

Report on Design and Construction of Drilled Piers

Reported by ACI Committee 336



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Report on Design and Construction of Drilled Piers

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Report on Design and Construction of Drilled Piers

Reported by ACI Committee 336

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This report covers design and construction of 30 in. (760 mm) diameter or larger foundation piers constructed by excavation of a hole in a subgrade that is later filled with concrete. The 30 in. (760 mm) diameter boundary is an arbitrary size; smaller-diameter drilled piers can be designed and installed in accordance with ACI 543R. Although determination of overall pier size and concrete section design are two basic drilled pier design procedures, emphasis is focused on the determination of overall pier size, which is affected by the interaction between subgrade and pier. Because pier capacity is significantly affected by construction means and methods, the licensed design professional should understand these limitations. Construction methods described include excavation, casing, reinforcing steel installation, and concrete placement. Acceptance criteria and recommended procedures for construction, engineering, and evaluation are presented.

Keywords: bearing capacity; caisson; casing; excavation; foundation; geotechnical engineering; lateral pressure; lining; slurry; tremie.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

This report addresses design and construction of drilled pier foundations constructed by digging, drilling, or otherwise excavating a hole in the subgrade that is subsequently filled with plain or reinforced concrete. Although structural design and construction of drilled pier foundations are the primary objectives of this report, relevant aspects of geotechnical engineering are also discussed, as variations in subgrade properties have a critical influence on design, construction, and subsequent performance. Successful drilled pier design, construction, and performance requires reliable data on the applied loads and supporting subgrade. Because construction limitations often govern design, combined cooperation among the geotechnical engineer, structural engineer, and drilled pier contractor are essential.

1.2—Scope

This report is generally limited to piers of 30 in. (760 mm) or larger diameter, made by open or slurry stabilized construction methods. A 30 in. (760 mm) diameter boundary is an arbitrary size. Although smaller-diameter drilled piers have been designed and installed in accordance with this report, it is difficult to detect sidewall collapse. Refer to **ACI 543R** for concrete piles having diameters smaller than 30 in. (760 mm), piles installed by the use of hollow stem augers, or other pile types. Also beyond the scope of this report are rectangular columns on spread footings in deep excavations and foundations constructed without excavations by methods such as mortar intrusion or mixed-in-place.

Piers installed by tapping or ramming concrete or aggregate into an excavated shaft are beyond the scope of this report. Engineers and contractors have used the terms “caissons,” “foundation piers,” “bored piles,” “drilled shafts,” and “drilled piers” interchangeably. The term “drilled pier” is used in this report. A drilled pier with an enlarged base can be called a belled caisson, belled pier, or drilled and under-reamed footing. Drilled pier foundations excavated and concreted with water or slurry in the hole have been called slurry shafts, piers installed by wet-hole methods, or piers installed by slurry displacement methods.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

- A_b = pier base area, in.² (mm²)
- A_p = pier shaft surface area, in.² (mm²)
- D = dead load, lb (N)

- D_g = dead loads from the supported structure and weight of the pier (gross weight of the pier), lb (N)
- d = diameter of pier, in. (mm)
- E = earthquake load, lb (N)
- E_c = modulus of elasticity, psi (MPa)
- F = vertical load, lb (N)
- FS = allowable strength design safety factor
- FS_1 = allowable strength design safety factor for bearing resistance
- FS_2 = allowable strength design safety factor for side resistance
- f_p = average side resistance, ton/ft² (kPa)
- f_z = unit load transfer from shaft to ground at depth z , ton/ft² (kPa)
- H_g = horizontal shear at ground surface, lb (N)
- I = moment of inertia, in.⁴ (mm⁴)
- k_s = modulus of horizontal soil beam reaction, psi (MPa)
- L = live load, lb (N)
- M_g = moment at ground surface, usually applied to pier by superstructure, in.-lb (N-mm)
- N = number of blows in a standard penetration test
- P_{an} = anchorage resistance, lb (N)
- P_q = ultimate end bearing acting at the base, lb (N)
- P_{up} = uplift force, lb (N)
- p = subgrade resistance per unit length along the pier, lb/in. (N/mm)
- p - y = lateral load deflection curve at an element of pier, lb/in., in. (N/mm, mm)
- Q = ultimate axial capacity, tons (kN)
- q_b = unit end-bearing pressure, ton/ft² (kPa)
- S_n = force from side friction, lb (N)
- S_p = positive side resistance, lb (N)
- S_{p1} = positive side resistance, acting upward on the pier; normally caused by downward movement of the pier relative to surrounding soil, lb (N)
- T = relative stiffness factor
- W = wind load, lb (N)
- w_b = movement of the pier at depth z , in. (mm)
- w_z = unit deflection corresponding to f_z , in. (mm)
- y = lateral deflection of pier, in. (mm)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://concrete.org/Tools/ConcreteTerminology.aspx>. Definitions provided here complement that source.

bearing-type pier—a pier that receives its principal vertical capacity from a subgrade layer at the bottom of the pier.

bell—an enlargement at the pier bottom to spread the load over a larger area, or to engage additional subgrade mass for uplift loading conditions; also called **under-ream**.

