ASCE Manuals and Reports on Engineering Practice No. 161

Overhead Power Line and Substation Foundations

Design Loads, Strength Factors, Threshold Criteria, and Design/Construction Methodologies

Task Committee on Overhead Power Line and Substation Structure Foundations

Edited by

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Overhead Power Line and Substation Foundations

Other Titles of Interest

Overhead Power Line and Substation Foundations: State of Practice, Basics, Type Selection, Geotechnical Topics, and Specialty Analysis, edited by Prasad Yenumula, Peter M. Kandaris, and Keith S. Yamatani (ASCE/SEI 2026). MOP 160 provides an overview of best practice guidance and recommendations for the design of electrical overhead power line structure and substation structure foundations. MOP 160 focuses on the state of practice, basic concepts in foundation design, guidance related to foundation type selection, geotechnical recommendations related to the subsurface geotechnical exploration program and the development of geotechnical design parameters, and various specialty topics. MOP 160 and MOP 161 were developed as a single body of work and are considered companion MOPs. (ISBN 978-0-7844-8666-5)

Substation Structure Design Guide: Recommended Practice for Design and Use, Second Edition, by the Task Committee on Substation Structural Design; edited by George T. Watson (ASCE/SEI 2023). MOP 113, second edition, documents electrical substation structural design practice and gives guidance and recommendations for the design of outdoor electrical substation structures. (ISBN 978-0-7844-8517-0)

Aesthetic Design of Electric Transmission Structures, by Task Committee on Aesthetic Design of Electric Transmission Structures (ASCE/SEI 2020). This book provides valuable aesthetic design insights and concepts to be considered during the design stage of electric transmission structures projects. (ISBN 978-0-7844-8304-6)

Prestressed Concrete Transmission Pole Structures: Recommended Practice for Design and Installation, by the Task Committee on Concrete Pole Structures (ASCE/SEI 2012). MOP 123 is a complete engineering reference for design and installation of static-cast and spun-cast prestressed concrete poles for electric distribution and transmission power lines. (ISBN 978-0-7844-7679-6)

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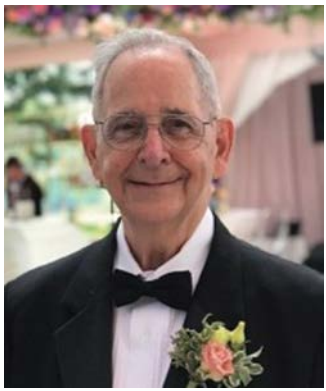
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In February 1962 (and revised in April 1982), the Board of Direction voted to establish a series titled "Manuals and Reports on Engineering Practice," to include the manuals published and authorized to date, future Manuals of Professional Practice, and Reports on Engineering Practice. All such manual or report material of the Society would have been refereed in a manner approved by the Board Committee on Publications and would be bound, with applicable discussion, in books similar to past manuals. Numbering would be consecutive and would be a continuation of present manual numbers. In some cases of joint committee reports, bypassing of journal publications may be authorized.

A list of available Manuals of Practice can be found at https://ascelibrary.org/page/books/s-mop.

DEDICATION



With heartfelt appreciation, this MOP is dedicated to the memory of Dr. Anthony M. DiGioia Jr., Ph.D., P.E., who passed away on December 25, 2023, at the age of 89.

We honor Dr. DiGioia for his pioneering advancements in geotechnical engineering-especially in overhead power line foundations-which have left an indelible mark on the civil engineering profession. Named an ASCE Distinguished Member, he was a national authority on deep foundation systems. Dr. DiGioia led transformative innovations in the design, testing, and software development for electric utility structure foundations. His leadership at GAI Consultants, where he served as CEO and helped the firm become a nationally recognized name in engineering, and his later work as co-founder of DiGioia Gray & Associates exemplified his lifelong dedication to excellence, innovation, and service to the industry. As Chair of ASCE's Committee on Transmission Structures, he was instrumental in crafting the standards and practices that continue to guide today's transmission infrastructure projects.

Beyond his technical accomplishments, Dr. DiGioia was known for his kindness, generosity, and dedication to his family. A father of eight children, his humility and approachability made him a beloved colleague, mentor, and friend. As an adjunct professor at Carnegie Mellon University, he shared his extensive field experience in the classroom, guiding generations of engineers with patience and enthusiasm. He truly embodied the ideal of a servant-leader elevating the profession through both expertise and genuine human connection. With deep respect and gratitude, we dedicate this Foundations Manual to Dr. DiGioia's remarkable legacy, celebrating his achievements, his commitment to education and industry, and the compassion that defined his life.

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PREFACE

The Task Committee on Overhead Power Line and Substation Structure Foundations under the Committee on Overhead Power Line Structures (OPS) from the Structural Engineering Institute (SEI) of ASCE developed this Manual of Practice (MOP). The task committee membership represented a multi-disciplined group of professionals from the electrical transmission, distribution and substation industry representing utilities, consulting engineering firms, and material vendors.

Manual of Practice 161 provides best practice guidance and recommendations for the design of electrical overhead power line structure and substation structure foundations. Manual of Practice 161 focuses on design loads, foundation design, and construction methodologies. Manual of Practice 161 and MOP 160, *Overhead Power Line and Substation Foundations: State of Practice, Basics, Type Selection, Geotechnical Topics, and Specialty Analysis*, were developed as a single body of work and are considered companion MOPs. The recommendations presented herein are based on the professional experience of the task committee members.

The task committee wishes to thank the peer review committee for their assistance and contributions to this document.

SOFTWARE DISCLAIMER

This manual of practice summarizes the most common and current foundation design practices for electrical overhead power lines and substation structures. As result of the ubiquity of certain commercially available software programs, several software programs are mentioned by name within the body of this manual. The use of the names of specific programs shall not be construed as an endorsement of these programs. Likewise, the omission of specific mention of other software programs that

may be in use is not intended to imply that the use of these programs is discouraged.

The following software programs were referenced in responses to the State of Practice survey that was performed by this committee in 2020 and mentioned in this MOP (listed in alphabetical order):

Table P-1. Software Programs Referenced in this MOP

Software	Company
APILE	Ensoft
AllPile	CivilTech
Enercalc	Enercalc
Excel	Microsoft
GRLWEAP	Pile Dynamics
GROUP	Ensoft
HAZUS	FEMA
LPILE	Ensoft
MathCAD	PTC
MFAD	FAD Tools International
CAISSON	Power Line Systems
QuickFooting	IES
RAM Elements	Bentley
RISA Foundation	RISA
Safe	CSI
Settle3	Rocscience
SHAFT	Ensoft
spColumn	StructurePoint
spMats	StructurePoint

(*Continued*)

Table P-1. (*Continued*).

