DESIGN AND ANALYSIS OF PILES

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Contents

Summary

Piles are part of the most frequent foundation solutions for most important structures, such as high-rise buildings, towers and offshore structures. Piles are slender structural elements that are inserted in the ground by driving, jacking or drilling. They may support structural loads individually, as part of a group of piles or as part of more complex foundation configurations, such as piled mats. When loaded axially, piles mobilize the resistance of the soil along their lateral surface area (which add up to the shaft resistance of the pile) and on its base or tip (its base resistance). When loaded laterally, they derive their resistance from the passive resistance of the soil that develops in order to resist the lateral motion of the pile. How much movement of the pile head is permissible depends on the structure that is being supported. In design of axially loaded piles in routine projects, the ultimate load is used to size the piles. The ultimate load is conceptually the smallest load leading to an ultimate limit state. Conventionally, it is defined by an ultimate load criterion (the load causing a settlement of 10% of the pile diameter being the most common criterion). There are both soil property-based methods and SPT- or CPT-based methods for calculation of the ultimate load of a pile. For laterally loaded pile design, deflection analyses are more commonly used, with the *p*-*y* method being most common among those.

1. General

1.1. Objectives

Pile foundations have existed since the beginning of civilization. Piles are deep foundation elements made of concrete, steel, timber, polymers or a combination of two or more of these materials. Their obvious use is in cases in which surface soils are too loose or soft to support shallow foundations safely and economically, but there are a variety of additional circumstances under which they are applicable (Salgado 2008).

There are a large number of pile types to choose from, and pile installation often requires the use of relatively sophisticated rigs. Pile installation also changes the state of the soil around the installed piles. Pile design must include proper selection of optimal pile types for every situation and must account for installation and its effects on the surrounding soil, which in turn affect the final pile resistance. In this chapter, we will initially discuss pile installation and its effects on soil and then the basics of the analysis and design of single piles.

1.2. Foundation Design Principles

Foundations should be built with the following basic principles in mind: (1) foundations should be as durable as the superstructure that they support, (2) foundations must move less than the level of movement that would lead to architectural or structural problems, (3) foundations must not themselves fail structurally. All of these unwanted outcomes are called limit states. Limit states that do not represent danger but merely impair structure functionality or performance or represent inconveniences are known as serviceability limit states. Serviceability limit states can sometimes be addressed by a maintenance program, which may or may not be preferable to having more robust foundations so that these limit states will not occur. Limit states that can lead to structural damage, collapse or loss of life are known as ultimate limit states. Ultimate limit states must always be avoided.

Foundation design is in essence a sequence of decisions regarding type, geometry and location of each foundation element with the goal of preventing all applicable limit states. Preventing limit states requires calculations of the maximum or limit resistance available to the foundation for comparison with applied loads, as well as foundation displacements under working loads. We discuss the design process in Section 2.1.

1.3. Pile Analyses and Design

Traditionally, two separate types of pile analyses have been conducted: deflection analyses (for calculating pile movement when acted upon by a load) or "geotechnical failure" analyses, which seek to calculate loads that would lead to collapse or very large movements of the pile. In truth, the loading process is continuous, and a rigorous, complete pile analysis would track the entire load-deflection response of the pile, from beginning to end. Such analyses are now, in 2009, becoming possible, but they are sophisticated, expensive analyses to perform. So the state of practice still relies on simple analyses that allow calculation of deflections and pile limit or ultimate resistances separately.

Deflection calculations can be of two types: continuum-based or Winkler analyses. In continuum-based analysis, the soil around the pile is idealized as a solid (often, in current practice, with linear elastic properties). In Winkler analyses, springs are used to model the load response of the soil in contact with the pile. In design, one would compare calculated deflections with deflections deemed tolerable; if the calculated deflections are found to be excessive, the foundation element geometry (cross section or length) is adjusted.

Analyses in which a limit or ultimate resistance is calculated for the pile are always part of the design of axially loaded piles. These analyses are intended to represent either the maximum resistance available to the pile (limit state associated with pile plunging) or the smallest resistance associated with an ultimate limit state for the pile and/or supported structure (determined by a specific settlement level). In design, one would compare these resistances with the loads the pile must carry. This comparison usually is made after the resistance has been reduced and/or the load has been magnified in order to account for uncertainties in the estimated loads and resistance.