cap—an upper pier termination, usually placed separately, to correct deviations from desired location, facilitate anchor bolt or dowel setting within acceptable tolerances, or combine two or more piers into a unit supporting a column.

casing—a protective temporary or permanent steel tube, usually cylindrical in shape, lowered into the excavated hole

to protect personnel from sidewall collapse or cave-in, or to exclude soil, water, or both from the excavation.

combination bearing- and side-resistance pier—a pier that receives its vertical capacity from bearing at the bottom and resistance developed along the shaft sides.

construction geotechnical engineer—a geotechnical engineer with experience in drilled pier construction who is designated by the owner to carry out the responsibilities defined in this report; also known as a soils engineer, soils and foundation engineer, or earthwork and foundation engineer.

construction geotechnical engineering—the interpretation and assessment of drilled pier construction observations, equipment and materials used therein, and the field testing and results necessary to permit the construction geotechnical engineer to render a professional opinion as to conformance with the contract documents and foundation design. Construction geotechnical engineering does not include drilled pier contractor direction or supervision.

drilled pier—concrete cast-in-place foundation element with or without casing that may have an enlarged bearing area and that extends downward through weaker soils, water, or both, to a subgrade stratum capable of supporting the loads imposed on or within it.

flexible pier—a pier with a length-to-diameter ratio that will allow flexural deformations from lateral loads; the theoretical point of fixity is within the pier shaft.

geotechnical engineer—an engineer with experience in geotechnical investigations for, and the design of, drilled piers who is designated by the owner to prepare the design geotechnical report and work with the structural engineer on the drilled pier design.

head—top of pier.

Kelly bar—drill stem used to advance pier excavation tools.

obstruction—underground material that prevents a drill rig from advancing the pier excavation to the desired final bearing level; may be concrete, concrete pipe, rubble, wood, or a boulder that is not part of the parent bedrock.

pig—a disposable device inserted into a tremie or pump pipe to separate the concrete from the pier excavation fluid inside the pipe. Also called rabbit, rabbit plug.

project specifications—the specifications stipulated by contract for a project that should employ ACI 336.1 by reference and that serve as the instrument for defining the mandatory and optional selections available under the specification.

rigid pier—a pier with a small depth-to-diameter ratio that will have negligible flexural deformations under lateral load. Lateral movements will be rotational type involving the entire length of the pier.

rock—a naturally formed mineral formation underlying the site including intact rock and partially weathered and weathered rock that should be defined by the geotechnical engineer for each project.

rock socketed pier—a pier that derives its capacity from both side resistance and end bearing within rock for some portion of its length.

shaft—portion of drilled pier above bearing surface exclusive of the base or bell, if any.

side resistance—subgrade friction or adhesion developed along the side surface of the pier. This resistance may resist force in either the positive or the negative vertical direction (uplift or compression).

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, collapse, or a borehole or drilled pier excavation, or both.

slurry displacement method—method of drilling and concreting, where drilling fluid is used to maintain the stability of the uncased drilled pier hold, to allow acceptable concrete placement, or both, when water seepage in a drilled pier hold is too severe to permit concreting in the dry.

socket—portion of pier within the bearing stratum.

underream—see **bell**.

wet method—construction procedure used when a pier extends through a caving stratum; typically includes inserting a casing past unstable subgrade layer then cleaning out the casing; the pier may continue to advance by drilling dry.

CHAPTER 3—GENERAL CONSIDERATIONS

3.1—General

The drilled pier's function is twofold: 1) to transfer axial loads, lateral loads, torsion loads, and bending moments to the surrounding subgrade; and 2) to support the subgrade surrounding. To perform these functions, the pier interacts with the subgrade around and below it, as well as with the superstructure above. The pier's relationship to the subgrade is one of the most important variables in pier design. The subgrade can act as both the driving force, such as in earth pressure in a failing slope, and as resistance. In the absence of a theory that can encompass all the factors involved, simplifying assumptions should be made. However, subtle aspects of construction often govern the design.

3.2—The structural and geotechnical teams

Drilled pier design is the joint responsibility of the structural and geotechnical engineers. Many variables are considered in successful drilled pier design, including the interdependence of the structure and soil interaction, structural materials, and construction means and methods. A structural and geotechnical engineering team approach provides a more rational design than an independent one. The structure, drilled pier, and subgrade stiffness can induce composite system loading variations relative to the loads calculated on the assumption that all drilled piers are sized for the same subgrade-bearing pressure and assumed settlement. A reasonable approximation of the state of compatibility can greatly improve design, and allow concrete and reinforcement to be placed where they will function efficiently. Achieving this goal usually requires an iterative design process with an examination after each step to decide the required adjustments necessary to accomplish compatibility at the next stage of the process. The proposed approach will lead to a rational understanding of the design requirements and reduced risk of unacceptable performance.

3.2.1 Continuity from design through construction—The importance of design continuity through construction by the structural and geotechnical engineers is emphasized because the design's success relies on the underground conditions along with construction means and methods. The geotechnical engineer should have a thorough understanding of the limitations of construction means and methods and their influence on design, and should provide the construction geotechnical engineering with assistance during assessment of the as-installed pier compatibility with design requirements (Ulrich 2007).

