EFFECT OF RADIAL DISTANCE OF A SINGLE CPT SOUNDING ON THE PROBABILITY OF OVER- AND UNDER-DESIGN OF PILE FOUNDATION

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ABSTRACT: It was expected that the distance between a cone penetration test (CPT) sounding and pile foundation would have a significant impact on pile design. It is commonly believed that the closer a CPT sounding is to the location of the pile foundation, the more reliable the data for designing the pile. This paper examines the maximum distance of the CPT sounding beyond which the pile design is effectively unreliable. This is achieved by carrying out 3D numerical simulations within a Monte Carlo framework and by varying distances of a cone penetration tests (CPT) to pile foundation. In this way, it is possible to determine the probabilities of design failure and pile over-design for a variety of site investigation scenarios represented by the distance of the CPT and levels of ground variability. It is observed, that beyond a certain distance of the CPT from the pile, the pile design seems to be unreliable. This is identified as the “critical distance” where its magnitude is influenced by the spatial variability of soil profiles.

Keywords: Site investigations, soil variability, pile foundations, distance, cone penetration test, axial pile load capacity.

INTRODUCTION

Generally, the scope of geotechnical site investigation is governed by minimum cost and time of completion (Institution of Civil Engineers 1991). Several studies have shown that ground engineering risk is one of the largest elements of technical and financial risk in civil engineering and building projects. Therefore, foundation failure can occur due to inadequate and/or inappropriate site investigations (Nordlund & Deere 1970, ASFE 1996). In addition, inadequate site investigations often can also lead to foundation over-design resulting in unnecessarily increasing foundation and construction costs.

The effect of inadequate site investigation on foundation design has been studied by Jaksa et al. (2005), Goldsworthy (2006). They performed a combination of random field simulations and finite element analysis to investigate the appropriate scope of site investigations for designing shallow foundations. Their research aimed to quantify the appropriate number of boreholes, including site investigation patterns and test type, specified by certain levels of variability. The spatial variability parameters included the mean, coefficient of variation (COV) and scale of fluctuation (SOF). The SOF is a measure of the distance over which properties exhibit strong correlation. By simulating various numbers of boreholes, the reliability of shallow foundation design was estimated using a Monte Carlo approach. Their research has been applied for other foundation, such as pile foundation, as conducted by Arsyad et al (2008, 2009).

This paper seeks to examine the effect of radial distance of CPT on the pile design. The radial distance is defined as the distance in radial way between a CPT and pile. The simulations of a CPT and a single pile foundation were then conducted on a 3-dimensional of soil profiles generated as a virtual model of site. The spatial variability of the model is specified by coefficient of variability (COV) and scale of fluctuation (SOF).

As seen in Figure 1, once the site and a CPT are ‘sampled’ from the virtual site, cone tip resistance, qc, profiles in the vertical and horizontal directions are obtained. The simulated qc profiles from the CPT are then used to compute axial pile load capacities for the pile foundation using the LCPC method (Bustamante and Gianaselli, 1982). This axial pile load capacity is termed the ‘pile design based on the site investigation (SI). In parallel, the ‘true’ axial pile load capacity for simulated pile foundation is obtained by utilizing the data from the entire site, and this benchmark pile design is referred to as the ‘pile foundation design based on complete knowledge (CK). At the end of the process, the study compares the pile load capacity based on the SI with that based on CK. The reliability of the pile foundation design is analyzed using a probabilistic

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SIMULATION OF CPT AND PILE FOUNDATION

The LAS simulation process involved generating sites consisting of $2^n$ elements (Fenton and Vanmarcke, 1990). In this case $256 \times 256 \times 128$ elements were generated (Figure 2). With each element representing a 0.25 m cube of soil, this translated into an interim site of $64 \times 64 \times 32$ m, which was subsequently sub-sampled to yield the $50 \times 50 \times 30$ m site incorporating a total of 4.8 million, 0.25 m cubic elements. The pile, therefore, consists of approximately 4 elements in the plan dimension by 80 in the vertical direction. In order to appropriately quantify the axial capacity of each pile, it is necessary to determine the lateral extent of soil elements which contribute to the pile’s load carrying capacity. Teh & Houlsby (1991) estimated the influence zone of a cone penetrometer as it penetrates the ground, which is similar in nature to that of a pile foundation. Assuming a rigidity index, $I_r$, of 200, they found the influence diameter was 12 times the diameter of the cone. Applying the results of Teh & Houlsby (1991) to the present scenario, a 0.5 m diameter pile influences a region of soil 6 m in diameter. Hence, when assessing complete knowledge (CK) of the site, a total of 576 elements in the plan dimension are averaged to yield the equivalent point value of $q_c$ at any particular depth, for simplicity assuming a square influence region in plan (Figure 3).

A CPT is located at a certain position from which its radial distances towards pile foundation are measured (Figure 3). Totally, there are 40,000 of radial distances ($R_d$) simulated on the model. The longest $R_d$ is 34.50 metres, whereas the shortest $R_d$ is 0.25 metres. The pile is assumed to be bored pile with the diameter of 0.5 m and the length of 20 m.

