An Introduction to
Drilled Shaft Foundation Design

By

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Table of Contents

I. A Brief History of Drilled Shafts

Drilled shafts foundations are known by a multitude of names. Among them are drilled piers, cast-in-drilled-hole, bored piles and caissons. "Caissons" are also a common reference to this type of foundation and reflects the history of the development of drilled shaft foundations. Historically, a caisson was the term used to describe very large footing which were sunk into position by excavation. For hundreds of years caisson construction was used in bridge foundation construction. A diagram of caisson construction on the Brooklyn Bridge in the 1870's is shown on the page below.

Some caissons were constructed as "pneumatic caissons". The idea of a "pneumatic caissons" was one in which air pressure was maintained below the caisson so as to prevent the caisson from sinking and prevent water from flowing into the chamber below where workers excavated beneath the caissons cutting edge to sink the caisson to the required bearing stratum. Because of safety issues pneumatic caissons are rarely used today, however, open well caissons are still occasionally used in bridge construction in deep water environments.

A significant evolution in the drilled shaft industry has occurred over the past 80+ years. Machine drilled shafts became more widespread during the 1930's and became increasingly used during the building boom after World War II.

Today the typical drilled shaft foundations are 2 to 12 feet in diameter and can be constructed to depths of as deep as 200+ feet and are used either as a single pile foundation or can be used in groups connected at their top with a concrete pile cap.

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Construction of Brooklyn Bridge showing Caisson Circa 1870

II. Advantages and Limitations of Drilled Shafts

Some of the advantages of using a drilled shaft are:

Low noise and vibration, therefore well suited to use in urban areas and near existing structures

Can be easily adjusted to accommodate variable conditions encountered in production

Small footprint for single shaft foundation without the need for a pile cap

Can penetrate below scour zone into stable scour-resistant formation

Easy construction in cohesive materials including rock

Possible to have extremely high axial load resistance

Suitable to a wide range of ground conditions

Visual inspection of bearing stratum

Excellent strength in flexure

Some of the limitations of using a drilled shaft are:

Requires thorough site investigation with evaluation of conditions affecting construction; potential for differing site conditions to impact costs and schedule

Structural integrity of cast-in-place reinforced concrete member requires careful construction

Requires an experienced and capable contractor which usually performed as specialty work by a subcontractor

Single shaft foundation lacks redundancy and must therefore have a high degree of reliability

Method of construction may be influenced by the performance of the drilled shaft

No direct measurement of axial resistance during installation as with pile driving

May not be efficient in deep soft soils without suitable bearing formation

Load testing of high axial resistance may be challenging and expensive

Construction is sensitive to groundwater or difficult drilling conditions

III. Construction Methods & Considerations

To the casual observer the construction of a drilled shaft appears to be a very simple matter, one simply drills a hole in the ground and concrete and rebar are placed into the hole. In actually, however, the process is much more complex.

A hole of a specific diameter is drilled to some depth depending on the design requirements and the auger must penetrate materials ranging from soft soils to hard rock. The hole must be kept open during the drilling process and measures may need to be in place to prevent the hole from caving in. Casing the hole with pipe with a diameter slightly larger than the auger diameter is typically used if the contractor believes that the soil has a propensity of caving in prior to the placement of the concrete. An additional consideration is if the material at the edge of the borehole wall is loose enough to slough off and fall to the bottom of the drilled shaft. This loose soil could adversely affect the bearing stratum and allows settlement to take place.

If the groundwater table is above the bottom of the drilled shaft and the soil is stable enough to prevent caving in dewatering may be an option to keep the bottom portion of the shaft from pooling.

Drilled shafts which are placed in sand or other types of permeable stratum where there also exists a high water table will require there to be drilling slurry or drilling fluid during the entire operation of drilling the hole and placing the reinforcing and concrete. Another method of preventing a shaft from caving in where a permeable stratum exist is to install a full length casing which provides a stable hole and plain water can often be used instead of slurry. When there is water or slurry in the excavation, the placement of the concrete must be provided using a tremie to prevent the contamination of the concrete.

There are two general procedures that are used when using the tremie method of concrete placement.
1. Using what is called an open tremie; an open pipe is installed into the slurry or water and held a few inches from the bottom of the shaft excavation, a traveling plug commonly called a “pig” is placed into the tremie pipe to act as a separator between the slurry and concrete before to the introduction of concrete.

2. Using what is called a closed tremie; a closed pipe is placed into the shaft, the closed pipe or closed tremie must be watertight to avoid mixing of concrete with water or slurry inside the tremie. Using a sacrificial closure plate placed at the bottom end of the closed tremie pipe provides a seal preventing the mixing of the concrete and slurry or water. The buoyancy of a watertight closed tremie is one limitation of the use of this method relative to an open tremie; in some situations it may be necessary to add weight to make the closed tremie sufficiently heavy to overcome buoyancy.

Knowledge of the construction methods used for the installation of drilled shafts requires an understanding of the sensitivity of the ground conditions. The consideration of drilled shafts requires experience with respect to costs and magnitude of effort in lieu of alternative foundation types.

An example of a partial length casing with the concrete being placed using the tremie method is shown below.

An underreamed or belled shaft is typically used when additional bearing area is desired. Belled shafts require the base of the shaft to be cut with a special tool and can only be achieved in materials which will stand open over an undercut hole. Belled shafts are normally conical in shape. The cylindrical shaft is drilled first and the auger is removed, the belling tool is then attached to cut the soil to form a belled shape at the bottom of the cylindrical shaft. See Figure No. 1 below.

The rebar cage will extend through the center of the shaft and the bell. The portion of the bell outside of the central shaft is not is not normally reinforced.

Underreamed or belled drilled shaft are used less often today due to a variety of factors including safety and the development of drilling rigs capable of drilling larger diameter shafts.

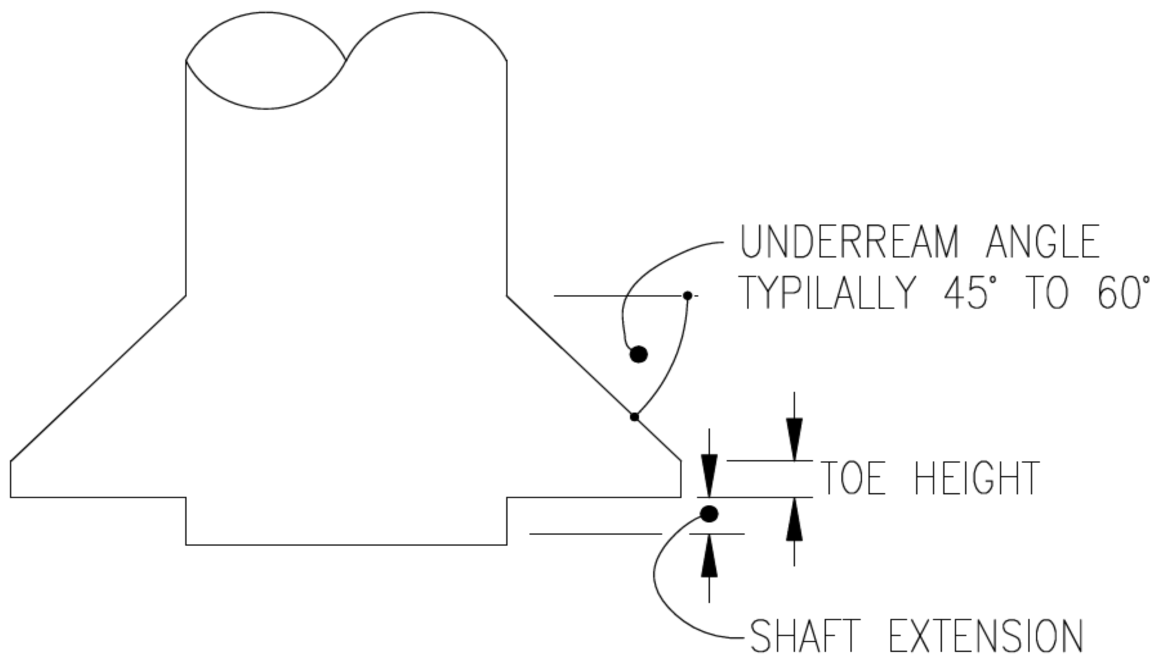


Figure No. 1

For additional information regarding Construction Methods and Considerations of drilled shafts see:

ACI 336.1-01 Specification for the Construction of Drilled Piers

Table of Contents of Specification are Shown Below

VI. Geotechnical Reports

A geotechnical engineering firm is typically hired to do soil borings at a location on the proposed construction site. From the soil borings or in-situ tests a report is produced that communicates the site conditions and design & construction recommendations. The data from the soil borings provide information which is used to estimate soil and rock properties. Frequently used in-situ tests in soils include: standard penetration (SPT), cone penetration (CPT) and piezocone (CPTu). These tests are used to determine the soil response necessary to evaluate the soil properties of both strength and stiffness.

For the design of drilled shafts, information required is divided into three categories:

(1) *Index properties and classification of geomaterials*

All geomaterials fall into one of the following four categories:

(a.) cohesionless soil
(b.) cohesive soil
(c.) rock
(d.) cohesive intermediate geomaterial

(2) *Specific engineering strength and deformation properties*

Shear strength, compressibility, and permeability are engineering properties which have a direct bearing on the behavior of soil and rock masses during and after construction.
Compressibility is used to analyze load displacement and shear strength is used to calculate foundation resistances. Drilled shaft design does not typically require knowledge of permeability.

