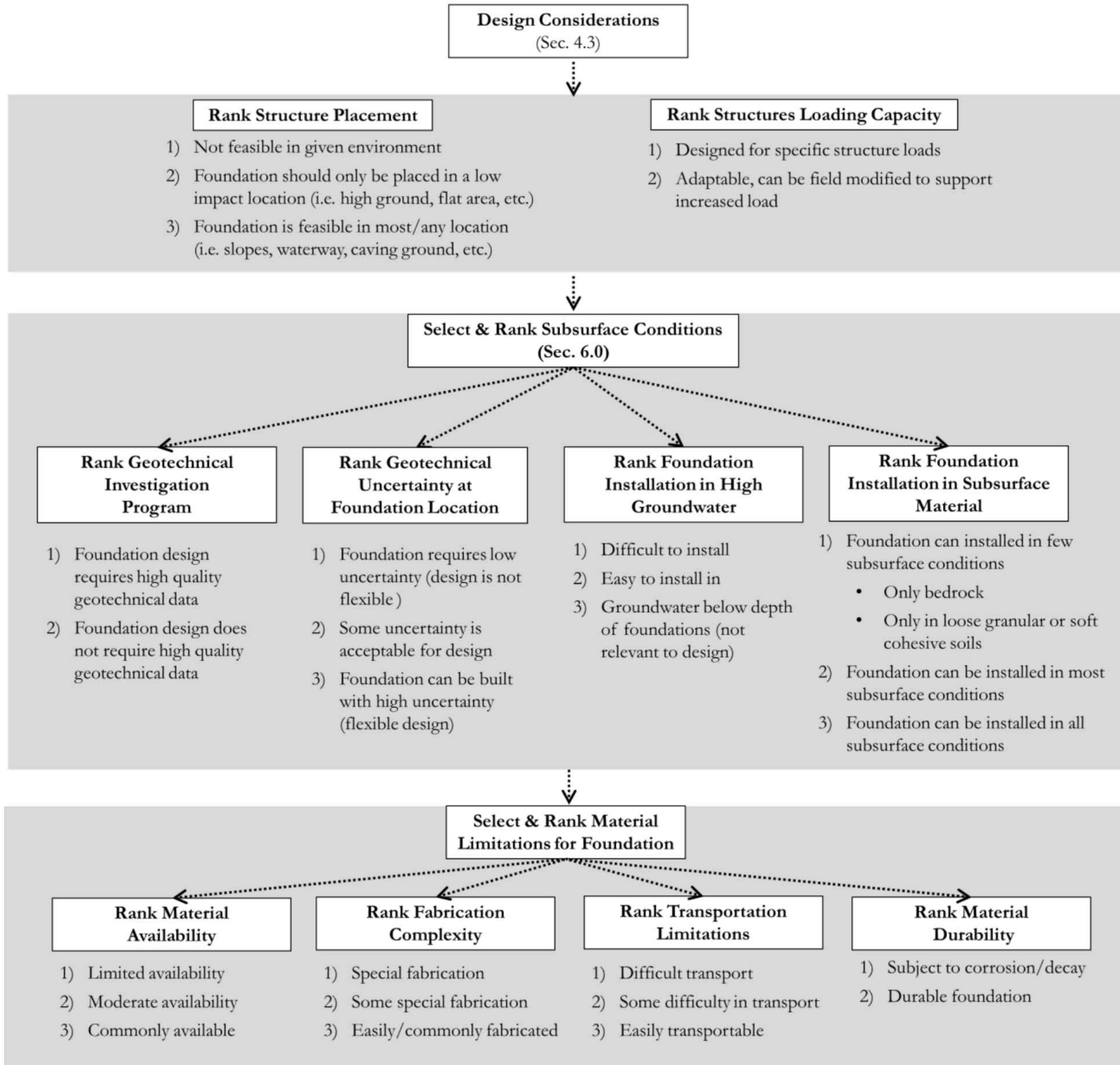
Each foundation alternative contains its own set of uncertainties, consequences, risk, and cost, and accordingly, the best option may not be clear from the outset. The process for evaluating alternatives should include a consistent strategy filtered through a logical and ordered process that addresses all critical elements needed for a successful outcome. The following discussion explains a process that organizes available options, and assesses important criteria in the framework of flow charts and decision matrices.

7.4.1 Criteria Flowcharts

Criteria flow charts address the major elements of foundation selection as identified in the case histories. These flow charts are presented as follows:

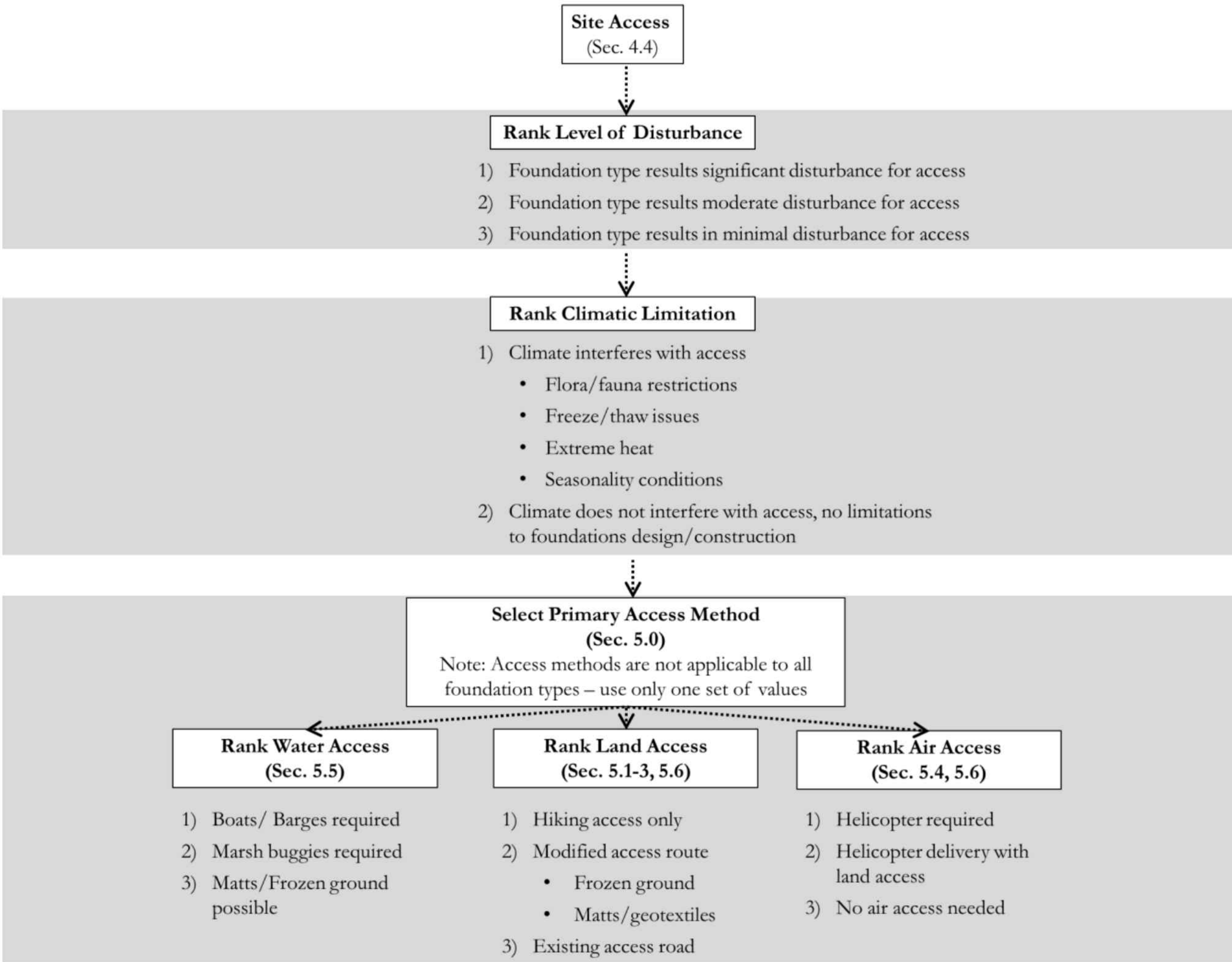
- Figure 7-2: Design Considerations
- Figure 7-3: Construction Controls
- Figure 7-4: Site Access Environment

Each criteria factor in the flowcharts is assigned rank related to environmental impact, flexibility/ adaptability, risk, and cost. The highest value is given to the most favorable condition. The lowest value is given to the least favorable condition. Often, the most favorable options (highest values) within each environment are the least costly; however, final determination of the selected foundation alternative is completed at a later time by estimators or contractors during final design.



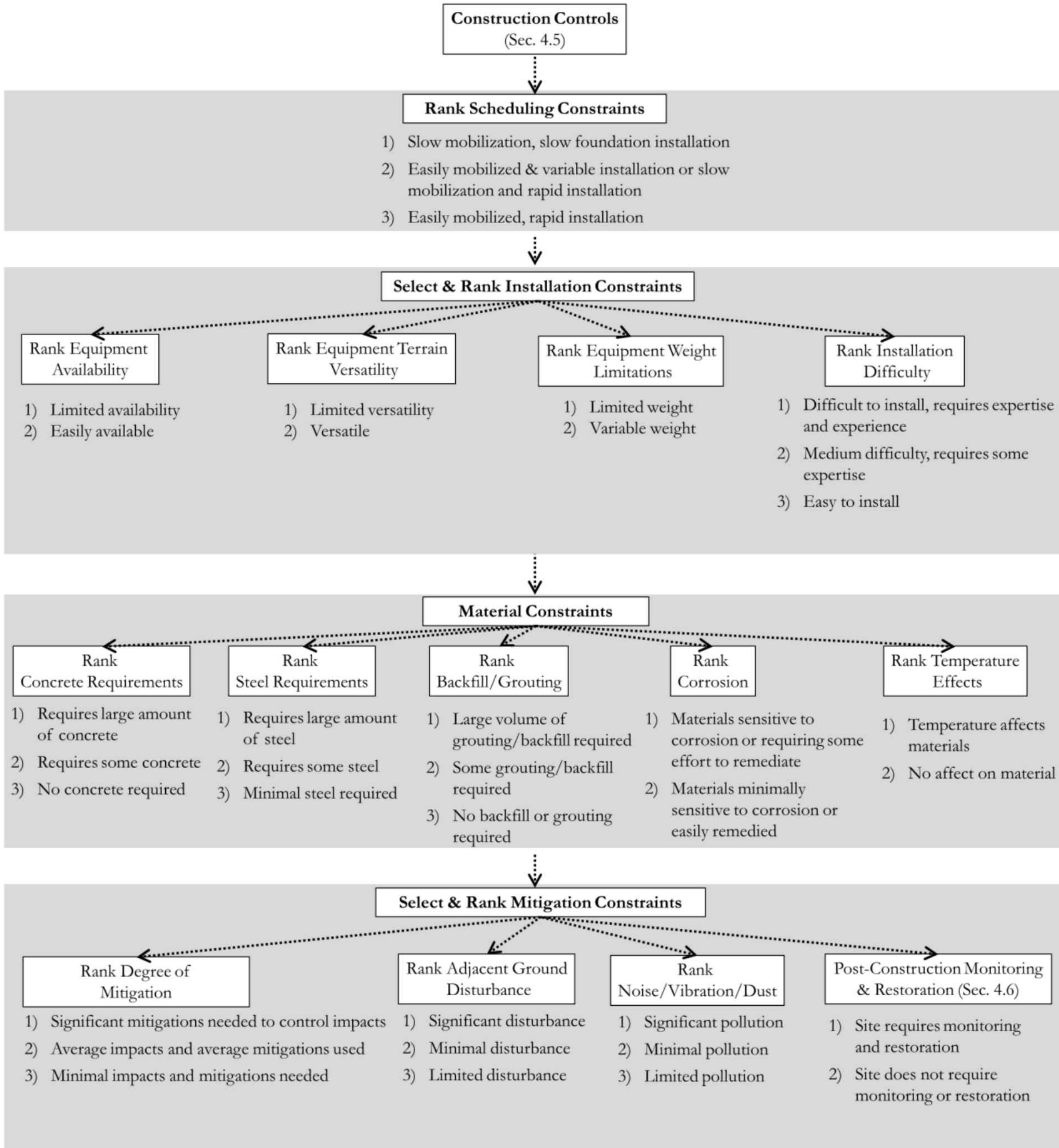
Design Considerations	Rank
Structure Placement/loading	(2-5)
Surface Conditions	(4-11)
Material Requirements	(4-11)

Figure 7-2: Design Consideration Environment Impact Factors.



Site Access	Rank
Permitted Disturbance	(1-3)
Climatic Limitations	(1-2)
Access Method	(1-3)

Figure 7-3: Site Access Environment Impact Factors.



Construction Controls	Rank
Scheduling Constraints	(1-3)
Installation Constraints	(4-9)
Material Constraints	(5-13)
Mitigation Constraints	(4-11)

Figure 7-4: Construction Control Environment Impact Factors.

7.4.2 Decision Matrix

Decision matrices provide a rational tool for the evaluation of possible foundation types that can be used in various environments where there is a wide variety of foundation options and criteria. The process allows for multiple criteria to be taken into account. For a specific environment, foundation alternatives are listed in a table, with the criteria indicated as rows. Each criteria is assigned a numerical score factor, influenced by the environment or by the foundation installation technique (see scoring criteria in **Figures 7-2, 7-3** and **7-4**). The score for each criteria factor is normalized (shown as "N" value in matrixes) so that the influence of each factor is equally balanced. An importance factor is then applied to each set of criteria factors, so that the subjective weight of project specific criteria is included. (**Section 7.4.2.1**). Numerical scores are then summed for each criterion, and for each foundation type. The factors are finally compared according to numerical score (highest to lowest), from the most favorable to least favorable foundation solution for a given environment.

Criteria factor scores must be normalized in order to account for relative differences in the range of selected numerical values from the flowcharts (**Figures 7-2, 7-3** and **7-4**). Normalized scores are employed to inhibit undue influence of one criterion or criteria factor over another, according to number value alone. Otherwise, a criteria factor with a high number of options (say, a value of 11) could have more significance than one with a lower number of options (say, a value of 3). Values are reduced or increased by a multiplier (N) to effect normalization, generally giving equally to each set of criteria (See **Tables 7.3**, **7.4**, **7.5**).

Importance factors for the three decision criterion are incorporated into the decision matrix, to give the designer the ability to subjectively assess the relative importance of each criterion for the specific project, and to provide correspondingly distinct weight to each. The importance factor is a multiplier that can increase the relative weight of site access, design considerations, and construction controls for a particular project or site. Application is discussed in **Section 7.4.2.1**.

This process is best completed as a unique evaluation on a project-by-project basis, taking into account regional or local variations in equipment availability, contractor/constructor experience, material availability, transportation/access, and economics. There is an element of subjectivity in the evaluation of foundation options, and each designer may score foundations slightly differently. **Tables 7.1** and **Figures 7-2, 7-3** and **7-4** provide an excellent base for decision making decisions regarding the selection of the foundation system that least impacts a particular environment.

Tables 7.3 through **7.5** present decision matrices for each of the identified environments, based on the findings of the case histories and case studies (**Section 2**). Since the ranking of each criteria is highly project dependent, the values shown in these criteria are noted as either favorable ("+" sign) or unfavorable ("-" sign). In reality, values are assigned for each applicable criteria based on the numerical rankings given in **Figures 7-2** through **7-4** (see detailed foundation information presented in **Section 6,** and as summarized in **Table 7.1**). Importance factors are typically unique to the project's priorities, and assigned to each criteria set (**Section 7.4.2.1**). Examples of the application of the full decision-making process are given in **Section 8**.

7.4.2.1 Importance Factors

For a particular project, the designer may decide that a given criterion has more importance in the final decision making process. Many codes include importance factors as a way to mitigate higher risks, or to protect lives and property. Importance factor multipliers are suggested as follows:

I Criteria of average importance or risk = 1.0
II Criteria of elevated importance or risk = 2.0
III Criteria is very significant or has high risk = 3.0

For example, a designer may identify site access as significantly linked to controlling project cost, risk, and schedule during previous work performed in a given area. In this case, site access criteria may be given an importance factor of 3.0, while design and construction consideration risks are considered average, accordingly assigned a normal importance factor of 1.0. In another case, scheduling influenced by to migratory species, outage, and/or weather factors may become the project driving need, and a high importance factor of 3.0 is then assigned to construction controls in relation to the other two criteria, with importance factors of 1.0.

Table 7-3: Wet Environment.

Criteria		**Importance Factor (1 – 3)**	**Foundation Type**											
			Driven Piles	**Drilled Shaft**	**Direct Embedment**	**Grillage**	**Spread Footing**	**Anchored Structure**	**Vibratory Steel Caisson**	**Auger Cast Piles**	**Micropiles**	**Rock Anchors**	**Helical Anchors**	**Horizontal Drilling**
Site Access	**N**													
Climatic Conditions	2.0		-	+	-	-	-	+	-	-	+	+	-	+
Permitted Disturbance	2.0		-	-	-	-	-	-	-	+	+	+	+	+
Access Method	2.0		-	-	-	-	+	+	-	-	+	-	-	-
		Subtotal												
Design Considerations	**N**													
Structure	1.0		+	+	+	-	-	-	-	-	-	+	-	+
Subsurface Conditions	0.5		+	+	-	-	-	-	+	+	+	-	+	+
Material Requirements	0.5		+	-	+	-	-	+	-	+	+	+	+	+
		Subtotal												
Construction Controls	**N**													
Scheduling Constraints	1.5		+	-	+	-	-	+	+	+	+	+	+	-
Installation Constraints	0.5		-	+	-	+	+	+	-	-	-	+	-	-
Material Constraints	0.5		+	+	+	-	-	+	-	+	+	+	+	+

Criteria		I n	Foundation Type											
Mitigation Constraints	0.5		+	-	+	-	-	+	+	+	+	+	+	+
		Subtotal												
		Total Score												
		Rank												

N = normalizing multiplier

Table 7-4: Rough Terrain Environment.

Criteria		Importance Factor (1 – 3)	Foundation Type											
			Driven Piles	Drilled Shaft	Direct Embedment	Grillage	Spread Footing	Anchored Structure	Vibratory Steel Caisson	Auger Cast Piles	Micropiles	Rock Anchors	Helical Anchors	Horizontal Drilling
Site Access	**N**													
Climatic Conditions	2.0		+	+	+	+	+	+	+	+	+	+	+	-
Permitted Disturbance	2.0		-	-	-	-	-	+	-	+	+	+	+	+
Access Method	2.0		-	-	-	-	-	+	-	-	+	+	+	-
		Subtotal												
Design Considerations	**N**													
Structure	1.0		+	+	+	-	-	-	-	-	-	+	-	+
Subsurface Conditions	0.5		-	+	+	+	+	+	-	-	+	+	-	-
Material Requirements	0.5		-	-	-	-	-	+	-	-	+	+	+	-
		Subtotal												
Construction Controls	**N**													
Scheduling Constraints	1.5		-	+	+	+	+	+	-	+	+	+	+	-
Installation Constraints	0.5		-	-	+	+	+	+	-	-	+	+	-	-
Material Constraints	0.5		-	-	-	-	-	-	-	-	+	+	+	-
Mitigation Constraints	0.5		-	-	-	-	-	-	-	-	+	+	+	-
		Subtotal												
		Total Score												
		Rank												

N = normalizing multiplier

Table 7-5: Frozen Environment.

