Introduction to Pile Foundations for Structures

Course No: G02-003

Credit: 2 PDH

J. Paul Guyer, P.E., R.A., Fellow ASCE, Fellow AEI

Continuing Education and Development, Inc.
22 Stonewall Court
Woodcliff Lake, NJ 07677

P: (877) 322-5800
info@cedengineering.com

An Introduction to Pile Foundations for Structures

Guyer Partners
44240 Clubhouse Drive
El Macero, CA 95618
(530)758-6637
jpguyer@pacbell.net

J. Paul Guyer, P.E., R.A.

Paul Guyer is a registered civil engineer, mechanical engineer, fire protection engineer, and architect with over 35 years experience in the design of buildings and related infrastructure. For an additional 9 years he was a senior advisor to the California Legislature on infrastructure and capital outlay issues. He is a graduate of Stanford University and has held numerous national, state and local positions with the American Society of Civil Engineers, National Society of Professional Engineers and Architectural Engineering Institute.

CONTENTS

This course is adapted from the *Unified Facilities Criteria* of the United States government, which is in the public domain, is authorized for unlimited distribution, and is not copyrighted.

The Figures, Tables and Symbols in this document are in some cases a little difficult to read, but they are the best available. **DO NOT PURCHASE THIS COURSE IF THE FIGURES, TABLES AND SYMBOLS ARE NOT ACCEPTABLE TO YOU.**

1. INTRODUCTION

1.1 PURPOSE. This course is an introduction to data, principles, and methods for use in planning, design, and construction of deep foundations. Deep foundations are braced column elements (piles) transmitting structure loads down to the subgrade supporting medium.

1.2 SCOPE. This course is introductory and presents only general information with respect to the selection and design of deep foundations. Single and groups of driven piles and drilled shafts under axial and lateral static loads are treated. This course is not intended for hydraulic structures.

1.3 GENERAL DESIGN METHODOLOGY. A single drilled shaft or a group of driven piles is typically designed to support a column load. The number of driven piles in a group is determined by dividing the column load by the design load of a single pile. The piles should be arranged in the group to provide a spacing of about three to four times the pile diameter B up to $6B$. The diameter of the piles may be increased to reduce the size of the pile cap if appropriate. Table 1-1 describes a general design methodology. Other design methodology aspects are as follows:

1.3.1 LOAD FACTOR DESIGN. This discussion applies load factors for design (LFD) of the structural capacity of deep foundations. The sum of the factored loads shall not exceed the structural resistance and the soil resistance. The LFD, the structural resistance, and the soil resistance are all related to the load factors as follows:

1.3.1.1 DEFINITION. The LFD may be defined as a concept which recognizes that the different types i of loads Q_i that are applied to a structure have varied probabilities of occurrence. Examples of the types of loads applied to a structure include the live load Q_{LL}, dead load Q_{DL}, wind load Q_{WL}, and earthquake load Q_{EL}. The probability of occurrence of each load is accounted for by multiplying each Q by a load factor $F_i > 1.0$. The value of F depends on the uncertainty of the load.

STEP	EVALUATE	DESCRIPTION
1	Soil profile of selected site	Develop depth profiles of water content, liquid and plastic limits, unit weight and overburden pressure, site and unconsolidated-undrained shear strength to a depth of a least twice the width of a pile group or five times the tip diameter of drilled shafts. Estimate shear strength and elastic soil modulus from results of in situ and laboratory triaxial tests. Determine water table depth and extent of perched water. Perform consolidation/swell tests if soil is potentially expansive or collapsible and plot compression and swell indices and swell pressure with depth. Evaluate lateral modulus of subgrade reaction profile. Compare soil profile at different locations on the site.
2	Group similar soils	Group similar soils and assign average parameters to each group or strata.
3	Depth of base	Select a potentially suitable stratum that should support the structural loads such as a firm, nonswelling, and noncollapsing soil of low compressibility.
4	Select type of deep foundation	Select the type of deep foundation such as driven piles or drilled shafts depending on requirements that the foundation includes vertical and lateral load resistance, economy, availability of pertinent construction equipment, and experience. Environmental considerations include allowable noise level, vibrations, overhead clearance, and accessibility of equipment to the construction site. Soil conditions such as potential ground rise (heave) or loss and expansion/collapse also influence type of foundation.
5	Check *Qa* with structural capacity	Allowable pile or shaft load *Qa* shall be within the structural capacity of the deep foundation
6	Design	The design procedure will be similar for most types of deep foundations and requires evaluation of the ultimate pile capacity $Qu = Qsu + Qbu$ where Qsu = ultimate skin friction resistance and Qbu = ultimate end bearing capacity. Reasonable estimates of vertical and lateral displacements under the probable design load Qd are also required. Qd should be within levels that can be tolerated by the structure over its projected life and should optimize operations. Qa = allowable pile capacity. $Qa = Qu/FS$ = factor of safety. A typical $FS = 3$ if load tests are not performed or if the deep foundation consists of a group of driven piles. $FS = 2$ if load tests are performed or 2.5 if wave equation analyses of the driven piles are calibrated with results of pile driving analyzer tests.
7	Verify the design	The capability of the deep foundation to support the structure shall be verified by static load and dynamic tests. These tests are usually nondestructive and allow the tested piles or drilled shafts to be used as part of the foundation.
8	Addition to existing structure	Calculate displacements of existing deep or shallow foundations to determine the ability to carry existing and additional loads and to accommodate new construction.
9	Effect on adjacent structure	Evaluate changes in bearing capacity and groundwater elevation and effect of any action which can result in settlement or heave of adjacent structures.

Table 1-1

General Design Methodology for Deep Foundations

1.3.1.2 STRUCTURAL RESISTANCE. The sum of the factored loads shall be less than the design strength:

$$N_{pf}\ Q_{cap} = F_i\ Q_i \qquad \text{(Eq. 1-1)}$$

where

N_{pf} = performance factor for structural capacity
Q_{cap} = nominal structural capacity, kips
F_i = load factor of type i
Q_i = applied load of type i

1.3.1.3 SOIL RESISTANCE. The sum of the factored loads shall be less than the ability of the soil to resist the loads. This evaluation may be determined by load factors. Factors of safety are often empirical values based on past experience and may lead to a more conservative design than the LFD concept. The FS and the LFD are presented as:

1.3.1.3.1 GLOBAL FS. The allowable load may be evaluated with global FS:

$$Q_a \text{ x } (Q_u/FS) = F_i \text{ x } Q_i \qquad \text{(Eq. 1-2a)}$$

where

Q_a = allowable load that can be applied to the soil, kips
Q_u = ultimate pile capacity, kips
FS = global factor of safety

The approach taken throughout this discussion is to select a global *FS* for analysis of soil resistance rather than partial *FS* or load factors.

1.3.1.3.2 LOAD FACTOR DESIGN. Analysis of soil resistance may also be determined by the LFD concept using performance factors:

$$N_{pfq} \times Q_u = F_i \times Q_i \qquad \text{(Eq. 1-2b)}$$

where N_{pfq} = performance factor appropriate to the ultimate pile capacity. Performance factors N_{pfq} depend on the method of evaluating Q_u and the type of soil resistance, whether end bearing, skin friction, uplift or a group capacity. Load factors and factors of safety taken in combination can lead to an uneconomical foundation design.

1.3.2 UNUSUAL SITUATIONS. Consideration should be given to obtaining the services and advice of specialists and consultants in foundation design where conditions are unusual or unfamiliar or structures are economically significant. Some unusual situations for deep foundations, discussed below, include expansive clay, under-consolidated soil, and coral sands.

1.3.2.1 EXPANSIVE CLAY. The swell of expansive clay can cause an uplift force on the perimeter area of deep foundations that can force the foundation to move up and damage the structure connected to the deep foundation.

1.3.2.2 UNDERCONSOLIDATED SOIL. The settlement of under-consolidated soil can cause negative skin friction on the perimeter area of the deep foundation that can increase the end-bearing load, which results in an increase in settlement of the foundation.

1.3.2.3 CORAL SANDS. Piles in coral sands may indicate low penetration resistance during driving and an apparent low bearing capacity, but the penetration resistance often increases over time as a result of the dissipation of excess pore pressure. Driving of piles into cemented, calcareous sands can crush the soil and lower the lateral stress, which results in a low value for skin friction and bearing capacity.

1.3.3 COMPUTER PROGRAM ASSISTANCE. Design of a deep foundation is normally accomplished with the assistance of several computer programs.

2. TYPES OF PILE FOUNDATIONS. Deep foundations are classified with respect to displacements as large displacement, small displacement and nondisplacement, depending on the degree to which installation disturbs the soil supporting the foundation (Table 1-2). Large displacement and small displacement piles are fabricated prior to installation, driven into the ground in situ, and are often called drilled shafts. Augered cast concrete shafts are also identified as drilled shafts.