1.4. CPT- and SPT-Based Pile Design

The cone penetration test (CPT) is the *in situ* test of choice for pile design. The test, which is described in detail in Salgado (2008), is performed by pushing a cylindrical penetrometer with a conical tip into the ground and measuring the unit resistance to penetration on the tip (force opposing penetration acting on the tip divided by its projected area). This unit resistance is known as the cone resistance and denoted by q_c. The cone penetrometer is like a scaled-down pile, and its plunging through the soil is like the plunging of a pile. So, not surprisingly, q_c is approximately equal to the stress on the base of a pile in a plunging state. The shaft resistance of a pile can also be related to q_c.

Given the similarities between the CPT and the loading of a pile, the test has been widely adopted in several countries for pile design. CPT-based pile design methods range from the purely empirical, in which pile resistances are calculated by multiplying q_c by coefficients determined from pile load test databases, to methods based at least partly on mechanistic considerations. In other countries, the standard penetration test (SPT) is more often used. There are empirical methods specifically developed for the SPT. Use of these methods is a more direct route than attempting to first establish soil properties from SPT blow counts. Another option is to empirically convert from SPT blow count to q_c and then use a CPT-based design method.

1.5. Soil Property-Based Pile Design

Although pile analysis methods based on soil variables (or "properties") have existed for a long time, most of these methods (all proposed in the late 19th or 20th century) were developed when the understanding of the mechanical processes responsible for the development of base and shaft resistance were not well understood. More recent methods, however, do attempt to capture the mechanics of pile loading, and these methods, which continue to be developed by researchers, may be used in design with good results. We will discuss in some detail the basis for analyzing the load capacity of a pile using soil mechanics.

2. Pile Foundation Design Principles

2.1. Limit States and Pile Design Sequence

For axially loaded piles, the key limit states are:

(IA) bearing capacity failure of a single pile, which may correspond to either
(IA-1) classical bearing capacity failure (plunging) of the pile or
(IA-2) crushing or yield of the pile cross-section upon loading (More of a possibility for cast-in-situ concrete piles installed in soil with large shear strength and less so for precast concrete or steel piles.);

(IB) collapse or severe damage to the superstructure due to foundation movement;

(II) loss of functionality or serviceability of the superstructure due to foundation movement;

(III) overall stability failure, consisting of the development of a failure mechanism enveloping the pile foundations or a part thereof (a classical example of this being foundations that are themselves safe but that, resting on an unstable slope, fail with the slope, carrying the structure they support with them).

For laterally loaded piles, the limit states IA would be the lateral collapse of the pile, more likely for short piles, and the formation of plastic hinges (rupture of the cross section due to bending), more likely for long piles.

The main steps in pile design are outlined by Salgado (2008):

1. Selection of piles over other types of foundations.
2. Selection of pile type.
3. Decision on the pile length based on the soil profile. Usually, pile foundations are best designed by first finding a suitable bearing layer for end-bearing piles or by deciding on a practical length for floating piles (An ideal floating pile is a pile deriving all of its resistance from shaft resistance. A pile with small non-zero base resistance is also referred to as a floating pile), then determining the cross-section dimensions required to develop the necessary load capacity.
4. Determination of the cross-section of each pile based on static analysis of pile capacity and the load to be carried by the pile (see Sections 2.2 and 2.3 for how pile load capacity is compared with the loads the pile must carry).
5. Selection of a driving system if the piles are driven piles. It is best to use wave equation analysis to make an informed decision.
6. Specification of a minimum pile length. We require a minimum length because calculations assume a certain embedment of the pile into the ground. A short pile (i.e., a pile that cannot be installed all the way down to the design depth), even if embedded into the intended strong layer (which would in this case be at a higher elevation), may develop an insufficient amount of shaft capacity, leading to an excessively low safety factor. The pile may also be short because it did not reach the bearing layer but rather an obstruction or intermediate layer that cannot be relied on to provide the required end-bearing resistance.
7. For driven piles, establishment of a minimum driving resistance (in blows per unit penetration depth) below which a pile will not be acceptable. For nondisplacement piles, we select the installation method based on knowledge of the soil profile and groundwater pattern at the site.

2.2. Working Stress Design

In working stress design (WSD), we calculate a resistance, divide it by a factor of safety F_s and then compare it with the applied load:

$$R > F_s Q \; . \tag{1}$$

If this inequality holds, the design is considered acceptable. What constitutes an optimal factor of safety depends on the geotechnical structure and has historically been left to a large extent up to the geotechnical engineer to decide. A conceptually flawed but relatively common use of the factor of safety, particularly for piles, has been to use it to indirectly limit settlement or deflections.