(3) *Subsurface stratigraphy and groundwater conditions*

Stratigraphy is the study of rock and soil layers while groundwater conditions are particularly important for both design and construction. Groundwater elevation is seasonal and should be anticipated that it could be several feet higher or lower than encountered during the time that the borings were taken.

V. A Brief Overview of Soil Mechanics

Soil mechanics is defined as the science of predicting and understanding how externally applied forces and pressures will cause soil to behave. Some soils are of organic origin. Most soil is the result of weathering rock, which over time is broken down by physical and chemical means into smaller particles. As rock weathers it becomes boulders, then cobbles, gravel, sand, silt and finally clay.

Soils can be divided into two basic types: Residual Soil and Transported Soil. Residual soil is soil which has remained over the rock from which it was produced. This type of soil generally has superior properties for supporting foundation loads than does transported soils.

Transported soils are soils which have been transported or deposited in areas away from the original rock from which they were produced. The manner of transporting these soils would have taken place by the movement of water (Alluvial), blown by the wind (Aeolian) or pushed by glaciers (Glacial).

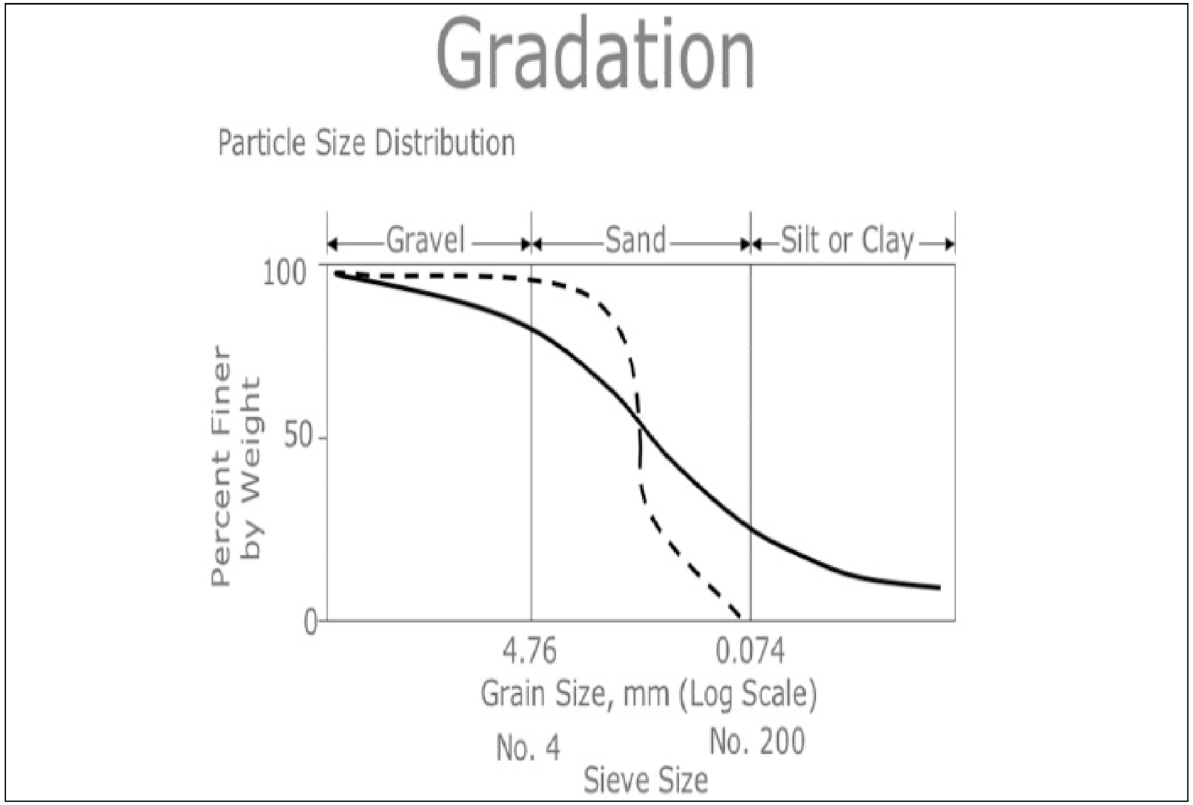
Most soils are comprised of a variety of sediments or particles in addition to air, water and sometimes organic matter. Soils are typically non-homogeneous with particle sizes varying greatly within a given sample. The soil particle sizes and distribution of soil particle sizes influence soil properties and performance. The chart below shows the classification of particle sizes used by the ASTM Unified Soil Classification System.

Soil Particle Sizes			
Type	**Fraction**	**Sieve Size**	**Diameter**
Boulders	**-**	**12″ Plus**	**300 mm Plus**
Cobbles	**-**	**3″ – 12″**	**75 – 300 mm**
	Coarse	**0.75″ – 3″**	**19 – 75 mm**
Gravels	**Fine**	**No. 4 – 0.75″**	**4.76 – 19 mm**
	Coarse	**No. 10 – No. 4**	**2 – 4.76 mm**
	Medium	**No. 40 – No. 10**	**0.42 – 2 mm**
Sand	**Fine**	**No. 200 – No. 40**	**0.074 – 0.412 mm**
Fines(silts & clays)	**-**	**Passing No. 200**	**0.074 mm**

The two basic soil types that are defined by particle size are coarse-grained soils and fine-grained soils. Coarse-grained soils consist of particles that are too large to pass through a #200 sieve (0.074 mm). A #200 sieve has 200 openings per inch. Cobbles, gravels and sands are coarse-grained soils and are commonly referred to as non-cohesive soils. The particles in a non-cohesive soil typically do not stick together unless sufficient moisture is present, which is caused by the surface tension of the water molecules. Fine-grained soils consist of particles that are small enough to pass through a #200 sieve. Silt particles typically range from 0.074 to 0.002 mm while clays are typically smaller than 0.002 mm. Silts and clays are fine-grained soils and are commonly referred to as cohesive soils. Molecular attraction causes the particles of cohesive soils to stick together. The chart below shows the classification of soils used by the ASTM Unified Soil Classification System.

Major divisions			Group Symbol	Group name
Coarse grained soils more than 50% retained on No. 200 (0.075 mm) sieve	gravel > 50% of coarse fraction retained on No. 4 (4.75 mm) sieve	clean gravel <5% smaller than #200 Sieve	**GW**	well graded gravel, fine to coarse gravel
			GP	poorly graded gravel
		gravel with >12% fines	**GM**	silty gravel
			GC	clayey gravel
	sand ≥ 50% of coarse fraction passes No.4 sieve	clean sand	**SW**	well graded sand, fine to coarse sand
			SP	poorly-graded sand
		sand with >12% fines	**SM**	silty sand
			SC	clayey sand
Fine grained soils more than 50% passes No.200 sieve	silt and clay liquid limit < 50	inorganic	**ML**	silt
			CL	clay
		organic	**OL**	organic silt, organic clay
	silt and clay liquid limit ≥ 50	inorganic	**MH**	silt of high plasticity, elastic silt
			CH	clay of high plasticity, fat clay
		organic	**OH**	organic clay, organic silt
Highly organic soils			**Pt**	peat

Grains size distribution of a soil is also conveniently presented by the use of a semi-logarithmic graph as shown in the figure below.



By the use of this type of visual representation of the soil's grain size distribution, it is clear that the solid line represents a well-graded soil, while the dashed line represents a poorly graded soil.

Shear strength is one of the most important engineering structural properties of soil. Shear strength refers to the soils ability to resist sliding along internal surfaces and is the property which influences bearing capacity. Shear strength results from three sources: the friction between the particles, particle interlocking, and the chemical bond between the particles. For non-cohesive soils, such as sands and gravels, the shear strength is expressed by the following equation:

$$S = \sigma \tan \phi$$

where: $S =$ shear strength or shearing stress at failure

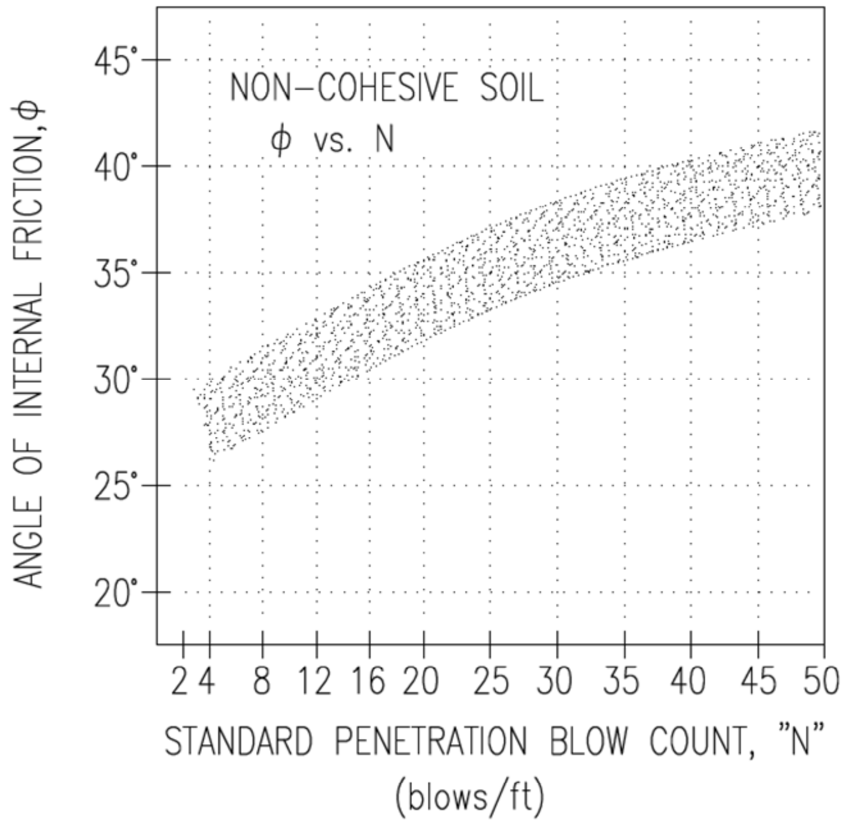
$\sigma =$ normal stress acting on the plane of failure

$\phi =$ angle of internal friction

There are several methods for determining ϕ, the angle of internal friction. A geotechnical engineering consultant typically performs one of the tests to determine the angle of internal friction following their sub-surface exploration. The Triaxial Shear test is the most accurate test to determine the angle of internal friction, however, there is a correlation between the "N" values (blows per foot) and ϕ if the Standard Penetration Test (SPT) ASTM D 1586 is used. The relationship between ϕ and standard penetration number for sands is shown in the chart below (*from* Peck 1974, *Foundation Engineering Handbook*).