Criteria		Importance Factor (1 – 3)	Driven Piles	Drilled Shaft	Direct Embedment	Grillage	Spread Footing	Anchored Structure	Vibratory Steel Caisson	Auger Cast Piles	Micropiles	Rock Anchors	Helical Anchors	Horizontal Drilling
Site Access	**N**													
Climatic Conditions	2.0		+	-	-	+	-	+	-	-	+	-	+	-
Permitted Disturbance	2.0		-	-	-	-	-	+	-	-	+	+	+	+
Access Method	2.0		-	-	-	+	+	+	-	+	+	+	+	-
		Subtotal												
Design Considerations	**N**													
Structure	1.0		+	+	+	-	-	-	-	-	-	+	-	+
Subsurface Conditions	0.5		-	+	+	+	+	+	-	-	+	-	-	-
Material Requirements	0.5		-	-	-	+	-	+	+	-	+	+	+	-
		Subtotal												
Construction Controls	**N**													
Scheduling Constraints	1.5		-	+	+	+	+	+	-	-	+	+	-	-
Installation Constraints	0.5		-	+	+	+	+	+	-	-	-	+	-	-
Material Constraints	0.5		+	-	+	+	-	+	-	-	-	-	+	-
Mitigation Constraints	0.5		-	-	-	-	-	+	-	-	+	+	+	+
		Subtotal												
		Total Score												
		Rank												

N = normalizing multiplier

7.5 Select Feasible Design Alternatives

The development of the decision matrix will result in various rank orders for each design alternative. The selection of one or more feasible alternative for final foundation evaluation and design can be completed via the consideration of rank values. A choice must be made to proceed with foundation design based on the most promising option, or to move forward with the optimal group of foundation alternatives to perform preliminary foundation design, that better assesses cost and risk impacts.

7.6 Final Foundation Evaluation and Design

The rational selection process via decision matrix methods presented herein is intended to provide feasible foundation options that have the least impact upon the environment. Although feasible, the highest ranked option may not necessarily be the least costly, as local experience, variable market prices, the availability of qualified contractors/equipment, etc., will influence pricing at any given time. Preliminary design and cost estimation should be performed for the most feasible options to determine the best course of action.

During final foundation selection, a designer typically conducts preliminary estimation for one or more foundation types as part of the design process. Detailed design is then performed based on the selected option, followed by final detailed cost estimates. When evaluating the use of alternate foundation types, the limited number of specialty contractors who can install these foundations must be considered in a competitive bid environment. Additionally, some contractors who install specialty foundation types use proprietary design processes that further limit detailed design prior to the bidding process. Unless the project owner allows for the sole sourcing of alternative foundations to a specialty contractor, a different approach is needed to assess costs in advance of construction, and to obtain competitive pricing.

The following discussion describes processes for traditional assessments of the cost and risk factors associated with transmission line foundations, as well as for alternative assessments of cost and risk in cases where alternative foundations limit final design and competitive bidding.

7.6.1 Traditional Foundation Assessment

In a standard design-bid-build project, engineering staff is tasked with the assessment of the cost and risk impacts of one or more detailed or preliminary foundation design(s). Risk is often evaluated in terms of the potential for schedule delay of the rest of the transmission line construction, or for the loss of service due to extended line outages. Detailed costs and schedules are developed based on the design work, and a final assessment of the foundation's impact to the project are performed to determine whether or how to proceed with the design.

The engineer must compile a great deal of information regarding material requirements, availability, construction and material costs, contractor availability, final installed foundation quality, and foundation construction methods or constraints. The information is prepared in terms of technical and project-specific conditions. All of these aspects of the work are needed to sufficiently address foundation cost and risk in advance of pricing, as determined by constructors. By having a good understanding of these job requirements, the engineer is able to develop reasonable estimates of foundation costs and the schedule required for construction. This process can be done for more than one foundation option resulting from decision matrices, but, due to budget constraints, typically only one type is selected for final foundation construction prior to constructor pricing.

Detailed cost estimation and schedule preparation is beyond the scope of this guide. Oftentimes, the utility will have internal experts with experience in cost estimation deploy well-developed metrics from previous projects for this effort. The engineering staff provides cost experts with detailed plans and specifications for final assessment. Infrastructure cost estimation guides and software are also available to aid in this process (i.e. RS Means Construction Cost Data, Chief Estimator Software).

7.6.2 Alternative Foundation Assessment

The power transmission industry recognizes the value of competitive bidding for both line and foundation construction, allowing for costs to be effectively managed. With traditional foundations, there are typically multiple contractors able to perform work in most areas of the world. Proposals can be evaluated by price, experience, and quality, as demonstrated in previous projects. When considering alternate foundations, however, fewer constructor options (especially within local regions) are available, thus limiting the competitive pricing of individual foundation types. Some foundation alternatives are designed and constructed by a limited number of specialty firms, which can result in difficulty obtaining multiple competitive bids.

Many of the foundation alternatives discussed in **Section 6.3** are done by specialty contractors or specialized construction crews. Sometimes, as indicated by the survey, alternate foundation types are excluded from evaluation based on internal standards and methods. Typically, only one foundation type is included in design packages for construction bidding (also indicated by the case histories). With design-build projects, known subsurface conditions are minimal or based upon desktop studies, further complicating the bidding process. Therefore, a different approach to foundation evaluation and competitive bidding is required to account for unique foundation alternatives from various contractors and project delivery methods.

The following alternate assessment offers a strategy for the comparison of the cost and risk involved in distinct foundation alternatives for a single project. The process has been used in other infrastructure industries for many years to help manage costs, and, at the same time, to give specialty contractors the opportunity to provide competitive alternatives to traditional options (often identified as "value engineering"). Allowing for the bidding of alternative designs can be effectively used in conjunction with the decision matrix process previously described, to select the most feasible, economical, and lowest risk foundation alternatives for transmission line structures. With sufficient engineering budgeting, the project scope can include multiple prepared foundation designs that either anticipate variations in subsurface conditions, or offer the constructor optional methods for foundation construction in whole (Wendland, 2015).

Value engineering included in the bid process can be used as a tool to perform a final assessment of the optimal foundation alternative with the least environmental impact. Prior to competitive bidding, the design professional only has intuitive knowledge of which contractor or design will result in the most cost effective foundation. Preliminary designs can be accomplished via desktop studies supplemented by minimal field reconnaissance or data. Each viable foundation option would accordingly have a range of possible dimensions. This method allows contractors with different capabilities to take advantage of proprietary or unusual techniques and knowledge specific to that contractor's firm (Hendrickson & Au, 1989).

Example 2 in **Section 8** demonstrates one possible method taken during this alternate assessment process. A limited number of base foundation types are conceptually designed, and subsequently become the basis for contractor pricing. In the bidding process, units representing increasing or decreasing foundation embedment should be added and deducted, or elements should to be included to allow for changing field conditions, providing flexibility in final contractor design. The engineering team must make their best prediction of the variation expected in the field. This prediction can utilize contractor unit prices to select the optimal cost alternative. Typically, contractors will prepare costs related to a specified schedule for foundation installation. By pricing multiple alternatives, schedule impacts for each foundation type can be directly compared and risk can be assessed.

7.7 References

Hendrickson, C., and Au, T. (1989) Project Management for Construction. Prentice Hall, New York.

Wendland, S. (2015). Alternatives for Transmission Line Foundation Design. October 5. Retrieved from http://www.kleinfelder.com/index.cfm/news-and-events/blog/alternatives-for-transmission-line-foundation-design/

8.0 EXAMPLES

8.1 Wet Environment

8.1.1 Project Description

A segment of a 200 km 500kV transmission line is to be installed along the East Fork of the Des Moines River, north of Fort Dodge, Iowa, US (**Figure 8-1**). The alignment crosses farmland, unprotected woodlands, and protected wetlands, and is to be constructed within the same right-of-way as an existing energized transmission line. During planning, the farmland and woodlands were identified as sensitive environments. Timber and HDPE mats are expected to provide access and environmental mitigation for drilled shaft reinforced concrete foundation construction, line construction, and equipment access to the sites. Five structures in this segment are within a protected wetland, with four structures located at a major river crossing. Conditions at these four structures include increased span lengths, as well as foundation scour potential within the active flood plain. Subsurface geotechnical analysis and rock probing was not permitted at this site prior to construction mobilization. During construction, it was ascertained that standard foundation construction could exceed the outage time frame allotted. Additional foundation alternatives were requested to determine if better optimized foundation options could meet the project needs without impacting the environment.

Figure 8-1: Site Location and Proximity to Wetlands.

8.1.2 Model

See **Flowchart 1** (**Figure 7-1**)

1) Define Environment (**Section 3.2, Section 7.2.2**)
2) Identify Criteria (**Section 7.3**)
   a) Identify access constraints (**Section 4.4**)
   b) Identify design considerations (**Section 4.3**)
      i) Identify load conditions
      ii) Evaluate subsurface data
   c) Identify construction controls (**Section 4.5**)
      i) Identify schedule, installation, material and mitigation constraints
3) Evaluate Alternatives (**Section 7.4**)
   a) Use criteria flowcharts to determine matrix values (**Section 7, Table 1 and 2)**
   b) Select Importance Factors for each criteria category (Section 7.4.2.1)
4) Select Feasible Design Alternatives (**Section 7.5**)
   a) Select single foundation alternative
5) Final Design Selection (**Section 7.6**)
   a) Calculate foundation dimensions, alternative designs, and compare to initial design (**Section 6**)
   b) Evaluate the impacts of design options on the schedule (**Section 7.6.1**)

8.1.3 Environment

Typical of the glacial plains of the Central Lowlands province, the surface conditions are dominated by low relief of hummocky hills, and the subsurface is dominated by glacial deposits. This line segment is located in the Des Moines Lobe of the Wisconsinan glaciation, overlying limestone bedrock. The depth to bedrock is highly variable due to past hydrologic processes that are not identifiable by surface features because of various glaciation events.

Four structure locations are within the active flood plain of the East Fork of the Des Moines River; a wet environment (**Figure 8-2**). The area is densely vegetated with large trees, and located near surface saturated, soft soils. Although the alignment crosses the river with foundations on land, the current river bed is unstable, and expected to shift during high flows (note the sinusoidal shape of the main river channel, with ox bows visible near the crossing location, **Figure 8-1**).

The site is located in a cold region where frozen ground conditions may exist during winter months. An outage is planned for construction at this site in the early spring, but frozen ground is likely not to be present (typically occurring during the December – March time frame). Low water is to be expected in the channel during foundation construction, which will permit driving access to the foundation sites using matting as mitigation.

Bedrock depth at the four structure locations was estimated from nearby borings and water well logs (no investigation is allowed at sites prior to construction).

Figure 8-2: Location of 500kV Structures in Sensitive Wetland Environment.

8.1.4 Criteria

8.1.4.1 Access constraints

The site is located in a protected wetland, with regulations restricting activity due to migratory bird and native bat species, as well as various plant species. Due to the proximity of water, the environmental monitoring of construction was conducted throughout the process, and minimal ground disturbance was permitted. Access to the four sites for subsurface investigation was not permitted. Access to the site is preferred during the cold season, as the frozen ground is easier to transverse with large equipment. Otherwise, sites are accessible via the matting of soft ground. Water is anticipated to be shallow during foundation construction, and to limit boat access by river near structures during the cold season.

8.1.4.2 Design Considerations

Structure relocation is not feasible at this later phase of the project. The structure moment reactions range from nearly 6,000 kN-m for the tangent structures, to nearly 25,000 kN-m for the large turning structures (See **Table 8.1**). The foundation design is required to accommodate the wide range in loads.

Table 8-1: Vendor Provided Structure Reactions.

Structure Type	Qty	Maximum Load Case		
		Shear (kN)	Moment (kN-m)	Axial (kN)
Tangent	2	196	5780	228
Angle 10°	1	415	13520	672
Angle 30°	1	923	24540	711

Foundation design must be flexible to accommodate the uncertainty in depth to bedrock for these four structures. The subsurface consists of glacial drift overlying glacial till from the Altamont advance, underlain by weathered limestone bedrock. A single soil boring was performed outside the protected wetland southeast of the four-structure alignment (**Figure 8-3**). Additional subsurface information was obtained from existing well logs at locations outside the wetland. The strength of the glacial till increases with depth and corresponds to soil color change, with the shallower material being a yellow color due to increased silt content, and the deeper material being a gray color due to increased clay content. The geotechnical properties are derived from similar soil conditions encountered elsewhere along the alignment, with properties accounting for variability that may be identified at each of the four structure locations (**Table 8-2**). The depth of each strata layer, particularly the depth to limestone, is highly uncertain at these four structure locations.

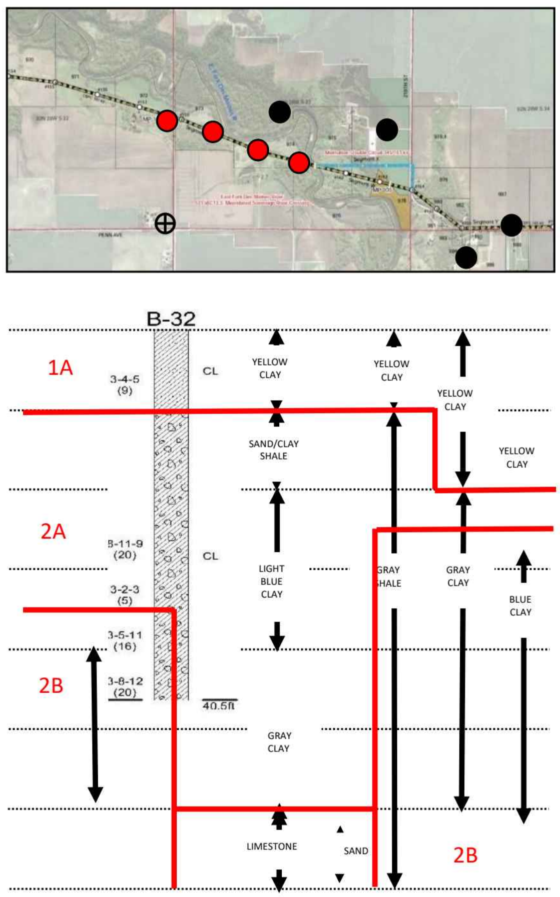


Figure 8-3: Location of borings (crossed circle), wells (black circles), structures (red circles) and the approximate cross-sectional profile for design

(Ground surface is normalized with depth below ground surface in meters)

Table 8-2: Geotechnical properties.

Strata No.	Description	γ_t (g/cm³)	ϕ' (°)	c' (kN/m²)	E_p (MPa)
1A	Glacial Drift Sediments	1.9	-	72	3
2A	Midrange Glacial Till	2.0	-	72	7
2B	Deep Glacial Till	2.1	-	192	16
3A	Limestone	2.2	50	145	689

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Foundation design will require flexibility to accommodate installation within and above bedrock. Prior experience on this project indicates that full depth permanent casing will likely be needed. Drilled shaft foundation diameters will range from 1.83 to 2.44 m. To accommodate 100-year flooding, these foundations must be at least 2.5 m above ground surface. Potential scour loss of the adjacent ground is estimated at 1 to 3 m below the existing ground surface. Depth to bedrock may range from 2.4 to 3.6 m below ground surface. Alternate foundation types will need to accommodate these conditions.

Additionally, the depth of the groundwater table is expected to be high, due to the proximity of the river way requiring foundation materials to withstand corrosion. Foundation materials need to be readily available to meet the short construction time frame. The transportation of material to the site can be via large trucks by the use of matting.

8.1.4.3 Construction Controls

Construction will be conducted during the early spring to minimize impacts on nearby farm roads (before planting). Site mobilization requires timber or HDPE matting for the transportation of site material and equipment access, including additional matting around foundation locations to support cranes and foundation installation/excavation equipment in soft soil conditions. Construction equipment will need to be versatile and properly sized to accommodate the limits of matting. Matting is intended to cause minimal disturbance to the ground, mitigating erosion and water turbidity. Noise and vibration are expected to be moderate, depending on planned equipment types and subsurface soils.

8.1.5 Evaluate Alternatives

Based on site conditions and structure loads, it is apparent that certain foundation types will not be feasible for the provided project sites, as scour resistant foundations are sometimes needed. These include shallow foundations (grillages, spread footings), guy anchored structures, anchored rock sockets, and helical anchors. Underground cable installation was also excluded from the analysis, due to the limited time frame available for ordering new material. Other foundation types (as described in **Section 6**) will be carried forward for final evaluation via the application of a decision matrix, using the criteria shown in **Figures 7-2, 7-3 and 7-4**.

The range of rankings for each criteria factor in the decision matrix can vary from as low as 2 to as high as 13 (see tables at the bottom of **Figures 7-2, 7-3 and 7-4**). To more equally balance the influence of each criterion, rank is normalized using a factor ranging from 0.5 to 2.0 (shown as "N" value in matrixes). An example of the calculations for "Construction Controls" with micropiles is shown following **Table 8-3**.

Each criterion is subjectively adjusted to reflect the importance of particular job constraints. The time available for construction (schedule) was of significantly elevated importance to the owner, and given a value of 3.0 in terms of construction controls. The risk of encountering unexpected subsurface conditions provided an elevated concern at the site, resulting in an importance factor value of 2.0. Site access constraints were mitigated by matting, and proved of average importance for this site area (factor of 1.0). Evaluation criteria and summary results of the evaluations for each foundation alternative are shown in **Table 8-2.**

Table 8-3: Criteria for Wet Environments.

Criteria for Wet Terrain		**Importance Factor**	**Foundation Type**											
			Driven Piles	**Drilled Shaft**	**Direct Embedment**	**Grillage**	**Spread Footing**	**Guy Anchors**	**Vibratory Steel Caisson**	**Auger Cast Piles**	**Micropiles**	**Rock Anchors**	**Helical Anchors**	**Horizontal Drilling**
Site Access (Figure 7-3)	**N**	1.0												
Permitted	2.0		3	2	3	-	-	-	3	2	3	-	-	-
Climatic Conditions	2.0		1	1	1	-	-	-	1	1	2	-	-	-
Access Method	2.0		2	2	2	-	-	-	2	3	3	-	-	-
Subtotal			12	10	12	-	-	-	12	12	16	-	-	-
Design Considerations	**N**	2.0												
Structure Conditions	1.0		3	5	2	-	-	-	3	2	5	-	-	-
Subsurface	0.5		8	8	7	-	-	-	6	6	10	-	-	-
Material	0.5		7	11	9	-	-	-	8	11	9	-	-	-
Subtotal			21	29	20	-	-	-	20	21	29	-	-	-
Construction Controls	**N**	3.0												
Scheduling	1.5		2	3	3	-	-	-	3	2	3	-	-	-
Installation	0.5		6	8	6	-	-	-	8	8	6	-	-	-
Material Constraints	0.5		9	10	9	-	-	-	10	12	11	-	-	-
Mitigation	0.5		8	8	8	-	-	-	11	7	9	-	-	-
Subtotal			44	53	48	-	-	-	57	50	53	-	-	-
		Total Score	77	92	80	-	-	-	89	83	98	-	-	-
		Rank	6	2	5				3	4	1			

(Detailed calculations are shown on the next page for yellow highlighted values)

Calculation Example: Construction Controls for Micropiles (highlighted values in **Table 8-3**) (See **Table 7.2.1** and **Section 6.3.3** for detailed information to derive rankings)

- Schedule constraints:

Rapid installation	**3**
N	x 1.5
Subtotal	4.5

- Installation constraints:

Limited availability	1
Versatile	2
Variable weight	2
Requires experts	1
Sum of Criteria Factors	**6**
N	x 0.5
Subtotal	3.0

- Material constraints:

Some concrete (cap)	2
Minimal steel	3
Some grout	2
Not subject to corrosion	2
Not temperature sensitive	2
Sum of Criteria Factors	**11**
N	x 0.5
Subtotal	5.5

- Mitigation constraints:

Average impacts	2
Limited disturbance	3
Minimal pollution	2
No post construction monitoring	2
Sum of Criteria Factors	**9**
N	x 0.5
Subtotal	4.5

Summary: Construction Controls:

Schedule constraints	4.5
Installation constraints	3.0
Material constraints	5.5
Mitigation constraints	4.5
Sum of Criteria	17.5
Importance Factor	x 3.0
Construction Controls (micropiles)	**53** (rounded up from 52.5)

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8.1.6 Select Feasible Design Alternatives

Following review of **Table 8-3**, the top three foundation options are micropiles, drilled shaft reinforced concrete foundations, and vibratory steel caissons. Each was further examined as follows:

- Case histories demonstrate that micropiles are an excellent option in wet environments, especially where bedrock is within reach. Piles can be load tested (lower risk). They are also flexible with variable bedrock. However, a specialty contractor is needed to provide final design, equipment, and materials, and they involve a high mobilization cost for just 4 foundation sites. Additional forming time would be required for large reveals due to high 100-year floodwaters. The on-site contractor would also need to subcontract this portion of the project, and it was uncertain if specialty contractor during the outage window would be available. As this was a Design-Build job, the contractor preferred to self-perform the work. Although likely the most cost-effective option, this alternative was rejected by the contractor.
- The project was already in the process of utilizing a crane-mounted vibratory hammer for the installation of large diameter casing, so this option was considered viable. However, the installation of a vibratory steel caisson could be problematic, as large boulders/bedrock and stiff clays were likely in the glacial till material, requiring predrilling to verify subsurface conditions, reducing the advantage of this alternative. Additionally, the caisson bottom section with flange would require design and rapid fabrication to meet the project schedule. Load carrying capacity was uncertain unless load test verification could be done, and corrosion protection would require consideration. This option was rejected due to a concern regarding successful installation within the allotted time.
- Drilled shaft reinforced concrete foundations were the primary foundation type used for the project, so suitable equipment and manpower were readily available. The contractor proposed to mitigate schedule risk by working continuously in this area until foundations were installed, proposing to mobilize a second drill rig and foundation crew if necessary, in order to reduce the risk of over-running the outage window. To mitigate the risk of variable bedrock depth, the contractor obtained suitable mechanical connections for the extension of full length anchor bars, if bedrock was encountered at greater depths than expected.

