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# Towards reliable and effective site investigations

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**It is widely appreciated that, in civil engineering and building projects, the largest element of financial and technical risk usually lies in the ground. Almost exclusively, the scope of geotechnical investigations is governed not by what is needed to characterise the subsurface conditions appropriately but, rather, by how much the client and project manager are willing to spend. There is often little correlation between the variability of the ground and the scope of the investigation. This paper presents the results of a Monte Carlo simulation incorporating many 3D single-layer soil profiles with different statistical characteristics. A three-storey building founded on nine pad footings is used to assess the reliability of various site investigation scopes and test methods. The pad footings are designed on the basis of settlement, and are examined using 3D finite element analysis and Schmertmann's method. It is observed, as expected, that the likelihood of underdesigning or overdesigning a footing decreases as the scope of the investigation increases. The relationship between these likelihoods and the variability of the ground is presented.**

**KEYWORDS: footings/foundations; numerical modelling and analysis; site investigation; statistical analysis;**

**Il est largement accepté que, pour les projets de génie civil et de construction, l'élément de risque financier et technique le plus important touche généralement au sol. Presque exclusivement, la portée des enquêtes géotechniques est gouvernée non pas par ce qui est nécessaire pour caractériser des conditions de sous-surfaces appropriées mais plutôt par les sommes que le client et le chef de projet sont disposés à dépenser. Il existe souvent peu de corrélation entre la variabilité du sol et la portée de l'investigation. Cet exposé présente les résultats d'une simulation de Monte Carlo incorporant de nombreux profils de sol unicouche en 3 dimensions avec diverses caractéristiques statistiques. Nous utilisons un bâtiment de trois étage fondé sur neuf assises coussin pour évaluer la fiabilité de diverses portées d'investigation du site et diverses méthodes d'essai. Les assises sont conçues sur la base d'affaissement et sont examinées en utilisant une analyse d'élément fini en 3 dimensions et la méthode de Schmertmann. Nous observons, comme on pouvait s'y attendre, que la probabilité de sous-concevoir ou de surconcevoir une assise diminue à mesure que la portée de l'investigation augmente. Nous présentons la relation entre ces probabilités et la variabilité du sol.**

## INTRODUCTION

The scope of geotechnical site investigations is rarely related to the anticipated variability of the ground, and is often chosen to minimise initial costs (Institution of Civil Engineers, 1991). Many studies over the last 15 years or so have clearly demonstrated that, in civil engineering and building projects, the largest element of financial and technical risk often lies in the ground and, as a result, minimum initial cost investigations can lead to significant cost over-runs and delays during construction (National Research Council, 1984; Institution of Civil Engineers, 1991; Littlejohn *et al.*, 1994; Whyte, 1995). Expenditure on geotechnical site investigations varies considerably, being sometimes as low as between 0·025% (Jaksa, 2000) and 0·3% (National Research Council, 1984) of the total project cost. Site investigations that inadequately quantify the variability of the ground can result in three possible cost outcomes:

(*a*) The foundation is underdesigned as a result of an overly optimistic geotechnical model, and hence fails to comply with the design criteria, which can ultimately lead to some level of structural distress.

(*b*) The foundation is overdesigned as a consequence of a pessimistic geotechnical model and/or inherent conservatism in the design process.

(*c*) Unforeseen conditions require substantial changes to the foundation system, which also result in construction delays.

This has led the Institution of Civil Engineers (1991) to conclude that: 'You pay for a site investigation whether you have one or not.'

There currently exists little guidance in relation to determining the scope of an appropriate investigation for a given site, other than in the form of generic, non-site-specific rules of thumb (Lowe & Zaccheo, 1991; Bowles, 1996). This paper investigates, using 3D numerical simulations, the effect of soil variability and site investigation scope on the design and subsequent performance of a three-storey building founded on nine pad footings and located on a site with plan dimensions of 50 m × 50 m. Two site investigation strategies are examined: one based on discrete sampling, as in the case of the standard penetration test (SPT), and the other based on continuous sampling, as would occur with a cone penetration test (CPT). Several numbers of boreholes and soundings are investigated in order to determine the optimal site investigation strategy for sites with different soil variability characteristics. It is demonstrated that, as expected, additional sampling yields better estimates of footing size up to a certain number of boreholes, beyond which, additional sampling and testing provide marginal improvement in footing size.

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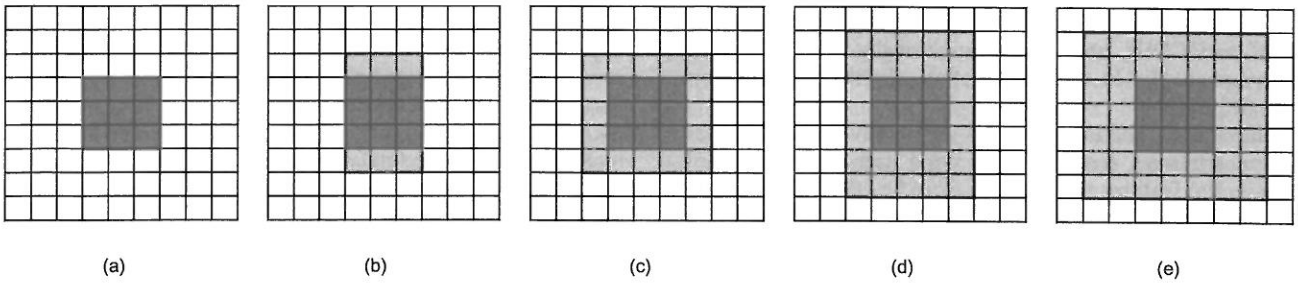