Software	Company
STAADPro	Bentley
System Earthquake Risk Assessment (SERA)	Pacific Earthquake Engineering Research Center (PEER)

Refer to Appendix A for additional details on the survey results. Other software programs may exist that are not reflected in the survey responses.

NOTE ABOUT REFERENCES

Citations of codes, standards, or other references with multiple versions are to the most recent version at the time of release of this document unless specifically noted otherwise.

DEFINITIONS

ABOVE GRADE: Any part of a foundation or structure located above the current or proposed future subsurface material.

ADMIXTURE: Material other than water, aggregate, cementitious materials, and fiber reinforcement used as an ingredient, which is added to grout, mortar, or concrete, either before or during its mixing, to modify the freshly mixed, setting, or hardened properties of the mixture.

ALLOWABLE STRESS DESIGN: A method of proportioning structural members and/or evaluating subsurface capacity such that elastically computed stresses produced in the members and/or subsurface material by nominal loads do not exceed specified allowable stresses (also called "working stress design").

ANCHOR BOLTS: A group of steel bars arranged in a pattern, often called a cage or assembly, that extend down into a concrete foundation and protrude above the top of concrete. A steel member may be fastened to the protruding threaded portion of the bolts and tightened in place with nuts.

ANGLE STRUCTURE: Structure where the conductor direction changes. This structure supports similar vertical and transverse loads as a TANGENT STRUCTURE, as well as significant transverse loads resulting from wire tensions being applied at an angle.

ANNULAR SPACE/ANNULUS: A space located between the excavated hole and the pole to be embedded in the center of the hole.

AUGER: A tool commonly used for foundation and anchor excavation.

BACKFILL: Material such as soil, crushed stone, concrete, or flowable fill that is placed to fill an excavation or annular space and provide support to the foundation system.

BEARING CAPACITY: The maximum compressive load that can be applied on a foundation, before failure of the subsurface material occurs.

BEARING PLATE: A structural element added to the bottom of the embedded portion of a direct embedded pole for increased axial subsurface resistance.

BELOW GRADE: Any part of a foundation or structure located below the ground surface.

BOND BREAKER: Material intended to separate or isolate curing cementitious material from other materials for purposes of post curing separation.

BUCKLING: Failure mechanism in which the slenderness of a structural element causes capacity to be limited by a sudden deflection (locally or globally) of the member in a direction perpendicular to the applied load.

BURIED SYSTEM: Anchors that resist tension loads through weight and earth pressure. (Also referred to as a deadman anchor or passive anchor)

CASCADING FAILURE: The failure of transmission line structures wherein multiple consecutive structures fail due to a single, origin structure or component failure.

CASING (TEMPORARY): A tube, typically cylindrical in shape, used to provide excavation sidewall support during construction. Casing is removed before construction is complete.

CASING (PERMANENT): A tube, typically cylindrical in shape, used to provide excavation sidewall support and/or provide additional stiffness to the foundation. Casing is left in place permanently.

CENTRAL PILE SHAFT: High-strength steel shaft of a helical pile, typically solid square bar, round hollow pipe, or hollow square section.

CONTINUOUS FLIGHT AUGER (CFA) PILES: Deep cast-in-place piles that are drilled in one uninterrupted process using continuous flight augers. Grout is pumped through the hollow center of the auger pipe while the augers are withdrawn.

COLD JOINT: A joint or discontinuity resulting from a delay in concrete placement, of sufficient duration, to preclude intermingling and bonding of the material.

CONCRETE PILE: Pile foundations that are prefabricated reinforced and/or prestressed concrete sections, typically round or square cross sections, but may also be available in other shapes.

CONCRETE: A mixture of portland cement or any other cementitious material, fine aggregate, coarse aggregate, and water, with or without admixtures.

CONSTRUCTION JOINT: A planned joint or discontinuity resulting from a delay in placement of sufficient duration to preclude intermingling and bonding of cementitious material, typically required in multi-component foundations.

CORROSION: A process causing degradation to metal, stone, or other materials by chemical action.

DEADEND STRUCTURE: Structures designed as termination points for wires and capable of supporting the loads resulting from the removal of all wires from one or more spans.

DESIGN LOADS: The loads that the structure or foundation is designed to support, comprised of NOMINAL LOADS multiplied by a specified LOAD FACTOR.

DESIGN STRENGTH: The capacity of a component to resist the DESIGN LOADS. It is calculated by multiplying the NOMINAL STRENGTH by the appropriate STRENGTH FACTOR.

DIRECT EMBEDDED FOUNDATION: Direct embedded foundations make use of pole structure extensions below grade into competent subsurface materials or backfill.

DRILLED SHAFT: Reinforced concrete cast-in-place deep foundation, wholly or partially embedded in the ground.

DRIVEN PILE: A slender, deep foundation, typically steel, timber, or precast concrete, installed using an impact or vibratory pile driving hammer.

EARTH: Term referring to subsurface materials, soil, and/or rock.

ENGINEER: An agent of the owner who is responsible for the design and is qualified by engineering education, experience, and/or professional licensure to complete the design. Various types of engineers discussed in this MOP include engineer of record, foundation, geotechnical, substation, substation civil/structural, structural, transmission line, and utility engineer.

FIBER REINFORCED POLYMER: Composite material made of polymer matrix reinforced with fibers.

FROST (FROZEN GROUND): A condition that occurs when water on the surface and in the near surface soil matrix freeze when the air temperature remains below freezing for extended periods.

GEOTECHNICAL ENGINEER: A professional responsible for the geotechnical investigation, quantifying the earth material, providing soil and rock design parameters, and foundation recommendations. Geotechnical Engineers also commonly perform foundation design.

GROUNDLINE: The point on a pole or foundation where it meets the subsurface material.

GROUTED ANCHOR: Steel reinforcing bar or a group of steel tendons that are placed in a hole drilled into the earth and grouted into place.

GUY WIRE: A wire attached to a structure on one end and an anchor installed into the subsurface on the other end, to provide increased strength and/or stability to the overhead power line structure and foundation system.

HELICAL ANCHOR: A helical pile, typically used to resist the tension loads from guy wires.

HELICAL PILE: Helical piles are manufactured steel foundations that are rotated into the subsurface to support structures.