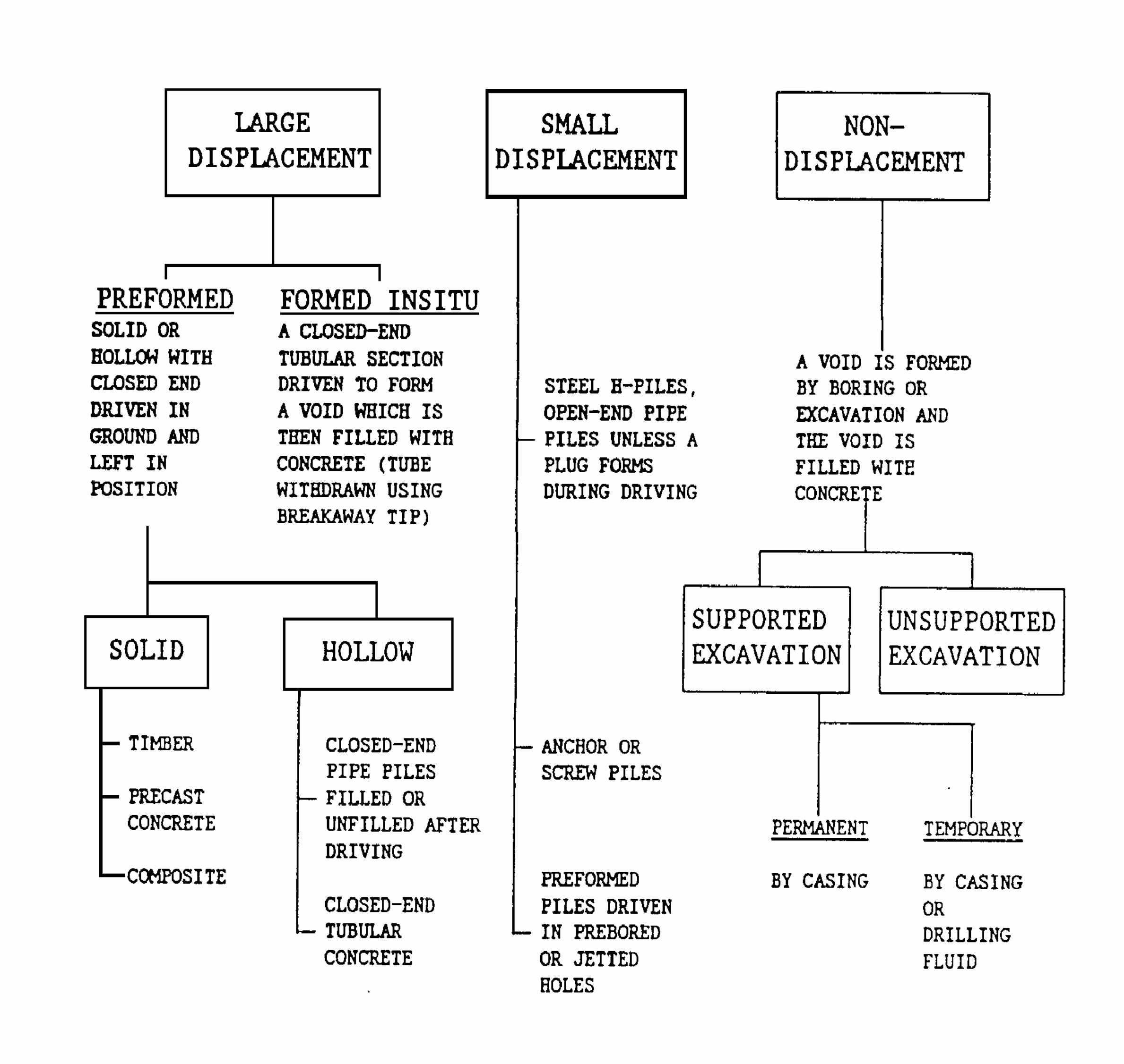


Table 1-2

Types of Deep Foundations

2.1 LARGE DISPLACEMENT PILES. Driven piles are classified by the materials from which the pile is constructed, i.e., timber, concrete, or filled or unfilled steel pipe.

2.1.1 TIMBER PILES. These are generally used for comparatively light axial and lateral loads where foundation conditions indicate that piles will not be damaged by driving, or exposed to marine borers. Overdriving is the greatest cause of damage to timber piles. Pile driving is often decided by a judgment that depends on the pile, soil condition and driving equipment. Overdriving typically occurs when the dynamic stresses on the pile head exceed the ultimate strength of the pile. Timber piles can broom at the pile tip or head, split, or break when overdriven. Such piles have an indefinite life when constantly submerged or where cut off below the groundwater level. Some factors that might affect the performance of timber piles are the following:

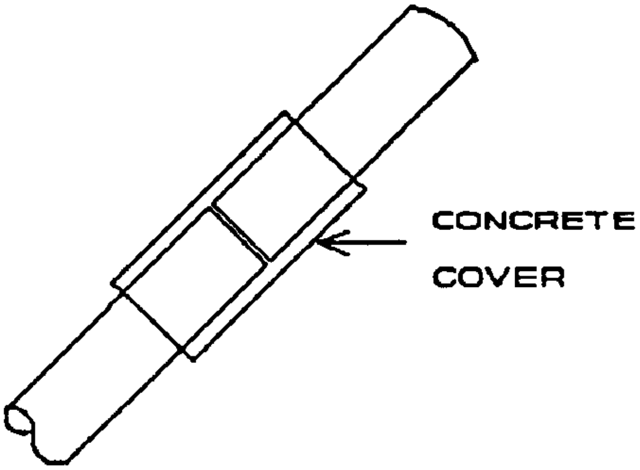
2.1.1.1 Splicing of timber piles is expensive and time consuming and should be avoided. The full bending resistance of timber pile splices may be obtained by a concrete cover (Figure 1-1a). Other transition splicers are available to connect timber with cast concrete or pipe piles.

2.1.1.2 Tips of timber piles can be protected by a metal boot (Figure 1-1b).

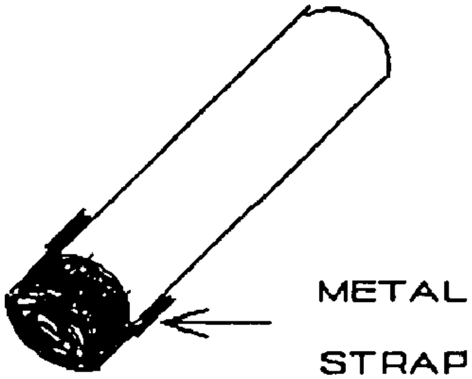
2.1.1.3 Timber piles are normally treated with creosote to prevent decay and environmental attack.

2.1.1.4 American Society for Testing and Materials (ASTM) D 25 provides physical specifications of round timber piles.

2.1.2 PRECAST CONCRETE PILES. These piles include conventionally reinforced concrete piles and prestressed concrete piles. Reinforced concrete piles are constructed with an internal reinforcement cage consisting of several longitudinal bars and lateral ties, individual hoops, or a spiral.



a. TIMBER-TO-TIMBER



b. METAL BOOT

Figure 1-1

Timber Pile Splice and Boot

Prestressed concrete piles are constructed using steel rods or wire strands under tension as reinforcement. Since the concrete is under continuous compression, transverse cracks tend to remain closed; thus, prestressed piles are usually more durable than conventionally reinforced piles. Influential factors for precast concrete piles include splices and steel points.

2.1.2.1 VARIOUS SPLICES are available to connect concrete piles. The splice will provide the tensile strength required during driving when the resistance to driving is low. Figure 1-2a illustrates the cement-dowel splice. Refer to “Foundations” (Pile Buck Inc. 1992) for additional splices.

2.1.2.2 SPECIAL STEEL POINTS can be attached to precast piles during casting of the piles and include steel H-pile tips or cast steel shoes (Figure 1-2).

2.1.3 RAYMOND STEP-TAPERED PILES. These consist of a corrugated steel shell driven into the ground using a mandrel. The shell consists of sections with variable diameters that increase from the tip to the pile head. A mandrel is a heavy, rigid steel tube shaped to fit inside the shell. The mandrel is withdrawn after the shell is driven and the shell filled with concrete. Raymond step-tapered piles are predecessors of drilled shafts and are still popular in the southern United States.

2.1.4 STEEL PILES. These are generally H-piles and pipe piles. Pipe piles may be driven either “open-end” or “closed-end.” Steel piles are vulnerable to corrosion, particularly in saltwater; however, experience indicates they are not significantly affected by corrosion in undisturbed soil. Schematics of H-piles and pipe piles are presented in Figure 1-3.

2.1.4.1 STEEL H-PILES. This type can carry larger loads, both axially and in bending, than timber piles and can withstand rough handling. H-piles can be driven into dense soil, coarse gravel, and soft rock with minimum damage, and cause minimal displacement of the surrounding soil while being driven. Hardened and reinforced pile tips should be used where large boulders, dense gravel, or hard debris may damage the pile. Splices are commonly made with full penetration butt welds or patented splicers (Figure 1-3a). H-piles can bend during driving and drift from planned location. Thus, H-piles may not be suitable when tolerance is small with respect to location and where absolute plumbness is required. Table 1-3 lists commonly available H-piles together with properties and dimensions.

