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Study of Electric Transmission Line Deep Foundation Design

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Abstract
Electrical system transmission line structures are typically supported by deep foundations such as concrete drilled shafts, driven piles, micropiles, and helical piles. Although a number of industry guidelines describe the fundamental design principles and construction/installation procedures of these foundation types, there is no comprehensive electrical system guideline, which relates all the elements needed to properly characterize loads imposed by electrical structures and extreme environmental conditions on foundations. There is a lack of guidance on relating electrical system loads developed from various industry codes to foundations governed by traditional civil engineering design standards. A task force assembled by the Deep Foundation Institute has conducted a survey of utility design professional to assess the state of the practice for transmission structure foundation design. This survey, in conjunction with a thorough literature review, will be used to develop a guideline design document with recommendations for uniform analysis and design of electrical system deep foundations. This paper provides a summary of task force efforts to date and the initial industry survey results. Included are discussions of existing design and code documents as they relate to electric transmission line foundations, and elements needed in a guide document to improve the efficiency and reliability of electrical transmission line foundation design.

ELECTRIC TRANSMISSION LINE FOUNDATION DESIGN

An electric transmission line foundation functions to transfer applied steady-state and transient loads into the surrounding soil and rock with limited structure movement. Loads are conveyed to the subsurface at the ground line interface. Either a separate foundation system is installed and connected to the structure or the above grade structure is directly buried and backfilled.

Various structure load cases are developed through codes and by utility owners for the unique environments of their service territories. Most load cases consider impacts of wind, ice and tension on lines and structures in addition to loading during construction and maintenance of transmission lines. Electric utility code organizations and standard utility design practices give ample guidance for loading on support structures and the various apparatus associated with transmission line elements. Implied in these documents is the thought that foundation design provides equal resistance to these loads. Unfortunately, codes offer little guidance in terms of the factors used in developing soil and rock resistance and no method for integrating design load cases and factors developed by civil code organizations for reinforced concrete foundation design with load factors for the transmission structure.

Traditional transmission line foundation design focuses on loads and load combinations applied to supporting structures. Unlike the commercial building and highway bridge construction industries, the power transmission and distribution industry do not have a unified code that explicitly covers the design and construction of the various foundation types used to support electrical structures. The joint IEEE and ASCE guide for transmission line foundation design (IEEE 691, 2001) presents general information on loads imposed on foundations by structures, various foundation design methodologies, subsurface and laboratory investigation approaches, and the rational/approach to load testing. The document provides a good primer in foundation investigation and design, but gives no firm guidance on how to match structure loads with subsurface resistances. Additionally, there is little mention of outside environmental conditions that could influence foundation performance. Other than general warnings on potential high groundwater, slope instability and anomalous soil/rock hazards, forces on foundations or ground loss due to hydrologic conditions and ground motion are not discussed. Evaluation of loads, load factors, safety, reliability, environmental/geographical conditions that solely impact foundations are left to judgment of foundation and structural engineers. Integration of structural design codes (such as: ACI) with electric utility codes is also poorly defined.

Transmission structure design is typically governed by national or regional codes (such as National Electric Safety Code, NESC; Canadian Electric Code, issued under CSA C22.3 No. 1-10; International Electrotechnical Commission, IEC, California General Order 95, GO95). Accidental, construction and maintenance events are primarily developed by utilities for the specific needs and conditions. These codes typically define structure and structure element load factors related to extreme weather. Industry practice standards have also been developed offering guidelines in the design of transmission line structures and structure elements (ASCE 74: Wong & Miller, 2010; ASCE 10: ASCE, 2000). IEEE 691 recommends the foundation design engineer establish the strength of the foundation relative to the strength of the structure it supports. Most utilities want the foundation designed equal to or stronger than the structure; thus, in the event the structure fails, its replacement can be erected on the same foundation (IEEE, 691). Yet, these documents give no guidance on how to develop factors involved in foundation resistance or how foundation factors should relate to defined structure load factors. There is no mention of how foundation performance parameters (foundation rotation, settlement and deflection) impact structure performance. Determination of geotechnical design parameters for use in foundation design is also ill-defined. This disconnect results in high levels of variability in foundation design methods due to geotechnical uncertainty, designer uncertainty, improper use of Allowable Stress Design and Reliability-Based Design techniques (RBD or Load and Resistance Factor Design – LRFD), and widely varying foundation performance criteria employed throughout the industry.