HOLLOW REINFORCING BAR: Hollow steel bar permitting the injection of neat cement grout down through the hollow center.

LAHARS: masses of rock, mud, and water that travel rapidly downslope or downstream under the action of gravity.

LAMINATED WOOD: Glued laminated timber elements that are an engineered, stress-rated product made up of assemblies of specially selected and prepared wood laminations securely bonded together with adhesives.

LATERAL LOAD: Loads that act in a direction perpendicular to the vertical axis. These can consist of loads applied in either the transverse or longitudinal axes or any resultant of the two. Moments are not loads but are loads acting at a distance. Lateral moments are the moments acting about, or in the direction of, the transverse or longitudinal axes or any resultant of the two.

LATERAL SPREAD: Lateral displacement of sloping ground as a result of pore pressure build-up or liquefaction in shallow underlying deposits during an earthquake.

LATTICED STRUCTURE: Latticed structures consist of relatively small steel angle and plate members bolted together.

LINE ANGLE: The change in orientation, measured in degrees, between two segments of an overhead power line centerline at a Point of Intersection (PI).

LIQUEFACTION: A process in which loose, granular soils below the ground water table temporarily lose strength during strong earthquake shaking.

LOAD AND RESISTANCE FACTOR DESIGN (LRFD): A simplified approach to Reliability Based Design (RBD) which uses independent factors to account for the uncertainty in the structure loading and resistance.

LOAD FACTOR: A multiplier used with NOMINAL LOADS to introduce a level of reliability to the design and establish the DESIGN LOADS.

MC1: Magnetic clearance to small metallic parts not forming closed loops

MC2: Magnetic clearance to large metallic parts or metallic parts forming closed loops

MICROPILE: A small diameter, drilled and grouted pile, typically less than 12 inches in diameter.

NOMINAL LOADS: Forces that result from meteorological conditions, physical configuration, construction activity, weight of structural members, wires, and equipment (without application of any LOAD FACTORS).

NOMINAL STRENGTH: The calculated strength of a component (without application of any STRENGTH FACTOR) to resist DESIGN LOAD effects.

NON-RECOVERABLE ROTATION: The permanent rotation that occurs at any point along the length of the foundation after the foundation has been loaded and then unloaded.

NON-RECOVERABLE TOP DEFLECTION: The permanent deflection deformation of the structure top that occurs after the foundation has been loaded and then unloaded.

PASSIVE ANCHOR: Anchors are not loaded until the structure loads are applied.

PILE CAP: A structural element (typically steel or concrete) used to provide attachment and load transfer between the overhead structure and the piles.

POINT OF INTERSECTION (PI): A point at which the centerlines of two overhead power line segments intersect.

REINFORCING BAR (MICROPILE): Central steel reinforcing element for a micropile. This is typically a standard reinforcing steel (ASTM A615/ASTM A706), continuous all-thread bar or continuous-thread hollow-core bars.

REINFORCING CAGE: Reinforcing steel used in concrete pier foundations formed in a cylindrical shape known as a cage consisting of vertical and horizontal bars and surrounding the anchor bolt cage.

RELIABILITY BASED DESIGN: A statistical design procedure used to set an acceptable level of probability of failure and design various components to satisfy this target reliability.

REVEAL: The projection of a foundation above ground.

ROCK: A naturally occurring mineral formation underlying the site including intact rock and partially weathered and weathered rock that should be defined by the geotechnical engineer.

SCOUR: The removal of soil or rock when water flows at high velocities past an object embedded in or resting on erodible subsurface.

SEISMIC LOAD: The force exerted on a structure and foundation by ground acceleration during an earthquake.

SETTLEMENT: The vertical displacement of a foundation due to applied loads or subsurface material changes.

SHALLOW FOUNDATION: A type of foundation with a bearing depth typically less than two-to-four times its cross-sectional size (smaller dimension between the width or length of the foundation). Types of shallow foundations include mats, spread footings, slabs on grade, combined, or grillages.

SIDE RESISTANCE: Subgrade friction or adhesion developed along the side surface of the foundation. This resistance may resist force in either the positive or the negative vertical direction (uplift or compression). Also referred to as skin friction.

SLURRY: Drilling fluid that consists of water or water mixed with one or more of various fine solids or polymers that is primarily used to help prevent sloughing or collapse of a borehole or drilled pier excavation, or both.

SOIL: The upper layer of the earth consisting of a mixture of organic, clay, and weathered rock particles.

SOIL/ROCK: Generic term used to describe the subsurface material in the context of performing an analysis, describing a parameter, and/or characterizing behavior.

STRENGTH FACTOR: A multiplier used with the NOMINAL STRENGTH of a component to account for variations in the material properties, introduce a level of reliability to the design, and establish the DESIGN STRENGTH.

SUBSURFACE MATERIAL: Generic term used to describe soil, rock, and/or other materials below the ground surface.

SURFACE RUPTURE: A visible break in the Earth's surface caused by the movement of two tectonic plates along a fault during an earthquake.

TIP: the bottom end or base of a deep foundation such as a pile or drilled shaft

TIP RESISTANCE: Resistance of the subsurface material at the bottom of a deep foundation under applied loading.

TORQUE FACTOR: An empirical correlation factor used to predict axial capacity from measured installed torque.

TOTAL ROTATION: The rotation that occurs at any point along the length of the foundation after the foundation has been loaded, including both elastic and plastic components.

TOTAL TOP DEFLECTION: The deformation of the structure top that occurs under the applied load, including both elastic and plastic components.

TREMIE PIPE: A watertight tube, fed from a pump or directly from a ready-mix concrete truck, used to place concrete or grout.

VIBRATORY STEEL CAISSON: A commonly used term to describe large diameter, open-ended tubular steel pipe foundations.

WATER TABLE: The level below which the subsurface material is saturated with water.