The experience of geotechnical engineers varies; one geotechnical engineer might assess observed field conditions differently than another who performed the design. It is not unusual for them to report differing evaluations for design soil resistance and loading conditions taken from the same site using similar tests.

The presence of the construction geotechnical engineer should be required during pier installation (Ulrich and Ehlers 1995; Ulrich 2007). The geotechnical engineer should develop the specifications, which should clearly define requirements for testing agency services and construction engineering because the construction geotechnical engineer will form the opinion on each pier's acceptability. The geotechnical engineer may collaborate with the structural engineer as needed to complete the specification for installation. Because field decisions and interpretations of contractor conformance with the design specification can affect design, the geotechnical engineer or construction geotechnical engineer could assume responsibility for both.

3.3—Factors to consider

Computational results and expected behavior should be evaluated based on 3.3.1 through 3.3.5.

3.3.1 Subsurface conditions—Soil stratification; ground water conditions; and the depth, thickness, and nature of the subgrade constituting the bearing stratum influence the choice of construction method and drilled pier design. Specifically, design-bearing pressure and side shear determine the required pier bottom area and socket length in the bearing stratum. The geotechnical engineer selects the design-bearing pressure and side shear based on soil and rock samples, tests, analysis, judgment, and experience, based on load character, tolerated settlements, and construction methods. Material properties above and in the bearing stratum vicinity and disturbance from construction activity determine the feasibility of constructing a socket or bell without slurry. Soil permeability, groundwater conditions, and soil gradation are factors that determine whether casing, slurry, or dewatering is required. These parameters also dictate the concrete placement method, and may influence ground loss considerations. Shear strength and deformation, including shrink and swell characteristics of the subgrade material penetrated by the shaft, determine whether side resistance in these materials should be a design consideration. Side resistance could act to resist superstructure loads or a major applied downward drag in consolidating subgrade or uplift load in swelling subgrade on the shaft.

The location and characteristics of rock on the site can have a significant impact, particularly on construction cost and duration. The geotechnical engineer should define rock for each project. Sedimentary, metamorphic, and igneous rock have highly varying capacity, and high-capacity piers may require special investigations of the rock character, sometimes below each pier. The use of drilled piers bearing in limestone susceptible to solution activity requires caution due to the risk of voids or other discontinuities.

3.3.2 Site conditions—Available construction area, site access, headroom, and existing facilities requiring protection against settlement, ground loss, noise, or contamination, influence the construction method and design. The choice of design and construction methods used for new piers may lead to subsidence, which can be caused, for example, by uncontrolled excavation or by removing fine-grained materials from the surrounding soil through water flow from dewatering or consolidation. These effects on adjacent and new structures should be design considerations.

3.3.3 Construction geotechnical engineering and quality control—Perform geotechnical engineering to confirm the validity of simplifying design assumptions and to assess compatibility of construction means and methods with design requirements. Scope and method of observation, obtainable tolerances, and quality control influence the degree to which the design can reasonably be refined.

Drilled pier design and installation are multiphase tasks where proper quality control and assurance in construction are vital. Without them, the probability of a successful foundation is reduced. Even the highest quality structural element can have its capacity as a load-carrying member significantly reduced from improper installation details and relationship between the installed pier to the surrounding subgrade.

3.3.4 Constraints—Available construction expertise and equipment, available materials, and building code requirements, including construction limitations, influence construction and design.

3.3.5 Design considerations—The licensed design professional should compute vertical and lateral loads and moments imposed on the pier. Length and section properties of the pier, distribution of load on end bearing, lateral resistance, and side resistance are determined based on loads and subsurface conditions. The subgrade may be part or all of the driving force, particularly in situations involving slopes or retaining walls.

The pier stiffness $E_c I$ surrounding subgrade response and their interaction are important in the analyses of laterally loaded piers. Subgrade response is the least predictable variable. Pier deflection is often the limiting factor in determining acceptable performance in response to lateral loads and moments.

3.4—Pier types

Piers can be divided into types according to the manner in which axial loads are transferred to the subgrade and the pier response to lateral load. The assignment of a given pier to a certain type can depend on the:

- a) Soil and rock qualities around the shaft and at the pier base;
- b) Character of the contact surface between pier and subgrade;
- c) Relative stiffness factor;
- d) Embedded length of pier.

3.4.1 Axially loaded piers—With respect to axial load capacity, there are three types of piers (3.4.1.1 through 3.4.1.3).

3.4.1.1 Bearing-type pier—A straight-sided or belled pier, drilled through weaker soils and terminating on subgrade of satisfactory bearing capacity, is considered a bearing-type pier if it is designed to achieve its capacity from that stratum.

The bearing area can be increased by a bell at the shaft bottom. However, the soils in which the bell is constructed should have sufficient cohesion to permit the excavation to stay open until the concrete is placed. In caving soils, bells are normally not used because the bell may require grouting or installation by the slurry displacement method, which involves increased risks for construction defects. Alternatively, the pier may be enlarged to eliminate the need for the bell, or extended into a material in which a bell is more easily excavated.

3.4.1.2 Combination bearing- and side resistance-type pier (Fig. 3.4.1.2)—A pier extended (socketed) into a bearing stratum in such a manner that part of the axial load is transferred to the sides of the shaft and the rest of the load is carried in end bearing.