8.1.7 Final Foundation Design

The embedment length for a drilled shaft foundation of a monopole structure is controlled by the applied moment load and the resistance of the subsurface materials. Embedment varies depending on subsurface conditions. The EPRI MFAD© Version 5.1.18 program was used for the foundation design of the laterally loaded foundations. The drilled shaft foundations are designed as rigid piers using Reliability-Based Design (RBD) methods alongside owner provided loads. The foundation designs are based on a maximum total displacement of 4% of the diameter and a maximum total rotation of 1 degree for the specified diameter drilled shafts. Lateral load analysis was performed as described in **Section 6.2.2.2**. Expected foundation designs are presented in **Table 8-4**.

Table 8-4: Drilled Foundation Depth.

Foundation Type	Quantity	Diameter (m)	Reveal (m)	Scour (m)	Embedment (m)	Total Foundation Length (m)
Tangent	2	1.83	2.5	1.0	9.0	12.5
Angle 10°	1	2.13	2.5	1.0	10.5	14.0
Angle 30°	1	2.44	2.5	3.0	12.0	17.5

8.2 Rough Terrain Environment

8.2.1 Project Description

Four-legged lattice 115kV tower structures located in very rough terrain environments, (originally installed between 1908 and 1930, **Figure 8-4**) are to be replaced and upgraded so that conductors meet new clearance requirements. The existing tower locations span roughly 75-miles of highly variable topography encircling the Superstition Mountains in Arizona (**Figure 8-5**). The structures are located in seven distinct volcanic geological areas. The structures are located in Tonto National Forest, a popular tourist destination and preservation area for wildlife and cultural sites. There are roughly 100 protected plant and animal species, including golden eagles and saguaro cacti, residing in the project area. Access roads for many of the tower sites no longer exist, and no new road construction will be permitted by the authorizing agency.

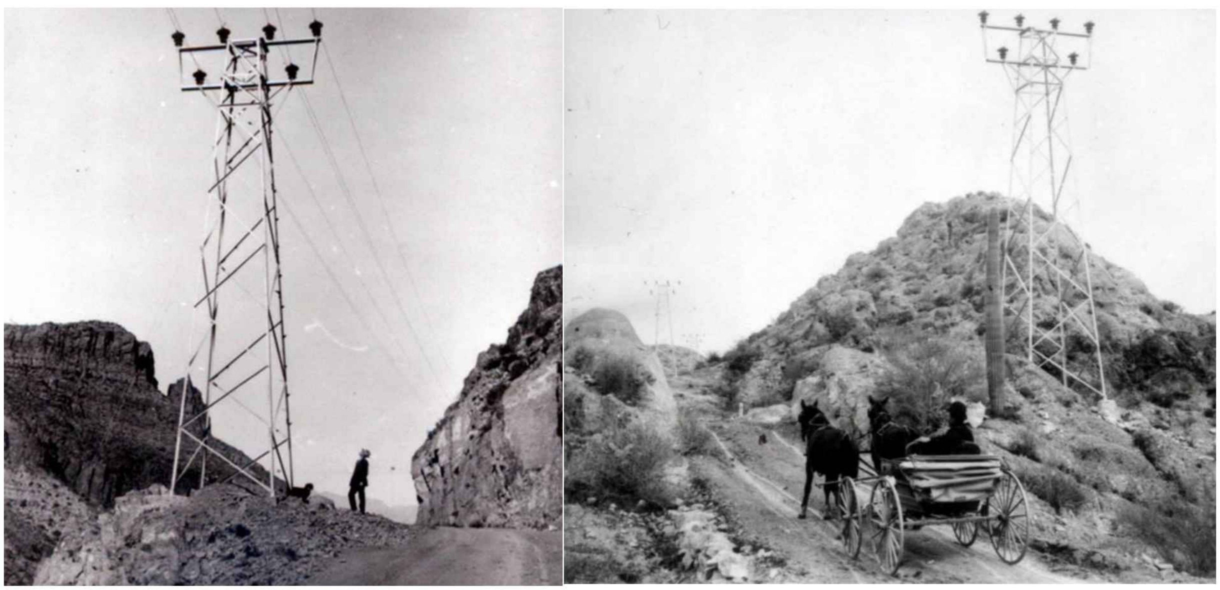

Figure 8-4: Existing Lattice Tower in Rough Terrain (Original Construction Photos).

The utility desires preliminary foundation design alternatives to support two possible structure types. The preliminary designs will be used for comparative pricing purposes, for the selection of the optimal structure/foundation option in terms of risk and cost. Upon the selection of the preferred option, final foundation design will be performed by the successful contractor. The utility's in-house construction forces will install structures on completed foundations, and perform required conductor relocations. Lines will remain active during foundation construction, and outages will be provided for foundation construction on a limited basis, primarily to transport equipment and materials to and from structure sites. Work will be done in the spring season to minimize outage needs.

Subsurface information is limited, as traditional sampling by drill rig was not permitted in this sensitive environment. Subsurface investigation consisted of seismic refraction geophysical surveys at 25 of the 75 structure locations. Geologic reconnaissance was conducted at each structure location to identify surface conditions and rock outcrops. Foundation designs require flexibility to

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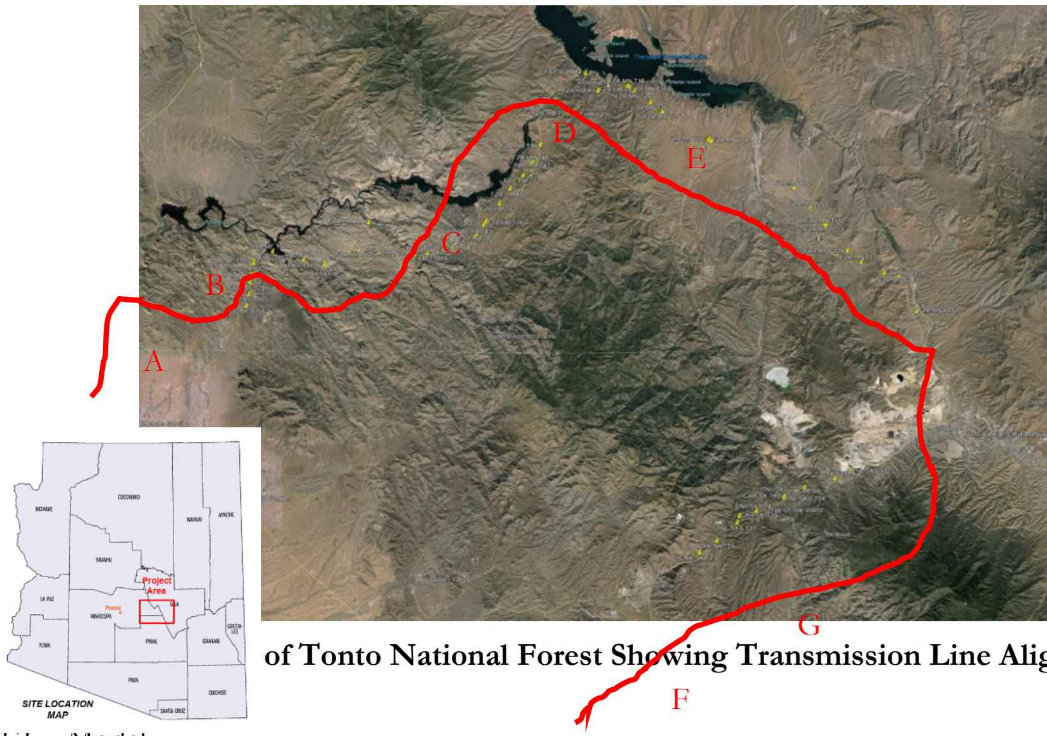
allow for uncertainty in depth-to and quality of bedrock, as this information is not well understood at 50 of the sites.



of Tonto National Forest Showing Transmission Line Alignment.

8.2.2 Model

See **Flowchart 1** (**Figure 7-1**)

1) Define Environment (**Section 3.3, Section 7.2**)
2) Identify Criteria (**Figures 7-2, 7-3, 7-4**)
    a) Identify feasible types of access for each structure location (**Section 3.3**)
    b) Identify design considerations (**Section 3.3**)
        i) Identify owners defined load conditions for two structure types
        ii) Obtain subsurface geotechnical design properties for rough terrain and estimate depth to bedrock at each structure location
        iii) Identify material limitations for foundation types due to access limitations and geologic conditions
    c) Identify construction controls (**Section 4.5**)
        i) Identify schedule, installation, material and mitigation constraints
3) Evaluate Alternatives (**Tables 7.1 and 7.2**)
    a) Use criteria flowcharts to determine matrix values (**Section 7, Table 1 and 2)**
    b) Select Importance Factors for each criteria category (**Section 7.4.2.1**)
4) Select Feasible Design Alternatives (**Section 7.5**)
    a) Choose several foundation alternatives for preliminary bidding
5) Final Design Selection (**Section 7.6**)
    a) For each foundation alternative, estimate foundation dimensions for expected range of field conditions – present in tabular format (**Section 6**)
    b) Create bid document that allows comparative evaluation of multiple foundation alternatives with structure types (**Section 7.6.2**)

8.2.3 Environment

The utility identified 75 towers as being located in difficult access locations within a sensitive environment. The terrain has highly variable ground elevations and variable depth to bedrock, as a result of multiple volcanic events occurring in the region, contributing to the creation of rugged geologic profiles. There is sparse vegetation coverage, although numerous protected flora and fauna are located in the area. The rough terrain environment (reference **Section 3.3**), consists of various subsurface conditions, ranging from steep slopes of volcanic bedrock, to wide broad drainages with upwards of 15 meters of alluvial material. The final foundation design will need to be feasible for both shallow bedrock and thick overburden conditions, and must be able to be installed on remote, steep slopes and high ground along the alignment.

8.2.4 Criteria

8.2.4.1 Site Access

Most access roads used during initial line construction have disappeared and are no longer usable. Many towers are located on high ground (some at the top of bedrock formations), with feasible access achieved primarily via helicopter and hiking. Small all-terrain vehicles (ATVs) can access some of the tower sites. Due to limited access, foundation installation is expected to be difficult, and the foundation contractor must minimize construction footprints to prevent the disturbance of protected plants, animals, and cultural sites in the national forest.

The utility classified the 75 replacement towers as "difficult access" locations, where the dismantling of existing structures, the construction of foundations for new structures, and the installation of new structures, will either require helicopter access (57 sites) or ATV access (18 sites). The majority of construction sites are located on high elevation bedrock outcrops well above or below the nearby highway, and as such, are not accessible by road. The typical regional practice is to found towers on drilled shaft reinforced concrete piers. This approach was determined unfeasible for the equipment that would be required to socket foundations into hard rock. The construction of staging areas in close proximity to the tower locations is consequently to be restricted to existing road spurs off the main highway. Dust control is to be maintained on unpaved portions of the highway and spur roads. The contractor is to be responsible for site access costs.

8.2.4.2 Design Considerations

Geologic site reconnaissance visits to each of the 75 structure locations included site characterization, the assessment of subsurface conditions, and estimated depth to bedrock. A summary of the number of structures located in each geologic region is presented in **Table 8-5**, as mapped in **Figure 8-5**. Seismic refraction surveys were performed at 25 structures sites accessible by foot, representative of subsurface conditions observed during geologic reconnaissance. Geophysical test results were combined with geologic study observations for the development of a soil and rock model simplifying the seven geologic zones shown in **Table 8-5** (as shown in **Table 8-6**). Groundwater is not expected during foundation installation, although perched water tables are possible.

Table 8-5: Overview of Key Geologic Features for Project Area.

Region	Number of Structures (#)	Subsurface Description	Depth to Bedrock (m)	Strata Zones
A	14	Basalt/Dacite Lava bedrock	0	3
B	6	Alluvial fan deposits over Ash Tuff and Volcanoclastic bedrock	0 to 1	1, 3
C	21	Alluvial fan deposits over Basalt/Dacite/Granite bedrock	0 to 3	1, 3
D	1	Pioneer formation sandstone bedrock	0	2
E	20	Alluvial fan deposits over sandstone/conglomerate and granite bedrock	1 to 14	1, 2
F	3	Apache Leap Tuff bedrock	0	3
G	10	Granite bedrock	0	3

Table 8-6: Subsurface Strata Descriptions with Nominal Seismic Velocities.

Strata Zone	Strata Description	Vp Range (m/sec)	γ_{dry} (g/cm^3)	ϕ (deg)	c (kg/cm^2)	E (kg/cm^2)
1	Alluvial deposits	360-660	1.75	40	0.05	210
2	Tertiary sedimentary deposits	880-1250	1.80	45	0.3	700
3	Tertiary volcanic deposits	750-2700	1.90	50	0.5	14000

Geotechnical design properties for preliminary foundation design were estimated for each strata zone from available data. Three general strata are defined: alluvial deposits, tertiary sedimentary deposits, and tertiary volcanic deposits. Results are presented in **Table 8-6**. To account for site variability (depth to bedrock), and changes in final design, an add/deduct value for the depth of overburden and bedrock is included in pricing worksheets (**Tables 8-12, 8-13 & 8-14**).

The utility has identified two potential structure types – small footprint (1.2 m square and 1.8 m square) 12 m to 27 m tall four-legged towers, and light-duty direct embedment steel monopoles of the same height. Ground line reactions for both structure alternatives are shown in **Table 8-7**. The final design will only consist of one foundation type corresponding to one structure type.

Table 8-7: Summary of Vender Loads.

Foundation Type	Height (m)	Moment (kN-m)	Shear (kN)	Axial (kN)
Lattice Tower (1.2m)	80	-	4.3 per leg	+/- 8.9 per leg
Lattice Tower (1.8 m)	80	-	1.85 per leg	+/-36.0 per leg
Direct Embed (0.9m diam.)	18-34	488-927	345	-

Materials used for the construction and installation of the foundations are to be restricted by access. The equipment and materials for the installation of the replacement towers and foundations must be light-weight, to allow for transport by manual methods, ATV's, and helicopters.

8.2.4.3 Construction Controls

The major cost factor for construction in rough terrain environments is the depth to and drillability of bedrock to found structures. Across the alignment, drilling conditions range from loose alluvial deposits (which may experience raveling during construction), to hard, difficult drilling in volcanic deposits requiring robust equipment. Foundation installation will need to accommodate specialized equipment that is light enough to access remote locations, and capable of excavating bedrock.

Concrete is available from local ready mix suppliers, and will require delivery by pump truck to sites near roads, or via helicoptered buckets, limiting the volume of concrete for foundations. Excavation is restricted to small track, portable rigs, or excavation equipment that can either crawl over rough terrain or be transported via helicopter. Subsurface rock precludes foundations that must be installed by impact or vibratory hammers.

As the alignment is located in the desert southwest, issues of extreme heat reduce workable times during the day, and place temperature constraints on concrete and grout materials. Dust control is a major concern, as dust needs to be controlled during travel to sites, and as drilling in bedrock produces spoils and overburden disturbance. Ground disturbance must be minimized to maintain the scenic viewscape within the national forest.

8.2.5 Evaluate Alternatives

Based on the criteria developed for project foundations, it is apparent that the use of specific foundation types is not feasible for the project sites, due to predominant hard rock and limited site access. These types include driven piles, vibratory caissons, auger cast piles, and helical anchors. Although drilled shaft foundations are questionable, they are to be carried forward in the assessment. Other foundation types as described in **Section 6** will be evaluated by the use of a decision matrix applying the criteria given in **Tables 7-4** for rough terrain environments.

The range of rankings for each criteria factor in the decision matrix can vary from as low as 2 to as high as 13 (see tables at the bottom of **Figures 7-2, 7-3 and 7-4**). To more equally balance the influence of each criterion, rank is normalized using a factor ranging from 0.5 to 2.0 (shown as "N" value in matrixes). An example of the calculations for "Construction Controls" with micropiles is shown following **Table 8-8**.

Each criterion is subjectively adjusted to reflect the importance of particular job constraints. Site access constraint is of significantly elevated importance for the project, and given an importance factor of 3.0. Due to geologic uncertainty (depth to bedrock), and the need for final design after contractor selection, design considerations are of elevated importance, and given an importance value of 2.0. As only limited outages will be allowed for foundation construction, and since the project completion is not a project driver, construction controls were of normal significance and assigned an importance factor of 1.0

The evaluation criteria and summary results of the evaluations for each foundation alternative are as follows in **Table 8-8.**

Table 8-8: Alternative Evaluation for Rough Terrain Project.

Criteria for Rough Terrain		Importance Factor	Foundation Type											
			Driven Piles	Drilled Shaft	Direct Embedment	Grillage	Spread Footing	Guy Anchors	Vibratory Steel Caisson	Auger Cast Piles	Micropiles	Rock Anchors	Helical Anchors	Horizontal Drilling
Site Access (Figure 7-3)	**N**	3.0												
Permitted Disturbance	2		-	1	2	1	3	3	-	-	3	1	-	-
Climatic Conditions	2		-	2	2	2	2	2	-	-	2	2	-	-
Access Method	2		-	1	1	2	2	3	-	-	1	2	-	-
		Subtotal	-	24	30	30	42	48	-	-	36	30	-	-
Design Considerations	**N**	2.0												
Structure Conditions	1		-	2	4	3	4	4	-	-	5	4	-	-
Subsurface Conditions	0.5		-	7	8	5	9	12	-	-	12	7	-	-
Material Requirements	0.5		-	10	8	5	11	10	-	-	9	9	-	-
		Subtotal	-	21	24	16	28	30	-	-	31	24	-	-
Construction Controls	**N**	1.0												
Scheduling Constraints	1.5		-	1	1	1	2	3	-	-	2	1	-	-
Installation Constraints	0.5		-	6	8	5	9	8	-	-	8	7	-	-
Material Constraints	0.5		-	9	9	5	10	10	-	-	11	9	-	-
Mitigation Constraints	0.5		-	5	8	7	11	11	-	-	9	6	-	-
		Subtotal	-	12	14	10	18	19	-	-	17	13	-	-
		Total Score	-	57	68	56	88	97	-	-	84	67	-	-
		Rank	-	6	4	7	2	1	-	-	3	5	-	-

*Detailed calculations are shown on the next page for yellow highlighted values.