SI CONVERSION FACTORS

Approximate Conversions to SI		
Known	Multiply by	Result
(a) Length		
inch (in)	25.4	millimeter (mm)
foot (ft)	0.305	meter (m)
mile (mi)	1.61	kilometer (km)
(b) Area		
square inches (in^2)	645.2	square millimeters (mm^2)
square feet (ft^2)	0.093	square meters (m^2)
(c) Volume		
cubic feet (ft^3)	0.0283	cubic meters (m^3)
cubic inch (in^3)	16,387	cubic millimeter (mm^3)
(d) Mass		
pound (lb)	454	grams (g)
(e) Force		
pound (lb)	4.448	Newton (N)
kip (k)	4.448	Kilonewton (kN)
ton (T)	8.896	Kilonewton (kN)

(f) Pressure, Stress, Modulus of Elasticity		
pounds per square foot (psf)	47.88	Pascals (Pa)
kips per square foot (ksf)	47.88	Kilopascals (kPa)
tons per square foot (tsf)	95.76	Kilopascals (kPa)
pounds per square inch (psi)	6.895	Kilopascals (kPa)
kips per square inch (ksi)	6,895	Megapascals (MPa)
(g) Density, Unit Weight		
pounds per cubic foot (pcf)	16.02	kilogram per cubic meter (kg/m^3)
pounds per cubic inch (pci or lb/in^3)	27,679	kilogram per cubic meter (kg/m^3)
kips per cubic foot (kcf)	16,019	kilogram per cubic meter (kg/m^3)
(h) Speed		
feet per second (fps)	0.305	meters per second (m/s)
feet per minute (ft/min)	0.305	meters per minute (m/min)
inches per second (in/s)	0.0254	meters per second (m/s)
(h) Bending Moment		
kip-feet (k-ft)	1.356	Kilonewton-meter (kN-m)
kip-inch (k-in)	0.113	Kilonewton-meter (kN-m)
pound-feet (lb-ft)	1.356	Newton-meter (N-m)

(h) Moment of Inertia		
in^4	41.62	cm^4
ft^4	0.00863	m^4
(h) Flexure Rigidity		
pound-square inch ($lb\text{-}in^2$)	28.7	Newton-square centimeter ($N\text{-}cm^2$)
kip-square inch ($k\text{-}in^2$)	28.7	Kilonewton-square centimeter ($N\text{-}cm^2$)
(i) Angle		
degree (°)	0.017453	radian
(j) Temperature		
Fahrenheit (°F)	5/9 (°F – 32)	Celsius (°C)
(k) Frequency		
Hertz (Hz)	6.283	radians per second (rad/s)
(l) Rate of Modulus of Elasticity with Depth		
kips per square inch per foot (ksi/ft)	22.607	Kilopascals per meter (kPa/m)

NOTATION

ENGLISH NOTATION

a	fractured rock mass parameter
A	surface area if the anchor plate
$A(t)$	acceleration at gage location at time t
A_1	vertical change in elevation across the width of the drilled shaft
A_2	depth equal to A_1 that will be neglected in the analysis
A_b	area of bottom helical plate
A_{bar}	area of grouted bar
ABC_o	anchor bolt circle outside diameter
A_c	cross sectional area of drilled shaft; concrete inside spiral steel
A_{casing}	area of the casing
ACD	rock anchor circle diameter
A_{ea}	effective area of threaded portion of an anchor
A_F	area of footing
A_{ga}	gross area of an anchor calculated using the nominal diameter
A_{gross}	area of gross cross-sectional area including bar and grout
A_p	area of shaft tip; effective pile toe area including any plug; area of pile
A_{grout}	area of the grout column
A_s	total cross-sectional area of steel reinforcing bars
A_{sh}	area of spread footing shaft
A_{si}	area of foundation surface embedded in layer i
A_{sp}	total vertical side shear area of the soil prism
A_u	area of shaft bell shaft minus shaft area
A_v	area of shear reinforcement within spacing

B	diameter; foundation width; pile group width
b	force multiplier; empirical exponent factor; horizontal setback distance from top of the slope
B'	effective width
B_h	excavated hole diameter
B_o	pole diameter
b_w	web width; diameter of circular section
c	cohesion; shear stress; damping for a single degree of freedom (SDOF) system (lb-sec/ft); force multiplier
C	compressive force
c'	effective cohesion
C_1	coefficient for calculation of effective rigidity of an encased composite compression member
C_2	coefficient for calculation of effective rigidity of an encased composite compression member
C_3	coefficient for calculation of effective rigidity of an encased composite compression member
C_c	column slenderness ratio
c_c	concrete clear cover
C_D	design bearing capacity; deflection amplification factor
C_N	nominal bearing capacity
C_P	empirical soil coefficient
c_r	adhesion resistance to the rock concrete interface
C_R	side resistance regression coefficient
C_s	seismic response coefficient
$C_S c$	empirical soil coefficient
c_x	cohesion at depth x
D	depth of foundation below surface
d	distance from extreme compression fiber to centroid of longitudinal tension reinforcement
D10	particle size at which 10 percent of sample is finer (by weight)
D30	particle size at which 30 percent of sample is finer (by weight)
D60	particle size at which 60 percent of sample is finer (by weight)
d_a	nominal anchor diameter
D_{avg}	average helical plate diameter
D_b	depth below bearing stratum for belled shaft; diameter of shaft bell; diameter of anchor bar shaft
d_b	nominal diameter of reinforcing bar, wire, or prestressing strand
D_c	critical depth
D_e	embedment depth of pole; total depth of embedment

d_{ea}	effective diameter of threaded portion of an anchor
d_{eff}	effective shaft diameter
D_f	depth of foundation
d_f	depth to fixity below ground
DIA_{bond}	design diameter of bond
$\text{DL}_{\text{Allowable}}$	unfactored controlling pile design load
$\text{DL}_{\text{Design}}$	factored controlling pile design load
DL_{LFD}	factored controlling pile design load
DL_{SLD}	unfactored controlling pile design load
d_{max}	maximum diameter
D_o	depth to maximum moment/zero shear force
D_p	diameter of belled shaft
D_r	depth of rotation
d_r	relative density
D_s	pole depth below ground water
d_{tb}	reinforcing steel tie bar diameter
D_w	depth to water level
e	eccentricity of horizontal or vertical load; shaft length above grade
E	modulus of elasticity
$e(t)$	measured strain at time t
E_{50}	strain at 50% of yield stress
E_c	modulus of elasticity, concrete
E_{grout}	modulus of elasticity, grout
EI	flexural stiffness of the drilled shaft
EI_{eff}	effective stiffness of composite section
e_L	eccentricity in the longitudinal direction
E_M	modulus of elasticity, rock mass
E_p	modulus of elasticity, pressuremeter or deformation modulus
E_{pile}	modulus of elasticity, foundation Shaft
E_R	modulus of elasticity, intact rock
E_s	modulus of elasticity, soil
E_{si}	shaft initial stiffness
E_s^{limit}	limiting lateral reaction soil/rock modulus for buckling
E_{steel}	modulus of elasticity, steel
e_T	eccentricity in the transverse direction
e_x	eccentricity in the x direction
e_y	eccentricity in the y direction
F	empirical factors based on soil friction angle and D/B ratio; force spectrum; forcing function
f	friction force; side friction resistance; vibration frequency
$F(t)$	force computed at the gage location at time t; force function with respect to time, t