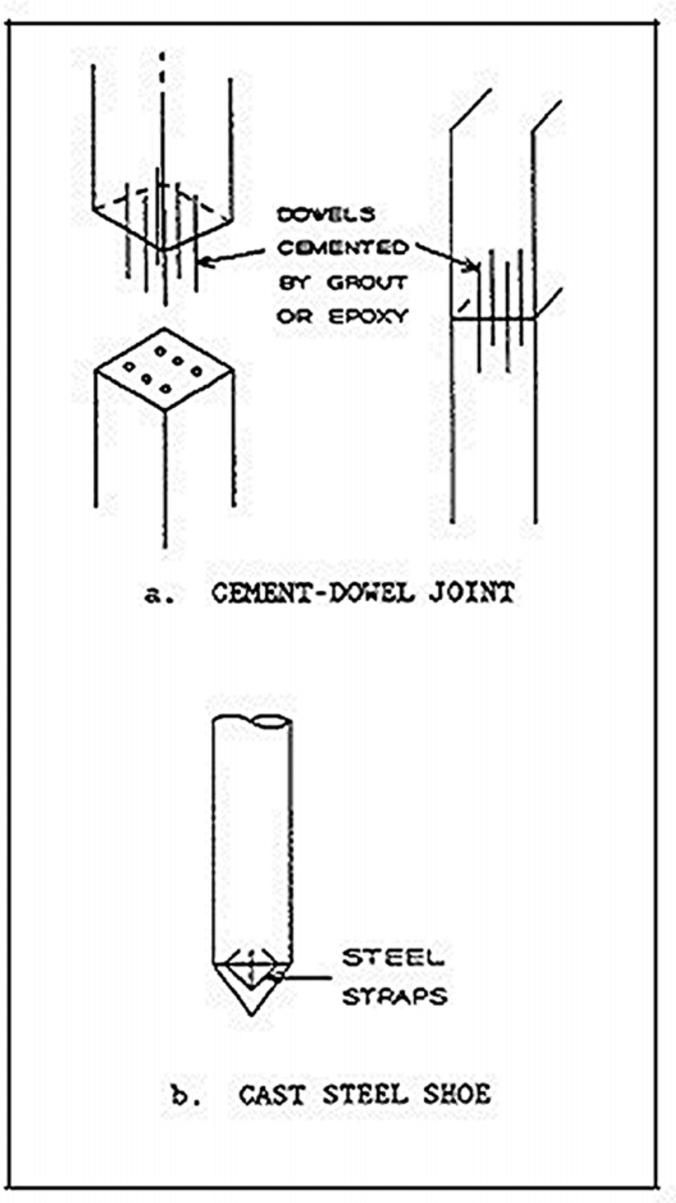
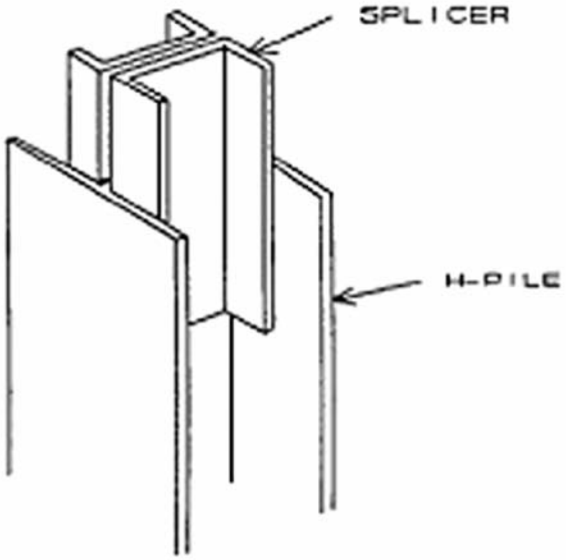
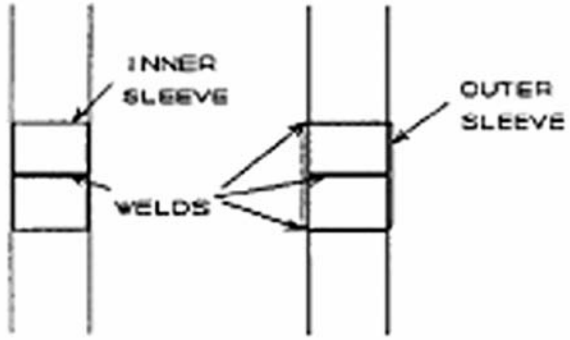


Figure 1-2

Concrete pile splice and boot



a. H-PILE SPLICE



b. PIPE PILE BUTT AND FILLET WELDS

Figure 1-3

Steel pile splices

2.1.4.2 STEEL PIPE PILES. Steel pipe piles are generally filled with concrete after driving to increase the structural capacity. If the soil inside the pipe is removed during driving, open-end piles in cohesionless soil will cause less soil displacement and compaction, and in cohesive soils will cause less heaving of adjacent ground and nearby piles. If the soil inside the pipe is not removed during driving, the pipe becomes plugged and acts as a closed-end displacement pile. Criteria are presently unavailable for computing the depth at which a driven, open-end pile will plug. In cases where the foundation contains boulders, soft rock, or other obstructions, the open-end pile permits inspection after removal of the plug material and ensures that the load will be transferred directly to the load-bearing stratum. Splices are commonly made by full penetration butt welds or fillet wells (Figure 1-3b) or patented splicers.

2.1.5 COMPACTION PILES. These are sometimes driven with the objective of increasing the density of loose, cohesionless soils and reducing settlement. Piles with a heavy taper are often most effective in deriving their support from friction.

2.2 NONDISPLACEMENT PILES. This pile consists of a drilled shaft with a concrete cylinder cast into a borehole. Normally, the drilled shaft does not cause major displacement of the adjacent ground surface. The hole is usually bored with a short flight or bucket auger. Loss of ground could occur if the diameter of the hole is decreased because of inward displacement of soft soil or if there is caving of soil from the hole perimeter. Such unstable boreholes require stabilization by the use of slurry or slurry and casing. Drilled shafts are not subject to handling or driving stresses and therefore may be designed only for stresses under the applied service loads. Nondisplacement may be categorized as follows:

2.2.1 UNCASED SHAFTS. Figure 1-4 illustrates a typical uncased drilled shaft with an enlarged base. The base is not perfectly flat because the shaft is drilled first, then the belling tool rotates in the shaft. Uncased shafts may be constructed in firm, stiff soils where loss of ground is not significant. Examples of uncased shaft are given in the American Concrete Institute (ACI) *Manual of Concrete Practice* (1986). Other terms used to describe the drilled shaft are “pier” or “caisson.” Large shafts greater than 36 inches in diameter are often called caissons. The term “pile” is commonly associated with driven deep foundations of relatively small diameter or cross section.

2.2.2 CASED SHAFTS. A cased shaft is made by inserting a shell or casing into almost any type of bored hole that requires stabilization before placing concrete. Boreholes are caused where soil is weak and loose, and loss of ground into the excavation is significant. The bottom of the casing should be pushed several inches into an impervious stratum to seal the hole and allow removal of the drilling fluid prior to completion of the excavation and concrete placement. If an impervious stratum does not exist to push the casing into it, the concrete can be placed by tremie to displace the drilling fluid.

2.2.3 DRILLING FLUID SHAFTS. Shafts can be installed in wet sands using drilling fluid, with or without casing. This procedure of installing drilled shafts can be used as an alternative to the uncased and cased shafts discussed previously.

2.2.4 PRESSURE-GROUTED SHAFTS. A special type of nondisplacement deep foundation is the uncased auger-placed grout shaft. This shaft is constructed by advancing a continuous-flight, hollow-stem auger to the required depth and filling the hole bored by the concrete grout under pressure as the auger is withdrawn. Careful inspection is required during installation, and shaft continuity should be verified by a combination of load tests and nondestructive testing.

3. SELECTION OF PILE FOUNDATIONS. Deep foundations provide an efficient foundation system for soils that do not have a shallow, stable bearing stratum. Selection of a deep foundation requires knowledge of its characteristics and capacity.

3.1 CHARACTERISTICS. Information adequate for reaching preliminary conclusions about types of driven piles or drilled shafts to be selected for a project is given in Table 1-4. This table lists major types of deep foundations with respect to capacity, application, relative dimensions, and advantages and disadvantages. Refer to *Foundations* (Pile Buck Inc. 1992) for general guidelines in the selection of a type of deep foundation. Relevant codes and standards should be consulted with respect to allowable stresses. A cost analysis should also be performed that includes installation, locally available practices, time delays, cost of load testing program, cost of a pile cap, and other elements that depend on different types of deep foundations.

3.2 CAPACITY. Deep foundations transmit structural loads to deep strata that are capable of sustaining the applied loads. Accurate predictions of load capacity and settlement are not always possible. Adequate safety factors are therefore used to avoid excessive movement that would be detrimental to the structure that is supported and to avoid excessive stress in the foundation. Driven piles or drilled shafts are often used to resist vertical inclined, lateral, or uplift forces and overturning moments which cannot otherwise be resisted by shallow footings. These foundations derive their support from skin friction along the embedded length and by end bearing at the tip (base). Both factors contribute to the total ultimate pile capacity, but one or the other is usually dominant depending on the size, load, and soil characteristics. The capacity of deep foundation is influenced by several factors:

3.2.1 DESIGN LIMITS. The limiting design criterion is normally influenced by settlement in soft and moderately stiff soil, by bearing capacity in hard soil or dense sand, and by pile or shaft structural capacity in rock.

3.2.2 SKIN RESISTANCE MOBILIZATION. Full skin resistance is typically mobilized within 0.5 inch of displacement, while end bearing may not be fully mobilized until displacements exceed 10 to 20 percent of the base diameter or under-ream for drilled shafts, unless the tip is supported by stiff clay, dense sand or rock. Figure1-5 illustrates an example of the vertical axial load displacement behavior of single pile or drilled shaft. The load-displacement behavior and displacements that correspond to the ultimate load are site specific and depend on the results of the analyses.

3.2.3 LATERAL LOADS. Lateral load capacity of a pile or drilled shaft is directly related to the diameter. Therefore, increasing the diameter, increases the load-carrying capacity.