SPT Penetration, N-Value (blows/ foot)	**Density of Sand**	ϕ (degrees)
<4	Very loose	<29
4 - 10	Loose	29 - 30
10 - 30	Medium	30 - 36
30 - 50	Dense	36 - 41
>50	Very dense	>41

Standard Penetration Numbers for Sand



Approximate correlation between ϕ and N for non-cohesive soils

For cohesive soils such as clays and some silts, the shear strength is expressed by the following equation:

$$S = c + (\sigma - u)\tan\phi$$

where: S = shear strength or shearing stress at failure, also denoted as C_u

c = cohesion

σ = total stress acting on the plane of failure

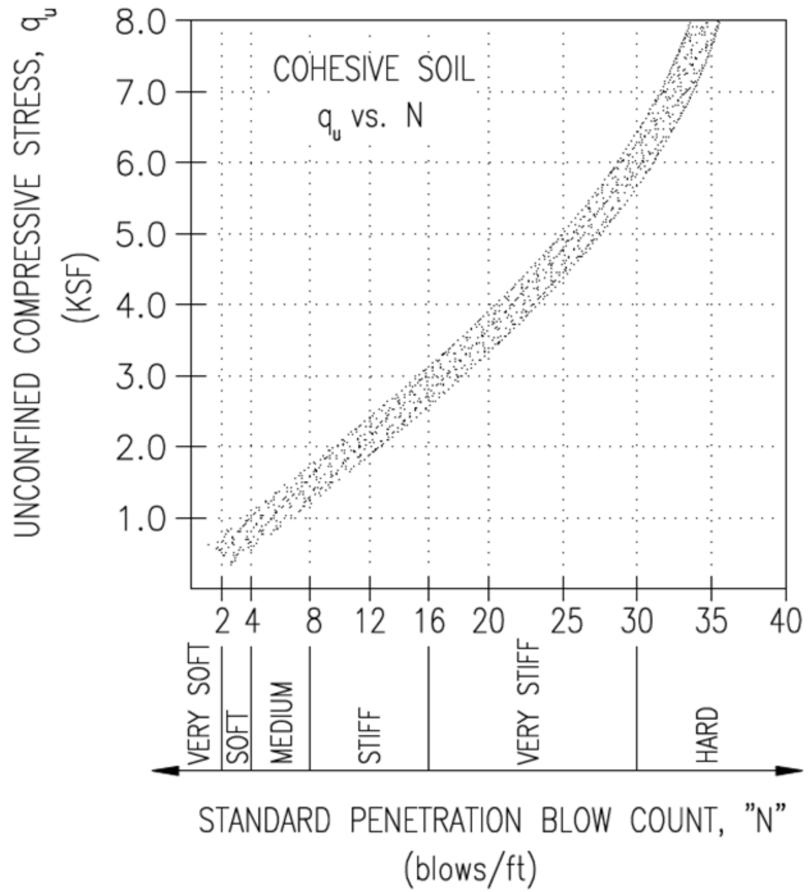
ϕ = angle of internal friction

u = pore water pressure

There are several methods for determining c, the cohesion. A geotechnical engineering consultant typically performs one of the tests to determine the cohesion following their sub-surface exploration. The Unconfined Compression Test is the most widely used method, however, there is a correlation between the "N" values (blows per foot) and cohesion if the Standard Penetration Test (SPT) ASTM D 1586 is used. The empirical relationship between the standard penetration number "N" for cohesive soils and the unconfined compressive strength is shown in the chart below (from Foundation Analysis, Bowels).

SPT Penetration (blows/ foot)	**Estimated Consistency**	C_u (kips/ft^2)
0 - 2	Very Soft	0 - 0.5
2 - 4	Soft	0.5 - 1.0
4 - 8	Medium	1.0 - 2.0
8 - 16	Stiff	2.0 - 4.0
16 - 32	Very Stiff	4.0 - 8.0
>32	Hard	>8

Most soils are neither completely cohesive (friction angle = 0^o) or completely non-cohesive (cohesion = 0). If cohesive and friction properties both exist, the soil is considered mixed or a c-ϕ soil. It is recommended that the engineer be familiar with this type of soil and that the properties of these types of mixed or c-ϕ soils be interpreted by a geotechnical engineer.



Approximate correlation between q_u and N for cohesive soils

VI. Drilled Shaft Supporting Axial Load Only

Note: The procedures described in this section are applicable to the design of drilled shafts without permanent casing.

Many applications for drilled shafts are for forces which transmit predominately axial compression to the drilled shaft with zero to small moment and shear. These drilled shafts can be designed for axial compression only.

a.) Compression Loading

The equation below can be utilized in LRFD for calculating the factored nominal structural resistance of a short, reinforced concrete column subjected to compressive axial load only.

$$P_r = \phi P_n = \phi\beta\, [0.85\, f_c'\,(A_g - A_{st}) + A_{st}\, f_y]$$

Where: P_r = Factored axial resistance of an axially loaded short column (drilled shaft)

P_n = Nominal axial resistance, (kips)

ϕ = Resistance factor, (see below)

β = Reduction factor, 0.85 for spiral reinforcement, and 0.80 for tie reinforcement.

f_c' = Specified minimum compressive strength of concrete, (ksi)

A_g = Gross area of section, (in^2)

A_{st} = Total area of longitudinal reinforcement, (in^2)

f_y = Specified yield strength of reinforcement, (ksi)

For compression-controlled sections with either spiral or ties used for transverse reinforcement the resistance factor, ϕ, is equal to 0.75.

The minimum amount of longitudinal reinforcement is affected by both the strength of the steel and the strength of the concrete. AASHTO specifies a range for the amount of steel reinforcement allowed in the cross-section of a drilled shaft. The maximum allowable area of longitudinal reinforcing steel, A_{st}, is 8.0% of the gross cross-sectional area of the shaft, A_g. The minimum allowable area of longitudinal reinforcing steel, A_{st}, is 1.0% for the portions of the shaft that behave as a column.

$$0.01 \leq \frac{A_{st}}{A_g} \leq 0.08$$

A reasonable percentage of steel is typically from 1 to 4 percent and preferably not more than 2% to 2.5% of the gross column section area, A_g., if the drilled shaft is subjected to an axial load and only a zero to small moment and shear.

For any portion of a drilled shaft above the depth at which the shaft is laterally supported, the drilled shaft behaves as a column and the minimum longitudinal reinforcement amount is determined by:

$$0.08A_g \geq A_{st} \geq 0.135 \frac{A_g f'_c}{f_y}$$

The minimum allowable diameter of longitudinal reinforcing bar is ⅝" (No. 5 rebar). The longitudinal reinforcing bars should be evenly distributed in a circular arrangement and not less than 6 bars in number. The minimum clear distance between longitudinal reinforcing bars shall be not less than 5 times the maximum aggregate size or 5.0 inches, whichever is greater. If the above minimum spacing cannot be achieved by evenly spacing single longitudinal reinforcing bars then bundled longitudinal reinforcing bars may be required in order to maximize the clear space between the reinforcement bars.

For a graphic depiction see Figure No. 2 below.