F_a	allowable axial stress
f_a	axial stress
F_b	allowable bending stress
f_b	bending stress
f_{bu}	ultimate bond stress between anchor rod and grout
F_c	uplift coefficient, cohesion component
f'_c	concrete compressive strength
$f'_{c\text{-grout}}$	grout compressive strength
F_{diag}	tower diagonal force
F_E	base shear
F'_e	Euler buckling stress
f_{eff}	efficiency factor
F_g	uplift coefficient, weight component
F_{leg}	tower leg force
f_{ND}	nominal unit down drag force
F_{ns}	negative skin stress
F_{p_h}	seismic horizontal load
f_s	side friction resistance
F_S	factor of safety
f_{si}	unit skin resistance at stratum i
f_{10}	empirical factor used to correlate ultimate bond strength to N-value
F_u	ultimate tensile strength
F_y	nominal yield strength of steel reinforcing
f_{ua}	specified tensile strength of a steel anchor
f_{ya}	specified yield strength of a steel anchor
$F_{y\text{-bar}}$	minimum yield stress of the bar
$F_{y\text{-casing}}$	minimum yield stress of the casing
$F_{y\text{-steel}}$	minimum yield stress of the bar and casing
f_{yt}	specified yield strength of transverse reinforcement
F_γ	uplift coefficients, weight component
G'	shear modulus of soil
g'	effective backfill or subsurface material unit weight
g_r	growth rate of soil resistance
G_s	specific gravity of solids
GSI	geologic strength index
H	height
h_{ef}	effective embedment of an anchor
H_f	fill height
H_l	length of shaft length considered in the side shear capacity
$H'_{n.c}$	nominal effective horizontal shear resistance for cohesive material
$H'_{n.g}$	nominal effective horizontal shear resistance for granular material

H_u	ultimate lateral capacity
I	moment of inertia
I_{bar}	moment of inertia of grouted bar
I_{casing}	moment of inertia of steel casing
I_e	earthquake event importance factor
I_{FE}	earthquake load importance factor
I_{grout}	moment of inertia of grout cross-section
I_{MV}	earthquake single or multi-mode importance factor
I_p	earthquake importance factor
I_r	rigidity index
I_{rr}	reduced rigidity index
I_w	moment of inertia of weak axis
I_x	moment of inertia of the pile group about the Y-axis
I_y	moment of inertia of the pile group about the X-axis
K	coefficient of horizontal soil pressure; effective length factor
k	spring stiffness for a single degree of freedom (SDOF) system (lb/ft); soil modulus parameter; shaft segment length from top of soil reaction to point of maximum moment (Broms theory)
K_c	earth Pressure Coefficient for Cohesion
K_{cx}	earth pressure coefficient for cohesion at depth x
K_h	modulus of horizontal subgrade reaction
K_o	at-rest coefficient of lateral earth pressure
K_p	Rankine's earth pressure coefficient
K_{pm}	combined passive coefficient for backfill and surrounding soil
K_q	earth pressure coefficient for overburden soil
K_{qx}	earth pressure coefficient for overburden pressure at depth x
K_t	empirical torque correlation factor
K/K_o	stress modification factor
l	length of pole; unbraced length of micropile, not to exceed l_0
L	length; laterally unbraced length; length between top & bottom helical plates
L'	effective length; depth to center of rotation
l_0	unbraced length for which the critical buckling load reaches a minimum in an elastic medium
l_b	depth of penetration in bearing strata
L_b	design bond length
l_{BP}	distance from the top of concrete to bottom of base plate
$L_{b\text{-}i}$	installed bond length
L_C	load case
L_c	KL, the effective length of the member
l_d	development length in tension of a deformed bar

l_{dh}	development length in tension of a deformed bar with a standard hook
L_e	total depth of embedment
L_f	free length of grouted anchor
l_{LN}	distance from the top of concrete to bottom of leveling nut
L_p	shaft length
L_r	total depth of point of rotation
L_{socket}	length of shaft embedded below the assumed neutral plane
m	mass for a single degree of freedom system; fractured rock parameter
$L_{1,2,3,4}$	thickness of soil layers 1, 2, 3, and 4.
M	moment base reaction
M_a	design moment capacity of anchor
$M_{\text{allowable}}$	allowable bending moment
M_{applied}	moment
m_b	fractured rock mass parameter
M_c	allowable; design flexural strength
m_i	dimensionless constant based on rock lithology
M_L	longitudinal moment base reaction
M_{max}	maximum bending moment
M_n	nominal Moment Capacity
M_{na}	nominal moment capacity of anchor
Mo	overturning moment
M_{OT}	overturning moment about toe
M_Q	mean of loads from probabilistic load case
M_r	required flexural strength
M_R	mean of probabilistic design capacity
M_{re}	resisting moment
M_T	transverse moment base reaction; required flexural strength
M_u	factored Moment
M_{ua}	ultimate applied moment on anchor
M_w	moment due to wind
M_x	moment about the foundation x axis
M_y	moment about the foundation y axis
n	porosity; number of threads per inch
N	standard penetration value, blows per foot; shaft mobility
N_a	axial (normal) design strength of an anchor
N_{30}	standard penetration test value, blows per 0.30 meters
N_{60}	standard penetration test value, blows per foot, normalized
N_c	non-dimensional bearing capacity factor
N_c^*	non-dimensional bearing capacity factor
$N\sigma^*$	non-dimensional bearing capacity factor
N_f	normal force
$N\gamma$	non-dimensional bearing capacity factor