3.4.1.3 Side resistance-type pier (Fig. 3.4.1.3)—A pier built into a bearing stratum in such a manner that the load is carried by side resistance.

3.4.2 Laterally loaded piers—Based on response to lateral load, there are two pier types (3.4.2.1 and 3.4.2.2).

3.4.2.1 Rigid pier (Fig. 3.4.2.1)—A pier so short and stiff in relation to the surrounding soil that lateral deflection is primarily due to the pier's rotation about a point along its length, its horizontal translation, or both. A rigid pier's rotational resistance is governed in part by the load deformation characteristics of the soil adjacent to and under the embedded portion of the pier, and by the restraint, if any, provided by the structure above. Piers shorter than approximately 10 diameters behave as rigid piers.

3.4.2.2 Flexible pier (Fig. 3.4.2.2)—A pier of sufficient length and with flexural rigidity ($E_c I$) relative to the surrounding soil such that lateral deflections are primarily due to flexure. Piers longer than 10 diameters typically behave as flexible piers. The depth below which the pier is considered fixed will vary depending on underground conditions, loading, and pier properties. Further discussion of flexible behavior is found in ACI 543R.

3.5—Geotechnical considerations

The geotechnical engineer should determine the scope of investigation needed for pier design, and should:

- a) Have adequate knowledge of the underground site conditions, selecting a foundation system that resists imposed loads and is compatible to design, and is economical and constructible;

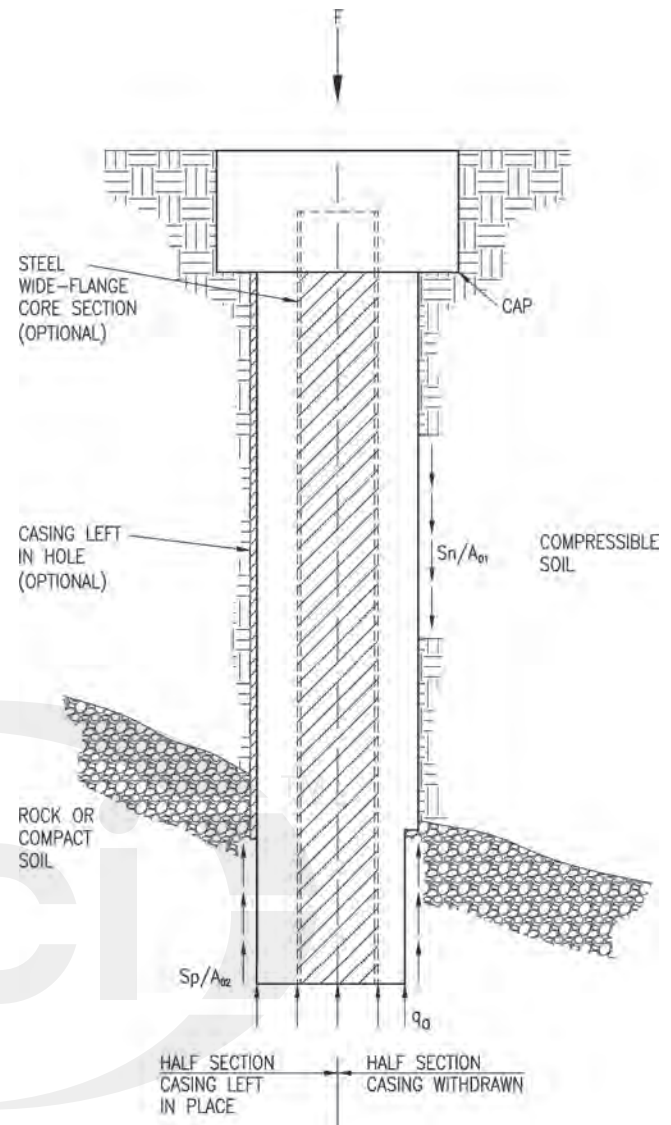


Fig. 3.4.1.2—Combination bearing-type and side resistance-type pier.

- b) Perform subsurface exploration that is thorough, and that has enough samples and data to establish that the soil, rock properties, or both are within the zones of interest;

- c) During investigation, consider the influence of geologic features on foundation design and performance;

- d) Consider and evaluate as needed: collapsing soils, random variation in fill character, shrinkage and swelling conditions, slope stability, soil liquefaction potential, rock cavities or other voids, potential rock collapse, progressive limestone solution, and weathering profiles.

The scope of the investigation should include the following (3.5.1 through 3.5.9).