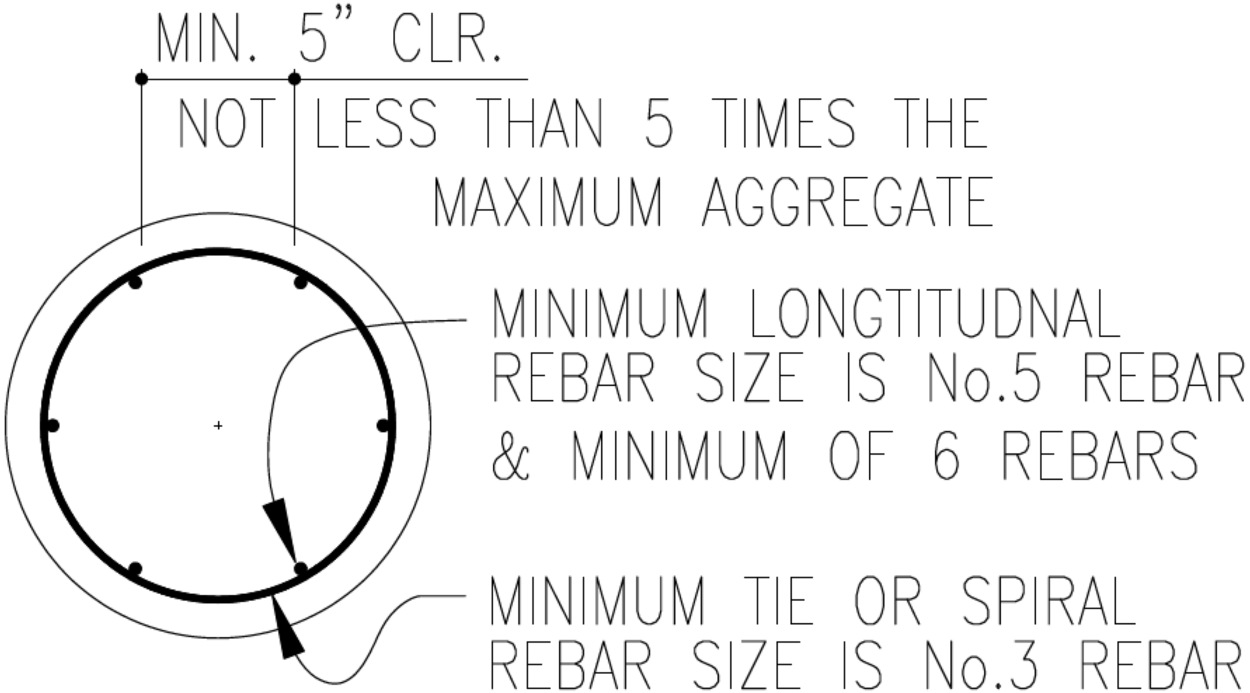

MIN. 5" CLR.
NOT LESS THAN 5 TIMES THE MAXIMUM AGGREGATE
MINIMUM LONGTITUDNAL REBAR SIZE IS No.5 REBAR & MINIMUM OF 6 REBARS
MINIMUM TIE OR SPIRAL REBAR SIZE IS No.3 REBAR

Figure No. 2

b.) Tension Loading

Drilled shafts subjected to uplift force effects, either from load combinations or from expansive soils, can be regarded as tension members and the axial forces are assumed to be resisted by the steel elements only. The LRFD equation for structural strength in tension is:

$P_r = \phi P_n = \phi f_y A_{st}$
Where: P_r = Factored axial resistance in tension
P_n = Nominal axial resistance in tension, (kips)
ϕ = Resistance factor = 0.90
A_{st} = Total area of longitudinal steel reinforcement, (in^2)
f_y = Specified yield strength of steel reinforcement, (ksi)

c.) Transverse Steel Reinforcement

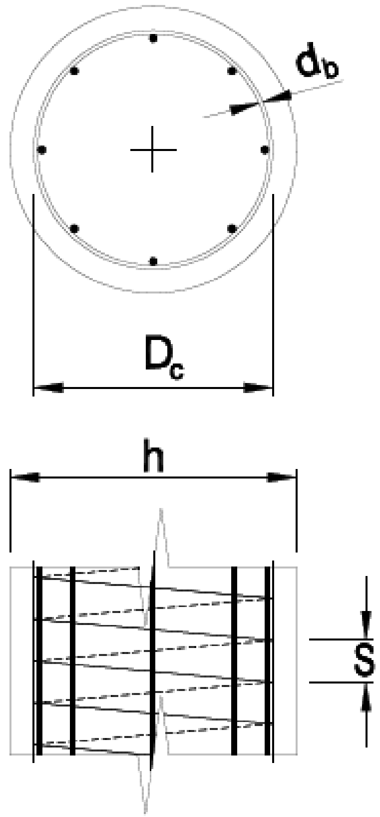
AASHTO specification for tied compression members states that "*all longitudinal bars or bundles shall be enclosed by lateral ties that shall be equivalent to:*

- *No. 3 bars for No. 10 or smaller bars*
- *No. 4 bars for No. 11 or larger bars*
- *No. 4 bars for bundled bars*

The spacing of ties along the longitudinal axis of the compression member shall not exceed the least dimension of the compression member or 12.0 in. Where two or more bars larger than No. 10 are bundled together, the spacing shall not exceed half the least dimension of the member or 6.0 in. Deformed wire or welded wire fabric of equivalent area may be used instead of bars."

AASHTO specification for spiral reinforcement members states that *"the ratio of spiral reinforcement to total volume of concrete core, measured out-to-out of spirals, shall satisfy:"*

$$\rho_s \geq 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f'_c}{f_{yh}}$$



where:

$$\rho_s = \frac{\text{volume of spiral steel per one revolution}}{\text{volume of concrete core contained in one revolution}}$$

D_c = diameter of concrete core out-to-out of spiral (in.)
h = diameter of concrete shaft (in.)
f_{yh} = specified yield strength of spiral reinforcement (ksi)
a_s = cross-sectional area of spiral reinforcement (in^2)
d_b = diameter of spiral reinforcement (in.)

which yields $A_g = \dfrac{\pi h^2}{4}$ & $A_c = \dfrac{\pi D_c^2}{4}$

where

A_g = gross area of column section (in^2) Figure No. 3

A_c = area of the concrete core measured to the outside diameter of the spiral (in^2)

The pitch can be determined by the equation; $s = \dfrac{4a_s(D_c - d_b)}{\rho_s D_c^2}$

Figure No. 3

d.) Splices for Compression Steel

When the length of the rebar cage exceeds the length of the available reinforcing bars, which is normally supplied in lengths of 60 ft, splicing of the longitudinal reinforcement is required. Lapping or splicing the longitudinal steel such that the length of each rebar is sufficient to develop the full capacity of each bar in tension or compression is required for the appropriate development length to be achieved by each bar.

Staggering the splices in the longitudinal steel is also required so that no more than 50 per cent of the splices occur at the same level along the rebar cage. In addition, with respect to constructability, a large number of lap splices occurring at the same level can result in an obstruction to concrete flow. Placing splices in zones near the location of maximum flexural stresses in the drilled shaft when large lateral loads are anticipated should be avoided.

The AASHTO specification for Compressive Development Length states, "*The basic development length, ℓ_{db}, for deformed bars in compression shall satisfy*:

$$\ell_{db} \geq \frac{0.63\ \mathrm{d}_b f_y}{\sqrt{f'c}} \qquad \text{or:} \qquad \ell_{db} \geq 0.3\ \mathrm{d}_b f_y$$

In no case should the development length ℓ_{db} be less than 8.0 inches for bars in compression.

where:

ℓ_{db} = basic development length for straight reinforcement steel to which modification factors are applied to determine ℓ_d (in.)

ℓ_b = diameter of bar (in.)

<u>NOTE</u>: See AASHTO Specification for Modifications Factors which apply to spirals and bundled bars.

e.) Splices for Tension Steel

The AASHTO specification for Tension Development Length states, "*The basic tension development length, ℓ_{db}, in inches shall be taken as*:

For No. 11 bars and smaller ………….. $\dfrac{1.25\ A_b f_y}{\sqrt{f'c}}$

But not less than……………… $0.4\ d_b f_y$

For No. 14 bars and smaller ………..….. $\dfrac{2.7\ f_y}{\sqrt{f'c}}$

For No. 18 bars and smaller ………..….. $\dfrac{3.5\ f_y}{\sqrt{f'c}}$

In no case should the development length ℓ_{db} be less than 12.0 inches for bars in tension.

where:

A_b = area of bar, (in^2)
d_b = diameter of bar, (in)
f_y = specified yield strength of reinforcing bars, (ksi)
f'_c = specified compressive strength of concrete at,(ksi)

It should be noted that the longitudinal steel may be in tension under some loading conditions due to bending even though the drilled shaft as a whole may be in net compression and therefore, the development lengths for tension reinforcement should be used. The basic development lengths for compression and tension also apply to the splices for transverse steel. Splices for longitudinal reinforcement under *axial tension only* for drilled shafts shall be made exclusively with full-welded splices or full-mechanical splices.

NOTE: See AASHTO Specification for Modifications Factors which apply to spirals, epoxy-coated bars and lightweight concrete.

f.) Effects of Groundwater levels

Groundwater levels will be needed by contractors and engineers to establish appropriate construction methods. Groundwater level encountered at the time the geotechnical boring is taken and at 24 hours after completion of boring should be recorded on the boring log. Seasonal fluctuations of the water table should be determined and will have significant impact on design and construction.

The level of the water table can have a dramatic impact on the total load which the drilled shaft will be required to support. When the water table is at or below the bottom of the drilled shaft the weight of the concrete will be 150 Lbs/Cu Ft, while if, on the other extreme, the water table is at the top of the drilled shaft the weight of the concrete will be [150 Lbs/Cu Ft – 62.4 Lbs/Cu Ft] = 87.6 Lbs/Cu Ft. To determine the maximum and minimum force which will be applied from the weight of the concrete cylinder which forms the drilled shaft the designer will be required to make two calculations based on the anticipated highest and lowest levels of the water table.

