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PILE DESIGN AND CONSTRUCTION RULES OF THUMB

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CCM – Certified Construction Manager
CCE – Certified Cost Engineer
PE – Professional Engineer

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Contents

UNITS

fps Units	SI Units
Length	
1 ft = 0.3048 m	1 m = 3.28084 ft
1 in. = 2.54 cm	
Pressure	
1 ksf = 1,000 psf	1 Pascal = 1 N/m^2
1 ksf = 0.04788 MPa	1 MPa = 20,885.43 psf
1 ksf = 47,880.26 Pascal	1 MPa = 145.0377 psi
1 ksf = 47.88 kPa	
1 psi = 6,894.757 Pascal	
1 psi = 144 psf	
Area	
1 ft^2 = 0.092903 m^2	1 m^2 = 10.76387 ft^2
1 ft^2 = 144 in^2	
Volume	
1 ft^3 = 0.028317 m^3	1 m^3 = 35.314667 ft^3
Density	
1 lb/ft^3 = 157.1081 N/m^3	1 kN/m^3 = 6.3658 lbs/ft^3
1 lb/ft^3 = 0.1571081 kN/m^3	
Weight	
1 kip = 1,000 lbs	1 kg = 9.80665 N
1 lb = 0.453592 kg	1 kg = 2.2046223 lbs
1 lb = 4.448222 N	1 N = 0.224809 lbs
1 ton (short) = 2,000 lbs	1 N = 0.101972 kg
1 ton = 2 kips	1 kN = 0.224809 kips

DENSITY

water => 1 g per cubic centimeter = 1,000 g per liter = 1000 kg/m^3 = 62.42 pounds per cu. feet

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Preface

Pile design is mostly about application of engineering concepts rather than use of elaborate mathematical techniques. Most pile design work can be done with simple arithmetic. I have provided necessary equations and concepts in a manner so that the reader would be able to refer to them with ease. All chapters are provided with plethora of design examples. The solutions to design examples are given in a step by step basis with many illustrations.

In geotechnical engineering, formulas and methodologies change significantly from sandy soils to clay soils. I made all attempts to separate equations based on soil type. Different pile types also would affect the design methods used. As often the case, one may find mixed soil conditions. I have provided necessary theory and design examples to tackle pile design in mixed soil conditions.

This book is mainly aimed at practicing geotechnical engineers, graduate and undergraduate students who are planning to become geotechnical engineers. The book should be a great addition to the civil professional engineer exam in USA or the chartered engineer exam in commonwealth countries. This book would also be of interest to structural engineers and architects who may run into piling work occasionally.

Ruwan Rajapakse, CCM, CCE, PE

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PART 1

Introduction to Pile Selection

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1

Site Investigation and Soil Conditions

The geotechnical engineer needs to develop an appropriate game plan to conduct a piling engineering project. Investigation of the site is a very important step in any geotechnical engineering project. The following major steps can be identified in a site investigation program.

- Literature survey
- Site visit
- Subsurface investigation program and sampling
- Laboratory test program

1.1 Literature Survey

The very first step in a site investigation program is to obtain published information relevant to the project.

Subsurface Information: Subsurface information can be obtained from the following sources.

- **National Geological Surveys:** Many countries have national geological surveys. In the United States, the United States Geological Survey (USGS) has subsurface information on many parts of the country. In some instances it can provide precise information in some localities. The USGS Web site, http://www.usgs.gov, is a good place to start.

- **Adjacent Property Owners:** Adjacent property owners may have conducted subsurface investigations in the past. In some cases it may not be possible to obtain information from these owners.
- **Published Literature:** Geologists have published many articles regarding the geological history of the United States. It is possible to find general information such as soil types, depth to bedrock, and depth to groundwater by conducting a literature survey on published scientific articles.
- **Aerial Photographs:** Aerial photographs are available from state agencies and private companies. *Google earth* now provides aerial maps for many parts of the world.