$N\gamma_q$	non-dimensional bearing capacity factor
n_h	rate of increase of soil modulus of elasticity with depth
N_M	shaft mobility
$N_{M\text{-theory}}$	theoretical shaft mobility
N_{na}	nominal axial strength of an anchor
N_p	number of piles
N_q	non-dimensional bearing capacity factor
N'_q	coefficient
N_σ	non-dimensional bearing capacity factor
N_ϕ	non-dimensional bearing capacity factor
n_t	thickness of annular space for the embedment depth of pole
N_u	uplift adhesion factor
N_{ua}	ultimate axial load on an anchor
O	organic soils
OCR	over-consolidation ratio
P	axial load; force
p	perimeter of pile or shaft; force due to soil resistance
P_1	transverse load 1; geometric mean of local resonant maxima
P_2	transverse load 2
P_a	atmospheric pressure
Pb	weight of breaker
P_c	axial compression load
$P_{c\text{-allowable}}$	compression allowable load
$P_{c\text{-design}}$	design compressive capacity
$P_{c\text{-nominal}}$	nominal compressive force
P_{cr}	critical buckling load
P_D	resultant (passive minus active) pressure per unit frontal area of foundation
P_e	elastic critical buckling load
P_f	foundation weight
P_g	pile group capacity
$P_{g/r}$	ultimate capacity based on anchor rod-grout bond
PGA_M	Mapped peak ground acceleration
$P_{G\text{-allowable}}$	allowable geotechnical bond capacity
$P_{G\text{-strength}}$	design geotechnical bond strength
$p_{\text{group shaft}}$	reduced lateral capacity of a drilled shaft from group effects
P_m	p-multiplier factor for p-y curve
P_n	ultimate pile capacity
P_{no}	allowable compression loading
Po	effective overburden pressure at the point in question
P_p	load per pile
P_r	required axial strength
P_s	pile side resistance
$p_{\text{single shaft}}$	lateral capacity of a single drilled shaft in a pile group

$P_{t\text{-allowable}}$	allowable tensile load
$P_{t\text{-design}}$	design tensile force
$P_{t\text{-nominal}}$	nominal tensile force
$P_{\text{transfer allowable}}$	allowable strength transferred through plunge length
$P_{\text{transfer design}}$	design strength transferred through plunge length
P_u	axial uplift base reaction
$P_{\text{ult.bond}}$	ultimate anchor capacity based on bond stress
$p_{\text{ult }i}$	Ultimate unit lateral capacity of annulus material
$P_{\text{ult }i}$	Ultimate lateral force per unit length on subsurface soil/rock and/or backfill material directly resisting the outside diameter of the pole and/or the backfill material
p_x	ultimate unit lateral resistance of an element
p_z	soil resistance at depth z
p_0	soil resistance at the surface
q	bearing pressure
Q	loads from probabilistic weather case
q_0	ultimate point resistance
Q_1	geometric mean of local resonant minima
Q_a	allowable grouted anchor capacity
q_a	allowable soil/rock bearing capacity
q_b	ultimate base resistance
Q_c	ultimate compression capacity
Q_D	axial downdrag force
Q_g	allowable capacity
Q_h	helix bearing plate capacity
q_L	bearing capacity limit
$q'_{\text{lat},1,2}$	nominal effective lateral bearing pressure of layer 1, 2, etc.
$q'_{\text{lat},n}$	nominal effective lateral bearing pressure
$q'_{\text{lat},u}$	design effective lateral bearing pressure
Q_{max}	Summation of head load and downdrag force (axial)
q_{max}	maximum soil bearing pressure
q_{min}	minimum soil bearing pressure
Q_N	nominal design load
q_n	nominal unit resistance
Q_p	net point load
q_p	nominal unit tip resistance
q_r	resulting bearing pressure (from 2:1 method)
Q_s	side resistance
q_s	unit side resistance
q_{sbell}	uplift resistance of belled shaft
q_{si}	nominal unit side resistance for i^{th} layer
$Q_{su.d}$	side shear resistance (Q_{su} = undrained, Q_{sd} = drained)
Q_T	axial load applied at the head
Q_{TN}	load transferred to top of shaft

$Q_{tu.d}$	tip bonding stress (Q_{tu} = undrained, Q_{td} = drained)
Q_u	axial (compression or uplift) capacity of helical pile; tension capacity of anchor
q_u	unconfined or uniaxial compressive strength; ultimate bearing pressure
q_{ult}	ultimate bearing capacity of bottom bearing plate
Q_{UN}	uplift force from expansive material
q_x	effective overburden pressure at depth x
r	radius of gyration
R	response modification factor; Probabilistic design capacity
R_{BN}	nominal base resistance
R_m	Mean nominal foundation capacity
R_N	nominal foundation capacity
R_n	Nominal strength
R_p	nominal shaft tip resistance
R_R	nominal (compression or tension) capacity
R_r	ratio of depth of point of rotation to total embedment depth of pole
R_{sbell}	nominal belled shaft resistance
RS_{H_L}	residual horizontal shear force in the longitudinal direction
RS_{H_T}	residual horizontal shear force in the transverse direction
R_{si}	unit shaft side resistance for i^{th} layer
R_{SN}	nominal side resistance
$R_{SN,i}$	nominal unit shaft side resistance for i^{th} layer
R_{st}	shaft relative stiffness factor in stiff over-consolidated clay
R_{stiff}	shaft relative stiffness cohesive soil
R_t	pile tip resistance
s	center to center spacing of items, such as longitudinal; transverse reinforcement, tendons, or anchors; fractured rock parameter
S	elastic section modulus
s'	effective stress of backfill or subsurface material at the depth of the anchor
S_a	design spectral response acceleration (g); elastic section modulus of threaded portion of anchor bolt
s_c	clear spacing between anchor bolt and vertical reinforcing steel
S_{DS}	design (5% damped) spectral response acceleration parameter at short periods
S_e	soil constant
$s_{\max}$	Calculated maximum transverse reinforcing permitted
S_u	undrained shear strength
$S_{u,bf}$	undrained shear strength of cohesive backfill material

S_u'	effective undrained shear strength
s_{u1}	weighted average of the undrained shear strength over the depth of pile embedment for the cohesive soils along the pile group perimeter
s_{u2}	average undrained shear strength of the cohesive soils at the base of the pile group to a depth of 2B below pile toe level
S_{ux}	undrained shear strength at depth x
T	tension; torsion; soil shear strength
t	time
T_1	component 1 of tension in ties for strut-and-tie model
T_2	component 2 of tension in ties for strut-and-tie model
T_{anc}	load resisted by anchor
T_b	base shear component of nominal torsional resistance
T_{guy}	resultant guywire load
T_m	unit length bond capacity, empirical
T_n	nominal torsional resistance
T_{NL}	wire tension load in longitudinal direction
T_{NT}	wire tension load in transverse direction
T_{NV}	wire tension load in vertical direction
T_q	installation torque
T_s	torsion
T_{SS}	side shear component of nominal torsional resistance
T_{st}	shaft relative stiffness factor in normally consolidated clays and for granular soils
T_{stiff}	shaft relative stiffness cohesionless soil
U	uplift force
$u(t)$	element displacement for dynamic equilibrium of a single degree of freedom with respect to time, t (ft).
U_{cr}	dimensionless ratio
U_D	ultimate design uplift capacity
U_n	nominal Uplift force or resistance
V	shear force
V_a	design shear strength of anchor
V_{applied}	shear force
$V(t)$	velocity computed at gage location at time t
V_b	baseline velocity over depth interval
V_c	nominal shear strength provided by concrete; side shear resistance due to cohesion; wave propagation velocity in concrete
V_L	longitudinal shear base reaction
V_n	nominal shear strength
V_{na}	nominal shear strength of anchor
V_p	side shear resistance due to passive earth pressure; assumed propagation velocity in concrete