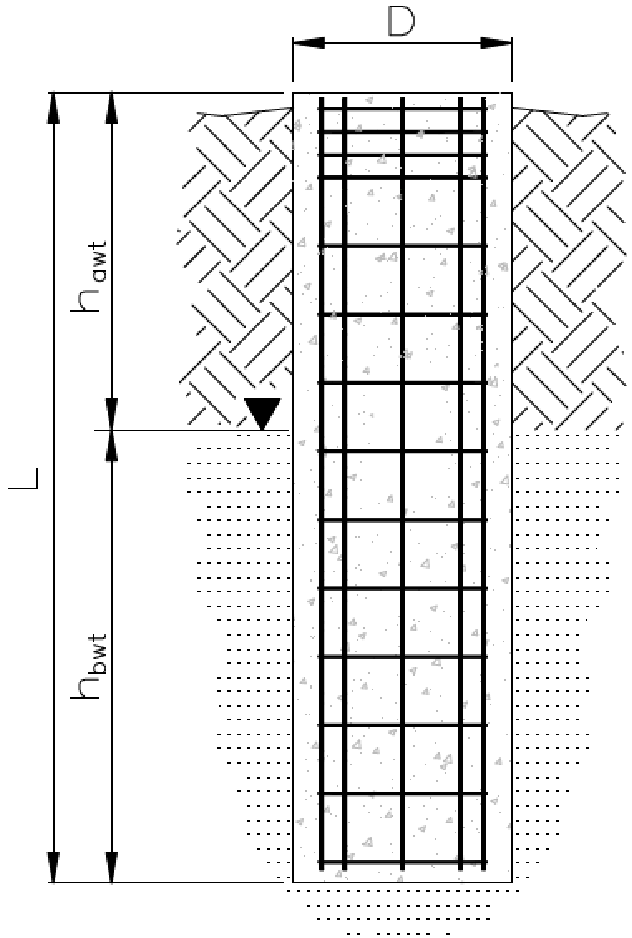
total height of the drilled shaft = L

the portion of the drilled shaft below the water table = h_{bwt}
and

the portion of the drilled shaft above the water table = h_{awt}

The maximum or minimum force (W_{ds}) which will be applied from the weight of the concrete cylinder which forms the drilled shaft will be equal to:

$$W_{ds} = \left(h_{bwt} \text{ X } \frac{\pi D^2}{4} \text{ X } 87.6\right) + \left(h_{awt} \text{ X } \frac{\pi D^2}{4} \text{ X } 150\right)$$



Axial Loaded Drilled Shaft Calculation Example

In this example a geotechnical report is provided with the following verbiage in italics.

The ultimate values given in the following table include a minimum factor of safety of 2.0.
Note: *Ultimate end bearing values are only valid below the depth of 4 shaft diameters.*

Consider an factored axial load, $P_n = 60$ kips, the shear and moment loads are near zero.
$f_c' = 4{,}000$ psi
$f_y = 60$ (ksi)
For the purpose of analysis, the water table will be presumed to be below the bottom of the drilled shaft.

Drilled Shaft Design Parameters

Depth (feet below existing grade)	Ultimate Skin Friction (Kips/Square Foot)	Ultimate End Bearing (Kips/Square Foot)
0 to 4	neglect	neglect
4 to 6	0.11	neglect
6 to 12	0.80	neglect
12 to 18	0.20	3.1
18 to 25	0.91	4.2

Based on the defined parameters stated above if the drilled shaft will be in part supported by End Bearing then the minimum diameter must be ≥ 3.0 feet. Note: Typically, shaft diameters are in increments of 6”,

therefore, for a drilled shaft 3.0 feet in diameter and 12.0 feet of embedment + 1.0 foot of projection = 13.0 feet

Weight of drilled shaft = h_{awt} X $\frac{\pi D^2}{4}$ X 150 = 13 X $\frac{\pi 3^2}{4}$ X 150 = 13,784 Lbs or 13.8 kips

The total factored load + the weight of the drilled shaft = 60 kips + 13.8 kips = 73.8 kips
Ultimate End Bearing using a factor of safety of 2.0 @ a depth of 12 feet = 3.1 kips/ft^2

The end bearing area = $\frac{\pi 3^2}{4} = 7.07$ ft^2 and $7.07 \text{ X } 3.1 = 21.9$ kips

Summing the skin friction resistance between the depths of 4 feet and 12 feet yields:

π X 3ft X [((6-4) X 0.11) + ((12-6) X 0.80)] = 47.3 kips
end bearing + skin friction = 21.9 + 47.3 = 69.2 kips ≥ 60 kips ***OK,*** based on soil resistance parameters

Determining the diameter of drilled shaft and the exact percentage of the area of longitudinal reinforcement steel is a trial and error process.

Assume that ties will be used rather than spirals for the Transverse Steel Reinforcement.

$P_r = \phi\beta\,[0.85\, f_c'\,(A_g - A_{st}) + A_{st}\, f_y]$

from this equation one can see that the axial resistance provided by the concrete portion equals

$\phi\beta\, 0.85\, f_c'\,(A_g - A_{st})$ or 0.80 X 0.80 X 0.85 X 4 X $(A_g - A_{st})$ and if $A_{st} = 0.01A_g$,

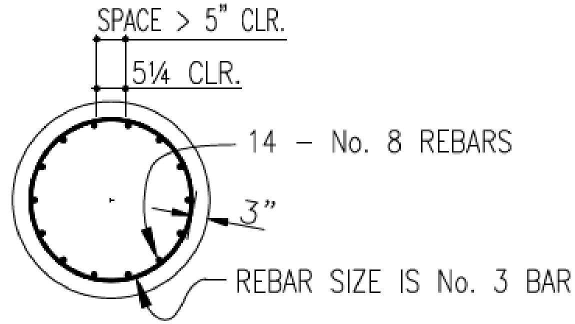
0.80 X 0.80 X 0.85 X 4 X (0.99 X 7.07 X 144) = 2,193 kips,

Add the 1% of longitudinal reinforcement steel

$\phi\beta\, A_{st}\, f_y$ or 0.80 X 0.80 X 0.01 X 7.07 X 144 X 60 = 391 kips

A_{st} required = 0.01 X 7.07 X 144 = 10.2 in^2

The minimum allowable diameter of longitudinal reinforcing bars is ⅝" (No.5 bar) which has a cross-sectional area of 0.31 in^2. Therefore, the number of No.5 rebars required = $\frac{10.2}{0.31} = 33$ - No.5 rebars, this number of rebars exceeds the minimum clear distance of 5.0 inches for a 36" diameter drilled shaft.



Try No.6 rebars which have a cross-sectional of 0.44 in^2,

the number of No. 6 rebars required = $\frac{10.2}{0.44} = 24$ - No. 6 rebars,

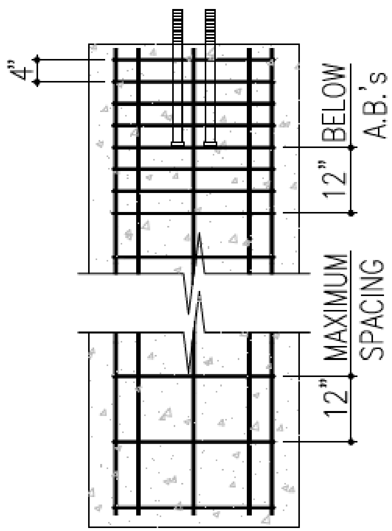
this number of rebars also exceeds the minimum clear distance of 5.0 inches for a 36" diameter drilled shaft.

Try No.8 rebars which have a cross-sectional of 0.78 in^2,

the number of No.8 rebars required = $\frac{10.2}{0.78} = 14$ - No.8 rebars,

Use 14 - No.8 rebars, $A_{st} = 11.0$ in^2 $\geq A_{st}$ required $= 10.2$ in^2.

The 14 - No.8 rebars should be evenly distributed in a circular arrangement.



The length of the rebar cage does not exceed the length of the available reinforcing bars which are 60 ft, therefore, splicing of the longitudinal reinforcement is will not be required.

The transverse steel reinforcement for tied No.8 compression members will be No. 3 bars and the maximum spacing is 12". Typically, ties are spaces at 4" at the top section of the drilled shaft for a distance of the length of the anchor bolts plus 12".

The splices for the transverse steel, (the No. 3 rebar ties) are:

ℓ_{db}, For No. 11 bars and smaller = $\dfrac{1.25\ A_b f_y}{\sqrt{f'c}}$

But not less than………………$0.4\ d_b f_y$

$\ell_{db\ min}$ = 12.0 in.

therefore,

A_b = area of No. 3 rebar = 0.11 in^2
d_b = diameter of No. 3 rebar = 0.375 in

$$\ell_{db} = \frac{1.25\ A_b f_y}{\sqrt{f'c}} = \frac{1.25\ X\ 0.11\ x\ 60}{\sqrt{4}} = 4.125 \text{ in}$$

and

ℓ_{db} = shall not be less than $0.4\ d_b f_y$ = 0.4 X .0.375 X 60 = 9 in

therefore,

The minimum splice length applies, $\ell_{db\ min}$ = 12.0 in.

VII. Drilled Shaft Supporting Lateral and/or Moment Load(s) Only

Lateral load resistance by the drilled shaft is provided by the width or diameter on one side of the drilled shaft from the upper portion and the opposite side from the lower portion of the length of the drilled shaft (See Figure No. 4 below).

Three components must be considered and analyzed for the design of a drilled shaft to support lateral loads and/or moments.

1.) The geotechnical strength of the soil provides the resistance to prevent the shaft from overturning. Therefore, the shaft must be of sufficient depth and diameter to support the factored design loads.

2.) The structural strength of the shaft in shear and flexure must be of sufficient diameter and the necessary reinforcement must be provided to resist the bending moment and shear loads that will be imposed upon the drilled shaft.

3.) Deflection, lateral deformations/ translation and even rotation must be computed to ensure that the supported structure is not compromised due to movement of the shaft.

