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Reliability-based code revision for design of pile foundations: Practice in Shanghai, China

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Abstract

This paper describes how the code for the design of pile foundations in Shanghai, China is revised based on the reliability theory. With quality static load test data, both within-site and cross-site variabilities for design methods of piles in Shanghai are characterized. It is found that the amount of uncertainties associated with the design of piles in Shanghai is less than the typical values reported in the literature. With the partial factors specified in the previous design code, the reliability indexes of piles designed with empirical methods are in the range of 3.08–4.64, while those of piles designed with the load test-based method are in the range of 5.67–5.89. The load factors in the revised local design code have been reduced according to the national design code. As a result, the resistance factors have been increased in the revised code based on a combination of a reliability analysis and engineering judgment. In the revised design code, the reliability level of piles designed with the empirical methods is similar to that in the previous design code; the reliability level of piles designed with the load test-based method is lowered to achieve cost-effectiveness. Partial factors have been suggested for side and toe resistances based on the reliability theory considering their relative importance as well as the uncertainties involved.

Keywords: Pile foundations; Design code; Load and resistance factor design; Reliability

1. Introduction

Although the global factor of safety (FOS) method has been successfully used for decades, its disadvantage is obvious, namely, that the true level of safety is uncertain for a given FOS, as the method does not explicitly consider the level of uncertainty involved in a design. As a result, designs with the same FOS may in fact correspond to different levels of safety. To overcome the limitations of the FOS method, probabilistic methods can be used to explicitly model the uncertainties, through which the safety of a design can be assured by limiting the chances of an unsatisfactory performance to an acceptably low level. In past decades, extensive research was conducted to develop partial factors for the design of pile foundations based on the reliability theory (e.g., Honjo et al., 2002; Phoon et al., 2003; AASHTO, 2007; Ching et al., 2008; Yu et al., 2012).

As part of the worldwide efforts to implement a reliability-based design in geotechnical engineering, resistance factors for

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Table 1
Suggested side and toe resistances in different soil layers.
Adapted from SUCCC (2010).

Layer no.	Soil description	Depth (m)	Driven piles		Bored piles	
			f_s (kPa)	q_t (kPa)	f_s (kPa)	q_t (kPa)
②	Brownish or grayish yellow clay	0–4	15		15	
	Gray clayed silt	4–15	20–40	500–1000	15–30	
	Gray sandy silt	4–15	30–50	1000–2000	25–40	600–800
	Gray silty sand	4–15	40–60	2000–3000	30–45	700–900
③	Very soft gray silty clay	4–15	15–30	200–500	15–25	150–300
	Gray sandy silt or silty sand	4–15	35–55	1500–2500	30–45	800–1000
④	Very soft gray clay	4–20	15–40	200–800	15–30	150–250
⑤ or ⑤$_1$	Gray clay	20–35	45–65	800–1200	40–55	350–650
	Gray sandy silt	20–35	50–70	2000–3500	40–60	850–1250
⑤$_2$	Gray silty sand	20–35	70–100	4000–6000	55–75	1250–1700
⑤$_3$	Gray or dark gray clay	25–40	50–70	1200–2000	45–60	450–750
⑥	Dark green or brownish yellow clay	22–26	60–80	1500–2500	50–60	750–1000
		26–40	80–100	2000–3500	60–80	1000–1200
⑦$_1$	Straw yellow sandy silt or silty sand	30–45	70–100	4000–6000	55–75	1250–1700
⑦$_2$	Gray fine sand with silt	35–60	100–120	6000–8000	55–80	1700–2550
⑧$_1$	Gray silty clay with silty sand	40–55	55–70	1800–2500	50–65	850–1250
⑧$_2$	Gray silty clay interlayed with silty sand	50–65	65–80	3000–4000	60–75	850–1700
⑨	Gray fine, medium or coarse sand	60–100	110–120	8000–10,000	70–90	2100–3000

the design of pile foundations were calibrated in Shanghai, China when the local foundation design code (SUCCC, 2000) was revised in 2000. After ten years of accumulating new data, knowledge and experience, the foundation design code was revised again recently (SUCCC, 2010). Previously, SUCCC (2000) was developed based on the national foundation design code MOC (1989), for which the load factor for a dead load (γ_D) was 1.2 and the load factor for a live load (γ_L) was 1.4. In 2002, the national design code (MOC, 2002) changed the load factors to $\gamma_D=1.0$ and $\gamma_L=1.0$, respectively. The mismatch between the local design code and the national design code caused inconvenience to those involved with foundation design in Shanghai; it is also one of the important reasons for the code revision.

A team of experts, including experts in the geotechnical reliability theory and experienced practitioners with sound engineering judgment, carried out the code revision work. For ease of communication, the resistance factors for the design of piles were calculated based on the simple, but sound, reliability theory. The calibrated results were then interpreted with engineering judgment, and the code was revised based on the consensus of all participating parties. The new features of the revised design code include:

(1) Both within-site variability and cross-site variability are calibrated and considered in the design of pile foundations.
(2) The reliability level of the static load test-based method has been assessed and lowered as supported by the reliability theory.
(3) Partial factors are developed based on the reliability theory for side and toe resistances considering their relative importance and the associated uncertainties.

The objective of this paper is to introduce how the resistance factors for the design of piles in Shanghai are revised based on the reliability theory supplemented with engineering judgment. It is hoped that the experience in Shanghai may provide a useful reference for developing and revising reliability-based geotechnical design codes in other regions. This paper is organized as follows. First, the engineering background of the subsurface deposits and piling practices in Shanghai is introduced. Then, the design methods and calibration database are described. Thereafter, the reliability level, corresponding to the existing partial factors, is assessed. Finally, the resistance factors for the design of piles are calibrated based on the reliability theory, and the design code is revised based on a combination of reliability-based calibration results and engineering judgment.

2. Engineering background

Shanghai is located at the deltaic deposit of the Yangtze River on the eastern coast of China. The subsoil of Shanghai is composed of sediments containing clay, silt and sand, resulting from the alternating warm and cold climates and the changes in sea level over the past 3 million years. The elevation of the ground surface is generally 3–5 m above sea level. The depth of the bedrock could be up to 300–400 m. The soil stratum in Shanghai is relatively uniform. Most civil engineering constructions are within a depth of 80 m below the ground surface, and the typical soil layers within such a depth are shown in Table 1. The left column in Table 1 shows the layer numbers used in the local profession. Among the eight layers shown in Table 1, layers ③, ④, and ⑧ are soft soils with low permeability, high compressibility, and low strength. One can refer to Dassargues et al. (1991), Shen and Xu (2011), and Ng