Aerial photographs can give information that is easily missed by borings. For example, a dark patch in the site could be organic material, or a different color stripe going through the site could be an old streambed.

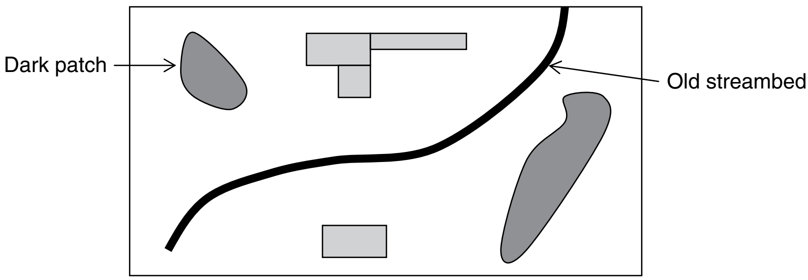

Figure 1.1 Aerial photograph

Groundwater Information: Groundwater information is extremely important during the design process.

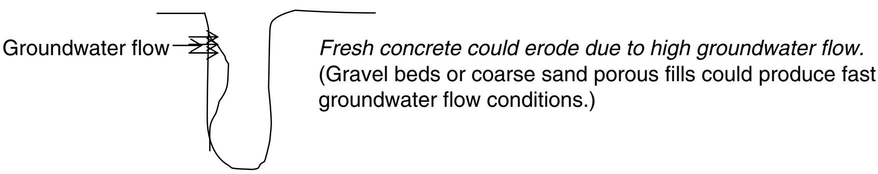

Figure 1.2 Erosion of concrete due to groundwater

Utilities: Existing utilities in the project site need to be researched and identified to avoid serious consequences. Special attention should be paid to gas and electrical utilities. Other utilities such as telephone, cable, water, sewer, and storm sewer also need to be fully and completely identified.

The next step is to mark the utility locations in the site. A site plan should be prepared with a utility markout, indicating the type of utility, depth to the utility, and location of the utility.

If the existing utilities are not known accurately, the following procedure should be adopted.

Hand Digging Prior to Drilling: Most utilities are rarely deeper than 6 ft. Hand digging the first 6 ft prior to drilling boreholes is an effective way to avoid utilities. During excavation activities, the backhoe operator should be advised to be aware of utilities. The operator should check for fill materials because in many instances utilities are backfilled with select fill material. It is advisable to be cautious because sometimes utilities are buried with the same surrounding soil. In such cases, it is a good idea to have a second person present assigned exclusively to watch the backhoe operation.

Contaminants: The geotechnical engineer should obtain all the available information pertaining to contaminants present in the project site. Project duration and project methodology will be severely affected if contaminants are present.

1.2 Site Visit

After conducting a literature survey, it is a good idea to pay a site visit. The following information can be gathered during a site visit.

- Surface soil characteristics. Surface soil may indicate the existence of underlying fill material or loose organic soil.
- Water level in nearby streams, lakes, and other surface water bodies may provide information regarding the groundwater condition in the area.

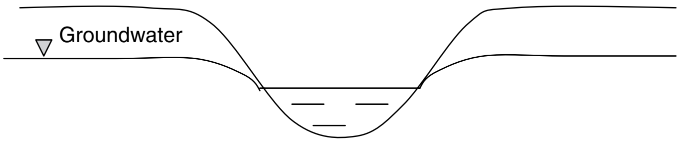

Figure 1.3 Groundwater flow near a stream

- Closeness to adjacent buildings. (If adjacent buildings are too close, noise due to pile driving could be a problem.)
- Stability of the ground surface: This information is important in deciding the type of pile-driving rig to be used. Pile-driving rigs often get stuck in soft soils owing to lack of proper planning.
- Overhead obstructions: Special rigs may be necessary if there are overhead obstructions such as power lines.