TASK FORCE

The Deep Foundation Institute has assembled a task force to study the State of the Practice for Transmission Structure Foundation Design. The task force is an ad hoc group of experienced individuals from the electric power industry, utility consultants, utility companies and academia with the following goals:

- Compile and review relevant published literature,
- Perform a survey of industry practices,
- Identify critical elements needed for uniform processes and guidelines,
- Make recommendations to industry for the development of standards.

SURVEY RESULTS

As a first step in defining the state of the practice, the task force created a 45-question survey with focus on nine electric system foundation topic areas: designer demographics, design approach, design practice, subsurface investigation practices, reinforced concrete foundation design practices, direct embedment pole foundation practices, alternative foundation designs, foundation field testing and validation and foundation construction considerations. 22 responses were received as of October 2014. The results of this preliminary information are delineated by topic area and given in the following discussion.

A. Designer Demographics (Tables 1 through 3)

Table 1. Engineering Discipline (19 responses).

Discipline	Civil	Geotechnical	Structural	Electrical	Other
% Respondents	51.9	11.1	22.5	11.1	3.7

Table 2. Design Experience (19 responses).

Years of Experience	0 - 5	5 - 10	10 - 20	+20
% Respondents	36.8	36.8	21.1	5.3

Table 3. Registered Professional Engineer (22 responses).

	Yes	No	No Response
% Respondents	77.3	9.1	13.6

B. Design Approach (Tables 4 through 8)

Table 4. Codes Used for Foundation Load Development (19 responses).

Code Descriptor	NESC	CAS C22.3	GO 95	Other
% Respondents	58.6	6.9	13.8	20.7

Table 5. Other Codes [1] (19 responses).

Descriptor	Local Climate	Construction	Maintenance	Security	Other
Response %	73.6	68.4	57.8	21.0	26.3

(1) Question: What additional load cases outside of the legislated loads per referenced codes are used?

Table 6. Use/Availability of an Internal Design Manual (IDM) (22 responses)

	Yes	No	No Response
Use of an IDM (% Respondents)	59.1	22.7	18.2
Availability of IDM for Review (% Respondents)	22.7	59.1	18.2

Table 7. Types of Deep Foundations Included in Internal Design Manual (22 responses)

Foundation Type	Drilled Shafts	Driven Piles	Micropiles	Helical Piles	ACP/CFAPiles[2]	Other
Response %	93.3	20.0	13.3	6.6	6.6	26.6

(2) Auger Cast Piles or Continuous Flight Auger Piles

Table 8. Primarily Foundation Design Methodology Employed (22 responses)

Design Method	Reliability-Based Design	Allowable Stress Design	No Response
% Respondents	50.0	36.4	13.6

C. Deep Foundation Design Practices (Tables 9 through 22)

Table 9. Magnitude of Load Factors / Safety Factors Used for Deep Foundation Design (15 responses)

Factor	2.0	1.0 to 2.0	Electric Code Factors	RBD Factors	N/A [3]	Other
% Response	26.7	26.7	20.0	13.3	6.7	6.7

(3) Not applicable – deflection parameters control design

Table 10. Use of Load / Safety Factors for Other Foundation Elements [4] (22 responses)

	Yes	No	No Response
% Respondents	40.9	45.4	13.6

(4) Question: Do you use the same magnitudes of load or safety factors for foundation construction materials, such as reinforced concrete or steel?