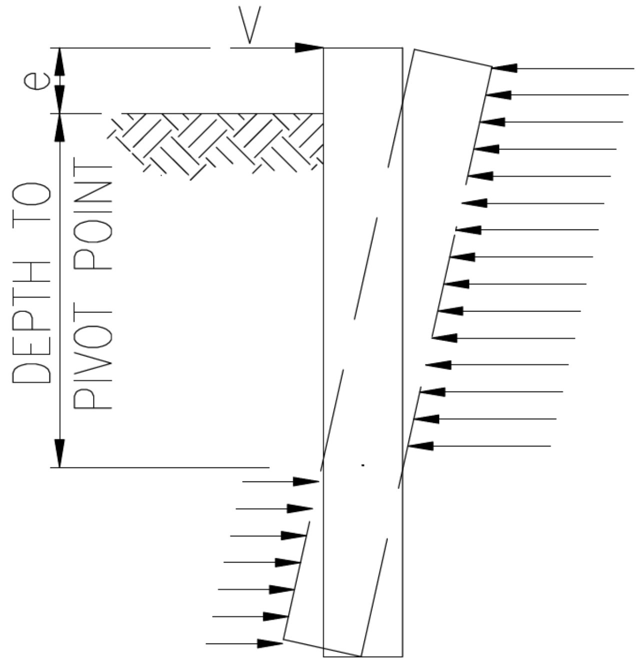


Figure No. 4

a.) Brom's Method

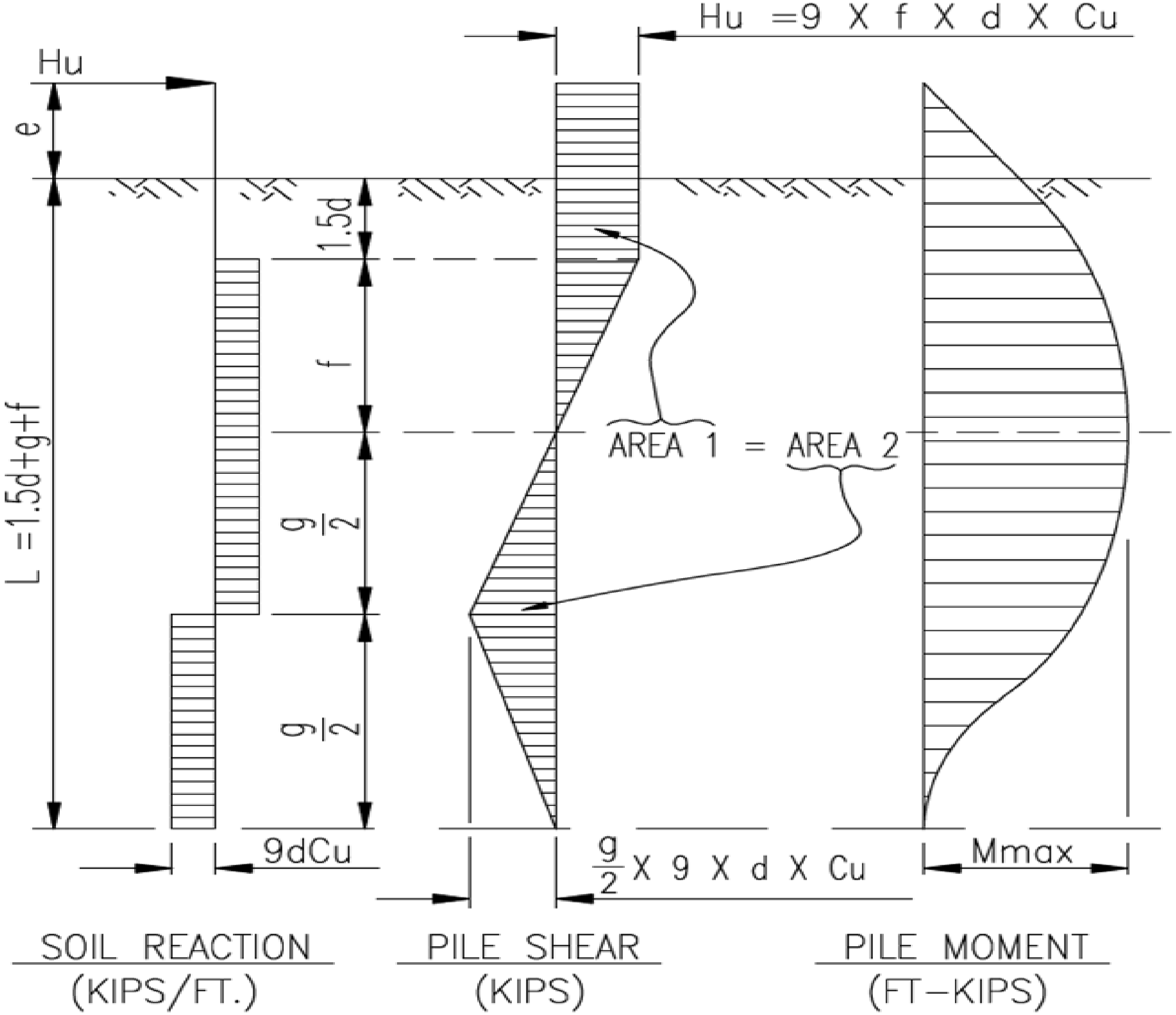
As an introduction to an analysis procedure for laterally loaded drilled shafts, Brom's Method is developed in the following pages. Brom's Method is typically used as an approximate method with significant limitations in its use for critical structures. Brom's Method is most useful for simple analysis of relatively short and stiff drilled shafts subject only to lateral loads and/or overturning moments in uniform and relatively simple soil profiles. Brom's Method may be used to evaluate the lateral capacity for short free-headed drilled shafts in cohesive and non-cohesive, homogeneous soils.

For the analysis procedure for cohesive soils the value of "C_u" in units of kips/ft^2 must be known. The Table shown below provides ranges of values based on SPT Penetration blow count and verbal description of soil.

SPT Penetration (blows/ foot)	Estimated Consistency	C_u (kips/ft^2)
0 - 2	Very Soft	0 - 0.5
2 - 4	Soft	0.5 - 1.0
4 - 8	Medium	1.0 - 2.0
8 - 16	Stiff	2.0 - 4.0
16 - 32	Very Stiff	4.0 - 8.0
>32	Hard	>8

The AASHTO code does not provide guidance for the evaluation of geotechnical strength of drilled shafts using the Brom's Method, however, a resistance factor of 0.4 is recommended. This recommendation is provided based upon engineering judgment considering the fact that the Brom's Method uses a bearing capacity type analysis similar to a bearing capacity analysis for shallow foundations.

Brom's Method for Short Free-Headed Drilled Shaft In Cohesive Soils



Recommended Units:

Dimensions f & g (FT)

d = Drilled Shaft Dia. (FT.)

H_u = Lateral Load (Kips)

C_u = Soil Cohesion (Kips/FT^2)

M_{max} = Maximum Drilled Shaft Bending Moment (FT-Kips)

F_b = Maximum Drilled Shaft Bending Stress (KSI)

The shear at the depth 1.5d + f = 0, therefore, $f \times 9dC_u = H_u$ or $f = H_u / 9dC_u$

AREA 1 = $(H_u \times (e + 1.5d)) + 0.5 \times f \times H_u$

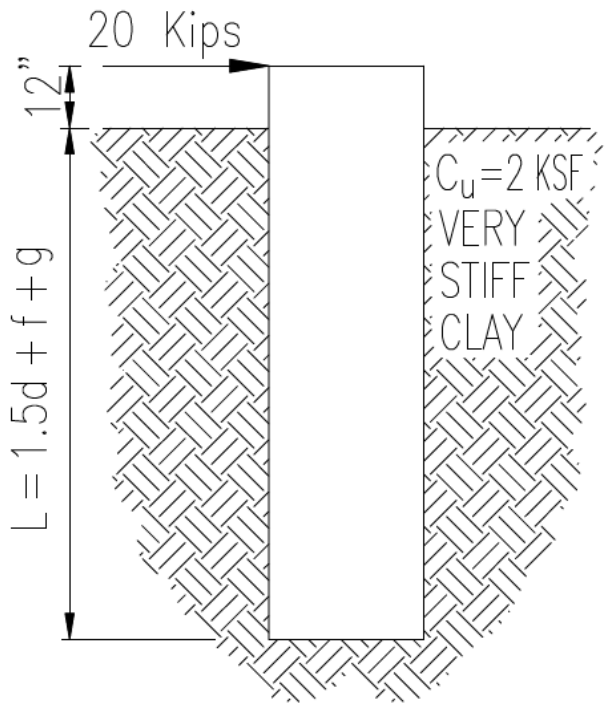
AREA 2 = $1/2\ g \times g/2 \times 9dC_u = 2.25 \times g^2 \times d\ C_u$ or $g = \sqrt{\frac{H_u(e+1.5d+0.5f)}{2.25dC_u}}$

$M_{max} = H_u \times (e + 1.5d + 0.5f)$

knowing the values of g, f & C_u, the required length L for Cohesive Soils can be determined by the equation

L = 1.5d + f + g

Cohesive Soils Example: A 30 inch diameter drilled shaft is installed in clay with a cohesion value of 2 kip/ft^2. Using a Safety Factor of 2.0 there is an ultimate lateral load of 40 kips applied 1 foot above the ground surface. Using a resistance factor of 0.4, what is the required embedment depth to resist the lateral load? And what is the location and the maximum bending stress F_b in the drilled shaft?