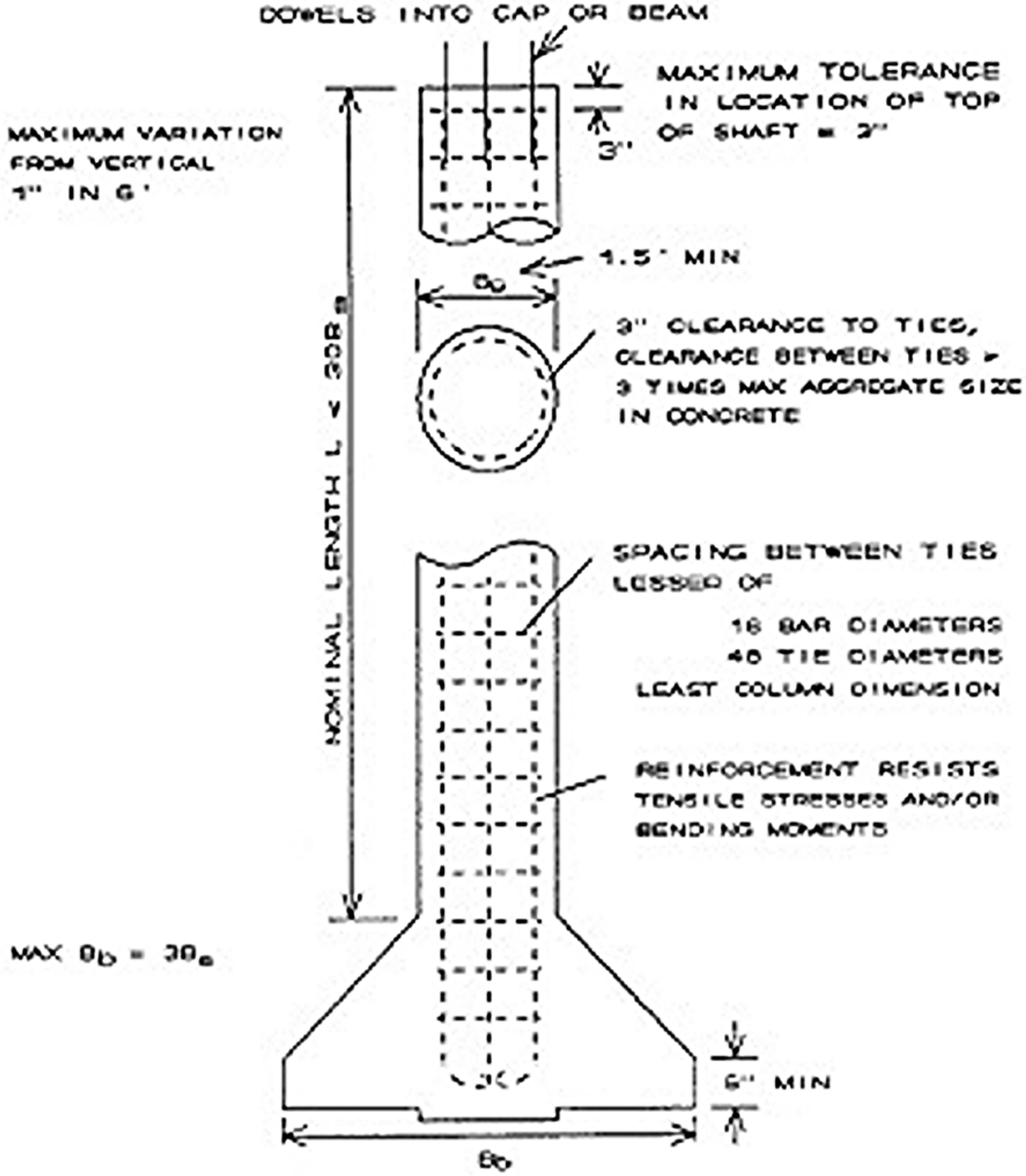
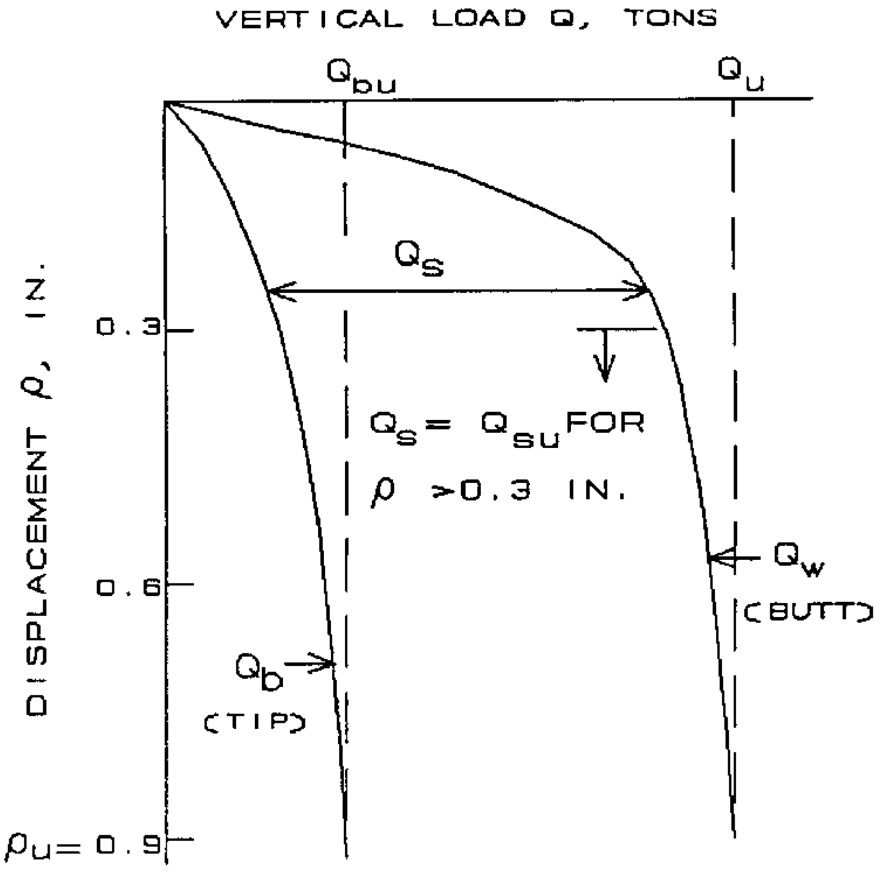


Figure 1-4

Drilled shaft details



$$Q_w = Q_s + Q_b$$

Q_u = ultimate applied load, tons

Q_w - applied load, tons

Q_s - mobilized skin resistance, tons

Q_{su} - ultimate mobilized skin resistance, tons

Q_b - end bearing resistance, tons

Q_{bu} - ultimate end bearing resistance, tons

ρ - displacement, inches

ρ_u - ultimate displacement, inches

Figure 1-5

Axial-Load Deflection Relationship

For a drilled shaft that sustains no axial load, the cost of construction may be optimized by the selection of rigid shafts without underreams and with length/diameter ratios less than 10. The selected shaft dimensions should minimize the volume of concrete required and maximize construction efficiency. The lateral load capacity of driven piles may be increased by increasing the number of piles and battering piles in a pile group. Batter piles are efficient in resisting lateral loads but significantly reduce ductility of the pile group in the lateral direction, resulting in a brittle failure. Vertical piles, though less efficient in resisting lateral loads, are also less stiff and do not fail suddenly. These conflicting characteristics need to be balanced in the design, and they are considered critical where seismic or dynamic lateral loads are involved.

3.3 APPLICATIONS. Driven pile groups are frequently used to support locks, dry docks, and other facilities constructed in river systems, lakes, lagoons, and other offshore applications. Drilled shafts typically support many permanent onshore structures such as administrative buildings, warehouses, and health care facilities. Drilled shafts are divided into two groups: displacement and nondisplacement.

3.3.1 DISPLACEMENT. Driven pile foundations are usually preferable in loose, cohesionless and soft soils, especially where excavations cannot support fluid concrete and where the depth of the bearing stratum is uncertain. Groundwater conditions can be a deciding factor in the selection of driven piles rather than drilled shafts. Uncased shafts are generally excluded from consideration where artesian pressures are present. Often more than one type of driven pile may meet all requirements for a particular structure. Driven piles according to their application are presented in Figure 1-6.

3.3.1.1 Figures 1-6a and 1-6b illustrate piles classified according to their behavior as end-bearing or friction piles. A pile embedded a significant length into stiff clays, silts and dense sands without significant end bearing resistance is usually a friction pile. A pile driven through relatively weak or compressible soil to an underlying stronger soil or rock is usually an end-bearing pile.

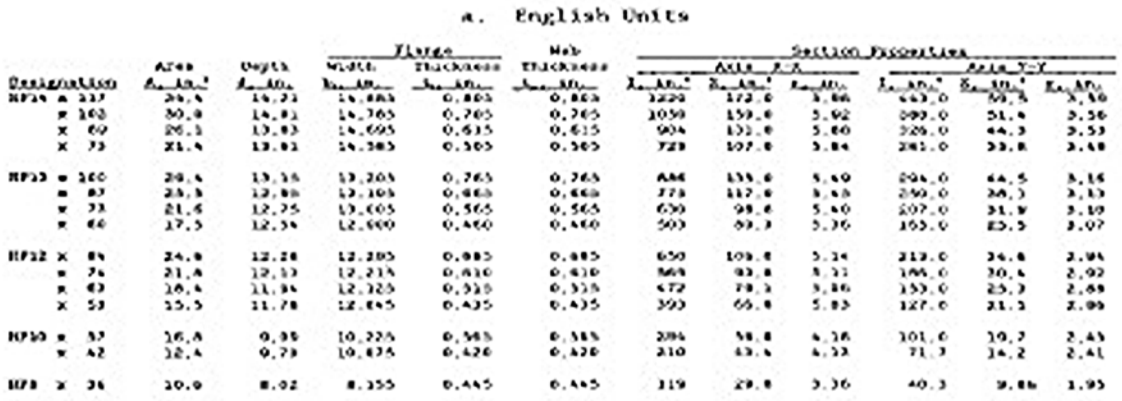
3.3.1.2 Piles designed primarily to resist upward forces are uplift or tension piles (Figure 1-6c), and the resistance to the upward force is by a combination of side (skin) friction and self weight of the pile.