3.5.1 Exploration—The geotechnical engineer should determine the type of exploration appropriate for the project needs including soil borings, depth and type of rock coring, cone penetrometer tests, dilatometer tests (DMTs), surface seismic profiling, and cross-hole seismic exploration. A sufficient number of explorations should be made to establish with reasonable certainty the subsurface

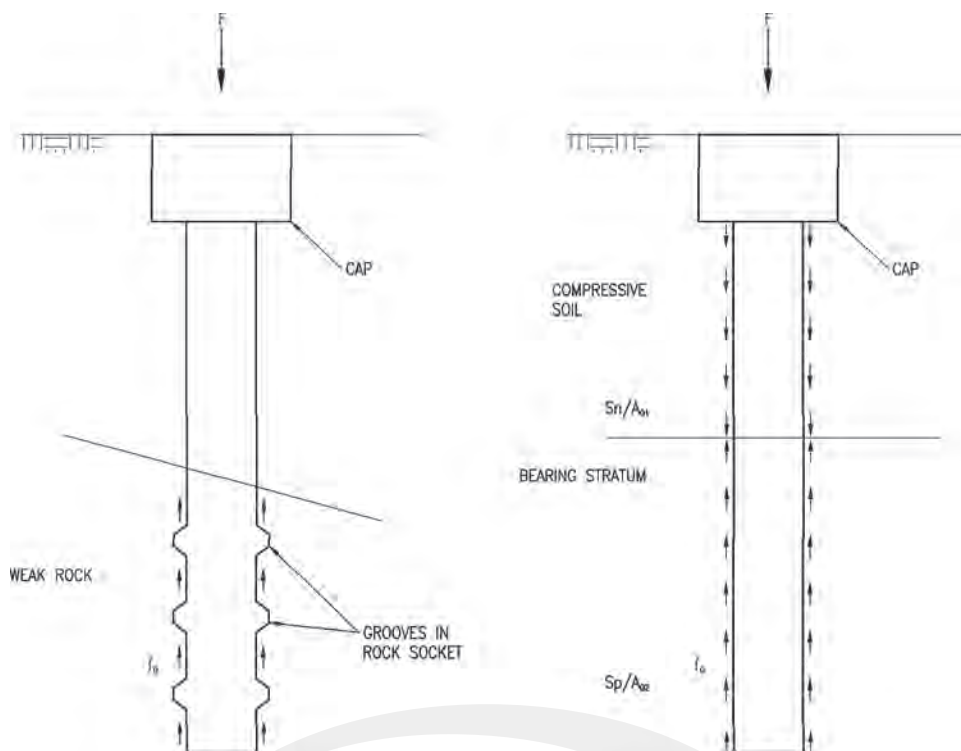


Fig. 3.4.1.3—Side resistance-type pier.

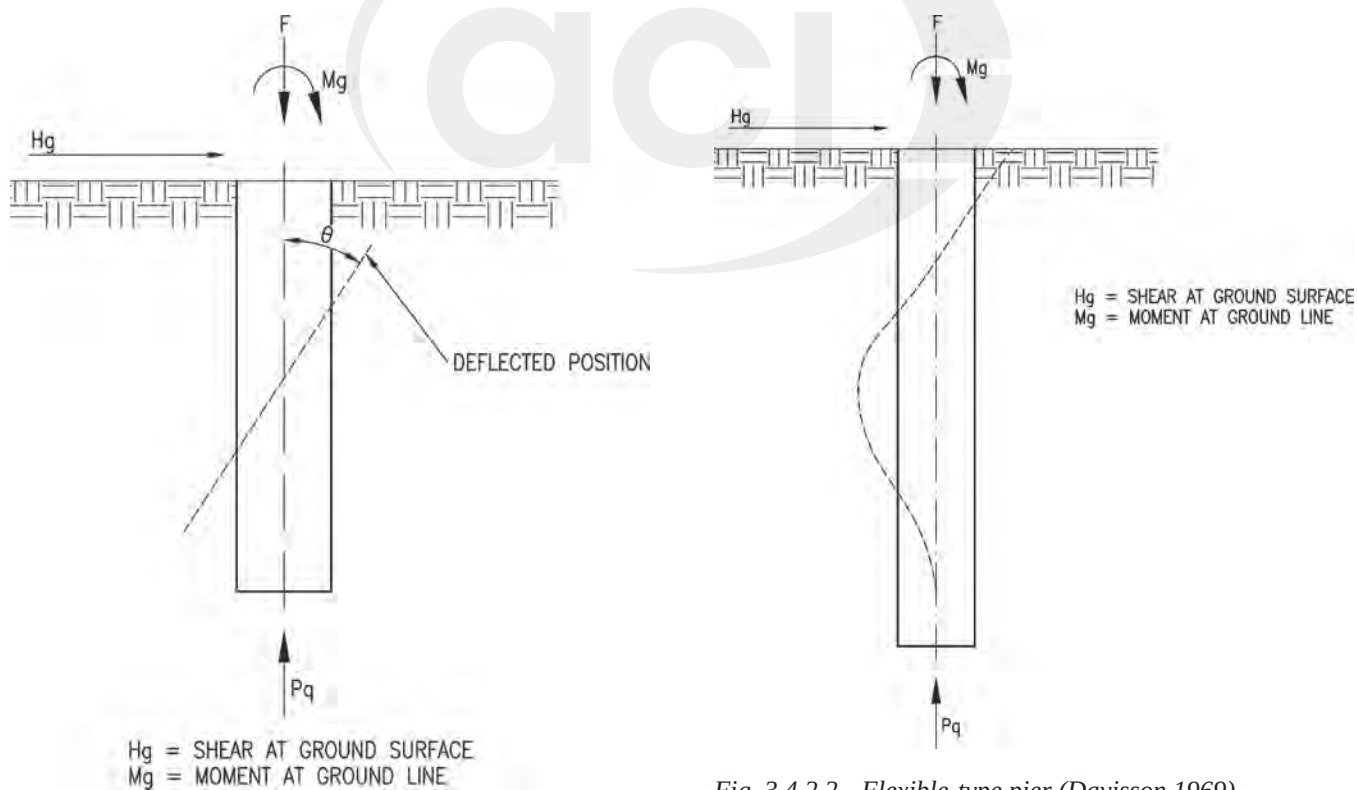


Fig. 3.4.2.1—Rigid-type pier (Davisson 1969) with notation altered.