Solution:

H_u = 40 Kips/0.4 = 100 Kips

e = 1 foot

d = 30 inches

C_u = 2 kip/ft^2

therefore, $f = Hu / 9dC_u = 100/(9 \times 2.5 \times 2) = 2.22$ feet

and $g = \sqrt{\frac{H_u*(e+1.5d+0.5f)}{2.25*dC_u}}$

$$g = \sqrt{\frac{100*((1+1.5*2.5)+(0.5*2.22))}{2.25*2.5*2}} = 7.22 \text{ feet}$$

The required depth L = 1.5d+f+g = (1.5 x 2.5)+2.22+7.22 = 13.2 feet

$M_{max} = H_u \times (e+1.5d+0.5f) = 100 \times (1+(1.5 \times 2.5)+(0.5 \times 2.22)) = 586$ ft-kips

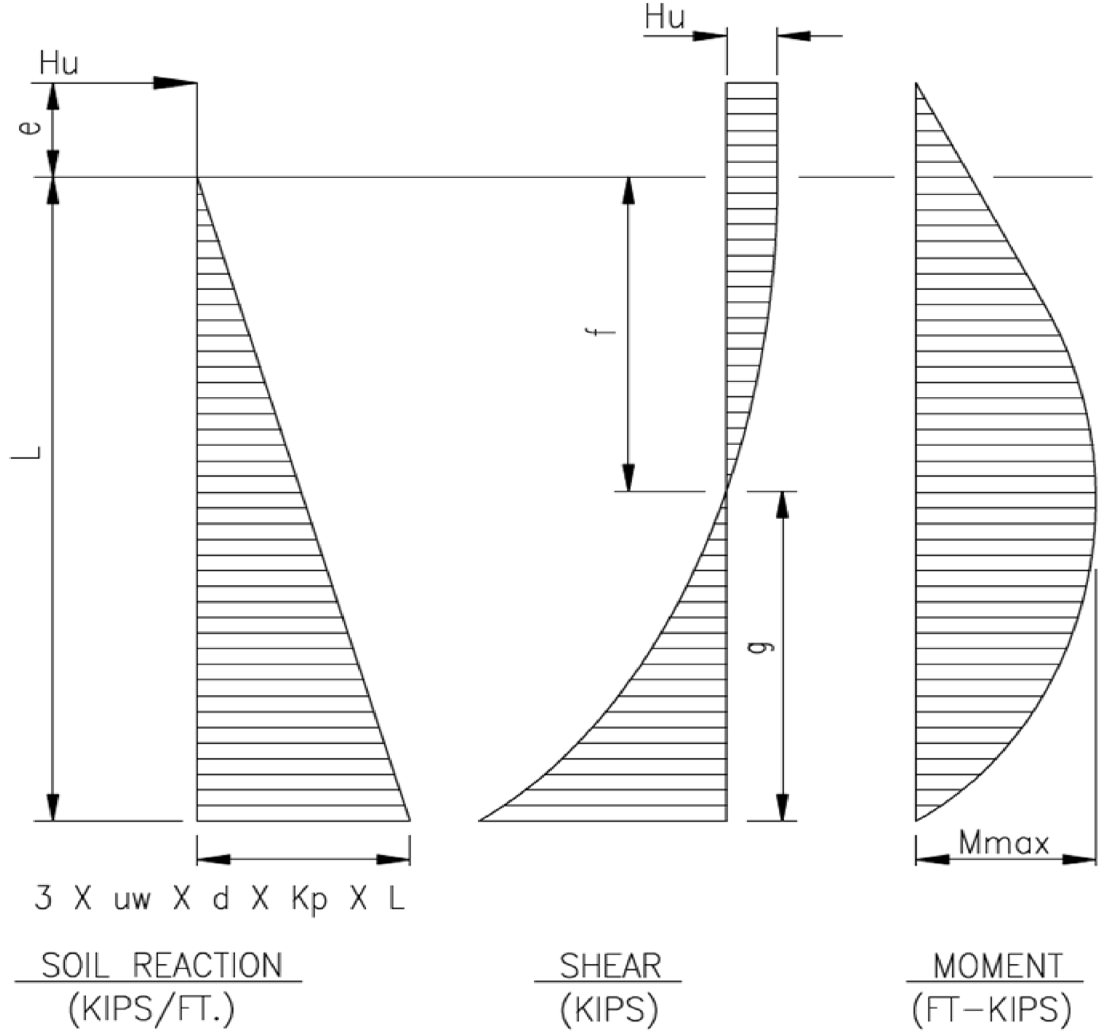
The maximum bending stress F_b in the pile = $\dfrac{M_{max} \ \mathbf{x} \ (O.D./2)}{I}$

$$I = \frac{\prod \mathbf{x} \ d^4}{64} = \frac{\prod \mathbf{x} \ 30^4}{64} = 39{,}761 \text{ in}^4$$

Therefore, $F_b = \dfrac{586 \ \mathbf{x} \ 12{,}000 \ \mathbf{x} \ (30/2)}{39{,}761} = 2{,}653$ psi

The maximum stress occurs at 1.5d + f below grade or 1.5 **x** 2.5 + 2.22 = 5.97 feet below grade

Brom's Method for Short Free-Headed Drilled Shafts In Non-Cohesive Soils



Recommended Units:

uw – Effective Unit Weight of Soil ($Kips/ft^3$)

K_p = Coefficient of Passive Earth Pressure = $\tan^2(45° + [\Phi/2])$

Φ =Soil's Angle of Internal Friction (Degrees)

Sum of Reaction Vectors = ∑R

$\sum R = 3 \times uw \times d \times K_p \times \int_0^L y\,dy$

$\sum R = 3/2 \times uw \times d \times K_p \times L^2$

The sum of reaction vectors at any depth y = ∑r

$\sum r = 3/2 \times uw \times d \times K_p \times y^2$

The depth of the maximum bending moment = f

$H_u = 3/2 \times uw \times d \times K_p \times f^2$

therefore, $f = 0.8165 \times \sqrt{\frac{H_u}{uw \times d \times K_p}}$

Summing moments about toe of soil reaction polygon yields

$H_u \times (e + L) = (3/2 \times uw \times d \times K_p \times L^2) \times \frac{L}{3}$

$$H_{u\,max} = \frac{0.5 \times uw \times d \times Kp \times L^3}{e + L}$$

Solving for L_{min} results in obtaining the solution to a cubic equation

$0 = 0.5 \times uw \times d \times Kp \times L^3 - H_u \times L - H_u \times e$

The bending moment = Area under shear curve,

and the maximum bending moment M_{max} = Area under shear curve at depth "f"

$$M_{max} = \int_0^e H_u \, dy + \int_0^f H_u - 3/2 \times uw \times d \times Kp \times y^2 dy$$

$$M_{max} = H_u \times y\Big]_0^e + H_u \times y - 3/2 \times uw \times d \times Kp \times \frac{y^3}{3}\Big]_0^f$$

$M_{max} = H_u \times (e + ⅔ f)$

The moment at any location on the Drilled Shaft is:

$M = (H_u \times e) + ((H_u \times y) – (0.5 \times uw \times d \times Kp \times y^3))$

The analysis of laterally loaded piles using Brom's Method for non-cohesive soils is affected by the location of the water table. For non-cohesive soils, the location of the water table must be either at the ground surface or below the bottom of the drilled shaft depth considered to resist the lateral loading.

Non-Cohesive Soils Example: A 30 inch diameter drilled shaft is installed in sand which has an Φ value of 30° and a unit weight of 110 pcf. There is an ultimate lateral load of 40 kips applied 1 foot above the ground surface. Using a resistance factor of 0.4, what is the required embedment depth to resist the lateral load? And what is the location and the maximum bending stress F_b in the drilled shaft?

Solution:
H_u = 40 Kips/0.4 = 100 Kips
e = 1 foot
d = 30 inch
Φ = 30°
uw = 110 pcf = 0.11 kcf

$K_p = \tan^2(45° + [\ 30°/2]) = 3.0$

Solving for L_{min} using $0 = 0.5 \times uw \times d \times K_p \times L^3 - H_u \times L - H_u \times e$

$0 = (0.5 \times 0.11 \times 2.5 \times 3.0) \times L^3 - 100 \times L - 100 \times 1$

$0 = 0.4125 \times L^3 - 100 \times L - 100$

L_{min} = 16.05 feet.

Consider that the drilled shaft is to be installed with an embedment length of 17 feet, the ultimate lateral capacity is:

$$H_{u\ max} = \frac{0.5 \times uw \times d \times Kp \times L^3}{e + L} = \frac{0.5 \times 0.11 \times 2.5 \times 3.0 \times 17^3}{1 + 17} = 112.6 \text{ Kips} > 100.0 \text{ Kips}$$

The depth of the maximum pile bending moment for the 100 kip load is:

$$f = 0.8165 \times \sqrt{\frac{H_u}{uw \times d \times K_p}} = 0.8165 \times \sqrt{\frac{100}{0.11 \times 2.5 \times 3.0}} = 9.0 \text{ feet}$$

The maximum drilled shaft bending moment for the 100 kip load is:

$M_{max} = H_u \times (e + ⅔ f)$

$M_{max} = 100 \times (1 + ⅔ \times 9.0)$

M_{max} = 700 Ft-Kips

The maximum bending stress F_b in the drilled shaft = $\frac{M_{max} \times (O.D./2)}{I}$