1.3 Subsurface Investigation

Borings: A comprehensive boring program should be conducted to identify soil types existing in the site. Local codes should be consulted prior to developing the boring program.

- Typically, one boring is made for every 2,500 sq ft of the building.
- At least two-thirds of the borings should be constructed within the footprint of the building.

1.3.1 International Building Code (IBC)

The IBC recommends that borings be constructed 10 ft below the level of the foundation.

Test Pits: In some situations, test pits can be more advantageous than borings. Test pits can provide information down to 15 ft below the surface. Unlike borings, soil can be visually observed from the sides of the test pit.

Soil Sampling: Split spoon samples are obtained during boring construction. They are adequate for sieve analysis, soil identification, and

Atterberg limit tests. Split spoon samples are not enough to conduct unconfined compressive tests, consolidation tests, and triaxial tests. Shelby tube samples are obtained when clay soils are encountered. Shelby tubes have a larger diameter, and Shelby tube samples can be used to conduct consolidation tests and unconfined compressive strength tests.

1.4 Soil Types

For geotechnical engineering purposes, soils can be classified as sands, clays, and silts. The strength of sandy soils is represented with friction angle (Φ), while the strength of clay soils is represented with "cohesion."

Pure silts are frictional material and for all practical purposes behave as sands, whereas clayey silts and silty clays behave more like clays.

1.4.1 Conversion of Rocks to Soil

How did the soil originate? Geologists tell us that the young earth was made of inner magma, and at the beginning outer layer of magma was cooled and the rock crust was formed. When the earth started to cool off from its hot origin, water vapor fell onto the earth as rain. The initial rain lasted many million years until the oceans were formed. Water and dissolved chemicals eroded the rocky crust for million more years. Other factors such as meteor impacts, volcanic eruptions, and plate tectonic movements also helped to break down the original rock surface. Today, four billion years after the earth began, the first few feet of the earth are completely broken down into small pieces and are known as soils. Chemical processes are capable of breaking the larger sandy particles into much smaller clay particles.

1.4.2 Conversion of Soils to Rock

As rock breaks up and forms soil, soil also can convert back to rock. Sandy particles deposited in a river or lake with time becomes sandstone; similarly, clay depositions become shale or claystone. Sedimentary rocks originate through the sedimentation process occurring in rivers, lakes, and oceans.

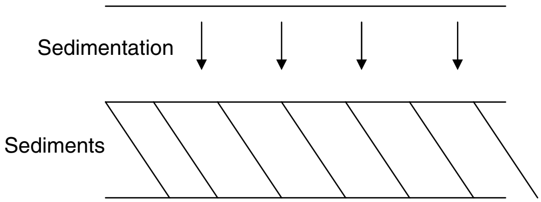

Figure 1.4 Sedimentation process in a lake

1.5 Design Parameters

1.5.1 Sandy Soils

The most important design parameter for sandy soils is the friction angle. The bearing capacity of shallow foundations, pile capacity, and skin friction of piles depend largely on the friction angle (Φ).

The strength of sandy soils comes mainly from friction between particles. The friction angle of a sandy soil can be obtained by conducting a triaxial test. There are correlations between friction angle and standard penetration test (SPT) values. Many engineers use SPT and friction angle correlations to obtain the friction angle of a soil.

To predict the settlement of a pile or a shallow foundation, one needs to use Young's elastic modulus and Poisson's ratio.

1.5.2 Clay Soils

The strength of clayey soils is developed through cohesion between clay particles. Friction is a mechanical process, whereas cohesion is an electrochemical process. Cohesion of a soil is obtained by using an unconfined compressive strength test. To conduct an unconfined compressive strength test, one needs to obtain a Shelby tube sample.

Settlement of clay soils depends on consolidation parameters. These parameters are obtained by conducting consolidation tests.

SPT — N (Standard Penetration Test Value) and Friction Angle

SPT (N) value and friction angle are important parameters in the design of piles in sandy soils. The following table provides guidelines for obtaining the friction angle using SPT values.