VR	velocity reduction
V_s	nominal shear strength provided by steel reinforcing; volume of soil
V_{signal}	signal velocity
V'_{ss}	effective vertical side shear resistance along the 45-degree/ angled faces of the soil prism
V'_{ss1}	effective side shear resistance along inside and side/bottom faces of the soil prism
V_T	transverse shear base reaction
V_u	factored shear force
V_{ua}	ultimate shear load on anchor
V_w	shear due to wind
w	moisture content
W	weight
w_b	base settlement
W_{bf}	weight of backfilled material
W'_{bf}	effective backfill material weight above the frustrum
W_F	weight of spread foundation
W_g	weight of the block of soil enclosed by the pile group, piles, and pile cap
w_{ground}	settlement at the ground surface
w_i	distributed load along the length of the shaft
w_l	distributed load along length of the shaft
W_N	NESC district wind load
w_n	settlement of the drilled shaft at the neutral plane
w_o	optimum moisture content
W_p	weight of concrete drilled pier
W_{prism}	weight of prism of subsurface material above an anchor
W_s	weight of steel grillage
W_S	weight of subsurface material
X	lateral distance
x	distance to the point of rotation below ground; perpendicular distance from Y-axis to pile n; distance between the forces T & C
$x(t)$	base or datum displacement for dynamic equilibrium of an SDOF with respect to time, t (ft).
X_1	distance from ground surface to P1
X_2	distance from ground surface to P2
X_n	perpendicular distance from Y-axis to pile n
x_o	distance from ground to center of rotation
y	lateral deflection; perpendicular distance from X-axis to pile n
y_g	deflection at groundline
Y_n	perpendicular distance from X-axis to pile n

z	anchor or pile displacement; depth from ground surface to point where increase in pressure is calculated
Z	depth from foundation base to point where increase in pressure is calculated
$Z_{1,2}$	depth from ground surface to point 1, 2, where pressure is calculated
Z_a	plastic section modulus of threaded portion of anchor bolt
z_f	length from ground line to point of fixity
z_i	depth from ground surface at any given analysis point
z_n	distance from new neutral plane above the assumed initial position

GREEK NOTATION

α	adhesion coefficient
α'	effective stress adhesion
α_b	geotechnical bond nominal strength
α_E	empirical reduction factor for rock fracturing
α_t	coefficient
α_1, α_2	angle of simplified failure surface inside a direct embedment pole backfill annulus under lateral loading
β	side resistance regression coefficient; load transfer coefficient; inclination angle
Δ	deflection
δ	friction angle between soil and pile wall at the point in question; effective stress friction angle for the grout-subsurface interface
δ'	effective stress friction angle for the soil-shaft interface; drained friction angle for cohesionless soil
δ_B	bottom of shaft deflection (duplicate)
Δ_{he}	elastic shortening of pile group
δ_T	top of shaft deflection
Δz_i	thickness of the i^{th} soil layer
Δz_s	thickness of the compressible soil layer
ϕ	angle of internal friction
ϕ'	effective friction angle
Φ	strength factor
ϕ_1	friction angle of backfill soil
ϕ_2	friction angle of in-situ native soil
Φ_5	Strength factor for 5% lower exclusion limit
Φ_b	strength factor for bending
ϕ_a	friction angle of direct embedment pole annulus backfill
ϕ_{bf}	friction angle of backfill

Φ_c	compression strength factor
Φ_G	geotechnical strength factor
Φ_i	strength factor for shaft side resistance
Φ_{qp}	strength factor for tip resistance
Φ_{qsi}	strength factor for shaft side resistance for i^{th} layer
Φ_{sw}	strength factor for self-weight of the pile
Φ_t	strength factor for pile tip resistance; tensile strength reduction factor
Φ_{up}	strength factor for uplift
Φ_v	strength factor shear
$\Phi_{X\%}$	Strength Factor with a Lower Exclusion Limit (LEL) of X
γ	unit weight of soil
γ'	effective unit weight of soil
γ'_{bf}	effective unit weight of backfill
γ_{conc}	effective unit weight of concrete
γ_d	dry density
γ'_f	effective unit weight of fill
γ'_i	either the effective unit weight of backfill or the effective weight of the native subsurface material outside the prism of backfill over an anchor
γ_P	shaft weight load factor
γ_T	shaft top load factor
γ_U	load factor for expansive soil uplift
γ_w	unit weight of water
η	group efficiency factor
η_1	group efficiency between in-line piles
η_2	group efficiency between side-by-side piles
η_g	pile group efficiency factor
η_h	coefficient of modulus variation
λ	modification factor for use of lightweight aggregate; pile length dependent empirical coefficient
λ_c	pile length dependent empirical coefficient
λ_d	dimensionless disturbance factor
λ_i	load factor
λ_k	fitting factor for empirical torque correlation
μ	coefficient of friction
θ	rotation
θ_B	bottom of shaft rotation
θ_T	top of shaft rotation
θ_P	angle between piles in a group
ρ_c	concrete density
σ	effective mean stress at the base of the pile
σ'	effective stress acting on the shear plane
σ'_0	the effective stress at any depth z

σ_{bond}	ultimate grout-to-ground bond stress
σ'_p	effective vertical pre-consolidation stress
σ_Q	standard deviation of probabilistic design capacity
σ_R	standard deviation of loads from probabilistic weather case
σ_V'	effective stress
σ'_v	vertical effective stress at soil layer mid-depth
σ'_{vb}	vertical effective stress at the top elevation
T	soil shear strength
τ_{avg}	average grout-soil bond strength along the bonded zone for grouted soil anchors
τ_{max}	maximum torsional base shear
τ_{nat}	total suction
τ_{ult}	ultimate grout-soil bond strength along the bonded zone for grouted soil anchors
Ω	overstrength factor
ψ	angle from vertical to soil failure surface
Ψ_e	modification factor for use of epoxy coatings
Ψ_s	modification factor for reinforcing size
Ψ_t	modification factor for reinforcement location
$\zeta_{Y\%}$	values used to increase the nominal load
τ_{avg}	average bond stress per meter, empirical
τ_{nat}	suction stress
τ_{ult}	ultimate bond stress per meter, empirical

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

Manual of Practice 160, *Overhead Power Line and Substation Foundations: State of Practice, Basics, Type Selection, Geotechnical Topics, and Specialty Analysis*, (MOP 160) and Manual of Practice 161, *Overhead Power Line and Substation Foundations: Design Loads, Strength Factors, Threshold Criteria, and Design/Construction Methodologies*, (MOP 161) were written in a singular effort. Users of MOP 160 and MOP 161 should therefore consider them to be an integrated set of manuals that represent a single body of work.