The factor of safety used in axially loaded pile design for modern design methods typically ranges from 2 to 3 but can under certain circumstances (when high-reliability conditions and good quality assurance are in place) be less than 2.

2.3. Load and Resistance Factor Design

An alternative to WSD was adopted three to four decades ago in the United States by structural engineers. In this method of design, called Load and Resistance Factor Design (LRFD), loads are multiplied by load factors, the resistance by a resistance factor, and the design inequality to satisfy is:

$$F_R R > \sum F_L Q \, , \tag{2}$$

where the sum is over all loads (dead, live, seismic, etc.) acting on the foundation, with the implication that the load factor is different for different types of load.

The load factors are typically set in design codes. The resistance factors need to be consistent with the load factors and with the methods of analysis and design used; each method has its own uncertainty and bias, and therefore should have its own resistance factor. Engineers should resist treating resistance factors in the same way they have traditionally treated factors of safety because that negates the benefits of using LRFD.

3. Pile Foundations

3.1. Pile Types Based on Method of Fabrication and Installation

The response of a pile to loading depends on the method of pile installation and what it does to the soil. We can identify two types of pile that are on the opposite ends of the spectrum of the changes caused in the soil by pile installation: nondisplacement and displacement piles. Nondisplacement piles are piles that are cast *in situ* in the space left after a volume of soil is removed from the ground. Soil elements around the pile are not pushed away or displaced from its original positions with this method of pile installation. Displacement piles, on the other hand, are piles that are inserted into the soil by either driving (most commonly) or jacking (more infrequently) without any soil removal before the piles are inserted. In the installation of displacement piles, soil elements originally located where the pile will be after installation or near it undergo large displacements. Between the two extremes, there are a growing number of pile types that are neither full-displacement piles nor nondisplacement piles. They are most commonly referred to as partial-displacement piles; most are installed using some type of auger.

Nondisplacement piles are cast in place. The various types of nondisplacement piles differ based on the equipment and method by which the soil is excavated and the concrete or other material placed into the excavation. Nondisplacement piles can be classified as (Salgado 2008):

- percussion bored (Strauss) piles
- rotary bored
    - in soil
    - in rock
- bored piles (drilled shafts)
    - straight shaft
    - under-reamed (base-enlarged)

Partial-displacement piles include the following:

- Small-displacement piles
    - H piles without soil plugging
    - open-ended pipe piles without soil plugging
- Continuous-flight-auger (CFA) piles
    - made with grout
    - made with concrete
- Drilled displacement piles
    - Atlas
    - Auger pressure-grouted displacement (APGD)
    - Fundex
    - Omega

Full-displacement piles can be either prefabricated and later transported to the site for installation or cast in place. Cast-in-place piles are usually made of concrete, grout or cement paste. Displacement piles can be classified as (Salgado 2008):

- Cast-in-place
    - Closed-ended concrete/steel pipe driven and filled w/concrete
    - Raymond piles
    - Franki piles
- Prefabricated
    - Concrete
        - precast concrete
        - full-length reinforced
        - prestressed
        - reinforced with connections ready for extension
        - tubular section
    - Steel
        - H piles (when soil adheres to pile between flanges)

- pipe piles (with closed ends or where soil plugging occurs)
- other cross-sections

This classification of piles as nondisplacement, partial-displacement or full-displacement piles is the most important from a pile design perspective because these classes of piles behave very differently when loaded, particularly under axial load. This difference in load response is mostly due to the state of the soil around the pile after installation. In displacement piles, both the density and stress state of the soil around the pile and beneath its base change significantly due to installation. Displacement piles may be seen as having preloaded the soil during the installation process. The installation of nondisplacement piles, on the other hand, preserves the soil density and state to a significant degree.

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Biographical Sketch

Rodrigo Salgado is a Professor of Civil Engineering at Purdue University. He is a graduate of the Universidade Federal do Rio Grande do Sul, Brazil (civil engineer, 1986) and of the University of California, Berkeley (M.S. and Ph.D. in civil engineering, 1990 and 1993). Prof. Salgado has consulted on a number of foundations projects all over the world. He is the author of "The Engineering of Foundations", published by McGraw-Hill, and has developed software for foundation design. Prof. Salgado is the recipient of various important awards, including the Huber Research Prize and the Arthur Casagrande Award from ASCE. More information on his work can be found on http://www.foundationengineering.info and http://www.ecn.purdue.edu/~rodrigo.