Table 1.1 Friction angle, SPT (N) values and relative density (*Bowles 2004*)

Soil Type	SPT (N_{70} value)	Consistency	Friction Angle (φ)	Relative Density (D_r)
Fine sand	1–2	Very loose	26–28	0–0.15
	3–6	Loose	28–30	0.15–0.35
	7–15	Medium	30–33	0.35–0.65
	16–30	Dense	33–38	0.65–0.85
	<30	Very dense	<38	<0.85
Medium sand	2–3	Very loose	27–30	0–0.15
	4–7	Loose	30–32	0.15–0.35
	8–20	Medium	32–36	0.35–0.65
	21–40	Dense	36–42	0.65–0.85
	<40	Very dense	<42	<0.85
Coarse sand	3–6	Very loose	28–30	0–0.15
	5–9	Loose	30–33	0.15–0.35
	10–25	Medium	33–40	0.35–0.65
	26–45	Dense	40–50	0.65–0.85
	<45	Very dense	<50	<0.85

Table 1.2 SPT (N) value and soil consistency

SPT (N) value vs. Total Density

Soil Type	SPT (N_{70} value)	Consistency	Total Density
Fine sand	1–2	Very loose	70–90 pcf (11–14 kN/m^3)
	3–6	Loose	90–110 pcf (14–17 kN/m^3)
	7–15	Medium	110–130 pcf (17–20 kN/m^3)
	16–30	Dense	130–140 pcf (20–22 kN/m^3)
	<30	Very dense	<140 pcf <22 kN/m^3
Medium sand	2–3	Very loose	70–90 pcf (11–14 kN/m^3)
	4–7	Loose	90–110 pcf (14–17 kN/m^3)
	8–20	Medium	110–130 pcf (17–20 kN/m^3)
	21–40	Dense	130–140 pcf (20–22 kN/m^3)
	<40	Very dense	<140 pcf <22 kN/m^3
Coarse sand	3–6	Very loose	70–90 pcf (11–14 kN/m^3)
	5–9	Loose	90–110 pcf (14–17 kN/m^3)
	10–25	Medium	110–130 pcf (17–20 kN/m^3)
	26–45	Dense	130–140 pcf (20–22 kN/m^3)
	<45	Very dense	<140 pcf <22 kN/m^3

Reference

Bowles, J., *Foundation Analysis and Design*, McGraw-Hill Book Company, New York, 1988.

1.6 Selection of Foundation Type

A number of foundation types are available for geotechnical engineers.

1.6.1 Shallow Foundations

Shallow foundations are the cheapest and most common type of foundation. They are ideal for situations when the soil immediately below the footing is strong enough to carry the building loads. In cases where soil immediately below the footing is weak or compressible, other foundation types need to be considered.

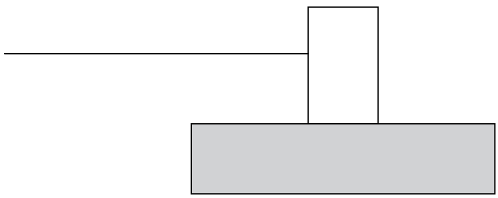

Figure 1.5 Shallow foundation

1.6.2 Mat Foundations

Mat foundations are also known as raft foundations. Mat foundations, as the name implies, spread like a mat. The building load is distributed in a large area.

Figure 1.6 Mat foundation

1.6.3 Pile Foundations

Piles are used when bearing soil is at a greater depth. In such situations, the load has to be transferred to the bearing soil stratum.