Calculation Example: Construction Controls for Spread Footing (highlighted values in **Table 8-8**) (See **Table 7.2.1** and **Section 6.2.5** for detailed information to derive rankings)

- Schedule constraints:

Easy to mobilize, slow installation	2
Sum of Criteria Factors	**2**
N	x 1.5
Subtotal	3.0

- Installation constraints:

Easily availability	2
Versatile	2
Variable weight	2
Easy to install	3
Sum of Criteria Factors	**9**
N	x 0.5
Subtotal	4.5

- Material constraints:

Some concrete	2
Some steel	2
No backfill	3
Not subject to corrosion	2
Temperature affects materials	1
Sum of Criteria Factors	**10**
N	x 0.5
Subtotal	5.0

- Mitigation constraints:

Minimal impacts	3
Limited disturbance	3
Limited pollution	3
No post construction monitoring	2
Sum of Criteria Factors	**11**
N	x 0.5
Subtotal	5.5

Summary: Construction Controls:

Schedule constraints	3.0
Installation constraints	4.5
Material constraints	5.0
Mitigation constraints	5.5
Sum of Criteria Factors	18.0
Importance Factor	x 1.0
Construction Controls (spread footing)	**18**

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8.2.6 Selection of Feasible Design Alternatives

Upon review of **Table 8-8**, the top three foundation options are anchored structures with spread footings, micropiles, and direct embedment foundations. Each of the three alternatives will be competitively bid. For bid purposes, assumed construction sequencing and preliminary foundation designs were determined.

8.2.6.1 Foundation Construction Sequence

- Spread footings with guy anchors: Manually level the pad area; form and pour pads. Installation of soil and rock guy anchors using track drills and jackhammers. Delivery of concrete by pump truck where structures are near access or bucket in via helicopter. All other materials to be delivered by track vehicle or helicopter.
- Micropile foundations: Portable drill rigs, casing, steel reinforcement, and grout to be applied to each construction site. All materials to be delivered by track vehicle or helicopter.
- Direct embedment foundations: Manual excavation of shafts using track drills and jackhammers. Placing of corrugated metal pipe (CMP) within alluvium and backfill annulus with cementitious grout. Backfill to be delivered by pump truck where structures are near access, or bucket in by helicopter. Angle structures are to also be guy anchored to limit pole size. Installation of rock guy anchors using track drills and jackhammers.

8.2.6.2 Guyed Towers with Slab Pedestals

Lattice tower legs are to be bolted to a concrete spread footing which will bear on the surface rock or soil. Lattice towers are to be supported with two guys for tangent structures, and four guys for angle structures, to reduce lateral loads at the base. Slab foundations act as a two-way bending beam, on grades supported by the subsurface that behaves as an elastic medium. Spread footing software was used to analyze slab foundations to determine internal reactions for reinforcement design, and bearing pressures were used to size the slab. See **Sections 6.2.5.1** and **6.2.5.2** for design methodology.

To simplify the analysis, all structures are combined into three foundation cases:

- 1.2 m square tower with slab foundation on soil
- 1.8 m square tower with slab foundation on soil
- 1.8 m square tower with slab foundation on rock

Maximum loading cases for tangent, angle, and dead end conditions were used for the preliminary design of the slab foundations. A summary of the foundation designs is provided in **Table 8-9**.

Table 8-9: Slab Foundation Design Summary.

Structure Type	Subsurface Condition	Width (m)	Length (m)	Thickness (m)	Number of Structures (#)
1.2m square	Overburden to depth	1.5	1.2	0.5	58
1.8m square	Overburden to depth	2.7	1.8	0.6	5
1.8m square	No Overburden	2.3	1.8	0.6	12

8.2.6.3 Lattice Tower Micropile Foundations

Single micropiles are to be used to support each of the four lattice tower legs. A pile cap of reinforced concrete is to be placed under the structure and join the micropiles. When loaded, two micropiles should be in compression, while the two opposite piles are in compression, with resistance primarily provided by side shear to uplift and compression forces. Cased micropiles are to be installed with a batter to improve performance and to enhance lateral stiffness, to provide for shear resistance, and to improve structural performance (deflection) of the pile group.

Micropile groups were preliminarily designed using GROUP 8 software developed by Ensoft, Inc. The program computes the distribution of vertical, lateral, and overturning moment loads for the pile group in up to three orthogonal axes from a hypothetical pile cap to the piles arranged in a group. The pile is designed as pinned-head attachments in two directions. See **Section 6.3.3.1** and **6.3.3.2** for design methodology.

To determine preliminary design values, depth of overburden was assumed at each structure site based on the site reconnaissance. Preliminary micropile embedment design is estimated according to the geotechnical properties in **Table 8-6**. Results are presented in **Table 8-10** for various estimated overburden thicknesses and tower loads at each structure site.

Table 8-10: Minimum Micropile Embedment.

Total Embedment (m)	Subsurface Condition		Number of Structures
	Overburden Thickness (m)	Depth into Rock (m)	
2.1	<0.3	2.1	4
2.4	<0.3	2.4	14
2.7	<0.3	2.7	14
3.0	<0.3	3	23
3.4	<0.3	3.4	1
3.7	<0.3	3.7	6
4.0	<0.3	4	3
4.3	<0.3	4.3	4
4.9	<0.3	4.9	2
5.2	<0.3	5.2	1
6.7	6.7	-	1
7.6	7.6	-	2

8.2.6.4 Direct Embedment Monopole Structures

A direct embedded monopole burial depth is controlled by the subsurface soil and rock resisting the pole applied moment/shear reactions at the ground line. Poles are prefabricated at standard lengths for embedment into weak soil conditions, with base sections that are able to be cut in the field, so as to reduce embedment in stronger soils and rock. In order to account for the variability in field conditions, preliminary design includes a table of minimum embedment for various depths of overburden over rock. To determine preliminary design values, depth of overburden was assumed at each structure site based on the site reconnaissance.

The EPRI MFAD© Version 5.1.18 program was used for the foundation design of laterally loaded foundations. The direct embedment poles are designed as rigid piers using Reliability-Based Design (RBD) methods (including a resistance factor of 0.63) with utility provided loads. The foundation designs are based on a maximum total displacement of 8% of the drilled shaft hole diameter, and a maximum total rotation of 2 degrees for the specified 0.9 m diameter drilled shaft hole. Lateral load analysis was done as described in **Section 6.2.2.2**. Initial design results are presented in **Table 8-11**.

Table 8-11: Minimum embedment requirements for 0.9m diameter direct embedment steel poles.

Total Embedment (m)	Subsurface Condition		Number of Structures
	Overburden Thickness (m)	Depth into Rock (m)	
1.5	-	1.5	39
1.8	0.9	0.9	8
	0.6	1.2	2
2.1	0.6	1.5	6
	0.9	1.2	2
	1.2	0.9	3
	1.5	0.6	1
2.4	1.5	0.9	2
	-	2.4	1
3.0	-	3.0	4
3.4	-	3.4	6
3.7	-	3.7	1

8.2.7 Pricing of Alternate Foundation Designs

The three foundation alternatives taken to pricing are applicable to the rough terrain conditions, however the total cost of installation is difficult to compare between different specialty contractors. Therefore, the utility decided to have contractors competitively price the preliminary designs to determine the lowest total installation cost, and to evaluate risk based on schedule and installation method reliability.

Contractors were requested to provide pricing based on their particular foundation alternative specialty (selecting only one). This process allowed for competitive pricing between alternate foundation designs for the same project. Preliminary foundation designs for the various anticipated site conditions were presented to the contractors in a tabular manner, as shown in **Table 8-12** through **Table 8-14**. Unit prices for mobilization and demobilization were included to evaluate the cost of access for each foundation alternative.

Add and deduct unit prices were also included for the direct embedment and micropile options, to allow for changes arising from actual field conditions. These unit rates can be used both for pricing sensitivity during bid evaluations, and for price adjustments during construction:

- Unit length of installed CMP casing;
- Unit length of installed micropiles,
- Unit diameter change in micropile casing.

Other elements of the construction that were not dependent on the foundation or structure options (laydown yards, dust control, etc.) were to be priced separately. Additionally, contractors were requested to include a work plan for comparative evaluation that included a schedule for foundation completion, methods to proof test foundation capacity, manpower levels, and safety in relation to the foundation installation process.

Table 8-12: Option 1 – Anchored Tower Foundation Construction.

E.	**Mobilization/Demobilization - Unit Price Items**			
Item	Work	No. of Sites	Unit Price	Total Price
5.	Access via track vehicles	17	$	$
6.	Access via helicopter	58	$	$
Subtotal E - Mobilization/Demobilization Price:				$

F.	**Anchored Tower Foundations - Unit Price Items**			
	Install reinforced concrete tower bearing pad with four (4) threaded anchors; install two (2) guy anchors with 4x4 towers and (4) guy anchors for 6x6 towers.			
Item	Work	Number	Unit Price	Total Price
1.	1.5m x 1.5m x 46cm thick reinforced concrete pad (4x4 Tower – All)	58	$	$
2.	7.1.5m x 7.1.5m x 61cm thick reinforced concrete pad (6x6 Tower – Rock)	12	$	$
3.	2.8m x 2.8m x 61cm thick reinforced concrete pad (6x6 Tower – Soil)	5	$	$
4.	Install rock anchor	102	$	$
5.	Install rock anchor with max 1.5m soil overburden	54	$	$
6.	Install rock anchor with min 1.5m to max 4.6m soil overburden	22	$	$
7.	Install soil anchor	6	$	$
Subtotal F – Anchored Tower Foundation Price:				$

Table 8-13: Option 2 – Direct Embedment Foundation Construction.

A. Mobilization/Demobilization - Unit Price Items				
Item	Work	No. of Sites	Unit Price	Total Price
5.	Access via track vehicles	18	$	$
6.	Access via helicopter	57	$	$
Subtotal A - Mobilization/Demobilization Price:				$

B. Direct Embedment Foundation - Unit Price Items				
Excavate 0.9m diameter shaft to the depth shown in both soil and rock. Stabilize overburden soil with CMP inner liner (concrete filled annulus).				
Item	Work	No. of Sites	Unit Price	Total Price
1.	1.5m bedrock, 0m soil	38	$	$
2.	1.5m bedrock, 0.3m soil	0	$	$
3.	1.2m bedrock, 0.6m soil	8	$	$
4.	1.5m bedrock, 0.6m soil	2	$	$
5.	0.9m bedrock, 0.9m soil	6	$	$
6.	1.2m bedrock, 0.9m soil	2	$	$
7.	0.9m bedrock, 1.2m soil	3	$	$
8.	1.2m bedrock, 1.2m soil	0	$	$
9.	0.6m bedrock, 1.5m soil	1	$	$
10.	0.9m bedrock, 1.5m soil	2	$	$
11.	2.4m bedrock, 0m soil	1	$	$
12.	3.0m soil (no bedrock)	4	$	$
13.	3.4m soil (no bedrock)	6	$	$
14.	3.6m soil (no bedrock)	1	$	$
15.	3.9m soil (no bedrock)	0	$	$
Subtotal B – Direct Embedment Foundation Price:				$
BB. Direct Embedment Foundation Anchors – Unit Price				
Item	Work	Number	Unit Price	Total Price
1.	Install rock anchor	22	$	$
2.	Install rock anchor with max 1.5m soil overburden	4	$	$
3.	Install rock anchor with min 1.5m to max 11.5m soil overburden	4	$	$
Subtotal – Anchored Tower Foundation Price:				$

BBB. CMP Casing Add/Deduct unit prices	**Unit Price Adjustments for B1 through B15**
a. Each 0.2m increase in casing depth	$__________
b. Each 0.2m decrease in casing depth	$__________

Table 8-14: Option 3 – Micropile Foundation Construction.

C.	**Mobilization/Demobilization - Unit Price Items**			
Item	Work	No. of Sites	Unit Price	Total Price
5.	Access via track vehicles	18	$	$
6.	Access via helicopter	57	$	$
Subtotal C - Mobilization/Demobilization Price:				$

D.	**Micropile Foundation - Unit Price Items**			
Install four (4) 8-inch diameter micropiles through soil overburden and into bedrock. 8-inch diameter casing 1-foot above grade through overburden and 3 feet into bedrock.				
Item	Work	No. of Sites	Unit Price	Total Price
1.	0m bedrock, 6.7m overburden	1	$	$
2.	0m bedrock, 7.6m overburden	2	$	$
3.	2.1m bedrock, <0.3m overburden	1	$	$
4.	2.1m bedrock, 0m overburden	4	$	$
5.	2.4m bedrock, <0.3m overburden	7	$	$
6.	2.4m bedrock, 0m overburden	6	$	$
7.	2.7m bedrock, <0.3m overburden	8	$	$
8.	2.7m bedrock, 0m overburden	6	$	$
9.	3.4m bedrock, <0.3m overburden	1	$	$
10.	3.7m bedrock, <0.3m overburden	4	$	$
11.	3.7m bedrock, 0m overburden	2	$	$
12.	3m bedrock, <0.3m overburden	10	$	$
13.	3m bedrock, 0m overburden	13	$	$
14.	4.3m bedrock, <0.3m overburden	2	$	$
15.	4.3m bedrock, 0m overburden	2	$	$
16.	4.6m bedrock, <0.3m overburden	0	$	$
17.	4.9m bedrock, <0.3m overburden	2	$	$
18.	4m bedrock, <0.3m overburden	3	$	$
19.	5.2m bedrock, <0.3m overburden	1	$	$
Subtotal D – Micropile Foundation Price:				$

DD.	**Micropile Add/Deduct unit prices**	**Unit Price Adjustments**
a.	**Each 2.5cm increase in casing & pile diameter (neat line)**	$__________
b.	**Each 2.5cm decrease in casing & pile diameter (neat line)**	$__________
c.	**Each 3m increase in rock embedment depth beyond values in Section D**	$__________
d.	**Each 3m decrease in rock embedment depth beyond values in Section D**	$__________
e.	**Each 3m increase in soil overburden depth beyond values in Section D**	$__________
f.	**Each 3m decrease in soil overburden depth beyond values in Section D**	$__________

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8.2.8 Final Foundation Selection

Foundation systems that could be proof tested were considered both lower risk and more reliable (micropiles and anchors - See discussion in **Section 6.3.3.3**). Micropiles offered the best schedule, thus a lower risk for work completion during outages, but were considered untried, since they had not previously been used by the utility for founding transmission structures. All contractors proposed helicopters for the transportation of manpower and crews to the 57 difficult sites. Additionally, micropile contractors proposed helicopter transport to all 75 difficult access sites.

Actual bid costs were not available due to their proprietary nature. The utility did provide a summary ranking of costs and risk by method, as used in their evaluation. Results are given in **Table 8-15**. Micropiles foundations and guyed anchors/spread footings were generally equivalent in ranking. Micropiles were selected as the foundation alternative with the least impact and best value. Guyed anchored structures were viewed as having a slightly higher reliability risk, and resulted in greater visual impacts when compared to micropile foundations. Micropiles required the least manpower, since all work was to be done using specialty drilling equipment (no manual drilling, concrete placement, or excavation). Competitive bidding for the evaluation of cost and risk was in general agreement with the ranking results, as shown in the decision matrix.

Table 8-15: Bid Evaluation.

Structure/Foundation Option	Relative Cost Rank	Relative Risk Rank
Direct Embedment Monopole Structures	3	3
Micropile Foundations	2	1
Guyed Anchors with Spread Footings	1	2

9.0 CONCLUSIONS AND RECOMMENDATIONS

Transmission line structures are located and types are selected primarily based on requirements related to span, topography, land use, land cover, and aesthetics. Access for conductor and structure construction is often thought of more than foundation type, as these elements are the more costly components of transmission line construction. For these reasons, foundations may be placed in less than desirable locations where their construction can result in impacts to the local environment. This guideline report seeks to identify transmission line foundation technologies used in sensitive environmental conditions, and to offer recommend best practices for both their design and selection so as to minimize impacts.

9.1 Conclusions

The following major conclusions are reached as a result of this guide document:

- Published and unpublished case studies presented in **Section 2** illustrate industry trends, and highlight details related to foundation installation in difficult environments. Based on this case history review, sensitive environments can be generally categorized as follows: wet environments (wetland, waterway, coast, estuary), rough terrain (mountainous, desert), and frozen ground (seasonal frozen ground, permafrost). Sensitive environments can also include woodlands, conservation/wilderness areas, and desert/rangeland.
- Traditional foundations support transmission line structures in just under 40 percent of the published cases, with access mitigation measures principally used to reduce construction environmental impacts. The remaining published cases indicate the use of alternate foundation types (e.g. micropiles, vibratory caissons, and helical piles) along with minimally invasive access methods (helicopters, barges, boats, marsh buggies, light/small equipment, etc.).
- Of the nineteen unpublished cases received through solicited surveys, nearly 85 percent of respondents indicate a preference for construction access mitigation measures (improved access or modular matted paths), over the use of alternative foundation types. Alternative access methods (helicopters, barges, boats, etc.) and alternative foundation designs are less common.
- Environmental impacts can be mitigated by a combination of good planning, design, and construction practices, including avoidance, activity minimization, and protection at sensitive sites. Plans developed as part of early studies evaluate site mitigation, monitoring, and compliance, and are often incorporated into construction activities. Foundations (or at least structure locations), should be assessed as part of this process to provide greater flexibility later in foundation design and construction. Best practices include avoiding sensitive environments, minimizing activity under these conditions, or using foundation installation practices that limit construction time.
- Geotechnical investigations are performed as part of the foundation design process to determine in-situ material properties of the subgrade, and to allow for efficient and economical design. Drilling and sampling is often done in advance of reasonable access to remote sites and prior to environmental clearances in sensitive areas. Oftentimes, these areas are excluded from the investigation process, lending to increased uncertainty and time spent during construction. Remote sensing (geophysics) transported by small 4-wheel drive ATV's or backpacked into sites can also be used in sensitive areas with limited access. Sampling can be accomplished with low impact, all-terrain, track-mounted drill rigs, which can traverse sensitive areas or modular drill equipment that can be disassembled and/or transported by helicopter, boat, or marsh buggy to

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sites, and reassembled for the investigation. The cost low impact investigation equipment can be significantly greater than standard methods, but have great potential to reduce overall foundation construction cost due to lower uncertainty.

- Improved access practices offer the best opportunity in all sensitive environments to minimize impacts. Most projects include a carefully thought-out construction access plan to minimize environmental impacts. These plans should be prepared in conjunction with final selected structure and foundation design alternatives. **Section 5** lists the best management practices for assessing access alternatives, and includes (in order of general use, as seen in the case studies):

    - Graded access or spur roads,
    - Temporary matts,
    - Ungraded paths (tracked or light-weight equipment),
    - Seasonal frozen ground,
    - Air access via helicopter,
    - Water access via boats, barges or marsh buggies, and
    - Manual methods – all equipment and materials carried into sites.

- Engineers have a wide array of tools and techniques for founding transmission line structures. Traditional foundation systems include driven piles, drilled shafts, direct embedment poles, steel grillages, spread footings, and anchored structures. Alternate foundation systems include helical anchors/piles, vibratory caissons, micropiles, rock sockets with anchors, and auger cast piles. Local practices, economy, available equipment, and site access generally control the selection of foundation alternatives for projects in sensitive environments.
- This guideline presents a great deal of information, options, and alternatives that must be assessed to select the optimal foundation alternative in sensitive environments. Organizing this information is critical to the performance of a logical assessment that arrives at the best foundation alternative for a project. A rational step-by-step model is presented in **Section 7** where information is organized and numerical values are assigned to criteria for each foundation option, in order to rank order foundation design alternatives for a given environment.
- There is an element of subjectivity in the evaluation of foundation options via the use of flowcharts and tables in **Section 7**. The flowcharts provide defined values for ranking each factor and criteria, but must be used along with summary data in **Table 7.1** and **Table 7.2,** and the detailed discussions for each foundation option in **Section 6**. The importance of criteria groups must be assessed as discussed in **Section 7.2.4.1**. When used together, these tools provide an excellent foundation for making good decisions on the selection of the foundation system that least impacts a particular environment.