MOPs 160 and 161 present a summary of current foundation design practice for overhead power lines and substation structures and equipment. These manuals (MOP 160 and MOP 161) provide information that Engineers can use to make informed decisions on these projects.

Currently, there is no uniform standard for the analysis and design of foundations in the overhead power line and substation industry. Overhead power lines and substation foundations have design requirements that are unique compared to buildings and other infrastructure.

The guidance provided herein was developed primarily for transmission line and substation foundations. Future document revisions may be extended to include distribution level foundations.

1.2 SCOPE

MOP 160 and MOP 161 provide a wide range of best practice guidance and discussion related to the analysis, design, and construction of foundations for overhead power lines and substations.

The Task Committee on Overhead Power Line and Substation Foundations of the Committee on Overhead Power Line Structures (OPS) is comprised of a multi-disciplined group of professionals from the electrical transmission, distribution and substation industry representing utilities, consulting engineering firms and material vendors. Task committee members have experience in geotechnical engineering, structural engineering, transmission line engineering, substation engineering, project management, construction, and material fabrication.

Task committee members developed the scope of MOP 160 and MOP 161 collaboratively through open discussions about foundation design development, construction process, state of practice regarding design methodology and criteria, common design and construction challenges, and a high-level review of existing and ongoing research and reference material.

1.3 CONTENTS

The contents of this manual (MOP 161) provide a collection of best practices related to foundation design loads, strength factors, and threshold criteria concepts as well as a detailed presentation of the best practices for foundation design development and construction processes for overhead power lines and substation structures. The manual (MOP 161) is comprised of 11 chapters covering the following topics:

- Foundation loads, Strength factors, Threshold criteria
- Design and construction methods/considerations for various foundation types (Drilled shafts, direct embedded pole foundations, shallow foundations, large diameter open pipe piles, driven piles, micropiles, helical piles, continuous flight auger piles, tension only anchors)

There is a "References" section provided at the end of each chapter which provides details on all external citations contained within the chapter.

1.4 INTENDED USE

MOP 160 and MOP 161, as an integrated set of manuals, are intended to provide useful and comprehensive information to Engineers with varying foundation design experience levels. Examples of foundation design/ construction methods and considerations are included in this MOP (161).

1.5 STATE OF PRACTICE

One prior survey of industry practice for foundation design was referenced in preparing MOP 160 and MOP 161. It was performed by the Deep Foundations Institute (DFI) in 2015 (Kandaris and Davidow 2015). The OPS task committee developing MOP 160 and 161 created a new survey and distributed it to foundation design professionals that work for electrical utilities and consulting firms to gather information on the current practices and standards used to perform foundation design and construction work. The task committee selected survey participants based on their design experience in either transmission line and/or substation foundations. The results of this survey are included in Appendix A of MOP 160.

1.6 FUTURE RESEARCH

During the development of MOP 160 and MOP 161, this task committee identified some design practices that lacked consistency in application, due to both the lack of standards, and insufficient research to fully understand the engineering processes related to electric system foundation design. The Deep Foundations Institute noted similar conclusions in their recent publication (DFI 2025). This task committee has identified the following topics that warrant additional research.

1.6.1 Design Models and Methodologies

- Combined lateral and axial loading foundation design methods for H-Frame structures that are calibrated based on full-scale foundation load test data
- Importance of combined side friction and end bearing component contributions with typical electric system deep foundation elements
- Validation of simplified theoretical models of direct embedment pole foundations under axial loads based on load test data related to failure mechanisms among pole / backfill / subgrade
- Vibrated open pipe pile foundation design methods based on full scale testing
- The influence of slopes, adjacent excavations, and nearby underground utilities on deep and shallow foundation performance

1.6.2 Codes, Loads, and Limit States

- Recommended load cases for overhead line foundation performance assessment to establish service limit state design guidance

- Assessment of the probability of simultaneous occurrence of multiple extreme load events (such as maximum design flood or seismic event concurrent with maximum design wind event)
- Develop standard approach to reinforcement in concrete design for overhead power line and substation foundations

1.6.3 Design Approach

- Develop target reliability index and the associated load/strength factors for use in RBD/LRFD developed specifically for the overhead power line industry. The foundation strength factors borrowed from other industry sectors (e.g. transportation) may result in conservative strength factors for powerline foundations
- The assessment of overhead power line capacity and performance using prescribed design methods for direct embedment pole foundations

1.6.4 Foundation Movement

- A better understanding of the effect of foundation (both shallow and deep foundations) movement on electric system structures and equipment is needed
- Research is lacking in non-linear computer modelling of structures and the full-scale testing of structures with imposed foundation movements
- The importance of assessing seismic effects on overhead power lines and remediation methods for seismic effects in substations
- Foundation deflection and rotation performance (within elastic ranges) under sustained loads based on long-term monitoring and data collection from in-situ instrumentation of overhead power line foundations

1.6.5 Site Conditions and Investigations

- A comprehensive review of the state of practice for geotechnical engineering investigations for overhead power line and substation projects and the development of a standard guideline (baseline) that summarizes best practices
- Research on the effect of sampling and testing of subsurface materials that are disturbed through standard sampling methods
- The impact of more sampling (test locations) on reducing foundation costs and/or increasing foundation reliability for overhead lines, especially long lines

REFERENCES

DFI (Deep Foundations Institute), Electric Power Systems Foundations Committee. 2025. *Design and construction of deep foundations to support electric system transmission lines*, State of the practice committee report. Hawthorne, NJ: DFI.

Kandaris, P. M., and S. Davidow. 2015. "Study of electric transmission line deep foundation design." In *Electrical transmission and substation structures 2015*. 577–587. Palo Alto, CA: ASCE.