# The effect of limited site investigations on the design of pile foundations

## L'effet des investigations limitées d'emplacement sur la conception des bases de pile

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ABSTRACT

When designing pile foundations, it is normal practice to perform a site investigation in order to quantify the physical and engineering properties of the ground. Often, the scope of the site investigation is dictated by construction time lines and budgetary constraints, rather than on the variability of the ground. It has been shown by a number of authors that as little as 0.04% – 0.3% of the total construction budget is spent on geotechnical investigations. Limited site investigations have the potential to impact significantly on the success or otherwise of the completed project. These include cost over-runs, construction delays, foundation failure and over-design. It has been suggested that "*You pay for a site investigation whether you have one or not*."

This paper examines the influence of limited site investigations on the design and performance of pile foundations with respect to pile load capacity. This is achieved by carrying out 3D numerical simulations within a Monte Carlo framework using varying numbers of cone penetration tests (CPTs) and the LCPC method for estimating pile load capacities. 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 various numbers of the CPTs and levels of ground variability. It is observed, as expected, that the probability of pile foundation design failure and over-design decreases as the number of CPTs increases. It is also identified that after a certain number of CPTs, little benefit is derived from additional soundings.

RÉSUMÉ

En concevant des bases de pile, il est dans des habitudes normaux d'effectuer une recherche d'emplacement afin de mesurer les propriétés physique et de genie vis-à-vis du terrain de construction. Souvent, la portée de la recherche d'emplacement est dictée par des lignes de temps de construction et des contraintes budgétaires, plutôt que sur la variabilité du terrain de construction. Elle a été montrée par un certain nombre d'auteurs qui aussi peu que 0.04% – 0.3% de tout le budget de construction est dépensé sur des investigations géotechniques. Les investigations limitées d'emplacement ont le potentiel d'effectuer de manière significative sur le succès ou autrement du projet réalisé. Celles-ci incluent des dépassements de coût, des retards de construction, l'échec de base et l'overdesign. On lui a suggéré que « vous payiez une recherche d'emplacement meme si vous en ayez un ou pas.

Ce document examine l'influence des investigations limitées d'emplacement sur la conception et l'exécution des bases de pile en ce qui concerne la capacité de charge de pile. Ceci est réalisé par les simulations 3D numériques de mise en oeuvre dans un cadre de Monte Carlo suivre des nombres variables d'essais de pénétration de cône (CPTs) et la méthode de LCPC pour estimer des capacités de charge de pile. De cette façon, il est possible de déterminer les probabilités de l'échec de conception et la pile au-dessus-conçoivent pour une série de scénarios de recherche d'emplacement représentés par de divers nombres du CPTs et niveaux de la variabilité au sol. On l'observe, comme prévu, que la probabilité de l'échec de conception de base de pile et au-dessus-conçoit des diminutions à mesure que le nombre de CPTs augmente. Cependant, on l'identifie qu'après un certain nombre de CPTs, peu d'avantage est dérivé des sondages additionnels.

Keywords : site investigations, soil variability, pile foundations, axial load capacity, cone penetration test

## 1 INTRODUCTION

Over the last 30 years or so geotechnical site investigation fees have been driven down, with the scope often being governed by minimum cost and time of completion (Institution of Civil Engineers 1991). Furthermore, 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. Indeed, foundation failure can often be attributed to inadequate and/or inappropriate site investigations (Nordlund & Deere 1970, ASFE 1996). In addition, inadequate site investigations often result in foundation over-design, thereby unnecessarily increasing foundation and construction costs.

A number of researchers have developed methods to seek the appropriate scope of site investigations. Toll (1998) reviewed artificial intelligence methods, known as knowledge based systems (KBSs), used in planning the scope of site investigations. The earliest KBS method, developed by Wharry & Ashley (1986) and Siller (1987), was SOILCON. Following this, a simple prototype KBS for soil investigation was introduced by Alim & Munro (1987) and further developed by Halim et al. (1991) in order to incorporate probabilistic analysis for planning site investigation programs.