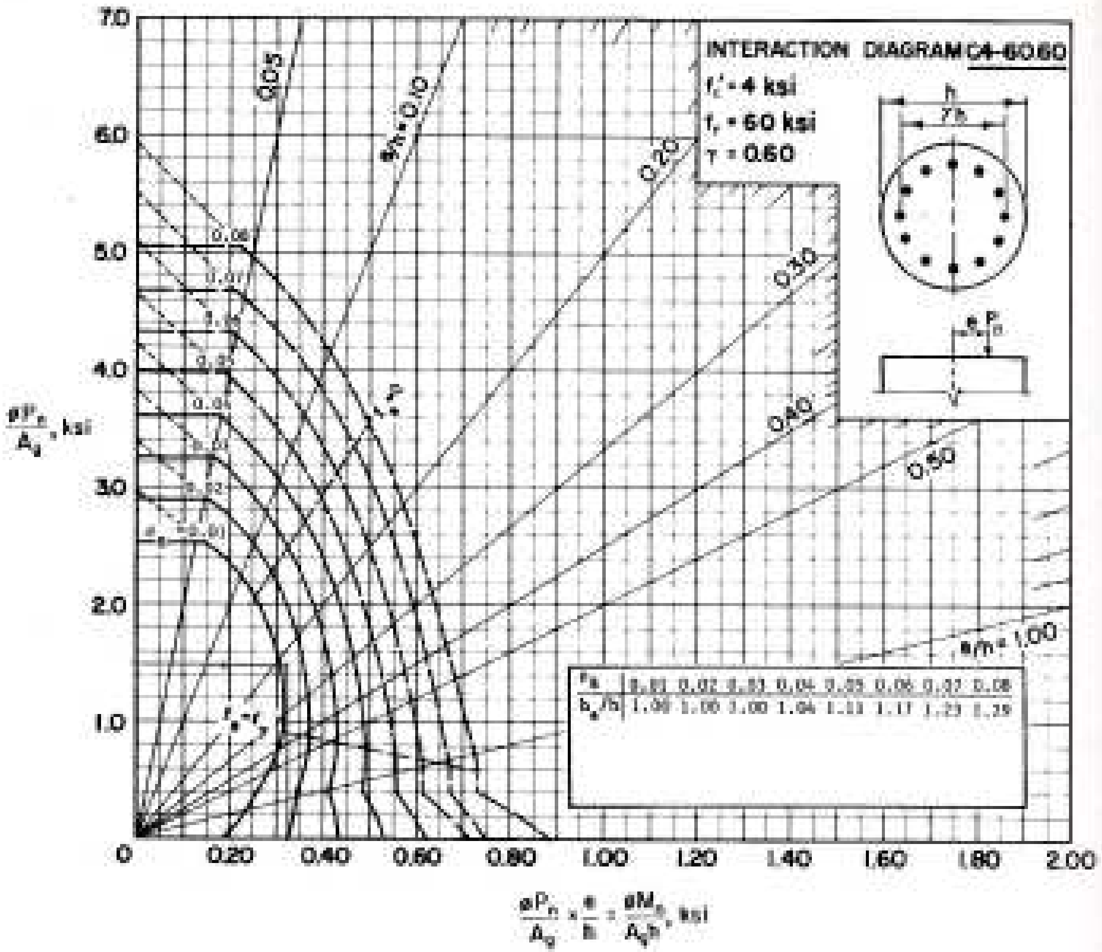
Therefore, $F_b = \frac{700 \times 12{,}000 \times (30/2)}{39{,}761} = 3{,}169$ psi

b.) Reinforcement Steel for Eccentrically Loaded Circular Concrete Sections

The design of the reinforcement steel for an eccentrically loaded circular concrete section is ***not*** a closed form analysis, in other words there does not exist a "plug and chug" formula which will provide a solution. Because the solution is a trial and adjustment process the most effective manner of analysis is a computer program.

Before the widespread advent of computer programs many engineers relied on Column Interaction Diagrams. The Concrete Reinforcing Steel Institute (CRSI) publishes design aids which include Column Interaction Diagrams for a variety of column parameters.

Shown below is a typical Column Interaction Diagram for a circular concrete section.



Another method of determining the reinforcement steel for an eccentrically loaded circular concrete section is Whitney's Approximate Solution. A more in-depth explanation on Whitney's Approximate Solution can be found at www.assakkaf.com/Courses/ENCE454/Lectures/CHAPTER9c.

c.) The "p-y Method"

The "p-y method" is the recommended methodology for computing the response of drilled shafts to lateral forces and overturning moments. This method models the shaft as a nonlinear elastic beam and uses a series of nonlinear springs to model the soil resistance. This method is most easily implemented using one of several available computer software programs. The "p-y method" gets its name from the relationship where the term "p" is the force due to the resistance of the soil modeled as a nonlinear spring and the term "y" is the deflection of the soil. The relations between the two are modeled as the p-y curve. In other words, the equations of equilibrium of the drilled shaft and compatibility between deflection and soil reaction must be satisfied. A hand calculated solution would be quite difficult, however, with computer software solutions to eccentrically loaded drilled shaft in a variety of types of layered soils can be obtained quite easily.

In Figure No. 5 below a typical drilled shaft is shown in a layered soil. Each layer has a different thickness and different soil properties. The drilled shaft is treated as a beam-column with lateral soil support and the behavior of the drilled shaft under a combination of lateral, axial and overturning moment loading can be obtained by one of the many computer software programs.

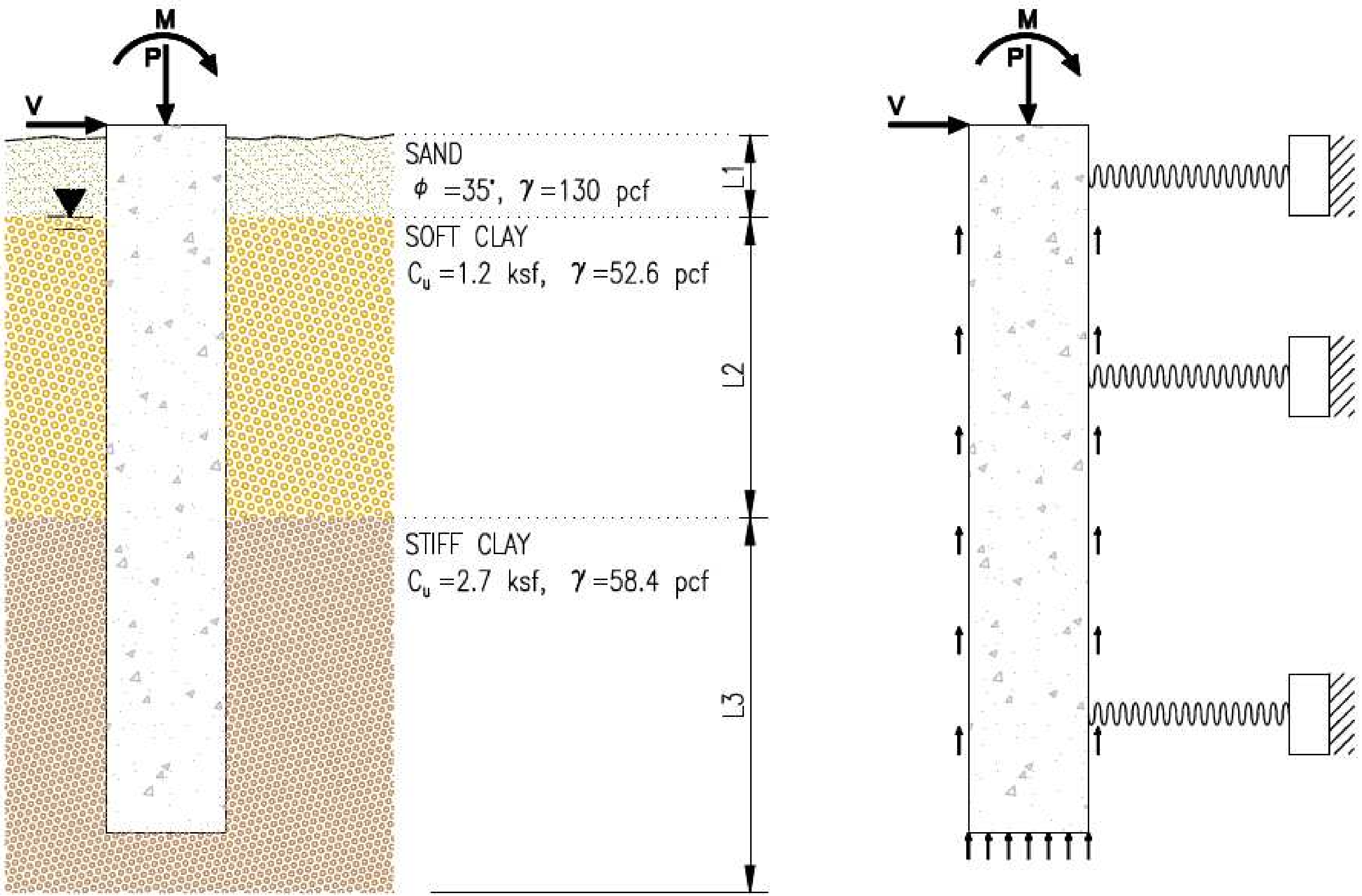

M
P
V
SAND
φ =35°, γ=130 pcf
SOFT CLAY
C_u =1.2 ksf, γ=52.6 pcf
STIFF CLAY
C_u =2.7 ksf, γ=58.4 pcf
L1
L2
L3
M
P
V

Figure No. 5

VIII. Summary

This course has provided a brief history of the development of drilled shafts in the United States as well as an introduction to drilled shaft foundations. As an introductory course many aspects of the design and construction of drilled shafts could not be included.

The design information on drilled shafts that is presented in this course is only a small portion of what is typically required for a comprehensive analysis.

A comprehensive plan includes, but is not limited to:

- Geotechnical investigation reports and geotechnical design
- Design equations for geotechnical resistances of drilled shafts under axial loading, lateral loading and overturning moments
- Sufficient subsurface information must be provided so that bidders can make an informed decision about equipment to use on the job
- Appropriate construction methods such as temporary or permanent casings or the use of drilling fluids
- Reinforcement cage design for tension, compression and moment or lateral loading
- Specification on concrete mix and concrete placement techniques
- Quality control plan and inspection