Table 11. Other Foundation Factors Relative to Embedment Design Factors (if "No" in Table 10) (10 responses)

Descriptor	Lower	Higher	Equal	Not Applicable	Other
% Response	50.0	10.0	10.0	10.0	20.0

Table 12. Foundation Lateral Deflection Design Criteria (Tubular Steel Monopoles) (16 responses)

Deflection (mm)	0	13–64	46	51	13-51	13-76	13-150	76	76-127	102	150
% Response	6.7	6.7	6.7	13.3	13.3	6.7	6.7	6.7	6.7	13.3	6.7

Table 13. Foundation Top of Pier Rotation Design Criteria (Tubular Steel Monopoles) (10 responses)

Rotation (degrees)	0	1.0	1.5	1.7	2.0	No Response
Response %	4.5	4.5	4.5	9.1	22.7	54.5

Table 14. Process for Determining Deflection / Rotation (Performance) Criteria (10 responses)

Process	In-House Stds	Past Performance/History	Consultant Rec	Published Info	Other
% Respondents	31.3	37.5	18.8	6.3	6.3

Table 15. Load Type for Checking Performance Criteria (22 responses)

Load Type	Factored Loads	Service Loads	Other	No Response
% Respondents	50.0	27.2	9.0	13.6

Table 16. Integration of Foundation and Structure Performance Criterion (5) (12 responses)

	Yes	No	No Response
% Respondents	54.5	27.2	18.1

(5) Question: Do you integrate the drilled pier deflection/rotation criteria with the similar allowable criteria for the top of steel poles for the pole manufacturer?

Table 17. Deep Foundation Design Software Used (18 responses)

Software	FAD Tools	LPILE	GROUP	Caisson	Shaft	AllPile	Other
Response %	88.9	50.0	11.1	5.6	5.6	5.6	16.7

Table 18. Typical Design Foundation Projection above Grade (18 responses)

Projection (m)	0.3	0.6	0.9	0.3-0.6	0.15-0.9	Varies
Response %	27.8	27.8	5.6	11.1	16.7	11.1

Table 19. Use of Soil Property Reductions for Near Surface Soils (22 responses)

	Yes	No	No Response
Response %	72.7	13.6	13.6

Table 20. Method for Soil Property Reductions for Near Surface Soils (if "Yes" in Table 19) (16 responses)

Descriptor	Diameter Based	Equivalent Ground	Specified Depth	Design Model	Varies	None
% Response	25.0	12.5	12.5	12.5	25.0	12.5

Table 21. Method Used to Account for Water Impacts (such as scour) (16 responses)

Method	Add Reveal	Ask Consultant	Engineering Eval.	Install Protection	None/Unknown
% Response	25.0	25.0	18.8	12.5	18.8

Table 22. Method Used to Account for Liquefaction (14 responses)

Method	Engineered Solution	Ask Consultant	Not Applicable/Unknown
% Response	21.4	21.4	57.2

D. Geotechnical Exploration Practices (Tables 23 through 27)

Table 23. Types of Geotechnical Exploration Techniques used to Obtain Parameters (19 responses)

Methods	Desktop Studies	Soils Boring	Cone Penetrometer	Geophysics	Rock Cores	Other
Response %	57.8	100.0	63.1	52.6	73.6	15.7

Table 24. Subsurface Test Frequency (17 responses)

	Each Site	1 per mile	At Critical Structures	Varies	Other
% Response	35.3	5.9	23.5	17.6	17.6

Table 25. Subsurface Test Frequency Methodology (16 responses)

Methods	Structure Based	Mileage Based	Geology Based	Other
% Response	31.3	31.3	18.8	18.8

Table 26. Use of Soil Corrosivity Analysis (22 responses)

	Yes	No	No Response
Response %	27.2	59.0	13.6

Table 27. Methods to Control Corrosion (if "No" in Table 26) (11 responses)

Methods	Coat Embedded Steel	Site Knowledge	Modify Cement	Not Applicable/Unknown
% Response	18.2	27.3	9.1	45.5

E. Reinforced Concrete Design Practices (Tables 28 through 32)

Table 28. Concrete Design Practices (22 responses)

	Yes	No	No Response
Concrete Placed at Strength > Design (% Respondents)	59.0	27.2	13.6
Use Predetermined Concrete Mix (% Respondents)	31.8	54.5	13.6

Table 29. Methods for Determining Minimum Longitudinal Reinforcement (15 responses)

Methods	Minimum Steel	Codes (ACI, CSA, etc.)	Computer Program	Other
% Response	20.0	46.7	20.0	13.3