stratification (profile) and water table location. Where the piers are to terminate in rock, exploration should include a bedrock surface profile and character. The structure type and

Fig. 3.4.2.2—Flexible-type pier (Davisson 1969).

geologic and geomorphic conditions will govern the exploration program. Exploration of foundations for a structure that will rest on igneous rock that is known to be boulder- and joint-free will vary significantly from exploration of the same structure that will rest on limestone with severe cavi-

ties and solution activity, even when the intact rock strength at both sites is similar.

3.5.2 Depth of explorations—Exploration depth should reach settlement of the bearing stratum below the pier. Where practical, at least one boring should extend into bedrock regardless of how far below it is to the anticipated bearing level of the piers.

3.5.3 Water table and dewatering—If water is encountered within the zone of pier penetration, the site exploration should identify the water table elevation(s), potential for fluctuations, permeability, and gradient across the site.

3.5.4 Piers to bedrock level—If piers are to be founded on rock or socketed into bedrock, probes or cores should be extended into the bedrock to a depth of at least twice the diameter of the bearing area below the base level, but not less than 10 ft (3 m). This depth is necessary to determine rock strength and condition, and the potential for suspended boulders above bedrock. The minimum size cores preferred are NX size when pier capacity is high and the rock quality is critical to establishing maximum pier capacity (**ASTM D2113**).

3.5.5 Boulders and obstructions—Geotechnical investigations should pay particular attention to identifying potential obstructions and boulders because drilled piers are not often easily relocated and the presence of unexpected obstructions to drilling could increase the cost, time, or both to construct drilled piers. This is one of the more common causes of contractor claims.

Suggested subsurface investigation procedures include:

- a) If high standard penetration test (SPT) values are observed and cobbles are suspected, use a larger sampling spoon;
- b) If boring refusal is encountered, do not terminate and relocate the boring but, instead, core through the obstruction and determine its size and character;
- c) Extend borings several feet (meters) below design penetration of the piers and do not terminate borings upon refusal at expected rock level. Instead, core into bedrock to determine if it is a disconnected boulder;
- d) If obstructions are encountered at a site, add more borings at pier locations;
- e) Shallow obstructions should be explored by test pits to uncover old foundations, abandoned and active utilities, and foundations of abutting buildings including left-in-place sheeting that may extend beyond their property line and obstruct the drilled piers.

Multiple test pier installations may be needed to finalize the foundation design. Specifications should be sufficiently flexible to allow design modifications during construction.

3.5.6 Subgrade strength—In cohesive soil, obtain the unit weight and strength parameters from sufficient samples taken at different depths to determine depth trends; individual samples may be erratic. In cohesionless soils, it is common practice to estimate the soil's relative density to determine the allowable soil pressure based on SPT, cone penetration test (CPT), DMT, or pressure meter test (PMT). Where lateral load behavior of drilled piers is important, special attention should be given to the determination of subgrade properties within 10 pier diameters of the surface.

3.5.7 Axial load tests—For large projects or in cases of inadequate experience with subsurface conditions, load tests should be performed. Given the potential variability of capacity prediction methods, load tests remain the best method of optimizing pier design capacity.

Load test reactions are provided by belled or socketed piers designed for tension and positioned around the drilled pier being compression tested. The reaction piers transfer load through a reaction frame and jacks positioned above the test pier (**ASTM D1143**).

Heavily loaded drilled piers are often tested using other methods. One such method, developed by **Osterberg (1989)**, consists of installing an embedded instrumented loading jack capable of applying a load in excess of the pier's maximum design load within a full-scale test pier. Both end bearing and side resistance are tested. The maximum test load is defined by failure in either side resistance or end bearing. If maximum side resistance is exceeded, the test can be extended further conventionally with a surface reaction frame and dead weights or anchor piers to permit applying higher end-bearing load. Another common test method accelerates an independent reaction mass upward using pressure contained in a chamber. The resulting reaction is applied to the pier (**ASTM D7383**). Load tests may also be performed on small-diameter, instrumented, drilled piers; however, care should be exercised in extrapolating the results to larger-diameter piers.

Where water inflow is not a problem, it is also possible to drill a full-sized pier and perform a plate load test at the pier base level to establish bearing capacity. Although such testing is uncommon, it has the advantage of allowing visual observation of the subsurface conditions before testing.

3.5.8 Lateral response load tests—Lateral load testing has become common, particularly where earthquake or wind loading is important. Often performed by placing a jacking frame between two drilled piers and jacking them apart, it measures the relative and absolute movement of each pier. If drilled piers are to be installed from a level above a basement subgrade, it is often important to perform the lateral load test after excavating to subgrade. This becomes an issue when the subgrade is below the groundwater table and the lateral load test requires completion before production pier installation begins.