3.3.1.3 Lateral forces are resisted either by vertical piles in bending (Figure 1-6d) or by batter piles or groups of vertical and batter piles (Figure 1-6e).

3.3.1.4 Piles are used to transfer loads from above water structures to below the scour depth (Figure 1-6f). Piles are also used to support structures that may be endangered by future adjacent excavations (Figure1-6g). In order to prevent undesirable movements of structures on shrink/swell soils, a pile anchored as shown in Figure 1-6h can be used.

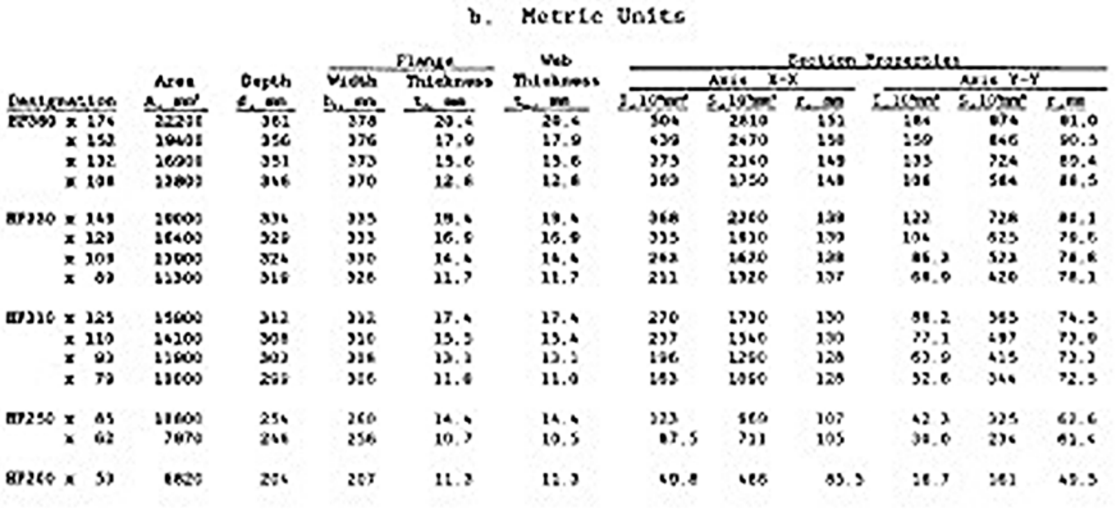
3.3.2 NONDISPLACEMENT. Drilled shafts are especially suitable for supporting large column loads of multistory structures and bridge abutments or piers. They are suitable for resisting large axial loads and lateral loads applied to the shaft butt (top or head) resulting from wind forces. They are also used for resisting uplift thrust applied to the shaft perimeter through soil-shaft interface friction and from heave of expansive soil. Figure 1-7 illustrates example load ranges for drilled shafts in different soils. The loads shown are for guidance only and can vary widely from site to site. Cylindrical shafts are usually preferred to under-reamed ones because of ease in construction and ease in inspection. Table 1-5 provides further details of the applications, advantages and disadvantages of drilled shafts. Other aspects of drilled shafts include the following:

3.3.2.1 Drilled shafts may secure much or all of their vertical load capacity from frictional side resistance (Figure1-7a). An enlarged base using a bell or underream may also increase the vertical load capacity, provide uplift resistance to pullout loads, and resist uplift thrust from heave of expansive soil.



a. English Units

			Flange		Web	Section Properties					
						Axis X-X			Axis Y-Y		
Designation	Area A, in.^{2}	Depth d, in.	Width b_f, in.	Thickness t_f, in.	Thickness t_w, in.	I, in.^{4}	S, in.^{3}	r, in.	I, in.^{4}	S, in.^{3}	r, in.
HP14 x 117	34.4	14.21	14.885	0.805	0.805	1220	172.0	5.96	443.0	59.5	3.59
x 102	30.0	14.01	14.785	0.705	0.705	1050	150.0	5.92	380.0	51.4	3.56
x 89	26.1	13.83	14.695	0.615	0.615	904	131.0	5.88	326.0	44.3	3.53
x 73	21.4	13.61	14.585	0.505	0.505	729	107.0	5.84	261.0	35.8	3.49
HP13 x 100	29.4	13.15	13.205	0.765	0.765	886	135.0	5.49	294.0	44.5	3.16
x 87	25.5	12.95	13.105	0.665	0.665	755	117.0	5.45	250.0	38.1	3.13
x 73	21.6	12.75	13.005	0.565	0.565	630	98.8	5.40	207.0	31.9	3.10
x 60	17.5	12.54	12.900	0.460	0.460	503	80.3	5.36	165.0	25.5	3.07
HP12 x 84	24.6	12.28	12.295	0.685	0.685	650	106.0	5.14	213.0	34.6	2.94
x 74	21.8	12.13	12.215	0.610	0.610	569	93.8	5.11	186.0	30.4	2.92
x 63	18.4	11.94	12.125	0.515	0.515	472	79.1	5.06	153.0	25.3	2.88
x 53	15.5	11.78	12.045	0.435	0.435	393	66.8	5.03	127.0	21.1	2.86
HP10 x 57	16.8	9.99	10.225	0.565	0.565	294	58.8	4.18	101.0	19.7	2.45
x 42	12.4	9.70	10.075	0.420	0.420	210	43.4	4.13	71.7	14.2	2.41
HP8 x 36	10.6	8.02	8.155	0.445	0.445	119	29.8	3.36	40.3	9.88	1.95



b. Metric Units

			Flange		Web	Section Properties					
						Axis X-X			Axis Y-Y		
Designation	Area A, mm^2	Depth d, mm	Width b_f, mm	Thickness t_f, mm	Thickness t_w, mm	I, 10^6mm^4	S, 10^3mm^3	r, mm	I, 10^6mm^4	S, 10^3mm^3	r, mm
HP360 x 174	22200	361	378	20.4	20.4	508	2810	151	184	974	91.0
x 152	19400	356	376	17.9	17.9	439	2470	150	159	846	90.5
x 132	16900	351	373	15.6	15.6	375	2140	149	135	724	89.4
x 108	13800	346	370	12.8	12.8	303	1750	148	108	584	88.5
HP330 x 149	19000	334	335	19.4	19.4	368	2200	139	122	728	80.1
x 129	16400	329	333	16.9	16.9	315	1910	139	104	625	79.6
x 109	13900	324	330	14.4	14.4	262	1620	138	86.2	522	78.8
x 89	11300	319	328	11.7	11.7	211	1320	137	68.9	420	78.1
HP310 x 125	15900	312	312	17.4	17.4	270	1730	130	88.2	565	74.5
x 110	14100	308	310	15.5	15.4	237	1540	130	77.1	497	73.9
x 93	11900	303	308	13.1	13.1	196	1290	128	63.9	415	73.3
x 79	10000	299	306	11.0	11.0	163	1090	128	52.6	344	72.5
HP250 x 85	10800	254	260	14.4	14.4	123	969	107	42.2	325	62.6
x 62	7870	246	256	10.7	10.5	87.5	711	105	30.0	236	61.6
HP200 x 53	6820	204	207	11.3	11.3	49.8	488	85.5	16.7	161	49.5

Table 1-3

Standard H-piles

Shafts subject to pullout loads or uplift thrust must have sufficient reinforcement steel to absorb the tension load in the shaft and sufficient skin friction and underream resistance to prevent shaft uplift movements.

3.3.2.2 The shaft may pass through relatively soft, compressible deposits and develop vertical load capacity from end bearing on hard or dense granular soil (Fig. 1-7b) or rock (Fig. 1-7c). End-bearing capacity should be sufficient to support vertical loads supplied by the structure as well as any downdrag forces on the shaft perimeter caused by negative skin friction from consolidating soil (Fig. 1-7b).