9.2 Contractor Best Practices

Ultimately, the cost and time required to permit the installation of traditional foundation design approaches that meet the needs of sensitive environments must be weighed against the cost and schedule risk of using unique foundation alternatives, with or without minimally invasive access methods. Most transmission line general contractors do not have the equipment and skilled labor for the installation of many alternative foundation types, or air/water access vehicles required for foundation construction. Often, the value of alternatives is not realized until the project is in the hands of these general contractors, who propose different methods to gain a competitive advantage in the bid process.

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Specialty contractors have developed innovative approaches and should be brought into the design and construction process early on if they are to be effectively used. Additionally, these specialists tend to be small in number, and focus on a limited number of foundation types, which additionally limits the competitive bid process. It is recommended that the evaluation of alternative methods is done at the time of design or planning to take advantage of economy and schedule. Following this approach, the geotechnical investigation can be oriented toward the data required for alternative methods. Additionally, access may need to be modified to accommodate alternative foundations, and can be readily included in construction scheduling.

Design-Build (DB) or Engineer-Procure-Construct (EPC) methods can both create and limit alternative foundation opportunities. The process for the selection of an EPC partner requires specifications open to alternative methods, giving credit to the minimization of environmental impacts and schedule improvements. The lowest total installed cost of the entire line should be thought of as the goal, not just the low contract bid amount for foundations or engineering.

In the traditional Design-Bid-Build model, there should be an opportunity to interact with specialty contractors if there is a need for minimizing impacts in sensitive environments. A technical prequalification process can be used to bring on board one or more of these specialists during design as consultants. A framework should be established during design to evaluate alternative foundation types. The elements in this process should include:

- Geotechnical investigation methods for use at remote and sensitive sites,
- Preliminary designs to establish bid quantities and associated technical specifications,
- Final design that includes input from or is done by the specialty foundation contractor,
- Multiple bid schedules including both traditional and alternate foundations (this is especially useful if actual conditions are better than expected and alternates are not needed),
- Bid unit rates for access to difficult sites,
- If needed, load test requirements or contractor testing at each site to validate final design,
- Flexibility in bid units. Unit price schedules with add and deduct units for either adjustment after final design, or field adjustment where final quantities are unknown until construction,
- Inspection manuals to manage units (and risk), and
- Specialty foundation load test requirements.

9.3 Technical Specification Recommendations

Technical specifications for transmission line foundations are readily available for most traditional and alternate methods. Numerous industry organizations, utilities, specialty manufacturers, state departments of transportation, and provincial standards agencies have developed foundation system technical specifications. It is noteworthy that a recent survey of transmission line foundation designers indicated that most allow the use of alternative foundation types. But only approximately 45% of respondents noted ownership of specifications for construction (Kandaris & Davidow, 2015). Below is a list of the most widely available engineering documents that contain guide specifications or construction specification language. Please note that general technical specifications for some foundation types, namely grillages and vibratory caissons, tend to be unique to the utility industry, and specifications have yet to be recognized on a large scale.

Reinforced Concrete Drilled Shafts:

- FHWA Geotechnical Engineering Circular No. 10, *Drilled Shaft : Construction Procedures and LRFD Design Methods*. FHWA-NHI-10-016
- ADSC Standards and Specifications for the Foundation Drilling Industry
- Draft Canadian Standard for Drilled Shafts (presently being considered for becoming a standard)

Direct Embedment Foundations:

- USDA Bulletin 1724E-204: Guide Specifications for Steel Single Pole and H-Frame Structures

Driven Piles:

- FHWA Design and Construction of Driven Pile Foundations Manual
- DFI Design and Construction of Driven Pile Foundations Reference Manual (2 Volumes)
- DFI Guidelines for Writing Construction Specifications for Piling
- PDCA Specification 103-07: Installation Specification for Driven Pile

Spread Footings:

- FHWA Implementation Guidance for Using Spread Footings on Soils to Support Highway Bridges
- FHWA LRFD Implementation of Shallow Spread Footings for Bridge Structures
- FHWA Geotechnical Engineering Circular No. 6: Shallow Foundations

Ground Anchors:

- FHWA Geotechnical Engineering Circular No. 4: Ground Anchors and Anchored Systems

Micropiles:

- Micropile Design and Construction Manual, Reference Manual for NHI Course 132078. Report No. FHWA-NH1-02-039.
- DFI Guide to Drafting a Specification for Micropiles
- CIGRE Design and Installation of Micropiles and Ground Anchors for OHL Support Foundations

Auger Cast Piles:

- Geotechnical Engineering Circular No. 8: Design and Construction of Continuous Flight Auger (CFA) Piles
- DFI Augured Cast-In-Place Piles Manual (3rd Edition)

Helical Pile Foundations:

- DFI Model Specification for Helical Pile Foundations – Compression Applications
- DFI Model Specification for Helical Pile Foundations – Tension Applications

- CHANCE Guide to Model Specifications: Helical Piles for Structural Support

Underground Transmission Cables:

- ERPI Underground Transmission Cable System Construction and Installation Practice Manual

9.4 Recommendations for Future Research

The document includes procedures that are considered common in standard foundation design. Local experience and practices should be used to supplement the concepts of these guidelines. Upon review of the state of the practice, the authors see great opportunities for future research in this area.

9.4.1 Vibratory caissons

Vibratory caissons are becoming more frequently used for the installation of foundations in wet environments. Yet, little work has been done to define an analytical/theoretical model, and full scale testing has not been performed to validate capacity. Further research effort is needed, to allow design methods to catch up with construction applications. **Section 6.3.2** of this report offers a framework for developing a theoretical model.

9.4.2 Trial cases for the evaluation of optimized alternatives

The evaluation framework recommended in **Section 7** includes elements from a limited number of trial efforts, and has rarely been completed in whole. It is likely the proposed decision-making processes can be improved over time, and with more trial uses. An effort should be made to encourage the use of this and other adaptations of rational alternative evaluation processes with tracking/data keeping, refining the criteria and weighting. A future report then can be focused solely on the decision methodology, with a larger base measure for analysis.

9.4.3 Formal guide specifications for electric system foundations

Most guide specifications for electric system foundation types are borrowed from other industries, and tend to be oriented toward single site structures (highway bridges, buildings, etc.). As transmission lines follow long linear paths, these specifications miss the essential difficulties in constructing foundations in difficult or sensitive environments. As such, individual (and usually large) utilities and agencies create their own standards for in-house use. The utility industry as a whole would benefit from standards directed towards the construction challenges presented by transmission lines.

9.5 References

Kandaris, P. & Davidow, S. (2015). Study of Electric Transmission Line Deep Foundation Design. *ASCE: Electrical Transmission and Substation Structures*, 577–587.

APPENDIX A. ANNOTATED BIBLIOGRAPHY

A.1 Regulatory Constraints

Rochester Area Reliability Project – Exhibit 4: Environmental Impacts

Rochester Gas and Electric Corporation. (n.d.). Rochester Area Reliability Project – Exhibit 4: Environmental Impacts. Retrieved November 10, 2015, from http://www.rge.com/MediaLibrary/2/5/Content Management/RGE/RARP/PDFs and Docs/RARP Exhibit 4 Environmental Impacts_Final.pdf

The Rochester Area Reliability Project (345kV & 115kV) will be designed, constructed and operated in a manner that avoids or minimizes impacts to environmental resources within the Greater Rochester area. The impact studies describe existing conditions, methodologies used in the investigation, the anticipated environmental effects of the transmission facilities, and where appropriate recommended mitigation measures can avoid or minimize adverse impacts. To meet regulatory needs, underground line segments will be installed by both open cut and horizontal directional drilling, access roads will be located to minimize impacts, grading will be minimized in floodplains and wetlands, work will be scheduled during dry and frozen ground periods to minimize rutting, and various foundation types will be utilized to minimize excavation.

330kV Usatove - Adjalyk Transmission Line Project

UKRENERGO. (2005). 330kV Usatove - Adjalyk Transmission Line Project. July. Retrieved November 10, 2015, from http://www.ebrd.com/english/pages/project/eia/33896e.pdf

The objective of this 330 kV transmission line Project is to increase the reliability of power supply to consumers, and to decrease dependency upon the unstable power supply. This project zone is located in a slightly rolling plateau area, and a number of environmental features, such as forest areas, nature reserves, and a landscape park were identified. Through the selection of alternative options, sensitive areas of the transmission line project are avoided. The evaluation of environmental impacts caused by the selected construction practices is addressed. The pertinent safety regulations and proven standard designs, including protection systems, work to minimize the potential risks and hazards of this project, and ensure that transmission lines are reliable and safe infrastructures.

Sustainable Development Indicators for the Transmission System of an Electric Utility

Searcy, C., McCartney, D., & Karapetrovic, S. (2007). Sustainable development indicators for the transmission system of an electric utility. *Corporate Social Responsibility and Environmental Management, 14(3)*, 135-151.

This paper presents a system of sustainable development indicators for the transmission system of a Canadian electric utility. The indicators were developed based on extensive consultations with internal experts at the case utility site, and external experts in the field of sustainable development indicators. A total of 98 indicators were incorporated into the system, with 70 developed as a part of this process, and 28 representing indicators previously developed by the company. Recognizing the difficulty of working with nearly 100 unstructured measures, four techniques were used to increase the utility of the indicators: (1) the indicators were clustered around eight key priority areas, (2) the indicators were organized according to a hierarchical approach linked to the business planning process, (3) the process of integrating the indicators with existing corporate initiatives was staggered over time, and (4) a tiered aggregate was developed. The development process of the indicators is discussed, with key takeaways emphasized throughout the paper.

Initial Environmental Examination: New Galle Power Transmission Development

Ceylon Electricity Board. (2010). Initial Environmental Examination: New Galle Power Transmission Development. November. Retrieved November 10, 2015, from http://www.adb.org/sites/default/files/linked-documents/39415-01-sri-ieeab-01.pdf.

The expansion of the Southern Ceylon province transmission network utilized existing rights of way to avoid populated areas, dense forests, cultivated lands, and railway lines. Different alternative options were considered wherever infringements were substantial. Route alignment focused on avoiding populated/forest/cultivated areas completely, or on keeping infringements to the barest minimum. Mitigation measures were involved whenever infringements became unavoidable due to the geographical locations and/or terrain. Impacts, avoidance practices, and mitigation measures are discussed in the report, with analysis summarized in tabular format.

Foundation Design Minimizes Environmental Impact

Chen, C.H.., & Salisbury, N. (2011). Foundation Design Minimizes Environmental Impact. September. Retrieved November 10, 2015, from http://www.burnsmcd.com/Resource_/PressRelease/2429/FileUpload/Future-of-Transmission-SCE-Wind-Power-2011.pdf

The US Forest service required for the construction of the Tehachapi Renewable Transmission Project to ensure minimal disturbance of land. This summary documents the unconventional design and construction solution that aided the owner to gain approval for the project. The foundation installation and lattice tower erection was largely completed with micropile technology, and via the use of helicopters due to inaccessible sites and restrictions upon work within the forest boundaries. Subsurface investigation was deployed to guide the selection of tower sites and to reduce the potential slope instability amid rugged terrain and potential land slide zones.

Permitting and Constructing a Transmission Line in a Sensitive Marine Environment: St. George Island 69kV and Apalachicola-Eastpoint 69kV Transmission Lines

Richardson, W., & Bennett, T. (2012). Permitting and Constructing a Transmission Line in a Sensitive Marine Environment: St. George Island 69kV and Apalachicola-Eastpoint 69kV Transmission Lines. October. Retrieved November 10, 2015, from http://www.eei.org/about/meetings/meeting_documents/2012oct-richardsonandbennett_session-5.pdf

This presentation addresses the rebuild of an existing 69kV redial tap line to St. George Island from Eastpoint, FL. This project was limited by a sensitive marine environment area, and included natural resource issue consideration for project design and construction. Illustrations and photographs demonstrate the challenges and current solutions for these environmental issues. Alternative routes were considered to minimize disturbance to oyster beds, and to allow existing lines to remain energized. Solutions addressing inaccessibility issues, such as matting for structures close to land, barges for structures with sufficient water depth, and the use of helicopters for conductor stringing and lineman transport, were applied in this project. Vibratory steel caissons were used to found poles in the marine environment.

Cricket Valley Transmission Line and Re-conductoring Project

Cricket Valley. (2014). Cricket Valley Transmission Line and Re-conductoring Project. Retrieved November 10, 2015, from http://www.cricketvalley.com/home.aspx

Environmental analysis is provided for a proposed 345kV transmission line and re-conduction project in the State of New York. The examination of the area for potential alternative routes is employed to avoid sensitive features, while the existing right of way is an available and direct route. Shallow bedrock is a very significant complicating factor for a number of the alternatives, along with sensitive environmental features, such as wetlands and water courses. Sub alternatives evaluated include structure configurations, undergrounding, and foundation options, including rock anchors and micropiles.

A.2 Mitigation and Remediation Methodology

Environmental Impacts of Transmission Lines

Public Service Commission of Wisconsin. (n.d.). Environmental Impacts of Transmission Lines. Retrieved November 10, 2015, from http://psc.wi.gov/thelibrary/publications/electric/electric10.pdf

This publication was prepared to present environmental issues and concerns raised by the construction and operation of electric transmission facilities. The first part provides a general summary of the types of analysis and the means to measure and identify environmental impacts. The second part lists potential impacts and the available methods to minimize or mitigate said impacts.

Construction Activities Overhead Transmission Lines

Dominion. (n.d.). Construction Activities Overhead Transmission Lines. Retrieved November 10, 2015, from https://www.dom.com/library/domcom/pdfs/electric-transmission/loudoun-pleasant-view/loudoun-pv-construction-flyer-041612.pdf?la=en

Dominion Power documents the process of line construction for property owners. The company has prepared this document to provide property owners important information on our construction practices and the activities that occur before, during, and after the installation of our transmission facilities. The pre-construction practices and techniques include initial inspection, Right-of-Way surveying, access roads, soil borings, and other necessary activities. The construction practices, such as structure erection, clearing, grading, and foundation installation are also presented in this document, and in Right-of-Way restoration, as post-construction remediation is mentioned.

Proposed Land Use & Environmental Mitigations

American Electric Power. (n.d.). Proposed Land Use & Environmental Mitigations. Retrieved November 10, 2015, from http://www.aep.com/newsroom/resources/docs/AEP_Interstate_Project-Land_Use_Environmental_Miti.pdf

A pamphlet was prepared by American Electric Power (AEP) to describe proposed land use and environmental mitigation measures to be undertaken for the future 765kV Interstate Project, which will extend transmission lines approximately 550 miles from West Virginia to New Jersey. This article shows design and construction practices employed by AEP to minimize the environmental impact of the project, including tower selection, low reflectivity materials, variable foundation options, helicopter use, access road erosion control, and minimal vegetation clearing.

Environmental Issues Drive Line Design: In Developing a 230kV Transmission Line, the Orlando Utilities Commission Met Energy Requirements with Substantial Savings and Minimal Environmental Impacts

Clark, P., Yildirim, G., Clark, I., & Beck, R. (1996). Environmental Issues Drive Line Design: In Developing a 230kV Transmission Line, the Orlando Utilities Commission Met Energy Requirements with Substantial Savings and Minimal Environmental Impacts. *Transmission and Distribution World.* (e-publication). December 1.

This article addresses the environmental issues and mitigations provided for the transmission network between the Stanton Energy Center and the Pershing Substation. The project team determined the structure locations and identified key hole clearing and wetland mitigation areas using aerial photography. Low-soil impact equipment was applied to clear forested wetlands, and best management practices were employed for controlling soil erosion on slopes. Wetland mitigations were provided to offset both wetland loss and habitat degradation resulting from transmission line construction. Socket-type driven steel caissons were used to contain direct embedment tangent structure poles to reduce cost and environmental impact.

Aesthetic Mitigation - The Challenge Confronting Future Expansion of Transmission Lines

Chau, M., Pugh, A., & Kennedy, S. (2009). Aesthetic Mitigation — The Challenge Confronting Future Expansion of Transmission Lines. *Electrical Transmission and Substation Structures 2009.* ASCE. Fort Worth, TX. November 8-12. 263-278.

Transmission line construction during the early 1900s was primarily dictated by engineering issues with little devotion to mitigating visual impacts on the surrounding environment. Beginning in the

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1960s and 70s, a new environmental ethic began be incorporated into the planning process. As a result, heightened sensitivities to visual impact issues are now a normalized factor of consideration for new transmission projects, thus making them a major objective on newer projects. This paper addresses the aesthetic challenges that confront future transmission line expansion, such as overcoming public objections, environmental stewardship, and improving the appearance of transmission facilities.

The paper uses illustrations, photographs, and case studies to review current solutions by American Electric Power ("AEP") and other utility companies working to reduce visual impacts on transmission projects. Current best practices involve route development, structure design, topographically sensitive siting techniques, off-site mitigation, accurate visual simulations, stakeholder input, construction management, and special structure and conductor finishes. Finally, the future of transmission line siting is discussed along with areas in need of further research. These issues present the engineering team with the opportunity to provide innovative, creative solutions.

Environmental and Social Impact Assessment of the Black Sea Regional Transmission Project

Black & Veatch. (2009). Environmental and Social Impact Assessment of the Black Sea Regional Transmission Project. May. Retrieved November 10, 2015, from http://www.eib.org/attachments/pipeline/20080080_esia_en.pdf

The implementation of a high-voltage transmission line across southern Georgia is a part of the expansion and upgrade of country's electricity. A general method for grading the significance of environmental impacts was adopted to ensure consistent significance terminology, whether in terms of beneficial or adverse impacts. Mitigation measures were adopted where there was the potential for significant impacts, with the intent to avoid, reduce, compensate, and/or remediate adverse impacts, and/or to enhance potentially beneficial impacts. Mitigation options included erosion control measures for road designs. A mitigation monitoring strategy of specific impacts was adopted to determine whether additional measures were required where there was uncertainty regarding the potential significance of that impact.

Vegetation Management for Eastside Transmission Line Corridor

City of Bellevue. (2010). Vegetation Management for Eastside Transmission Line Corridor. January 5. Retrieved November 10, 2015, from http://www.bellevuewa.gov/pdf/land use/10-102653-LO_VegetationManagmentforEastsideTransmissionLineCorridor.pdf

Seattle City Light proposed a vegetation management plan to control growth within its Eastside Transmission Line corridor. The transmission line crosses various regulated critical areas, including streams, riparian areas, wetlands, and geologic hazard zones. Plan restrictions and limitations are discussed.

58KM 330kV QIT-Ikot Abasi Transmission Line Project

Transmission Company of Nigeria. (2012). 58KM 330kV QIT-Ikot Abasi Transmission Line Project. November. Final Draft Report (EIA) No. S-1103. Retrieved November 10, 2015, from https://www.miga.org/documents/EIA_Nigeria_QIP_Transmission_Line_EIA.pdf

This environmental impact assessment of the proposed 58 kilometer long 330kV QIT to Ikot Abasi Transmission Line Project evaluates and documents the potential ecological, social, and health impacts associated with the proposed project. Of interest is the lack of alternative structures and/or foundations throughout the mitigation process. The report provides a unique view of and approach toward transmission line construction impact mitigation in a developing country.