More recently, Parsons & Frost (2002) introduced a method incorporating a geographic information system (GIS) and geostatistics in order to assess quantitatively the scope of site investigations. The GIS was used to optimize multiple sampling locations of investigations within a site, while geostatistics, involving ordinary and indicator kriging, was employed to generate probabilistic values of those sampling locations.

Jaksa et al. (2005) and Goldsworthy (2006) 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.

Based on the site investigation reliability framework introduced by Jaksa et al. (2003) and performed by Goldsworthy (2006), this paper seeks to investigate the effect of limited site investigations on the design of pile foundations. The study employs a method incorporating the generation of three-dimensional random fields, as virtual models of a site, using the local average subdivision (LAS) technique developed by Fenton & Vanmarcke (1990), and the computation of axial pile load capacity using the Laboratoire Central des Ponts et Chausseés (LCPC) method developed by Bustamante & Gianeselli (1982). A number of site investigation scenarios are simulated and their reliabilities on the design of pile foundations are quantified within the Monte Carlo framework.

As shown in Figure 1, the simulation process is initiated by generating a 3D random field consisting of a single-layer soil profile at a certain level of variability. The model also incorporates various numbers of pile foundations and cone penetration tests (CPTs). Once the site and CPTs are 'sampled' from the virtual site, cone tip resistance, $q_c$, profiles in the vertical and horizontal directions are obtained. The simulated $q_c$ profiles from the CPTs are then used to compute axial pile load capacities for the pile foundation. 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 each 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 approach based on the Monte Carlo technique and incorporating 1,000 realizations. In Figure 1, the reduction method refers to the averaging technique used to combine the various $q_c$ values into a single value. In this paper, standard arithmetic averaging is used. Arsyad (2008), however, examined the influence of using the harmonic and geometric average.

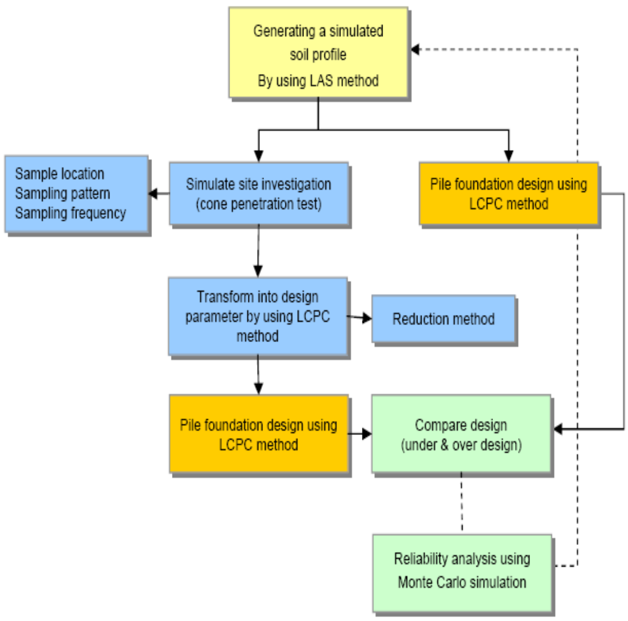


Figure 1. Flowchart of simulations (adapted from Jaksa et al. 2005 and Goldsworthy 2006).

## 2 SIMULATION OF CPTS AND PILE FOUNDATIONS

The site configuration simulated in this study is shown in Figure 2. It can be seen that the plan dimensions of the site are assumed to be 50 m × 50 m × 30 m in depth. The site incorporates 9 piles, arranged on 3 rows and 3 columns, and their spacing is 12.5 m in both directions. The piles themselves are assumed to be bored, 0.5 m in diameter and 20 m long. The mean of the $q_c$ values was set at 5.0 MPa.