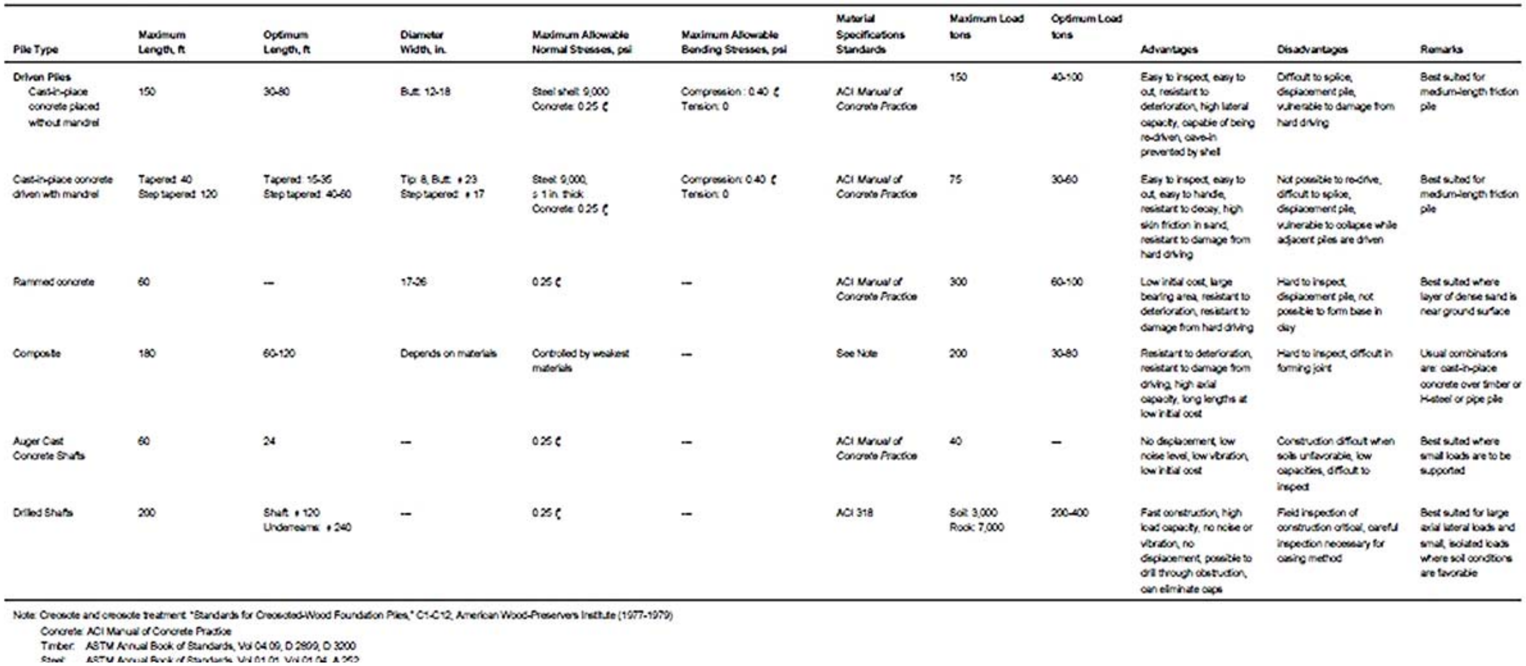
3.3.2.3 Single drilled shafts may be constructed with large diameters, typically 10 feet or more, and can extend to depths of 200 feet or more. Drilled shafts can be made to support large loads and are seldom constructed in closely spaced groups.

3.3.2.4 Drilled shafts tend to be preferred compared with driven piles as the soil becomes harder. Pile driving becomes difficult in these cases, and the driving vibration can adversely affect nearby structures. Also, many onshore areas have noise control ordinances which prohibit 24-hour pile driving (a cost impact).

3.3.2.5 Good information on rock is required when drilled shafts are supported by rock. Drilled shafts placed in weathered rock or that show lesser capacity than expected may require shaft bases to be placed deeper than anticipated. This may cause significant cost overruns.

3.4 LOCATION AND TOPOGRAPHY. Location and topography strongly influence selection of the foundation. Local practice is usually an excellent guide. Driven piles are often undesirable in congested urban locations because of noise, inadequate clearance for pile driving, and the potential for damage caused by vibration, soil densification and ground heave. Prefabricated piles may also be undesirable if storage space is not available. Other variables may restrict the utilization of a deep foundation as follows:

3.4.1 Access roads with limited bridge capacity and head room may restrict certain piles and certain construction equipment.



Pile Type	Maximum Length, ft	Optimum Length, ft	Diameter Width, in.	Maximum Allowable Normal Stresses, psi	Maximum Allowable Bending Stresses, psi	Material Specifications Standards	Maximum Load tons	Optimum Load tons	Advantages	Disadvantages	Remarks
Driven Piles											
Cast-in-place concrete placed without mandrel	150	30-80	Butt: 12-18	Steel shell: 9,000 Concrete: 0.25 ¢	Compression : 0.40 ¢ Tension: 0	*ACI Manual of Concrete Practice*	150	40-100	Easy to inspect, easy to cut, resistant to deterioration, high lateral capacity, capable of being re-driven, cave-in prevented by shell	Difficult to splice, displacement pile, vulnerable to damage from hard driving	Best suited for medium-length friction pile
Cast-in-place concrete driven with mandrel	Tapered: 40 Step tapered: 120	Tapered: 15-35 Step tapered: 40-60	Tip: 8, Butt: • 23 Step tapered: • 17	Steel: 9,000, ≤ 1 in. thick Concrete: 0.25 ¢	Compression: 0.40 ¢ Tension: 0	*ACI Manual of Concrete Practice*	75	30-60	Easy to inspect, easy to cut, easy to handle, resistant to decay, high skin friction in sand, resistant to damage from hard driving	Not possible to re-drive, difficult to splice, displacement pile, vulnerable to collapse while adjacent piles are driven	Best suited for medium-length friction pile
Rammed concrete	60	—	17-26	0.25 ¢	—	*ACI Manual of Concrete Practice*	300	60-100	Low initial cost, large bearing area, resistant to deterioration, resistant to damage from hard driving	Hard to inspect, displacement pile, not possible to form base in clay	Best suited where layer of dense sand is near ground surface
Composite	180	60-120	Depends on materials	Controlled by weakest materials	—	See Note	200	30-80	Resistant to deterioration, resistant to damage from driving, high axial capacity, long lengths at low initial cost	Hard to inspect, difficult in forming joint	Usual combinations are: cast-in-place concrete over timber or H-steel or pipe pile
Auger Cast Concrete Shafts	60	24	—	0.25 ¢	—	*ACI Manual of Concrete Practice*	40	—	No displacement, low noise level, low vibration, low initial cost	Construction difficult when soils unfavorable, low capacities, difficult to inspect	Best suited where small loads are to be supported
Drilled Shafts	200	Shaft: • 120 Underreams: • 240	—	0.25 ¢	—	ACI 318	Soil: 3,000 Rock: 7,000	200-400	Fast construction, high load capacity, no noise or vibration, no displacement, possible to drill through obstruction, can eliminate caps	Field inspection of construction critical, careful inspection necessary for casing method	Best suited for large axial lateral loads and small, isolated loads where soil conditions are favorable

Note: Creosote and creosote treatment: "Standards for Creosoted-Wood Foundation Piles," C1-C12, American Wood-Preservers Institute (1977-1979)
Concrete: ACI Manual of Concrete Practice
Timber: ASTM Annual Book of Standards, Vol 04.09, D 2899, D 3200
Steel: ASTM Annual Book of Standards, Vol 01.01, Vol 01.04, A 252

Table 1-4

Characteristics of Deep Foundations

3.4.2 The cost of transporting construction equipment to the site may be significant for small, isolated structures and may justify piles that can be installed using light, locally available equipment.

3.5 ECONOMY.

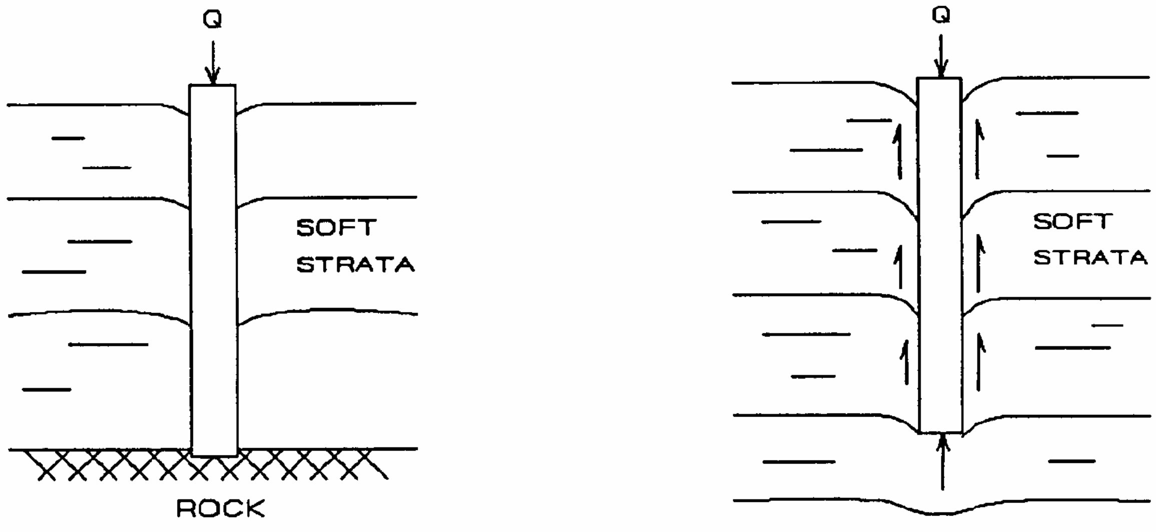
3.5.1 DRIVEN PILES. Costs will depend on driving rig rental, local labor rates, fuel, tools, supplies, cost and freight of pile materials, driving resistance, handling, cutoffs, caps, splicing, and jetting. Jetting is the injection of water under pressure, usually from jets located on opposite sides of the pile, to pre-excavate a hole and to assist pile penetration. Costs are also influenced by downtime for maintenance and repairs, insurance, overhead, and profit margin. An economic study should be made to determine the cost/capacity ratio of the various types of piles. Consideration should be given to including alternative designs in contract documents where practical.

3.5.2 DRILLED SHAFTS. Drilled shafts are usually cost effective in soils above the water table and installation in cohesive soil, dense sand, rock, or other bearing soil overlaid by cohesive soil that will not cave when the hole is bored. Drilled shafts, particularly auger-placed, pressure-grouted shafts, are often most economical if the hole can be bored without slurry or casing.