Environmentally Sensitive Areas Associated with the Proposed Rebuild of the Existing Transmission Line from the Cecil Substation to the Maryland/Delaware State Line

Maryland Department of Natural Resources. (2014) Environmentally Sensitive Areas Associated with the Proposed Rebuild of the Existing Transmission Line from the Cecil Substation to the Maryland/Delaware State Line. Maryland Power Plant Research Program. PSC Case No. 9321. DNR Exhibit SSP-3. January 17.

The rebuilt Cecil to Glasgow 138-kV transmission line will include the replacement of an existing 138-kV overhead transmission line currently on wooden H-frame structures, via new conductors on steel monopole structures. This exhibit focuses on the environmentally sensitive areas associated with the proposed construction and operation of the new transmission line, including potential impacts on streams; rare, threatened, or endangered species; wetlands; forests; Green Infrastructure and FIDS; vegetation management, and; cumulative impacts. Each location was then evaluated by environmental specialists to determine the natural resources at the site, as well as the issues presented by the construction and operation of a transmission line right of way.

A.3 Site Access & Alternatives

Burlington to Camden 230 kV Conversion Project: New Jersey

CASE Foundations (n.d.) Burlington to Camden 230 kV Conversion Project: New Jersey. Retrieved November 10, 2015, from http://www.casefoundation.com/ResourceCenter/CaseStudies/default.aspx

This case study pamphlet identifies the construction of 17 foundations required to support new 230kV monopoles at four existing stations. This technical summary addresses the unique design and installation of large diameter drilled shaft reinforced concrete foundations. The foundations were majorly installed during short outages of the lines directly overhead, requiring several working weekends at multiple locations simultaneously. In cases where overhead limitations were encountered, splicing of the cage over the drilled shaft was performed.

Geography, Environmental Analysis, and Route Selection of Extra High Voltage Transmission Lines

Buvinger, B. (1978). Geography, Environmental Analysis, and Route Selection of Extra High Voltage Transmission Lines. *Geographical Review*, 68:2. American Geographical Society. 215-215. April.

Geographers can have a critical role in the conduction of environmental analyses, since the routing of extra high voltage (EHV) transmission lines can have a major effect on the environment. Geographers possess varied backgrounds with combined training in physical subjects as well as in cultural fields. This paper describes the procedures usually implemented in the preparation of an environmental analysis for an extra high voltage (EHV) transmission line, and it comments on the appropriateness of geographers' educational training for professional work in the environmental field.

International Best Practices for Assessing and Reducing the Environmental Impacts of High-Voltage Transmission Lines

Williams, J. H. (2003). International Best Practices for Assessing and Reducing the Environmental Impacts of High-Voltage Transmission Lines. *In Third Workshop on Power Grid Interconnection in Northeast Asia, Vladivostok, Russia (September 2003).*

This paper discusses internationally-recognized best practices for assessing, avoiding, reducing, and mitigating the environmental impacts associated with the siting, construction, and operation of high-voltage electric power transmission lines and associated facilities, such as substations and converter stations. It also discusses the environmental assessment and mitigation requirements of international financial institutions (IFIs), such as the World Bank and the Asian Development Bank (ADB), that are relevant to obtaining IFI financial and/or technical assistance (TA) for transmission projects.

Quantifying Siting Difficulty: A Case Study of US Transmission Line Siting

Vajjhala, S. P., & Fischbeck, P. S. (2007). Quantifying siting difficulty: A case study of US transmission line siting. *Energy Policy*, 35(1), 650-671.

The worldwide demand for new energy infrastructures has been paralleled in recent years by the increasing difficulty of siting major facilities. Siting difficulty is the subject of widespread discussion, but because of the complexity of the issue, potential solutions are not obvious or well understood. This paper presents a two-step policy-level framework, which first develops an empirical measure of siting difficulty, and proceeds to quantitatively assess its major causes. The approach is based on the creation and aggregation of four siting indicators that are independent of the common causes and localized effects of siting problems. The proposed framework is demonstrated for the case of US transmission line siting. Results of the analyses reveal significant variations between state siting difficulty and industry experts' perceptions of its dominant causes. Implications for the long-term success of Regional Transmission Organizations (RTOs) and knowledge transfer among siting professionals in the deregulated industry are also discussed.

Deepwater Transmission Line Foundations Meet Trophy Bass Lake Environment

Norman, R., DiGioia, A.M. Jr., & Goodwin, E. (2009). Deepwater Transmission Line Foundations Meet Trophy Bass Lake Environment. *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 300-307.

Wood County Electric Cooperative has recently implemented a service pumping station for the Dallas Water Utilities on Lake Fork in eastern Texas. The optimum route required a lake crossing of over 1,738m (5,700 ft.) for a double circuit 138 kV line. Lake Fork is an internationally recognized bass fishing environment, as it holds the Texas record for the largest bass, weighing over 8kg (18 lbs.). The placement of the foundations for the crossing structures presented several unique challenges, including limiting the number of structures set in the lake, providing clear channels for boating traffic, minimizing environmental impacts, and working in lake depths of over 15m (50 ft.). This paper discusses the types of foundations considered, as well as the sketch and installation of the most effective design.

Golden Pass LNG 230kV Double Circuit: Foundations.

Williamson, E. C., & Rowland, R. (2009). Golden Pass LNG 230kV Double Circuit: Foundations. *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 289-299.

This paper describes the foundation challenges involved in building a new 12-mile 230kV double circuit line. The project consists of 228 pole structures on base plated steel caissons. Portions of this line are located in a coastal salt marsh, adjacent to a state wildlife sanctuary. Other portions wind their way along an environmental superfund site, as well as through multiple refinery, petrochemical, and heavy industrial facilities that have been under continuous use since the early 1900's. Current environmental and wildlife restrictions, as well as requirements for hurricane loadings, ruled out many conventional forms of design and construction, as did restrictions imposed by industrial facilities along the route that severely limited access. Because of this, a decision was made to use helicopter construction over much of the course of the project. Structures and caissons were designed and constructed in sections to enable a helicopter to lift to its maximum capacity. The helicopter then transported and installed each section at its intended location. In some instances where the steel caisson foundations were too heavy for the helicopter to lift, they were manufactured in two pieces, and subsequently field welded. The various foundations features, including meeting an aggressive in-service date under difficult conditions, are described in the paper.

Large Catenary Structures for High Voltage Transmission Lines.

Catchpole, P., & Ruggeri, E. (2009). Large Catenary Structures for High Voltage Transmission Lines. *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 253-262.

Transmission Line Catenary structures are steel cable structures from which transmission circuit conductors are suspended. The objective is to keep the entire support structure above locations subject to high avalanche risk, and in places where other structure types have little chance of surviving. The world's first Catenary was built in 1955 in British Columbia, Canada. The authors have engineered and provided construction management for the installation of the world's second (and slightly larger) Catenary. It was installed 1,000 meters north of the first. The authors have also installed a smaller Catenary, and performed preliminary engineering for thirty four other Catenaries, all in British Columbia. This paper discusses transmission line Catenaries in general, and describes the 2007-2008 engineering and installation of Catenary 2 in detail.

Transmission Line Construction in Sub-Arctic Alaska Case Study: "Golden Valley Electric Association's 230kV Northern Intertie"

Wyman, G. (2009). Transmission Line Construction in Sub-Arctic Alaska Case Study: "Golden Valley Electric Association's 230kV Northern Intertie" *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 329-341.

Construction projects worldwide have become more complicated and logistically challenging as environmental stipulations become more demanding and as the effects climate change become more pronounced. Nowhere is this more evident than in the sub-arctic, in this case interior Alaska, where Golden Valley Electric Association, Inc. (GVEA) owns the recently constructed 230 kV Northern Intertie transmission line project. This transmission line project is underlain by "warm" discontinuous permafrost prevalent throughout interior Alaska. The potential for change in marginal permafrost over the project lifecycle required consideration during the design phase to provide the most economical project. This case study discusses the challenges that engineers and contractors alike faced in scheduling, accessing, and constructing a project across four distinct geographic areas, with an emphasis on permafrost zones. Contractors faced extreme weather conditions, ranging from the 21 hours of straight summer sun, to winter conditions with as little as 3 hours of daylight. Temperatures during construction varied between 32ºC (90° F) and -45° C (-50° F). Without a clear understanding of design parameters between the Engineer and Contractor, projects can easily become problematic.

Hampton to Rochester to La Crosse 345-kilovolt (kV) Transmission Project (Route Permit Application)

Northern States Power Company. (2010). Minnesota portion of the Hampton to Rochester to La Crosse 345-kilovolt (kV) Transmission Project. January. Retrieved November 10, 2015, from http://mn.gov/commerce/energyfacilities/documents/25731/CAPX%20HRL_Chp%201%20thru%206.pdf.

This route permit application addresses the design and construction parameters of the Hamptons - Rochester - La Crosse 345 kV transmission project. It includes project description, engineering design, substation design, and foundation design. Detailed descriptions are provided for line access alternatives, including direct access to the ROW via existing roads or trails, the use of private field roads or trails, and upgrades and/or new access construction initiatives necessary to accommodate heavy equipment. The use of construction mats is also discussed.

Transmission Line at St. Andrew Bay

Rengaswamy Shanmugasundaram, P. E. (2010). Transmission Line at St. Andrew Bay. *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 354-366.

This project resulted in an unusual challenge, requiring the augmentation of two existing 46kV underwater circuits, with an overhead double circuit line designed for future 115kV operations. The probable rationale informing the underwater installation of the original 46kV circuit lines, and the reasons for the new 115kV circuit lines overhead are discussed in detail under "Project Background and Requirements". The new line had to cross approximately 3,600 ft. of the Gulf Intracoastal Waterway at St. Andrew Bay. In addition to constructing facilities in an active waterway, the design of the overhead line needed to consider and accommodate water depths of 60 ft., and to provide sufficient span and clearance allowing for barge traffic. The 115kV overhead crossing of the St. Andrew Bay required the installation of four structures within the waterway, consisting of tubular steel poles supported by concrete caisson foundations. Foundation and structure installation was performed off of two barges. The concrete caisson foundations were constructed via the installation of 6 ft. diameter pipe piles using a vibratory hammer, and subsequently filling the pipe piles with reinforced concrete. Environmental issues and shoreline stabilization were also part of the considerations involved in this project. This paper describes the various design and construction challenges encountered in this project.

McClellanville Area 115 kV Transmission Line Project Environmental Impact Statement Addendum to Scoping Report

Mangi Environmental Group, Inc. (2011). McClellanville Area 115 kV Transmission Line Project Environmental Impact Statement: Addendum to Scoping Report. US Department of Agriculture Rural Utility Service. October. Retrieved November 10, 2015, from http://www.rd.usda.gov/files/UWP_SC50-SouthCentral_McClellanville_ScopingRpt-Addendum.pdf

This article addresses the scoping, environmental impacts, and alternatives of a new 115 kV transmission line near the proposed new McClellanville substation. The AES described the purpose of and need for the proposed project, and proceeded to assess technological alternatives, with a primary focus on alternative routes and access issues. Project challenges included sensitive forested lands, wetlands, and river crossings. The evaluation methodology and criteria, development of alternatives, and results of evaluations are provided in tabular form.

Wetlands and waterbodies: impact avoidance and minimization protocols

The Connecticut Light and Power Company. (2013). Wetlands and waterbodies: Impact avoidance and minimization protocols. Interstate Reliability Project Development and Management Plan. August. Retrieved November 10, 2015, from http://www.transmission-nu.com/residential/projects/irp/DM_Plans_Submitted_to_CSC/Volume_1_OH_Construction/Appendix B -- Wetlands & Waterbodies Protocols.pdf

The Interstate Reliability Project extends across various water resources, including wetlands and water bodies (i.e., watercourses, lakes, and ponds). This report appendix presents the procedures used to avoid or minimize impacts to wetlands and waterbodies during construction, and those used to restore such water resources, following the completion of the 345-kV transmission line installation, and the related minor modifications to adjacent lines. To minimize or avoid adverse effects to wetlands, new transmission line structures have been located in upland areas (wherever

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practical), avoiding the alignment of construction access roads across wetlands. The post-construction monitoring process has been performed to verify the success of Project restoration, and to identify additional restoration measures that may be required. Monitoring can include inspections of percent vegetative cover, wetlands functions, and permanent erosion controls on the restored ROWs. A number of steps and mitigation measures to further avoid and minimize impacts to waterbodies were applied.

A.4 Alternative Foundations

High Capacity Helical Piles Limited Access Projects

O'Donoghue, B. (n.d.). High Capacity Helical Piles Limited Access Projects. Retrieved November 10, 2015, from http://kcengineers.org/geotech/wordpress-content/uploads/2012/02/ODonoghue.pdf

This slide presentation gives the background of large diameter pile shafts with helices, as well as the applications and considerations involved in using helical piles as alternative foundations. These foundation systems are frequently used in cold weather environments. Difficult access issues are addressed via the demonstration of two study cases. The framing assembly and connections are shown via photographs.

Transmission Towers, Costa Rica

CHANCE Civil Construction. (n.d.). Transmission Towers, Costa Rica. Retrieved November 10, 2015, from http://www.abchance.com/resources/case-histories/transmission-towers-costa-rica/

A case history of the foundation challenges encountered during the construction of a 230kV transmission project and the solution using helical piles is presented. Poor ground conditions are shown to require massive concrete floating foundation to support tower structures. A field test of helical pile was conducted for proving the foundation design. This case illustrates the value of helical piles for soft subsurface conditions.

Uplift Capacity of Helical Anchors in Soil

Hoyt, R., & Clemence, S. (1989). Uplift Capacity of Helical Anchors in Soil. Proceedings: *12th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2. Rio de Janeiro, Brazil. 1019-1022.

Helical anchors have been used in various applications, including transmission tower foundations, pipeline anchors, and excavation bracings. Methods for predicting the uplift capacity of anchors using geotechnical parameters are categorized into "cylindrical shear" and "individual bearing" methods. An empirical method for predicting capacity based on installation torque has been widely used in practice. The authors analyze numerous helical anchor tests to determine ultimate uplift capacities. Capacities based on the three methods were calculated for each anchor, and compared to actual capacity. Ratios of actual to calculated capacities were computed, and statistical analyses of the distributions of these ratios are presented. The results indicate that the torque correlation method yields more consistent results than either of the other two methods, although all three methods exhibit a wide range of values. The installation torque method may be used as an independent check of the other two to establish bounds of expected capacity.

Helical Pile Engineering Handbook

Helical Pier Systems. (2010). Helical Pile Engineering Handbook. 7th Ed. January. Retrieved November 10, 2015, from content/uploads/2012/03/EngineeringHandbook_low.pdf

The purpose of this handbook is to present a user-friendly summary of helical pile design and construction. Helical pile foundations are also referred to as anchors, screw anchors, and/or torque piles. For this manual, screw anchors are assumed to be in tension, and helical piles in compression.

Quick Fix for Frost Heave: Helical piles

Milbradt, M., & Vasbinder, S. (2011). Quick Fix for Frost Heave: Helical piles. Retrieved November 10, 2015, from http://www.hubbellpowersystems.com/magazine/best-of/quick-fix-for-frost-heave-sept-2011.pdf

This source comprises a case history pamphlet presenting foundation remediation at Basin Electric Cooperative's Logan substation, following frost heave. Design challenges and obstacles to construction due to environmental issues, as well as a consideration of the helical piles foundation solutions used in this project are discussed. The benefits and installation of helical piles are presented.

Installing Test Helical Screw Pile in a Frozen Lake for a Dock and Boathouse in North West Ontario

Winnipeg Screw Piles (2013) Installing Test Helical Screw Pile in a Frozen Lake for a Dock and Boathouse in North West Ontario. The Blog, February 13. Retrieved November 10, 2015, http://winnipegscrewpiles.com/2013/02/13/installing-test-helical-screw-pile-in-a-frozen-lake-for-a-dock-and-boathouse-in-north-west-ontario/

A technical case history articling the use of helical screw piles is presented, alongside the ways in which the system is different and more effective than a steel driven pile. Helical screw piles are installed using low impact equipment, do not create vibration, and operate at a low noise level.

Unique Installation Used In Sensitive Environment

White, B., & Eisinger, B. (1997). Unique Installation Used In Sensitive Environment. *T&D World Magazine.* (e-magazine). May 1.

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A case history is presented for the foundation design and installation of a 115 kV transmission line in Snohomish County, WA using vibratory steel caissons. The alignment crossed dozens of wetlands, rivers, and freeways. Vibratory caissons for steel pole structures were used in environmentally sensitive areas. Numerous routing and construction obstacles needed to be circumvented for installation. Foundation setting was also completed, in part, by helicopter, thus allowing for line construction to move forward more quickly than other foundation systems.

Installation of Steel Vibratory Caissons with Internal and External Cathodic Protection

Pridmore, M. (2013). SCE&G Back River Crossing Project: Installation of Steel Vibratory Caissons with Internal and External Cathodic Protection. Presentation from South Carolina Electric & Gas to the Edison Electric Institute on October 7. Retrieved November 10, 2015, from http://www.eei.org/meetings/meeting_documents/pridmore.pdf

Slide presentation case history is presented regarding the Back River 230/115kV Crossing Project. Four transmission lines cross the Back River and associated wetlands. Three-pole wood piling structures were replaced with steel vibratory caissons foundation. The alternate foundations evaluated included driven piles with cast-in-place concrete caps. Sites were accessible only by boat. For investigation, mats were used to install a number of the foundations. Cathodic protection corrosion protection also used for the project is discussed along with project costs.

Settlement and Vibration Monitoring for Transmission Line Foundation Installation

Forbes, R.H., & Camp, W.M. III (2013). Settlement and Vibration Monitoring for Transmission Line Foundation Installation. *Geotechnical, Geophysical, and Geoenvironmental Engineering Technology Transfer Conference and Exposition (Geo3 T2)*, Cary, NC, April 4,

A case history slide presentation is delivered, regarding the vibratory hammer steel caisson installation of 54 transmission line pole foundations in close proximity to residential and commercial structures. Vibratory caissons were used in lieu of reinforced concrete drilled shafts, due to their low cost and ease in depth field optimization. Extensive monitoring of settlement and vibration was performed to assess impacts upon adjacent structures. Advantages disadvantages, design detail, and the installation of vibratory caissons foundations are presented.

CTS/TITAN Injection Bore (IBO) Micropiles

Con-Tech Systems Ltd. (n.d.). CTS/TITAN Injection Bore (IBO) Micropiles. Retrieved November 10, 2015, from http://www.contechsystems.com/cts-cd/Micropiles/CSFwM.pdf

This technical bulletin presents the methods and equipment adopted in the installation of injection bore micropile foundations, intended for use in single shaft poles and latticed transmission towers. This article also presents the calculations of micropiles in terms of their load capacity and bond length, including design methodologies for both foundation systems. Multiple micropiles are incorporated within pile caps for individual tower legs, and within a single pile cap/spread footing for monopole shafts.

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Micropiles – an Introduction.

GeoProfound Engineering Sdn Bhd. (n.d.). Micropiles – an Introduction. Retrieved November 10, 2015, from http://www.geoprofound.com/download/Micropiles-all.pdf

This slide presentation uses illustrations, photographs, and case studies to present the histories, applications, types, and benefits of micropiles for transmission line projects. The methods for the calculation of pile capacity are shown.

Innovative Foundation Techniques Using TITAN Self Drilling, Dynamic Grouting Hollow Micro Piles

Ischebeck, E.F. (2002). Innovative Foundation Techniques Using Titan Self Drilling, Dynamic Grouting Hollow Micro Piles. Proceedings: 7th International Seminary: Reinforcement, Sealing and Anchoring of Rock Massif and Building Structures. Retrieved November 10, 2015, from http://fast10.vsb.cz/science/seminar2002/pics/05.pdf. February 15.