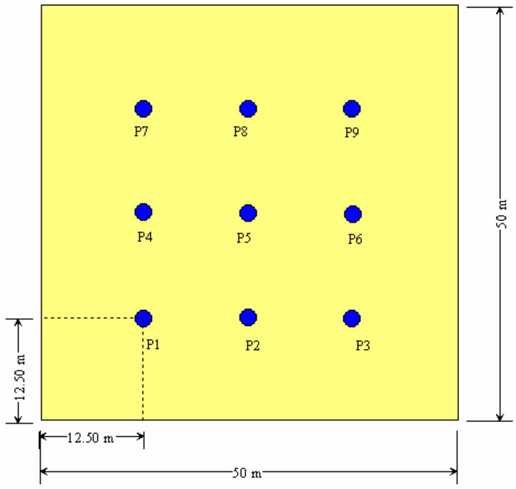


Figure 2. Plan view of site with 9 piles.

The LAS simulation process involved generating sites consisting of $2^n$ elements. In this case 256 × 256 × 128 elements were generated. With each element representing a 0.25 m cube of soil, this translated into an interim site of 64 × 64 × 32 m, which was subsequently sub-sampled to yield the 50 × 50 × 30 m site, incorporating a total of 4.8 million, 0.25 m cubic elements. Each 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.

As shown in Figure 3, 12 different site investigation plans are examined, containing between 1 and 16 CPTs at various plan locations. The positions of the CPTs are typical of those used in standard site investigation practice.

When simulating each CPT, a sounding involves a vertical transect of a single $q_c$ value intercepted at each depth. Hence, each 20 m deep CPT incorporates 80 (20 × 0.25) elements along a vertical line through the site.

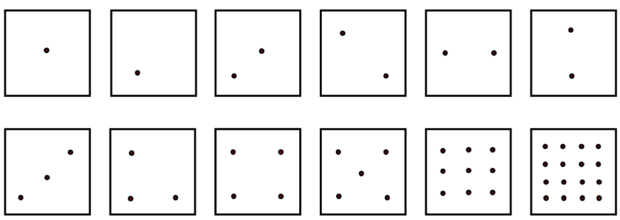

Figure 3. Site investigation plans.

## 3 RESULTS AND DISCUSSION

Figures 4 and 5 show the influence of varying the scope of a site investigation with respect to the probabilities 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 the site investigation (SI), for any of the piles, 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 probabilities 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, for a soil with a COV of 20% and SOF of 10 m, the minimum sampling (one CPT) yields a probability of under-design of 11%, whereas the maximum sampling (16 CPTs) yields a probability of under-design of only 3%. Similarly, for a soil with a COV of 100% and a 10 m SOF, a single CPT yields a probability of under-design of 22%, whereas 16 CPTs yields a probability of 5% under-design.

It is also shown in Figures 4 and 5, for a soil SOF of 1 m, a sampling effort greater than 5 CPTs has little impact on the

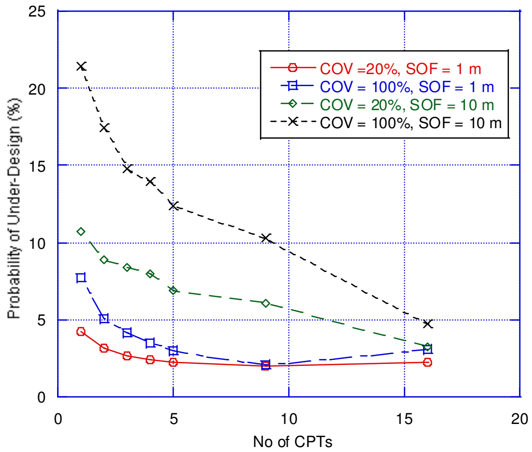


Figure 4. Effect of sampling effort of the probability of under-design.