3.6 LENGTH. The length of the deep foundation is generally dependent on topography and soil conditions of the site.

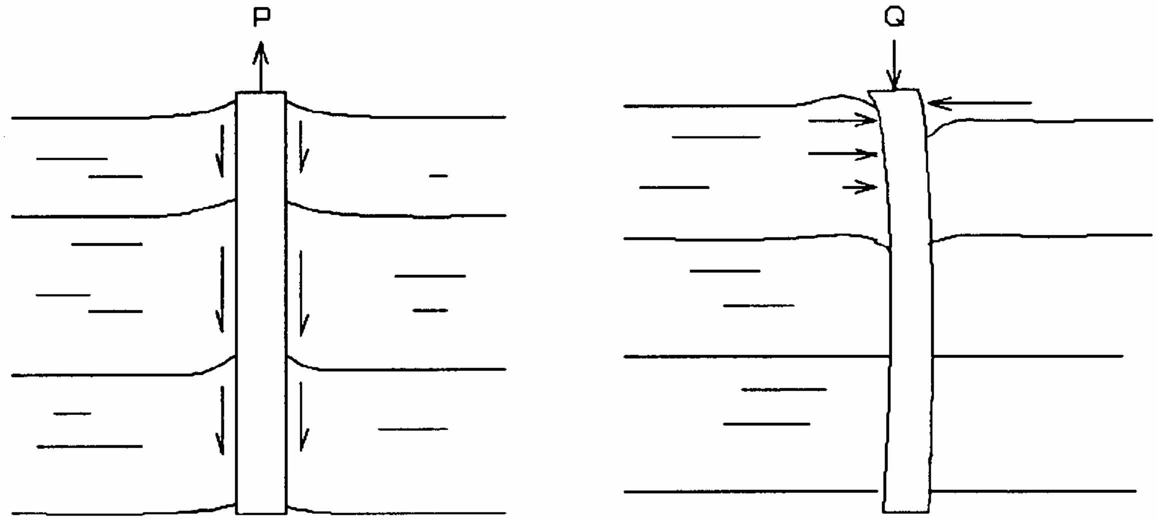
3.6.1 DRIVEN PILES. Pile length is controlled by soil conditions, location of a suitable bearing stratum, availability and suitability of driving equipment, and total pile offshore. Piles up to 150 feet are technically and economically acceptable for onshore installation.

3.6.2 DRILLED SHAFTS. Shaft length depends on the depth to a suitable bearing stratum. This length is limited by the capability of the drilling equipment and the ability to keep the hole open for placement of the reinforcement steel cage and concrete.



a. ENDBEARING PILE

b. FRICTION PILE

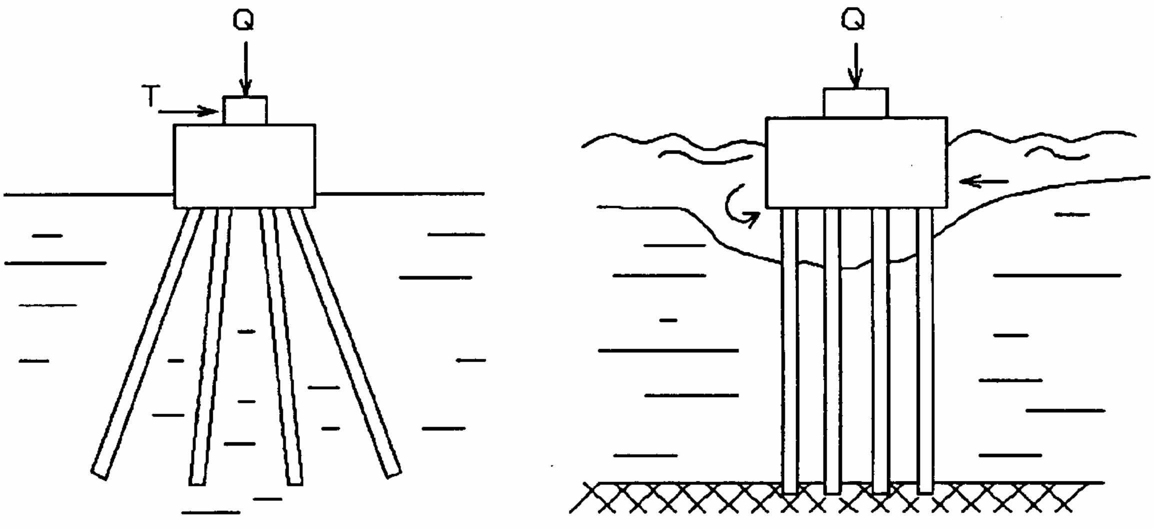


c. TENSION PILE

d. RESISTANCE TO BENDING

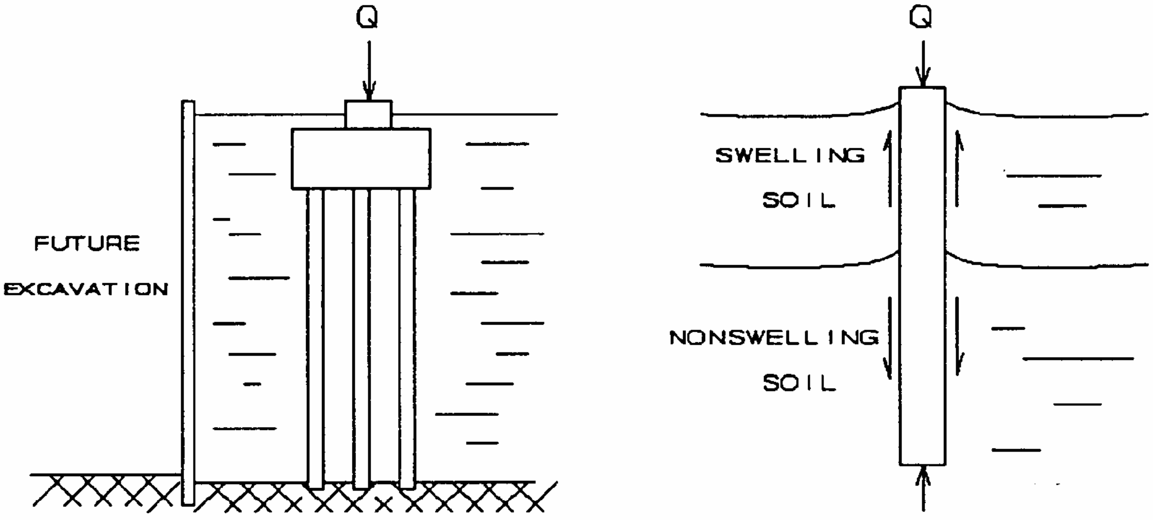
Figure 1-6

Driven pile applications



e. BATTERED GROUP

f. LOAD TRANSFER BELOW SCOUR DEPTH

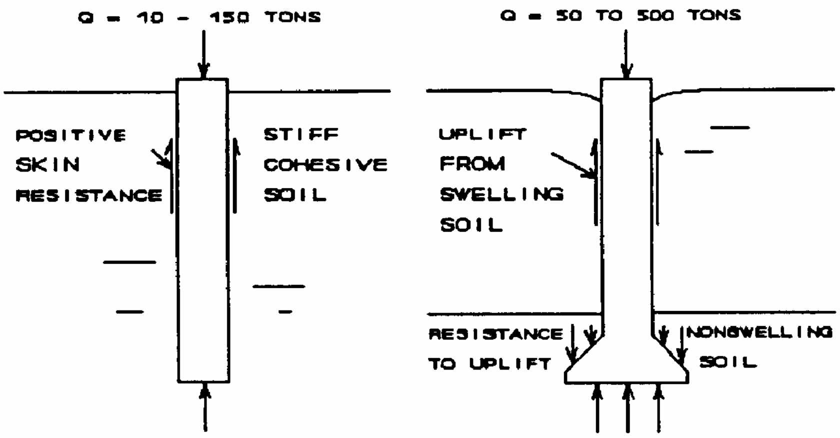


g. SUPPORT FOR FUTURE EXCAVATION

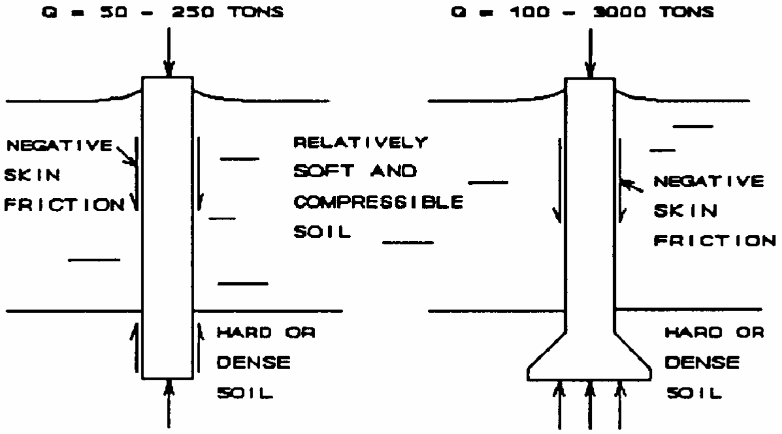
h. PILE ANCHORED IN NONSWELLING SOIL

Figure 1-6 (continued)