This technical lecture includes three sections. The first part demonstrates the general information and details regarding new anchor techniques. The second part addresses applications for electric transmission tower foundations, providing examples. The last part presents design calculations, performance, and feasibility factors pertaining to micropiles.

Integration of Optimum, High Voltage Transmission Line Foundations

Thompson, F., Salisbury, N., Khattak, A., Hastings, A., & Foster, M. (2009). Integration of Optimum, High Voltage Transmission Line Foundations. *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12.

High voltage electric power transmission lines span across various regions and geology. With these variations in venue and subsurface condition, there is a need for efficient foundation design control and for the construction of conventionally deep foundations. These prove to be economical in design and construction, and thus optimal for foundation systems. In some locations, however, site conditions cause conventional foundations to be overly expensive or impractical, and micropile foundations consequently become the prime solution. This paper will introduce and illustrates the basic advantages and disadvantages of both conventional and micropile foundations in this industry, and how they are being integrated to provide design solutions. A brief history of the introduction of micropiles into this industry is also discussed.

Micropiles are often thought of as an emerging technology, even though they were conceived over 50 years ago and have been used in the United States for more than 30 years. The electric power transmission industry has recently discovered this "emerging technology," and it is beginning to take advantage of it. As the need to transfer electricity from remote locations continues to expand, the use of micropile foundations is expected to become more common as a practical solution for addressing the challenges encountered.

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This paper seeks to introduce and illustrate the basic advantages and disadvantages of both conventional and micropile foundations in this industry, and how they are being integrated to provide design solutions.

Micropile Foundation Design Minimizes Environmental Impact for Southern California Edison Project

Chen, C., & Salisbury, N. (2012) Micropile Foundation Design Minimizes Environmental Impact for Southern California Edison Project. *Foundation Drilling*. ADSC. September/October. 16-20.

The article describes the use of micropiles as a deep foundation solution for transmission line towers in a very remote environment in California. Other alternatives, including pre-stressed or post-tensioned rock anchors, were considered in this project. However, micropile foundations were selected due to their high-capacity and small diameter. This solution provided cost and schedule advantages over other designs, due to restrictions imposed by working within the forest. This article also describes the design and construction challenges encountered during this project.

Micropiles as Alternative Foundations for Electrical Transmission Infrastructures

Davidow, S. (2015). Micropiles as Alternative Foundations for Electrical Transmission Infrastructures. *Superpile 2015*. Kissimmee, FL. May 6-8.

Difficult to access, environmentally sensitive sites and/or challenging geotechnical conditions require alternative foundation options. This electrical transmission presentation provides the rationale explaining how micropiles as alternative foundations can provide an ideal foundation solution for transmission infrastructure. This slide presentation provides three project case histories as example to demonstrate the applications and benefits of mircropiles for founding transmission line structures.

Micropile Design and Construction in a Limited Access Wetland Habitat

Davidow, S.A., & Carr, D.G. (2015). Micropile Design and Construction in a Limited Access Wetland Habitat. *Electrical Transmission and Substation Structures 2015*. Branson, MO. ASCE. September 27-October 1. 35-46.

This paper discusses the use of micropiles as a specialty deep foundation solution to limited construction access challenges within the Troy Meadows wetland portion of PSE&G's 500 kV Susquehanna to Roseland Electric Reliability Project. Micropile foundations were constructed utilizing primarily helicopter access for seven 500 kV double-circuit tubular steel pole structures within the protected habitat. The successful implementation of a design-build strategy between the overhead design team and the contractor led to significant refinements in the foundation design. Value engineering efforts focused on the refinement of tower loading geometry and load cases, the assessment of geotechnical conditions, and the reduction of foundation footprints within the wetlands environment. The paper details the design and routing of the overhead alignment, as well as the permitting restrictions and area of impact limitations. It then provides an in-depth analysis of concrete cap micropile design, and detailed construction methodologies.

Rock socket transmission line foundation performance

DiGioia, A.M., & Rojas-Gonzalez, L. (1994). Rock socket transmission line foundation performance. *IEEE Transactions on Power Delivery IEEE Trans. Power Delivery, 9*, 1570-1576.

A major goal of overhead transmission line design is to achieve a minimum cost for a given level of reliability and safety. The greatest uncertainty in this process is foundation design. Recognizing the opportunity to improve economic savings related to transmission line design, the Electric Power Research Institute (EPRI) has sponsored, since 1977, a comprehensive program of activities in foundation design. Since little high quality foundation test data existed, a recent task involved the performance of well documented full-scale load testing of drilled shafts and direct embedment pole foundations for single transmission line poles, partially or totally socketed in rock and subjected to high lateral forces and overturning moments. The tests are presented. Based on the load tests, a provisional design guideline is also proposed. A summary of the results obtained for fourteen load tests is also offered. Based on the load tests, a provisional design guide line is proposed.

Horizontal Directional Drilling for Utility Line Installation

Ohio Division of Surface Water (2013). Horizontal Directional Drilling for Utility Line Installation. Fact Sheet. December. Retrieved November 10, 2015, from http://www.epa.state.oh.us/Portals/0/general%20pdfs/HorizontalDirectionalDrillingforUtilityLineInstallation.pdf

This fact sheet provides basic information regarding the management of Horizontal Directional Drilling (HDD) wastes and the protection of water resources. Guidance is given for line siting and for best management practices.

Improved Performance of Electrical Transmission Tower Structure Using Connected Foundation in Soft Ground

Kyung, D., Choi, Y., Jeong, S., & Lee, J. (2015). Improved Performance of Electrical Transmission Tower Structure Using Connected Foundation in Soft Ground. *Energies*, 4963-4982.

A connected foundation is an effective foundation type that can improve the structural performance of electrical transmission towers in soft ground, being a resilient energy supply system with improved stability. The performance of a connected foundation for transmission towers was investigated in the present study, focusing on the effect of connection beam properties and soil conditions. A finite element analysis was performed for various foundation and soil conditions for this purpose. In order to validate the finite element analysis, the calculated results were compared with measured results obtained from field load tests. The use of connection beams was more effective for uplift foundations, usually controlling the design of transmission tower foundations. In terms of the effect of soil conditions, the use of connected foundations is more effective in soft clays with lower undrained shear strength (su). Smaller amounts of differential settlement were observed in all soil conditions for both unconnected and connected foundations, when a bearing rock layer was present. When the foundation was not reinforced by connection beams, the values of lateral load capacity of tower structures (Hu) were similar for both with- and without-rock layers. It was confirmed that introducing haunch-shaped connection beams is effective for increasing connection beam stability.

A.5 Foundation Design and Contracting

Transmission Structure Foundation Design Guide

DiGioia, A.M. Jr. (2012) *Transmission Structure Foundation Design Guide.* EPRI, Palo Alto, CA. 1024138.

This guide contains the most current and comprehensive information for the design of foundations for overhead line structures. The guide covers the complete transmission structure foundation design process, ranging from subsurface investigations and the design of the foundations, to the construction and inspection of the foundation. Reference documents are provided to assist transmission structure foundation designers in the development of specifications, such as for subsurface investigations and foundation construction. The guide provides recommended procedures for the geotechnical design of transmission line structure foundations, using a reliability-based design framework. A brief overview of the reliability-based load and resistance factor design format is presented, along with descriptions of appropriate load factors; applied to the structure and foundation loads, as well as resistance factors applied to the nominal foundation strength are obtained. The suitability of various types of foundations for single-pole, H-frame and lattice steel structures are reviewed and discussed. In addition to the design of drilled shaft and direct embedded foundations, information on the design of grillage, Micropile, and rock anchor foundations is also provided. The guide also includes ten foundation design examples covering single pole, H-frame, and lattice steel structures using the Electric Power Research Institute (EPRI) foundation design software. Reports and research results from previous years were incorporated in the development of this guide.

Geotechnical Investigations for a Transmission Line Are More than Drilled Borings

Johnson, K. (2009). Geotechnical Investigations for a Transmission Line Are More Than Drilled Borings. *Electrical Transmission and Substation Structures 2009.* ASCE. Fort Worth, TX. November 8-12. 106-117.

With the increasing need for transmission line design support, engineers must be comfortable evaluating limited geotechnical foundation design data that is spread out over long distances. This report demonstrates that through merging engineering geology and geotechnical engineering evaluations, data can be grouped into sections comprised of different design parameters along the length of a transmission line. The goal of this merger is to create a better characterization of the foundation design data along an entire alignment. Some tools and methods used by others are presented for consideration. When completed efficiently, the engineer can better understand the nature of the foundation conditions along the alignment, as well as where and why the geotechnical design parameters should be used and altered as a result of how they are grouped around similarities in geologic conditions.

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Construction Challenges of Extra High Voltage Transmission Lines: Building in the Most Difficult Terrain in the World

Lakhapati, D. (2009). Construction Challenges of Extra High Voltage Transmission Lines: Building in the Most Difficult Terrain in the World. *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 367-378.

This paper describes the challenges faced during the construction of EHV transmission lines, which travel hundreds of miles in difficult terrain, under varying and extreme environmental conditions, and using a variety of construction equipment. The engineering challenges become much more difficult under higher voltages, as structures become very tall and heavy. Every country has individual challenges unique to that country or region. Engineering solutions need to be suitable for overcoming working challenges, described throughout the paper.

Design and Construction Challenges of Overhead Transmission Line Foundations (NU's Middletown Norwalk Project)

McCall, C. L., Hogan, J. M., & Retz, D. (2009). Design and Construction Challenges of Overhead Transmission Line Foundations (NU's Middletown Norwalk Project). *Electrical Transmission and Substation Structures 2009*. ASCE. Fort Worth, TX. November 8-12. 319-328.

The project includes 69 right-of-way miles of 345-kV and 115-kV overhead and underground transmission line. Given the large scale and the conditions of this project, there have been many challenges to overcome regarding the use of these foundations. Initially, one of the greatest challenges involved determining the type of foundation to use, given the rocky terrain. Creating a design process incorporating the various possibilities was necessary. Geotechnical and environmental questions, as well as issues encountered during the actual construction, have also provided significant challenges. Additionally, the unusually long project timetable sparked challenges, requiring a massive coordination effort. This paper will discuss these distinct challenges, and the ways in which they were overcome. Terrain, soil conditions, and foundation design are included.

Foundation Design and Construction Challenges at River Crossing for 345kV Transmission Line

Karels, L.D. (2014). Foundation Design and Construction Challenges at River Crossing for 345 Kv Transmission Line. *Proceedings: T&D Conference and Exposition 2014*. IEEE PES. Chicago, IL. April 14-17.

River crossings are inevitable when designing and constructing foundations for cross-country transmission lines. Factors such as dramatic terrain changes, long spans, heavy loading, and unfavorable soil conditions present significant challenges for engineers and contractors. This paper presents a case history of one particular river crossing on the CapX20201 Brookings County to Hampton 345 kV Transmission Project, and how the design team worked with contractors to overcome several obstacles to construct the foundations.

Helical piles: A practical guide to design and installation

Perko, H.A. (2009). *Helical piles: A Practical Guide to Design and Installation*. Hoboken, N.J.: J. Wiley. 528p.

Helical piles are a valuable instrument in the geotechnical tool belt. From an engineering/architecture standpoint, they can be adapted to support many types of structures impeded by a number of problematic subsurface conditions. From an owner/developer standpoint, their rapid installation can often result in overall cost savings. From a contractor perspective, they are easy to install, and their capacity can be verified to a high degree of certainty. From the public perspective, they are perhaps one of the most interesting, innovative, and environmentally friendly deep foundation solutions available today. This book contains an introduction, a primer on installation and basic geotechnics, as well as advanced topics in helical pile engineering, practical design application, and other topics. The introduction starts with an explanation of the basic features and components of helical piles.

Relationship between Installation Torque and Axial Capacities of Helical Piles in Cohesionless Soils

Sakr, M. (2015). Relationship between Installation Torque and Axial Capacities of Helical Piles in Cohesionless Soils. *Canadian Geotechnical Journal*. 52(6). 747-759.

With the rapid growth of the helical piling industry and oil and gas projects and transmission lines, reliable installation torque estimates and measurements have become crucial. This paper presents a theoretical model developed ranging from estimate of the torsional resistance of cohesion-less soils to helical pile installation. The theoretical torque model was verified using installation records collected from distinct sites. The paper also highlights factors that affect helical pile installation, including soil properties, fluctuation in groundwater levels and shape of pile shaft, pile geometry, and methods for helical pile installation. The proposed torsional resistance model was then used to establish the traditional torque factors to proportionally correlate the axial capacity of helical pile and the installation torque. The results of the study indicate that the torque factor is a function of the load path (i.e., tension or compression). Therefore, torque factors in compression and tension, Kc and Kt, respectively, are formulated and presented.

Micropile Design and Construction Guidelines

Sabatini, P.J., Tanyu, B., Armour, T., Groneck, T. & Keely, J. (2005) *Micropile Design and Construction Manual, Reference Manual for NHI Course 132078)*. Report No. FHWA-NH1-02-039. December. 434p.

The use of micropiles has grown significantly since their conception in the 1950s, in particular, since the mid-1980s. Micropiles have been used mainly as foundation support elements that resist static and seismic loads, and, to a lesser extent, as in-situ reinforcements to provide stabilization for slopes and excavations. Many of these applications are for transportation structures. This manual is intended to be a "practitioner-oriented" document, containing sufficient information regarding the geotechnical and structural design of micropiles for foundation support, and for slope stabilization. Information is also provided regarding inspection and load testing procedures, cost data, and

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contracting methods facilitating the safe and cost-effective use of micropiles on transportation projects. Two detailed design examples and a generic commentary guideline specification for micropiles is included in the manual.

On The Tower Footing Resistance of Micropile Anchors

Pretorius, P.H., & Semmelink, C.J. (2009). On The Tower Footing Resistance of Micropile Anchors. *Proceedings: 16th International Symposium on High Voltage Engineering*. (Paper No. G-34). SAIEE. Johannesburg, South Africa. 1-5.

The lightning performance of an overhead power line is one design aspect that needs to be addressed regarding the overall electrical reliability of the line. A family of new towers for high power transmission lines, constrained by servitude availability, is currently being developed in South Africa. High reliability requirements by the client demand specific attention to and focus upon the lightning performance of the line. This paper addresses specific aspects considered during the application of new micropile technology applied as anchors for the towers. Although anchors demand mechanical considerations relating to high voltage structure, its electrical characteristics and performance are also important design considerations in view of the lightning performance of the line. This paper addresses the electrical performance of the micropiles in various soil conditions via a software model, also compared with measurements. Particular attention is given to the tower footing resistance presented by the micropiles considering the various soil conditions modeled.

Load Transfer Mechanisms in Rock Sockets and Anchors

Pease, K.A. and Kulhawy, F.H. (1984) *Load Transfer Mechanisms in Rock Sockets and Anchors*. Electric Power Research Institute, Report No. EL-3777. Palo Alto, CA. November

This study presents a comprehensive analysis of rock socket and anchor behavior, which includes the failure mode, capacity, and deformations. The methods for analysis were obtained from a combination of original concepts and summaries from preexisting methods. The original concepts are based on both theoretical considerations and observations of actual socket behavior. The data used for both analytical and verification purposes was obtained from published sources. The results show that rock sockets and anchors can fail by any one of four modes, including: tensile failure of the tendons, pullout of the tendons from the grout, grout-rock interface slip, and rock mass uplift. Only the latter two are geotechnical problems investigated in detail.

Grout-rock interface failure is outlined as a progression of behavior, ranging from elastic, to secondary, and finally to residual stages. The elastic stage is characterized as an intact system in which displacements develop following elastic deformations of the foundation and rock mass. Comparatively, the secondary stage is characterized by a relative displacement between the foundation and the rock mass. Finally, the residual stage results from large displacements between the foundation and rock mass, and is characterized by complete degradation of the interface between the foundation and the rock mass. Equations and data are presented for the evaluation of behavior in each stage.

For shallow foundations installed in highly fractured rock masses, failure can arise from rock mass uplift. In this case, failure is associated with the cracking and loosening of rock mass, which can be approximated by a cone failure. This mode gradually transitions to the grout-rock interface failure mode with increasing depth.

Analysis and Design of Drilled Shaft Foundations Socketed into Rock

Carter, J.P. & Kulhawy, F.H. (1988). *Analysis and Design of Drilled Shaft Foundations Socketed into Rock*. Electric Power Research Institute, Report No. EL-5918. Palo Alto, CA. August.

A comprehensive investigation has been conducted regarding the behavior of drilled shaft foundations socketed into rock. Methods of analysis are presented to predict the ultimate capacity and the load-displacement behavior under axial load (compression or uplift), lateral load or moment, and for torsion. Simple approximate models have been developed, allowing for closed form predictions for all of these loading modes. The models for axial loading have been used in the interpretation of 25 load tests from the literature, to deduce the likely range of design parameters. Only two load tests were available for lateral load analysis, and no torsional load tests were available. More data is needed from these loading modes for model verification. A detailed design example is also included to illustrate the use of the design equations presented.

Characteristics Value in Rock Socket Design

Look, B., & Lacey, D. (2013). Characteristic Values in Rock Socket Design. *Proceedings: 18th International Conference on Soil Mechanics and Geotechnical Engineering: Challenges and Innovations in Geomechanics*, (Paper No. 2753). Paris. September 2-6. 2795-2798.

The substructure of the Gateway Bridge comprises 1.5 meter diameter bored piers socketed into sedimentary rock. The characterization of the rock strength properties, through goodness-of-fit tests, showed that the use of non-normal distributions produced realistic characteristic strengths, while comparable predictions based on Normal distribution conveyed unrealistically low values existing below the 20th percentile reliability. Since limit state codes imply that characteristic design strengths should be derived from conservative (low) percentile values, erroneous characteristic strength values may be produced due to an assumption of a Normal distribution. Two land based test piles fitted with Osterberg cells tested the sedimentary bedrock for shaft capacity at the bridge site, and “Characteristic” rock strengths required by various rock socket design methods to replicate observed pile shaft capacity were back-calculated. This paper assumes that all of the considered design methods are equally “correct”, and compares the required design values (the selection of which is often subjective) to their relative location within the applied strength profile distributions.

APPENDIX B. QUESTIONNAIRES AND FORMS

B.1 Case History Questionnaire

The consultant was commissioned by CEATI International, Inc. to develop a guide for transmission line foundations with the least impact to the environment. As part of the work scope, various utilities and consulting firms were requested to participate in gathering case history information regarding foundations located in various environmentally sensitive conditions.

The survey function worked to collect published and unpublished case histories of environmentally sensitive locations, which have: (1) adversely impacted foundation construction, (2) required special remediation techniques for site access and construction, or (3) required use of alternative foundation design to minimize environmental impact. In particular, the research team was interested in obtaining case history information regarding foundations located in wetland environments, difficult access terrain, and frozen ground conditions. The research team was also interested in gathering information regarding the use of unique foundation designs and innovative construction practices.

The researchers requested that each survey participant complete the following "State of the Practice Survey" form to identify the conditions encountered, investigated, or studied, either on their utilities transmission line system, or on their clients' systems as consultants. The survey also requested information on design practices in difficult environments. The survey language was modified to obtain parallel responses from both utility personnel and consultants in the utility industry. Questions relating to construction or post-construction activities were sent only to utilities.

The version sent to utility participants is provided in the following pages.