Table 30. Methods for Designing Longitudinal Reinforcement Splices (18 responses)

Methods	ACI 318	CRSI	FHWA	Other
% Response	88.8	5.5	22.2	16.6

Table 31. Methods for Determining Anchor Bolt Design (16 responses)

Methods	ASCE 48 / CSA C23.3	Vendor Supplied	ACI	Not Applicable
% Response	50.0	37.5	6.3	6.3

Table 32. Methods for Reinforced Concrete Design (15 responses)

Methods	FHWA/ DOT	ACI 318	Varies	CSA C23.3	Computer Program	Not Applicable
% Response	20.0	46.7	6.7	6.7	13.3	6.7

F. Direct Embedment Pole Foundation Design (Tables 33 through 35)

Table 33. Material Used for Direct Embedment Pole Backfill (19 responses)

Materials	Compacted Native	Engineered Aggregates	Concrete	Other
Response %	57.8	78.9	73.6	

Table 34. Engineering Properties for Direct Embedment Pole Backfill Design (18 responses)

Properties	Friction Angle	Cohesion	Unit Weight	Lateral Modulus	Other
Response %	72.2	50.0	83.3	38.8	0.0

Table 35. Design Methodology for Direct Embedment Poles (19 responses)

Methods	Analytical	General Practice [5]	Other
Response %	84.2	78.9	5.2

(5) General Practice: Embedment @ 10% of pole length plus defined length (0.6 - 1.2 m)

G. Alternate Foundation Types (Tables 36 and 37)

Table 36. Alternate Deep Foundation Methods (6) (22 responses)

	Yes	No	No Response
Allowance of alternate deep foundation methods(6) (Response %)	77.2	4.5	18.1
Specifications for alternate deep foundation methods(6) (Response %)	45.4	36.3	18.1

(6) Micropiles, auger cast piles, helical piles, etc.

Table 37. Types of Alternate Deep Foundations Specified (17 responses)

Properties	Driven Piles	Micropiles	Helical Piles	ACP/CFA	Not Applicable	Other
Response %	58.8	58.8	52.9	23.5	17.6	11.7

H. Foundation Field Testing and Validation (Tables 38 and 39)

Table 38. Use of Field Testing to Validate Installed Foundation Capacity (22 responses)

	Yes	No	No Response
Response %	31.8	50.0	18.1

Table 39. Types of Field Testing Required (if "Yes" in Table 38) (10 responses)

Types	Compression	Tension	Lateral	Combination	Other
Response %	20.0	70.0	20.0	20.0	30.0

I. Construction Considerations (Tables 40 and 41)

Table 40. Limitations on Concrete Freefall (22 responses)

	Yes	No	No Response
Response %	45.4	36.3	18.1

Table 41. Procedures for Cold Joints in Drilled Shaft Foundations (13 responses)

Procedures	Not Allowed	Defined Depth	Designed as Needed
Response %	53.8	15.4	30.8

The responders seemed confused by two questions in the survey (referring to use of performance parameters for lattice tower foundations and special provisions for rock conditions), therefore these results are not reported in the prior tables.

CONCLUSIONS

Review of survey data (although preliminary due to the low number of respondents to date) makes it clear that there is little consistency in the approach to transmission line foundation design among designers, consultants and utilities. Load and performance factors used by designers vary greatly. Foundation design methodologies are not consistent. Methods to integrate structure load factors used for foundation design with reinforced concrete code factors differ or not used at all. The following may be inferred by the survey results:

- Many utilities and consultants develop internal design manuals (13 out of 22 in the survey) in response to the lack of uniform guidance or to consolidate learned knowledge.
- 50% of the respondents report using reliability-based design methods, yet only 13.3% report using RBD factors in load development.
- Respondents seem evenly split on whether to use higher or lower load factors for the design of foundation elements (steel and reinforced concrete).
- Foundation performance parameters used in design widely vary, with allowable top of pier deflection ranging from zero to 6 inches and top of pier rotation from zero to 2.0 degrees.
- Just over half (54.5%) of respondents integrate pole and foundation movement into design standards.
- 50% report using factored loads when evaluating foundation performance criteria, while the rest either use service loads or do not identify load type.
- Most of the designers (72.7%) assume some reduced foundation resistance due to near surface soil conditions, but no more than one-quarter agree on the method for determining the reduced resistance.
- Nearly twenty percent of the respondents either do not account or do not know if they account for water flow impacts in deep foundation design, and only 42.8% note how they account for ground motion impacts on deep foundations.