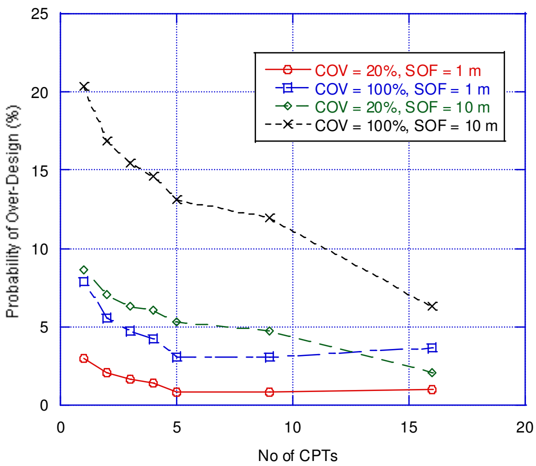


Figure 5. Effect of sampling effort of the probability of over-design

probabilities of under- and over-design. Therefore, it can be suggested that 5 CPTs is the optimum for achieving the lowest probability of under- and over-design of the piles for the site scenario examined in the present study. However, for a soil SOF of 10 m, it is observed that 16 CPTs is the optimum sampling effort, bearing in mind that 16 CPTs is the maximum sampling effort investigated in this study. It is found that there is benefit from increasing sampling effort for either soil with low or high SOF. In addition, the results clearly demonstrate that, as expected, more thorough investigation (i.e. a greater number of CPTs) is needed as the COV increases and, perhaps less intuitively, as the SOF increases. The latter is due to the fact that soil profiles with low SOFs are highly erratic, whereas soils with higher SOFs exhibit large pockets of material with very similar soil properties. If a CPT encounters one of these pockets, but the pile is located in a region outside of the pocket, the properties recorded by the CPT may be significantly different from the 'true' values adjacent to the pile. As a consequence, higher SOFs result in higher probabilities of under- and over-design. However, as the SOF tends to infinity, the probabilities of under- and over-design will decrease because the soil becomes more uniform. This suggests the presence of a 'worst case' SOF which, in the authors' experience, is related to the characteristic dimension of the problem; in this case approximately 10 m. These results are consistent with those observed by Fenton & Griffiths (2002) and Goldsworthy (2006).

Figures 6 and 7 present the results of the simulations conducted on soil with a COV of 50% and SOFs of 1 and 10 m. It can be observed that an increased number of CPTs decrease the probability of under- and over-design, as one would expect. For example, in terms of soil with a SOF of 10 m, a site investigation consisting of a single CPT produces a probability of under-design of 16% and 13% for over-design. By performing 16 CPTs, the probability of under-design reduces significantly to 4% and over-design to 3%. It is also observed that site investigations conducted on soils with a higher SOF (i.e. 10 m) yield higher probabilities of under- and over-design of the piles than those on soils with low SOFs.

The simulations above were developed based on a site incorporating 9 piles. In order to examine the influence of the number of piles with respect to the conclusions presented above, simulations are also conducted for various numbers of piles (between 25 and 100), as shown in Table 2. The configurations of the piles are again in regular grids, with the same number of row and columns. The length of the piles is again 20 m, however, for these simulations the pile diameter is set at 1.0 m. The soil COV and SOF is set to 50%, and 10 m, respectively, and the mean of the $q_c$ values is again 5.0 MPa.

From the results given in Figures 8 and 9, it can be seen that, as observed above, for each of the pile configurations examined,

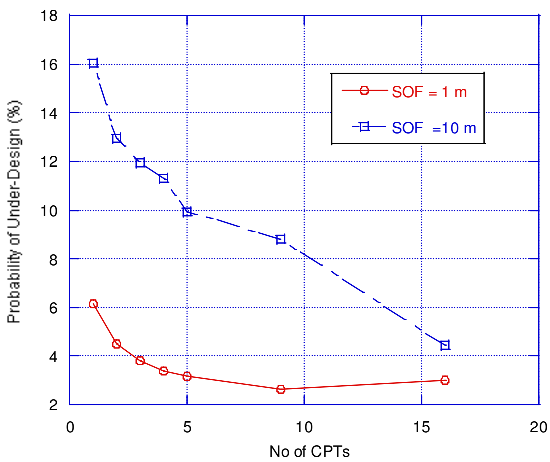


Figure 6. Effect of sampling effort on the probability of under-design, with increasing SOF for COV = 50%.

increased sampling effort reduces the probabilities of under- and over-design. In addition, the number of piles appeared to have minimal impact on these probabilities.