RESULTS AND DISCUSSION

Figure 4 and 5 show the influence of varying the radial distance with respect to the probability of under- and over-design, respectively. In this context, the probability of under-design refers to the number of times
divided by the total number of Monte Carlo realizations (in this case 1,000) expressed as a percentage, when the axial design capacity resulting from site investigation (SI) yielded a value higher than that obtained by complete knowledge (CK). This would imply that the SI has yielded an unconservative design, which would ordinarily lead to some form of failure, the extent of which would depend on the difference between the SI and CK capacities.

In contrast, the probability of over-design refers to the proportion of times that the axial design capacity resulting from the SI yielded a value lower than that obtained by CK. This would imply that the SI provided a design capacity lower than the ‘true’ or CK capacity, thereby incorporating an unnecessary level of conservatism. In addition to the probability of under- and over-design, there is also the probability that the SI results in a design equal to that from CK, within a certain tolerance. This probability is, of course, equal to the difference between unity and the sum of the probabilities of under- and over-design.

With reference to Figure 4 and 5, as the radial distance increases, the probability of under-design and over-design increases. At certain distances, the probabilities seems to be constant. For example, in the SOF of 1 metre, the distance of probability under- and over-design being constant is around 5 metres of the CPT located towards the pile. Compared to that, for the SOF of 10 metres, those are at 22 metres. It is also observed that, as one would expect, at the same distance, the probability of under- and over-design for soil with large COV is higher than that for soil with small COV. However, in general, it can be suggested that the increase of radial distances of the CPT would have a significant impact on the magnitude of probability of under- and over-design of the pile.

The level of spatial variability o, represented by SOF and COV, also has a marked influence on the design. At the same radial distance, the CPT simulated in the soil with a high COV would yield a higher probability of under- or over-design than that in soil with a low COV.

Figure 4 and 5 also reveals that, as previously explained, at a certain distances, the probability of under- and over-design levels off. These distances are considered as the critical distances where beyond those distances, the pile design become unreliable. Those critical distances have correlation with the SOF. The higher SOF, the longer critical distance would be (Figure 6). However, the SOF is larger than 10 m, the critical distance become declined. Therefore, the SOF of 10 meter is the worst case SOF.

The worst case SOF of 10 metres found in this study is similar to what Goldsworthy (2006) found, as long as 8 metres. The reason why it is different is due to the different type of foundation simulated. Goldsworthy (2006) focused on shallow foundation whereas this study of pile foundation. In addition, the axial design capacity computed in this research is based on axial load capacity, whereas Goldsworthy (2006) employed serviceability (foundation settlement). However, it should be noted that the concept of critical distance as examined here, is based on the assessment of the statistical properties and it is expected to different to that which would be obtained if an examination of soil mechanics was carried out.
The influence of the size and the type of the foundation in this study was also investigated as part of the research. It was expected that the size and type of the pile would affect the simulation with respect to the probability of under- and over-design. Therefore, the simulations were conducted for 4 different lengths (5, 10, 20 and 30 metres), and for 3 different types of pile foundation.

Figure 7 and 8 show that, even for the different type and size of pile foundation, the result is similar. The increase of radial distance of CPT results in increasing the probability of under- and over-design. However, it is different for their levels of magnitude. For example, the probability of under- and over-design for the pile of 5 metres is higher than that for the pile of 20 metres. Therefore, the probability of under- and over-design for a shorter pile is higher than that for a longer pile. This is because for a shorter pile, the CPTs are averaged over a shorter length. As a result, the variations over this pile are more significant than a longer pile where the CPTs located over the pile average on the longer length.

In the case of the influence of pile construction methods, this study performed simulations for three different piles. They are driven pre-cast, bored, and cast screw piles. It was expected that those types of piles have significant effect on the probability of under- and over-design. However, Figure 9 and 10 show that the type of foundation have little impact on simulation. This is due to the fact that, the method employed to compute axial load capacity (the LCPC method), were performed consistently for each pile construction method. The LPC method estimates the axial load capacity for a simulated pile foundation and for a simulated site investigation. Once those capacities are compared, the results will be similar for all types of foundation.
CONCLUSIONS

This paper has examined the influence of radial distances of a CPT sounding on the reliability of pile foundation design involving axial load capacity using the LCPC method and incorporating spatial variability of soil properties using the LAS technique within Monte Carlo framework. It has been observed that, as one would expect, the closer CPT located to the pile designed, the lower probability of under- and over-designing pile foundation would be. In addition, at beyond a certain distance, the pile design would not be reliable. The distance is considered as the critical distance whose magnitude depends on the level of spatial variability of the soil (COV and SOF).

Future work will examine the effect of radial distance of CPT on a pile group as well as the use of serviceability (pile settlement).

Other type of site investigation such as standard penetration test (SPT) will be incorporated.

REFERENCES