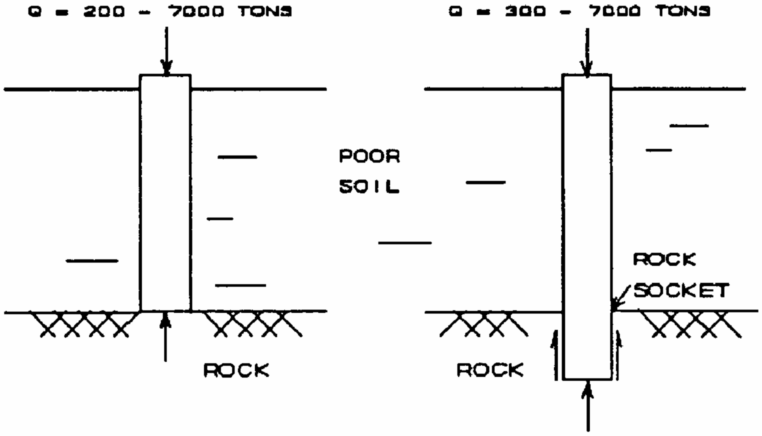
Driven pile applications



a. FLOATING SHAFTS IN HOMOGENENOUS SOIL



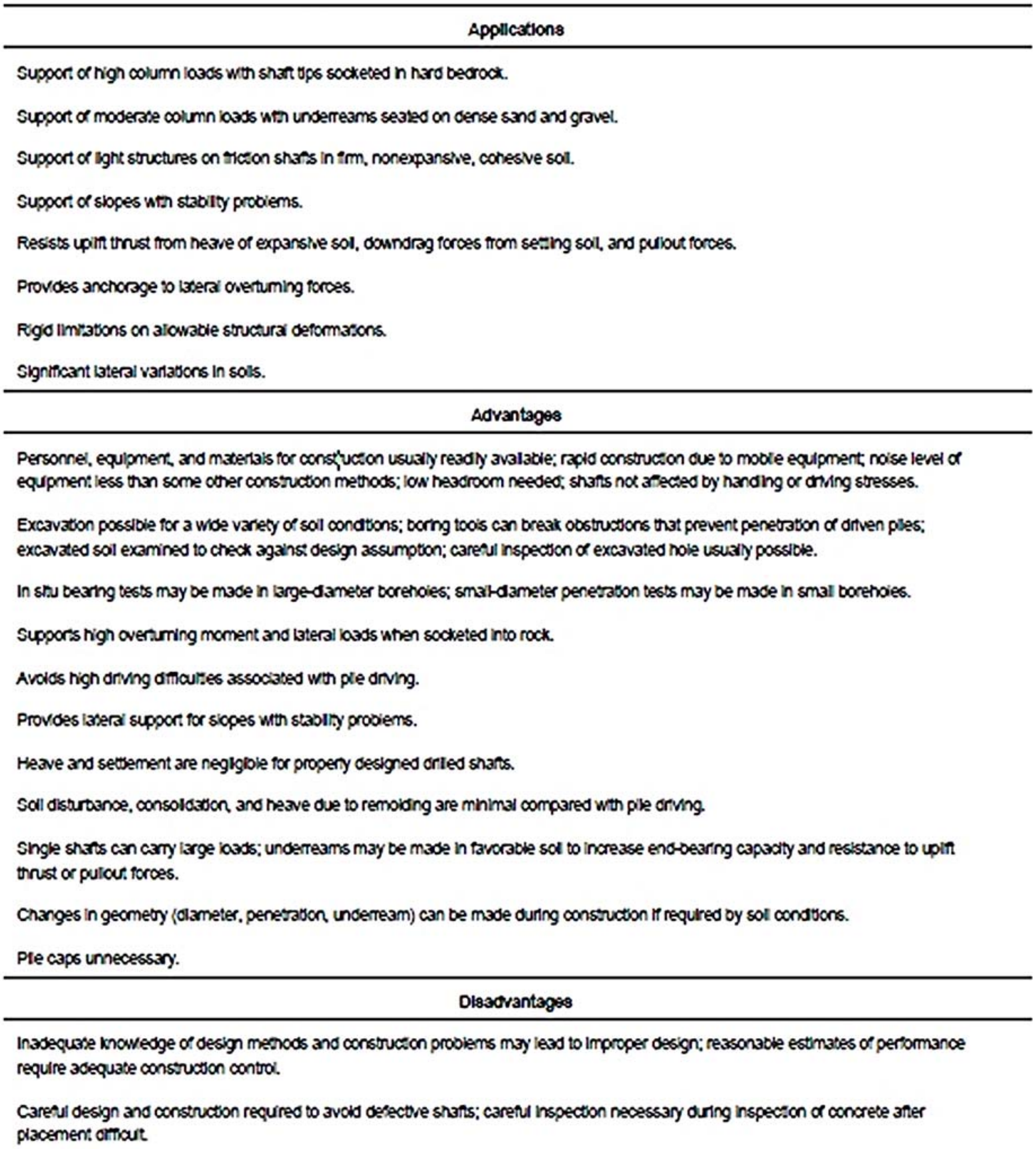
b. SHAFTS END BEARING IN HARD SOIL



c. SHAFTS END BEARING IN ROCK

Figure 1-7

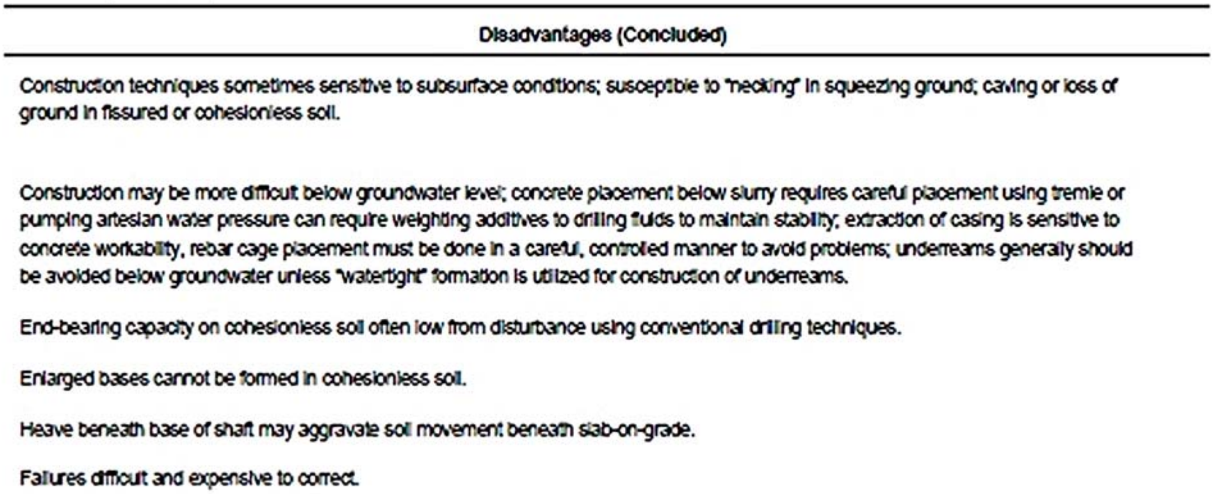
Load resistance of drilled shafts in various soils



Applications
Support of high column loads with shaft tips socketed in hard bedrock.
Support of moderate column loads with underreams seated on dense sand and gravel.
Support of light structures on friction shafts in firm, nonexpansive, cohesive soil.
Support of slopes with stability problems.
Resists uplift thrust from heave of expansive soil, downdrag forces from settling soil, and pullout forces.
Provides anchorage to lateral overturning forces.
Rigid limitations on allowable structural deformations.
Significant lateral variations in soils.
Advantages
Personnel, equipment, and materials for construction usually readily available; rapid construction due to mobile equipment; noise level of equipment less than some other construction methods; low headroom needed; shafts not affected by handling or driving stresses.
Excavation possible for a wide variety of soil conditions; boring tools can break obstructions that prevent penetration of driven piles; excavated soil examined to check against design assumption; careful inspection of excavated hole usually possible.
In situ bearing tests may be made in large-diameter boreholes; small-diameter penetration tests may be made in small boreholes.
Supports high overturning moment and lateral loads when socketed into rock.
Avoids high driving difficulties associated with pile driving.
Provides lateral support for slopes with stability problems.
Heave and settlement are negligible for properly designed drilled shafts.
Soil disturbance, consolidation, and heave due to remolding are minimal compared with pile driving.
Single shafts can carry large loads; underreams may be made in favorable soil to increase end-bearing capacity and resistance to uplift thrust or pullout forces.
Changes in geometry (diameter, penetration, underream) can be made during construction if required by soil conditions.
Pile caps unnecessary.
Disadvantages
Inadequate knowledge of design methods and construction problems may lead to improper design; reasonable estimates of performance require adequate construction control.
Careful design and construction required to avoid defective shafts; careful inspection necessary during inspection of concrete after placement difficult.

Table 1-5

Drilled Shaft Applications, Advantages, and Disadvantages



Disadvantages (Concluded)
Construction techniques sometimes sensitive to subsurface conditions; susceptible to "necking" in squeezing ground; caving or loss of ground in fissured or cohesionless soil.
Construction may be more difficult below groundwater level; concrete placement below slurry requires careful placement using tremie or pumping artesian water pressure can require weighting additives to drilling fluids to maintain stability; extraction of casing is sensitive to concrete workability, rebar cage placement must be done in a careful, controlled manner to avoid problems; underreams generally should be avoided below groundwater unless "watertight" formation is utilized for construction of underreams.
End-bearing capacity on cohesionless soil often low from disturbance using conventional drilling techniques.
Enlarged bases cannot be formed in cohesionless soil.
Heave beneath base of shaft may aggravate soil movement beneath slab-on-grade.
Failures difficult and expensive to correct.

Table 1-5 (continued)

Drilled Shaft Applications, Advantages, and Disadvantages