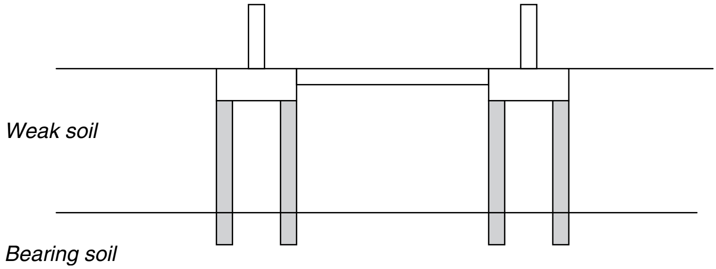

Figure 1.7 Pile foundation

1.6.4 Caissons

Caissons are simply larger piles. Instead of a pile group, one large caisson can be utilized. In some situations, caissons can be the best alternative.

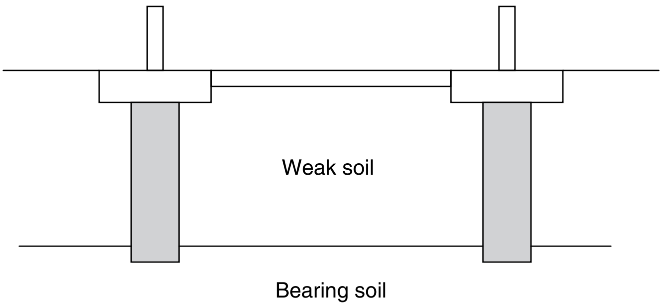

Figure 1.8 Caissons or drilled shafts

1.6.5 Foundation Selection Criteria

Normally, every attempt is made to select shallow foundations. This is the cheapest and fastest foundation type. The designer should look into bearing capacity and settlement when considering shallow foundations.

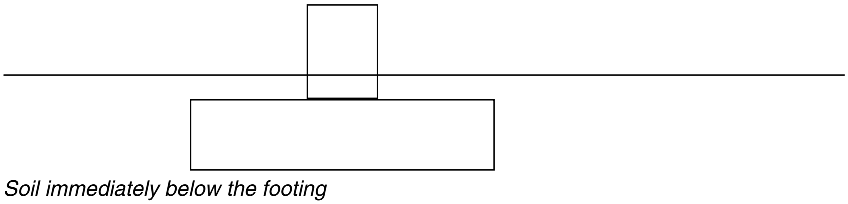

Figure 1.9 Shallow foundation

The geotechnical engineer needs to compute the bearing capacity of the soil immediately below the footing. If the bearing capacity is adequate, settlement needs to be computed. Settlement can be immediate or long term. Both immediate and long-term settlements should be computed.

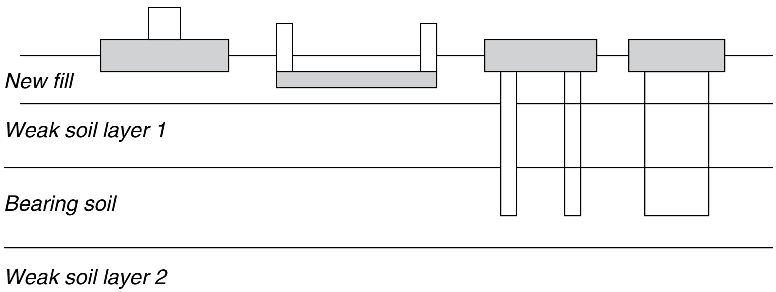

Figure 1.10 Foundation types (Shallow, mat, pile and caisson)

Figure 1.10 shows a shallow foundation, mat foundation, pile group, and a caisson. The geotechnical engineer needs to investigate the feasibility of designing a shallow foundation owing to its cheapness and ease of construction. In the above situation, it is clear that a weak soil layer just below the new fill may not be enough to support the shallow foundation. Settlement in weak soil due to loading of the footing also needs to be computed.

If shallow foundations are not feasible, then other options need to be investigated. Mat foundations can be designed to carry large loads in the presence of weak soils. Unfortunately, cost is a major issue with mat foundations.

Piles can be installed as shown in the figure ending in the bearing stratum. In this situation, one needs to be careful of the second weak layer of soil below the bearing stratum. Piles could fail due to punching into a weak stratum below.