Although the designers seem experienced and well-trained (77.2% professional engineers with 57.8% having more than 10 years of experience), survey results indicate the need for more guidance with electric transmission line foundation design. This guidance is important in consistently estimating load influence on foundations and their ability to perform as desired.

The survey gives insight to methods for obtaining subsurface data used in determining foundation geotechnical design properties. All respondents use soil borings and over half include other methods such as desktop studies, CPT, rock cores and geophysics. But investigation approaches show little consistency:

- 35.3% note borings taken at every structure site, while 23.5% report boring only at critical structure locations (Of interest, only 31.3% of respondents determine of bore spacing based on structure type).
- While 31.3% base borings on structure type, 31.8% distribute borings on a mileage basis and 18.8% identify bore locations as dictated by the regional geology (most likely derived from desk top studies or geologic reconnaissance).

There is some consistency in the design of reinforcement within concrete drilled shaft foundations. In general, most designers use some form of code or computer program based on code for design of longitudinal reinforcement (46.7% and 20%, respectively). Based on FHWA guideline documents, though, this practice likely results in an overdesign of reinforcement as most codes and computer programs are for use in above-grade structural construction. More reinforcement is needed in building construction than for below grade deep piers where continuous lateral support exists (exclusive of seismic requirements). The survey also gives insight into reinforced concrete drilled shaft design and construction practices:

- 59% of respondents design with a lower concrete compressive strength than specified for construction,
- Only 31.8% of respondents give specific concrete mix designs for use by contractors,
- 50% use ASCE 48 or CSA C23.3 guidelines for design of monopole anchor bolts. Of note, 37.5% of respondents rely on vendors to perform anchor bolt design. Vendors typically use proprietary analytical methods for design of base plates, but use ASCE 48 for anchor bolt design. The survey indicates a high degree of industry consistency with anchor bolt design.

Based on pole type and condition, direct embedment monopoles and H-frames are backfilled with compacted native soil (57%), engineered aggregate fills (78.9%) and concrete (73.6%). Results may not be universal for all pole materials (steel, concrete and wood) since the survey did not specify type of pole. Most designers use analytical (84.2%) and general practice (78.9%) methods for embedment depth design. Again, the survey did not differentiate between pole materials and voltage levels that likely influence design approach.

Respondents allow the use of alternative deep foundation types such as micropiles, auger cast piles and helical piles (77.2% responded in the affirmative). But only 45.4% note having specifications for these alternate foundation types. Respondents generally mention driven piles (58.8%), micropiles (58.8%) and helical piles (52.9%) as the most common alternate deep foundations specified for transmission lines.

Only about 1/3 of respondents use of field tests to confirm foundation capacity (either proof or ultimate testing), with most testing in the uplift mode (70%).

Additionally, 36.3% of respondents have no limits to free fall placement of concrete within drilled shafts. 53.8% do not allow cold joints within concrete drilled shaft foundations.

The database at present must be recognized as small when compared to the number of practitioners in the US and worldwide. No clear design practices should be derived from the survey at present. DFI task force has reviewed the data and plans to resend the survey to others in the utility industry in hopes of obtaining more responses.

This survey, in conjunction with a thorough literature review, will be used to develop a guideline design document with recommendations for a uniform analysis and design approach with electrical system deep foundations. The importance of better guidance with the electric power industry lies in the fact that presently there are more than $164 billion in planned and under-construction transmission line projects in the North America alone (ELP, 2014). Thousands of miles of transmission lines will include the need to design and construct tens of thousands of deep foundations. Better guidance in the investigation, design and construction aspects of this work will result in improvement in cost, quality and construction schedule for the industry.

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