3.5.9 Design geotechnical report—The design geotechnical report, written by the geotechnical engineer in nonmandatory language to guide foundation design and construction, may be included with the contract documents for information only. The design geotechnical report is distinguished from a geotechnical data report in that it provides design parameters and recommendations on construction methods. Wholesale inclusion of reports into specifications is not advisable. They should instead be listed as a reference document and used to prepare plans and specifications.

CHAPTER 4—DESIGN

4.1—Loads

Pier design consists of two steps



Documents

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- (1) Determination of pier dimensions;
- (2) Design of the concrete pier element and any necessary reinforcement.

In Step (1), which involves interaction between the subgrade and pier, all loads are traditionally service loads and all subgrade stresses are at allowable values. The applied service loads do not include load factors. If load and resistance factor design (LRFD) methods are used, factored loads are compared with soil resistances that have been reduced to account for their variability and uncertainty. Great care should be taken that soil resistances are calibrated. In either approach, it is critical that the stresses in the subgrade and the predicted deflections are compatible with the principles of soil mechanics.

In Step (2), the pier is structurally designed by the strength design method as adjusted in this report, although some prefer to use the alternate design method (4.6). The alternate design method employs the use of service loads in the structural design. Pier-subgrade capacity compatibility is not part of the analysis. Normally, service loads are used to calculate the resulting moments, shears, and axial forces, which are multiplied by the appropriate load factors for the various cases of loading for structural design of the pier. If factored loads are applied to the pier, the soil pressures required to maintain equilibrium with these factored loads are used to obtain the moments, shears, and axial forces necessary for strength design of the concrete pier (4.6). Where moments or eccentric loading conditions are involved, the soil pressures required to resist factored loadings could have distributions different from those found for the service load conditions. The soil pressures used for evaluation of the geotechnical capacity should be compatible with the principles of soil mechanics.

4.2.1.1 Axial loads—Axial loads may consist of the axial components of D , D_g , LL , W , E , S_{p1} , S_n , P_q , P_{up} , and P_{an} .

4.2.1.2 Lateral loads and moments—Lateral loads may be caused by unbalanced subgrade pressures, thermal movement of the superstructure, wind, wave, ice, impact, or earthquake-generated forces. Moments may be caused by axial loads applied with eccentricity, by lateral loads, and may be induced by the superstructure through connections to the pier. Moments or lateral loads may also be applied by the subgrade directly or indirectly.

4.2—Loading conditions

Pier forces are determined from whichever combination of loading produces the greater value for the item under investigation.

4.2.1 Axial loads—Maximum and minimum loading conditions should be investigated for pertinent stages of construction and for the completed structure. Load factors should be incorporated in loading equations as indicated in the applicable code.

4.2.1.1 Maximum loading—Excess weight of the pier foundation over the weight of the excavated soil, negative side resistance or downdrag, loads applied due to swelling soils, and long-term redistribution effects on side resistance

should be considered. For example, an initial upward acting side resistance may lessen, disappear, or reverse with time to act as downdrag.

a) *Dead load, live load, side resistance, and uplift, if consistently present:*

When positive, upward acting side resistance is present:

$$(D + L + P_{up}) < (P_q/FS_1 + S_{p1}/FS_2) \quad (4.2.1.1a)$$

If negative side resistance is present:

$$(D + L + P_{up}) < ((P_q + S_{p1})/FS - S_n) \quad (4.2.1.1b)$$

Equation (4.2.1.1a) or (4.2.1.1b), whichever applies to the condition investigated, should always be satisfied.

b) *Dead load, live load, side resistance, uplift and wind or earthquake:*

If positive side resistance is present:

$$(D + 0.75(L + (W \text{ or } E) - P_{up})) < (P_q/FS_1 + S_{p1}/FS_2) \quad (4.2.1.1c)$$

If negative side resistance is present:

$$(0.6D + (L + (W \text{ or } E) - P_{up})) < ((P_q + S_{p1})/FS - S_n) \quad (4.2.1.1d)$$

Often, a factor of 1.33 may be applied to the resistance under short-term loading, but this factor may range from 1.0 to greater than 1.33, depending on the confidence in the resistance and the factor of safety adopted. Some codes may not permit factors greater than 1.0. In Eq. (4.2.1.1c) and (4.2.1.1d), W or E should be entered at its maximum downward acting value. Side friction resistance and end bearing develop at different displacements and are dependent on subgrade properties.

In Eq. (4.2.1.1d), only the value of W that exceeds S_n should be used because at the point of bearing capacity failure, wind load and downward friction cannot be additive. Side resistance is often developed at low displacements of 0.1 to 0.4 in. (3 to 10 mm) whereas tip resistance is developed at large displacements (2 to 5 percent of pier diameter in cohesive soils and elastic parts of the resistance in granular soils) (O'Neill and Reese 1999). Factors of safety should be applied separately to these resistances when considering relative displacement. The value of S_n in Eq. (4.2.1.1d) is sometimes reduced or reversed due to pile strain from applied temporary vertical loading (Terzaghi et al. 1996). A more complete discussion of negative side friction is found in Davisson (1993).

In Eq. (4.2.1.1a) through (4.2.1.1d), uplift P_{up} should be entered at its lowest permanent value only.