CEATI • 1010 Sherbrooke Street West, Suite 2500, Montreal, Quebec, Canada H3A 2R7
www.ceati.com • info@ceati.com • Phone +1 (514) 866-5377 • Fax +1 (514) 904-5038

Guide for Transmission Line Foundations with Least Impact to Environment

State of the Practice Survey

Company: ______________________________

Contact Name: ______________________________

Contact Email: ______________________________

Contact Phone Number: ______________________________

Confidentiality statement: *All survey information will be incorporated into the report. CEATI retains all distribution rights. Summary survey data will be provided to all survey responders, unless indicated otherwise below.*

Exceptions: ______________________________

A. GENERAL QUESTIONS:

1. Please identify your utility type (select all that apply):
   - ☐ Governmental Utility
   - ☐ Privately Owned Utility
   - ☐ Public Utility
   - ☐ Other (please describe): ______________________________

2. Which geographic region best identifies your utility's service area (select all that apply):
   - ☐ North America
   - ☐ South America
   - ☐ Africa
   - ☐ Europe
   - ☐ Asia
   - ☐ Australia & Pacific
   - ☐ Other (please describe): ______________________________

3. Please identify the environments encountered in your utility's service territory (select all that apply):
   - ☐ Wetlands/ Waterways
   - ☐ Woodlands
   - ☐ Desert/ Rangeland/ Open land
   - ☐ Mountainous/ Rough terrain
   - ☐ Permafrost/ Frozen ground
   - ☐ Conservation/ Wilderness areas

4. Has your utility designed/constructed foundations in environmentally sensitive areas?

   ☐ YES ☐ NO

   a. If yes, are there written case history studies?

   ☐ YES ☐ NO

   b. If yes, would your utility be willing to share the studies with the investigation team?

   ☐ YES ☐ NO

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B. PROJECT PLANING:

Please mark responses with a "check"

1. Does your utility have an established best practice plan for foundation construction in environmentally sensitive areas?
   ☐ YES ☐ NO

2. Does your utility consult with regulatory agencies to identify environmentally sensitive areas?
   ☐ YES ☐ NO

   a. If yes, please list the regulatory agencies your utility consults:

3. Select the number rank that best describes your utility's practices when working or planning transmission line work in environmentally sensitive areas (Always = 1, Never = 5):

	Select Number
a. We avoid placing transmission structures in environmentally sensitive areas	Select
b. We identify environmentally sensitive areas during the transmission line planning process (prior to design)	Select
c. Existing ROW's determine the location of transmission structures no matter what the environment	Select
d. We perform geotechnical field investigations in environmentally sensitive areas as part of the design process	Select
e. We allow for multiple foundation alternatives (drilled shafts, direct embedment, micropiles, etc.) for individual transmission line structure designs in sensitive environments	Select
f. We install mitigation measures for foundation construction in sensitive environments instead of modifying foundation designs to reduce impacts/footprints	Select

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C. DESIGN:

Geotechnical Field Investigation in Support of Foundation Design:

1. Does your utility require geotechnical field testing prior to design at environmentally sensitive sites?
   ☐ YES ☐ NO ☐ JOB SPECIFIC DECISION

   If yes or job specific decision:
   a. Does your utility provide access for geotechnical testing field drill rigs in sensitive environments during the foundation design process?
      ☐ YES ☐ NO ☐ JOB SPECIFIC DECISION
   b. Is the geotechnical firm required to provide mitigation (mats, etc.) for drill rig access?
      ☐ YES ☐ NO ☐ JOB SPECIFIC DECISION
   c. If no access is available, does your utility require testing by remote methods (geophysics, soil probes, etc.)?
      ☐ YES ☐ NO ☐ JOB SPECIFIC DECISION

   If no:
   a. Does your utility require the foundation construction contractor to perform some kind of subsurface testing in environmentally sensitive areas prior to construction?
      ☐ YES ☐ NO ☐ JOB SPECIFIC DECISION

2. At what stage is geotechnical field testing done for foundation designs (mark the one that best applies to most projects)?

   ☐ Prior to line design
   ☐ After staking structure locations (as part of line design)
   ☐ As part of an Engineer-Procure-Construct contract
   ☐ Preliminary investigation as part of utility project scoping (prior to EPC)
   ☐ Other (please describe): ______________________________

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Alternative Foundation Design

3. Does your utility consider multiple foundation alternatives for design?
   ☐ YES ☐ NO ☐ JOB SPECIFIC

4. If yes, please indicate with a "check" the foundation alternatives considered (standard foundations include driven piles, drilled shafts, direct embeds, grillage foundations, spread footings, anchored structures).
   ☐ Auger cast piles
   ☐ Helical anchors/piles
   ☐ Micropiles
   ☐ Rock sockets/anchors
   ☐ Underground transmission line
   ☐ Other (please describe): ______________________________

5. Does your utility have a standard/technical specification for alternative foundation construction?
   ☐ YES ☐ NO

   a. If yes, can a copy of the standard/technical specification be provided to the research team?
   ☐ YES ☐ NO

6. Does your utility design alternative foundations in-house?
   ☐ YES ☐ NO

   a. If yes, are the software tools supplied by the manufacture of the alternative foundation type?
   ☐ YES ☐ NO

   b. If yes, what software tools does your utility use to evaluate the design of alternative foundations? (if the tools are property to your utility please indicate "utility specific tool")

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7. Please indicate with an "X" the reasons why your utility does not use or rarely uses the following types of foundations:

	Driven piles	Drilled shaft	Direct embed	Grillage foundations	Vibratory caissons	Spread footings	Guy anchored structures	Auger cast piles	Helical anchors/piles	Micropiles	Rock sockets/anchors	Underground T/L
Not practical in your service area												
Not part of standards or methods												
Too costly & time consuming												
Management resistant to change												
Unfamiliar contractors												
Design too complicated/technical												
Uncertainty of foundation reliability												
Not applicable (foundation used regularly)												
Other:												

Other (elaborate as needed):

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D. CONSTRUCTION:

Site Access:

1. Select the number rank that best describes your utility's practices to access transmission line foundation sites in sensitive environments (Always = 1, Never = 5):

	Select Number
Construct new standard access roads	Select
Construct spur roads to structure sites	Select
Improve existing access roads	Select
Haul in equipment by manual methods	Select
Install modular mat paths	Select
Ground stabilization/improvement	Select
Relocate structure	Select
Use all-terrain vehicles (no road access)	Select
Fly in by helicopters	Select

2. If helicopters are used, please identify the type typically used and typical weight limits:

Please mark the following with a "check":

3. My utility generally provides site access for foundation construction crews.
   ☐ YES ☐ NO ☐ JOB SPECIFIC ISSUE

4. Site access is the responsibility of the foundation contractor.
   ☐ YES ☐ NO ☐ JOB SPECIFIC ISSUE

5. My utility identifies transmission line construction staging areas.
   ☐ YES ☐ NO ☐ JOB SPECIFIC ISSUE

6. Staging areas are the responsibility of the transmission line contractor.
   ☐ YES ☐ NO ☐ JOB SPECIFIC ISSUE

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Constructed Foundations:

If your utility has installed transmission line foundations in environmentally sensitive areas during the past 10 years, please provide an estimate for the following:

7. Structure types pleasewrite an estimate quantity for each box, if quantity is unknown but is applicable write an "X", otherwise leave blank):

	Transmission Voltage Range	Number of Structures	Number of Lines
Wood poles			
Steel Pole with base plate			
Direct embed pole			
H-Frame			
Lattice Tower			
Underground			

Other: ____

8. Number of foundation types in sensitive environments during the last ten years (please write an estimate quantity for each box, if quantity is unknown but is applicable write an "X", otherwise leave blank):

	Driven piles	Drilled shaft	Direct embed	Grillage foundations	Vibratory caissons	Spread footings	Guy anchored structures	Auger cast piles	Helical anchors/piles	Micropiles	Rock sockets/anchors	Underground T/L
Wetlands/ Waterways												
Woodlands												
Desert/ Rangeland/ Open land												
Mountainous/ Rough terrain												
Permafrost/ Frozen ground												
Conservation/ Wilderness areas												

Other: ____

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Challenges Encountered During Foundation Construction:

9. Please select a number rank that best describes the challenges encountered during foundation construction in sensitive environments (Always =1, Never = 5):

	Select Number
Access restrictions	Select
Deadline date for completion/ schedule contracts	Select
Difficulty with materials getting to sites	Select
High cost of constructing access	Select
Limited number of specialty foundation contractors available	Select
Poor performance by general contractors	Select
Limited options for foundation design	Select
Damage to sites from standard foundation construction equipment	Select
Reluctance or lack of experience with alternative foundations	Select
Cost of alternative foundations	Select
Regulatory restrictions	Select
Large footprint using standard foundations on limited space sites	Select

Other: ____

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E. Post-Construction Phase:

1. Please select a number rank that best describes post-construction practices used by your utility in sensitive environments (Always = 1, Never = 5):

	Select Number
Site monitoring for contamination	Select
Site restoration of vegetation	Select
Removal of drilling spoils	Select
Restoration of ground (discing/loosening soil)	Select
Site restoration for aesthetics	Select
Site monitoring for foundation performance	Select

2. Does your utility maintain access to structures located in sensitive environment sites for maintenance/inspections?
   ☐ YES ☐ NO

3. How are sensitive site structures accessed where there are no access roads (select all that apply)?

☐ Access by foot
☐ Access by horseback
☐ Access by ATV
☐ Access by helicopter
☐ Other (please describe): ____________________

Survey Responses

A. GENERAL QUESTIONS:

1. Please identify your utility type:

Governmental Utility	7
Privately Owned Utility	3
Public Utility	7
Other	1
- Partially owned by government, partially traded on market	

2. Which geographic region best identifies your utility's service area:

North America	19
South America	0
Africa	0
Europe	1
Asia	0
Australia/Pacific	0
Other	0

3. Please identify the environments encountered in your utility's service territory:

Wetlands/ Waterways	18
Woodlands	16
Desert/ Rangeland/ Open land	6
Mountainous/ Rough terrain	16
Permafrost/ Frozen ground	6
Conservation/ Wilderness areas	15

4. Has your utility designed/constructed foundations in environmentally sensitive areas?

Yes	18
If yes, are there written case history studies?	1
If yes, would your utility be willing to share the studies with the investigation team?	3

B. PROJECT PLANNING

1. Does your utility have an established best practice plan for foundation construction in environmentally sensitive areas?

8

2. Does your utility consult with regulatory agencies to identify environmentally sensitive areas?

18

- Alberta Sustainable Resource Development (Gov. of Alberta), NAV Canada (Gov. of Canada), Department of Fisheries and Oceans (Gov. of Canada), Environmental and Landowner groups
- Federal Agencies, Tribes or Tribal Groups, State Agencies, State Agencies
- Regional and National agencies are listed below: DENR (Department of Environmental and Natural Resources) FDEP (Florida Department of Environmental Protection)Corps of Engineers USFWS (US Fish & Wildlife Services) SHPO (State Historic Preservation Office)National Forest Service; National Park Service
- Principally National Parks and Wildlife Service.
- Federal, state and county/parish agencies.
- MDE - Maryland Department of the Environment
- BLM, Forest Service, Fish and Wild Life, CORPS of Engineers, DOE, Bureau of Recreation, City, County
- BC Ministry of the Environment
- US Fish and Wildlife Service, State Game Commissions, State Fish and Boat Commissions, State Historic Preservation Offices, State Department of Conservation and Natural Resources, State Departments of Environmental Protection
- NYSDEC, Army Corps

3. Select the number rank that best describes your utility's practices when working or planning transmission line work in environmentally sensitive areas (Always = 1, Never = 5):

	1- Always	2- Frequently	3- Sometimes	4- Rarely	5- Never
We avoid placing transmission structures in environmentally sensitive areas	4	11	3	0	1
We identify environmentally sensitive areas during the transmission line planning process (prior to design)	14	5	0	0	0
Existing ROWs determine the location of transmission structures no matter what the environment	0	5	10	3	0
We perform geotechnical field investigations in environmentally sensitive areas as part of the design process	5	6	7	1	0
We allow for multiple foundation alternatives (drilled shafts, direct embedment, micropiles, etc.) for individual transmission line structure designs in sensitive environments	5	6	5	1	1
We install mitigation measures for foundation construction in sensitive environments instead of modifying foundation designs to reduce impacts/footprints	4	7	5	1	0

C. DESIGN:

1. Does your utility require geotechnical field testing prior to design at environmentally sensitive sites?

Yes	18
a. Does your utility provide access for geotechnical testing field drill rigs in sensitive environments during the foundation design process?	15
b. Is the geotechnical firm required to provide mitigation (mats, etc.) for drill rig access?	15
c. If no access is available, does your utility require testing by remote methods (geophysics, soil probes, etc.)?	10
d. Does your utility require the foundation construction contractor to perform some kind of subsurface testing in environmentally sensitive areas prior to construction?	7

2.At what stage is geotechnical field testing done for foundation designs (mark the one that best applies to most projects)?

Prior to line design	6
After staking structure locations (as part of line design)	10
As part of an Engineer-Procure-Construct contract	1
Preliminary investigation as part of utility project scoping (prior to EPC)	0
Other	2

- We adopt a different approach depending on the appetite for risk / access restrictions (environmental or otherwise). Where we can get access post-planning (i.e. position fixed) this is usually our earliest opportunity
- in parallel to line design

Alternative Foundation Design

3. Does your utility consider multiple foundation alternatives for design?

Yes	18

4. If yes, please indicate with a "check" the foundation alternatives considered.

Auger cast piles	6
Helical anchors/piles	7
Micropiles	10
Rock sockets/anchors	11
Underground transmission line	4
Other:	6

- All options listed above
- Vibratory caissons
- Typically pad and chimney but piles where required - peat, silt
- Steel Vibratory Base-plated Caissons, Steel Vibratory Socket Piles, Drilled Piers, Direct Embed, Drilled shafts
- Steel Grillages, Guys and anchors

5. Does your utility have a standard/technical specification for alternative foundation construction?

Yes 1

a. If yes, can a copy of the standard/technical specification be provided to the research team? 0

6. Does your utility design alternative foundations in-house?

Yes 8

a. If yes, are the software tools supplied by the manufacture of the alternative foundation type? 1

b. If yes, what software tools does your utility use to evaluate the design of alternative foundations?

- We design piled foundations in conjunction with piling contractor (industry norm over in Ireland). Piling contractor undertakes the vast bulk of the design.
- FAD, CHANCE by EBSL-PILE

7. Please indicate with an "X" the reasons why your utility does not use or rarely uses the following types of foundations:

	Driven piles	Drilled shaft	Direct embed	Grillage foundation	Vibratory caissons	Spread footings	Guy anchored	Auger cast piles	Helical anchors/piles	Micropiles	Rock sockets/anchors	Underground T/L
Not practical in your service area	1	0	0	1	4	0	2	1	0	1	0	5
Not part of standards or methods	7	3	2	6	4	6	1	10	9	11	1	5
Too costly & time consuming	4	3	0	1	2	2	0	0	0	1	0	13
Management resistant to change	0	0	0	0	0	0	0	0	0	0	0	2
Unfamiliar contractors	2	0	0	1	1	1	1	2	3	1	0	0
Design too complicated/technical	1	0	0	0	0	0	0	1	1	2	0	2
Uncertainty of foundation reliability	0	0	0	3	0	0	0	0	1	0	0	0
Not applicable	0	10	12	5	2	7	10	2	2	4	12	3
Other*	2	0	0	0	1	0	2	1	1	1	0	0

***Other:**

- Conditions rarely applicable
- Maintenance issues
- Union Issues
- Wood poles are directly embedded.

C. CONSTRUCTION:

1. Select the number rank that best describes your utility's practices to access transmission line foundation sites in sensitive environments.

	1- Always	2- Frequently	3- sometimes	4- Rarely	5- Never
Construct new standard access roads	1	1	12	5	0
Construct spur roads to structure sites	0	5	9	5	0
Improve existing access roads	0	10	9	0	0
Haul in equipment by manual methods	0	2	4	12	1
Install modular mat paths	1	8	5	3	2
Ground stabilization/improvement	0	4	6	8	1
Relocate structure	0	6	11	2	0
Use all-terrain vehicles (no road access)	1	6	7	5	0
Fly in by helicopters	0	5	3	9	2

2. If helicopters are used, please identify the type typically used and typical weight limits:

- Sikorsky ski-crane for construction Bell 201/401 for stringing and worker movement. Small by North American Standards - approx. 2t lifting capacity max!
- Erickson Sky crane - 16,000 lbs. routine limit, up to about 20,000 lbs. for special lifts. Kmax - 6,000 lbs.2500 lb.
- Used for one job. Steel H-frame structures.
- 205/407For lifts up to 4,500lbs....Super Huey.....for crew and lifts up to 2,000lbs....A4, A5 Star and Bell 500. For big lifts up to 10,000lbs....Siskorsky S61, and have used the Erickson Skycrane...for up to 20,000lbs....
- Hughes 500C 1000#?

3. My utility generally provides site access for foundation construction crews.

Yes	10
Job Specific	5

4. Site access is the responsibility of the foundation contractor.

Yes	6
Job Specific	5

5. My utility identifies transmission line construction staging areas.

Yes	5
Job Specific	9

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6. Staging areas are the responsibility of the transmission line contractor.

Yes	5
Job Specific	12

7. Structure types

	Transmission Voltage Range	Number of Structures	Number of Lines
Wood poles	15	14	10
Steel Pole with base plate	12	11	8
Direct embed pole	14	12	9
H-Frame	15	12	10
Lattice Tower	11	9	10
Underground	6	3	3

***Other:**

- We haven't installed new lines in environmentally sensitive areas in past 10 years
- Directly embedded composite pole

8. Number of foundation types in sensitive environments during the last ten years

	Driven piles	Drilled shaft	Direct embed	Grillage foundations	Vibratory caissons	Spread footings	Guy anchored structures	Auger cast piles	Helical anchors/piles	Micropiles	Rock sockets/anchors	Underground T/L
Wetlands/ Waterways	5	11	13	4	3	3	7	3	4	4	1	4
Woodlands	0	9	13	4	1	2	9	1	3	5	1	1
Desert/ Rangeland/ Open land	1	7	7	3	2	3	4	1	2	2	0	2
Mountainous/ Rough terrain	0	7	9	5	0	2	6	0	1	4	8	0
Permafrost/ Frozen ground	0	1	2	3	0	1	3	0	0	0	1	0
Conservation/ Wilderness areas	3	7	8	4	2	4	7	2	4	4	2	2

***Other:**

- We haven't installed new lines in environmentally sensitive areas in past 10 years.

9. Please select a number rank that best describes the challenges encountered during foundation construction in sensitive environments

	1- Always	2- Frequently	3- sometimes	4- Rarely	5- Never
Access restrictions	2	11	5	0	0
Deadline date for completion/ schedule contracts	1	5	11	0	0
Difficulty with materials getting to sites	1	4	11	1	0
High cost of constructing access	3	6	7	2	0
Limited number of specialty foundation contractors available	0	2	5	10	1
Poor performance by general contractors	0	2	7	7	2
Limited options for foundation design	1	1	9	6	1
Damage to sites from standard foundation construction equipment	0	3	13	2	0
Reluctance or lack of experience with alternative foundations	1	3	6	7	1
Cost of alternative foundations	1	4	7	5	1
Regulatory restrictions	1	7	10	0	0
Large footprint using standard foundations on limited space sites	0	4	10	4	0

D. Post-Construction Phase:

1. Please select a number rank that best describes post-construction practices used by your utility insensitive environments

	1- Always	2- Frequently	3- sometimes	4- Rarely	5- Never
Site monitoring for contamination	8	3	3	3	1
Site restoration of vegetation	10	7	1	0	0
Removal of drilling spoils	6	7	4	1	0
Restoration of ground (disking/loosening soil)	7	7	2	2	0
Site restoration for aesthetics	3	9	5	1	0
Site monitoring for foundation performance	3	0	6	7	2

2. Does your utility maintain access to structures located in sensitive environment sites for maintenance/inspections?

Yes 11

3. How are sensitive site structures accessed where there are no access roads (select all that apply):

Access by foot 17
Access by horseback 0
Access by ATV 16
Access by helicopter 12
***Other:** 6

- E3
- Low impact vehicles (Nodwell or Foremost)
- Boat
- Airboats / Marsh buggies
- Track Machines
- Matting, NYPA's primary sensitive environments are wet areas

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