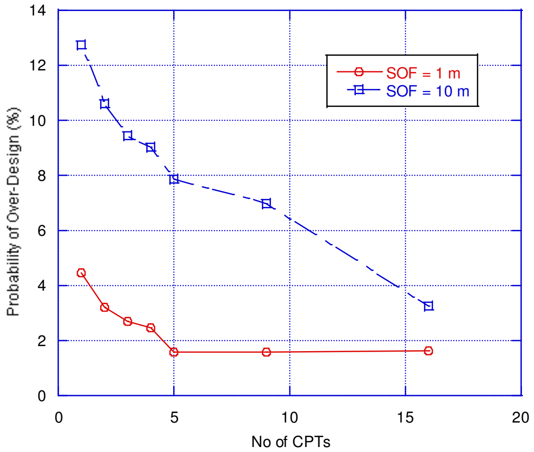


Figure 7. Effect of sampling effort on the probability of over-design, with increasing SOF for COV = 50%.

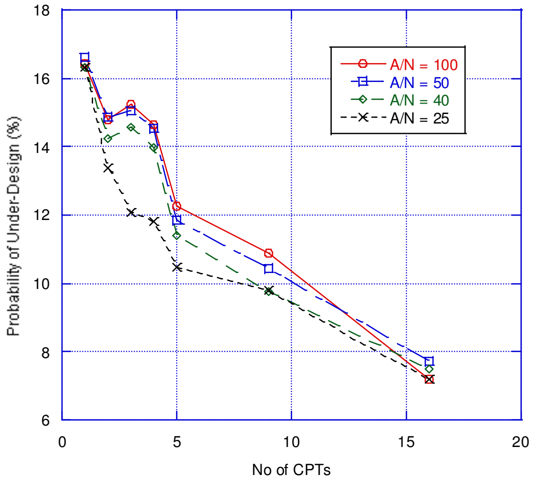


Figure 8. Effect of sampling effort on the probability of under-design, for different numbers of piles.

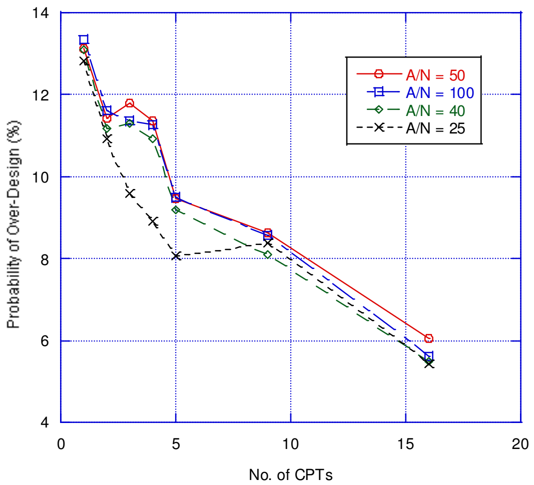


Figure 9. Effect of sampling effort on the probability of over-design, for different numbers of piles.

Table 1. Number and configuration of piles used in the simulations.

| No. of piles, N | 25 | 49 | 64 | 100 |
|---|---|---|---|---|
| Pile configuration | 5×5 | 7×7 | 8×8 | 10×10 |
| Pile spacing, d, m | 10 | 8 | 7 | 5 |
| Area ratio, A/N, $m^2$/pile | 100 | 50 | 40 | 25 |

## 4 CONCLUSIONS

This paper has examined the influence of various numbers of cone penetration tests (CPTs) on the reliability of pile foundation design involving axial load carrying capacity using the LCPC method and incorporating spatial variability of soil properties using the LAS technique within a Monte Carlo framework. It has been observed that, not unexpectedly, the probability of under-designing and overdesigning a pile foundation decreases as the scope of the investigation increases. In addition, as the COV and SOF increases, so too does the level of investigation needed to characterize the soil properties appropriately. However, it has also been observed that in some of the situations examined, there appears to be an optimal level of investigation, beyond which the probabilities of under- and over-design increase marginally.

Future work will examine pile group effects as well as serviceability aspects of pile design, using an approach similar to that adopted by Goldsworthy (2006). In this way, it will be possible to incorporate costs of failure and over-design, as outlined by Jaksa et al. (2003). This will enable the reliability of site investigations to be quantified, thereby enabling the scope of site investigations to be planned more effectively so as to minimize foundation failures and over-design.

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