4.2.1.2 Minimum loading—In Eq. (4.2.1.2a) through (4.2.1.2c), uplift P_{up} is entered at its maximum value. If

$$(P_{up} + (W \text{ or } E)) < D_g \quad (4.2.1.2a)$$

no further investigation is needed. Otherwise, Eq. (4.2.1.2b) and (4.2.1.2c) should be satisfied.

$$(P_{up} - 0.9D_g) < S_n = (P_{an}/FS_2) \quad (4.2.1.2b)$$

$$P_{up} - 0.9D_g + 1.25W < (S_n + P_{an}/FS_2) \quad (4.2.1.2c)$$

If sufficient side resistance is available, anchors to rock or soil (P_{an}) will not be necessary. In Eq. (4.2.1.2a) and (4.2.1.2c), W should be entered at its maximum upward acting value.

4.2.2 Combined loadings—The lateral loads and moments should be superimposed on simultaneously occurring axial loads in any of the combinations listed in 4.2.1.

4.3—Vertically loaded piers

4.3.1 Capacity from subgrade—The total ultimate axial capacity may be a combination of end bearing and side friction. The theoretical ultimate capacity is expressed in Eq. (4.3.1a)

$$Q = S_{p1} + P_q \quad (4.3.1a)$$

The geotechnical engineer should consider strain compatibility and deflection in determining the safety factor. Safety factors could vary from 1.5 to 5 for side friction or end bearing, depending on the subsurface conditions, structural loads, and degree of confidence in the subsurface parameters. The side friction and end bearing may be described further by the following equations

$$S_{p1} = f_p \cdot A_p \text{ and } P_q = q_b \cdot A_b \quad (4.3.1b)$$

The geotechnical engineer should provide values for f_p and q_b using the soil, rock, or both soil and rock properties and construction method. The values of f_p and q_b vary widely and are depth dependent. Determination of these values may require iterative estimates of the allowable capacity of the drilled pier foundation in collaboration with the structural engineer to satisfy both factor of safety and allowable settlement requirements. Due to strain compatibility requirements, the total ultimate capacity will be less than the maximum theoretical determined from the individual end and side resistance components because peak side resistance typically develops much faster than maximum end-bearing resistance.

Load testing continues to be the most reliable method of developing or confirming design capacities for drilled piers because load-carrying capacity can be impacted by construction means and methods, and no single accepted method of developing service load capacity exists.

4.3.2 Pier settlement—The subgrade compression properties should be determined to permit estimates of total and differential settlement. In-place tests, such as cone penetrometer, DMT, PMT, or plate load at pier subgrade, full-scale load tests, and laboratory tests of undisturbed pier subgrade are commonly used. Total pier settlement is the sum of pier base movement plus elastic pier shortening considering side resistance. The geotechnical engineer's settlement estimate

should consider the effects of adjacent foundations, which can influence the behavior of individual piers (Ulrich and Ehlers 1995; Ulrich 2007).

4.4—Laterally loaded piers

At present, the most complete method for evaluating lateral response of piers is a beam on an elastic foundation mathematical model using a computer and a nonlinear soil response (Reese 1977, 1984; Reese and Wright 1977). Commercial lateral analysis software is available and widely used. The major variables are the subgrade response and pier stiffness ($E_c I$). Subgrade reaction may be modeled as a linear spring or as an elastic-plastic material using p - y data (Reese 1977, 1984; Reese and O'Neill 1988; Reese and Wright 1977). Because no unique method of modeling the subgrade response is universally accepted, the geotechnical engineer should develop the subgrade response model based on the model for which the licensed design professional has relevant local experience.

4.4.1 Lateral loads and moments—Drilled piers will be subject to large lateral loads along the pier length in cases when piers are used as retaining walls; walls to arrest slope movement; anchors; and foundations for power poles, elevated tanks, and tall buildings. When the subgrade pressures on the basement walls are unequal or insufficient to resist the lateral loads within allowable deformation of the superstructure, the foundations should provide the necessary resistance. The piers will then be loaded with lateral forces at the top. Axial forces result from overturning and sometimes moments at the top.

The allowable pier head deflection in each design case may be a few tenths of an inch or a few inches (mm) depending on the project requirements.

Piers that resist lateral load have been designed successfully by approximate methods. The allowable lateral load on a vertical pier is obtained from a table of presumptive values found in some handbooks, building codes, or from simplified solutions that assume a rigid pier and one soil type. These allowable loads, however, might not be appropriate compared with values computed by the method recommended in 4.4.4, and they provide no information on pier deflection. Simplified solutions could be misleading for many drilled pier foundations.

4.4.1.1 Inclined piers—To avoid analyzing a pier for lateral loads, some licensed design professionals assume, according to the approach used for driven piles, that the lateral loads are resisted by the lateral component of axial loads taken by piers installed on an incline. Most methods available for the analysis of a pier group that includes inclined piers are approximate; the movements of the pier head under load are not considered. Inclined piers in design should be used with caution because the contractor often cannot install the piers at the angle desired. Inclined piers provide a much stiffer response at small deflections, often attracting the entire lateral load and causing high localized shear in the pier cap and rotation of the cap. Designs should provide for these loads and deflections.