**Fig. 4. Process of determining footing dimensions (plan view of ground surface)**

area is increased by six elements, three either side of the original nine-element footing (Fig. 4(b)). If the design criteria again fail to be satisfied, the area of each violating footing is further enlarged, as shown in Fig. 4(c)–(e). The footing areas continue to be enlarged about the original nine-element footing until the design criteria are satisfied. An inherent limitation of such an approach is that the optimal footing is determined in discrete, and sometimes relatively large, increments. As a result, the size of the optimal footing is not known with great precision. However, this is not unlike the actual situation where footings are increased in size by discrete steps of 0·25 or 0·5 m, for example. There is, of course, a trade-off between the precision of the optimal footing size and the number of elements included in the finite element mesh. Although a finer mesh will result in the size of the optimal footing being known with greater precision, a significant increase in computational time will also occur.

In order to model the process of conventional footing design practice, a site investigation is simulated. In this paper, two testing schemes are examined. First, samples are taken or tests are performed at discrete vertical intervals of 1·5 m, as would occur with the SPT or triaxial tests. This is achieved by sampling every third element along a vertical 'boring' or transect. Second, a continuous sounding is simulated, as would occur with the CPT, where every element along a vertical 'boring', or transect, is intercepted. In addition, 12 site investigation schemes are investigated, as shown in Fig. 5. The solid line surrounding each strategy represents the building footprint (20 m × 20 m), which is located centrally on the 50 m × 50 m site, and the solid circles represent the boreholes or soundings. As shown in Fig. 5, the 12 site investigation schemes that are examined incorporate between 1 and 25 boreholes in a regular grid pattern: the adopted nomenclature refers to the investigation number, regular grid ('RG') pattern and the total number of boreholes. The purpose of the 12 schemes is to investigate the value of performing an increased scale of sampling and testing, as well as the location of the boreholes themselves. Future studies will examine the optimal location and pattern of boreholes in greater detail.

In order to compare the SPT and CPT investigations appropriately, it is necessary to include testing errors. It is widely recognised that the SPT is associated with much greater testing uncertainty than the CPT. This is due to equipment, procedural and operator-induced uncertainties (Orchant *et al.*, 1988; Jefferies and Davies, 1993). Lee *et al.* (1983) suggested that the COV for the SPT varies between 27% and 85%, whereas Phoon & Kulhawy (1999) suggested that it varies between 25% and 50%. On the other hand, Orchant *et al.* (1988) recommended that the COV for the CPT varies between 7% and 12%, whereas Phoon & Kulhawy (1999) found that it varies between 5% and 40% in clays. Studies by Jaksa (1995) suggest a much lower value. Hence, in the analyses described below, the following values are adopted: $COV_{SPT} = 50\%$ and $COV_{CPT} = 20\%$. Note that these values account solely for measurement error, and do not include spatial variability or model uncertainty, the latter accounting for errors associated with the relationship between the measured parameter and the derived soil property, e.g. SPT $N$ and $E$. The measurement errors are applied as an additional uncertainty derived from a uniform distribution. For example, once each test location is determined, and the simulated values of $E$ are obtained from these locations, the measurement uncertainty ($COV_{SPT}$ or $COV_{CPT}$) is added to account for testing error.

As most footings that are designed in practice do not involve 3D FEA, the settlements are calculated using the commonly adopted approach developed by Schmertmann (1978). Hence the footings are designed based on the limited knowledge obtained from the simulated geotechnical investigations and implemented by Schmertmann's method. In order to design the nine footings more appropriately, the influence of adjacent footings is included in the settlement calculation of each by evaluating the resulting additional stresses using the Boussinesq equations and adopting the relationships described by Holtz (1991). In addition, in order to integrate Schmertmann's strain influence factor triangle

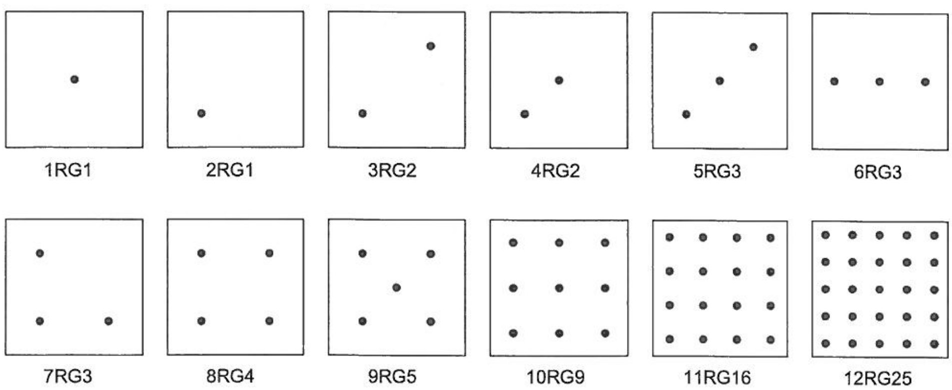


**Fig. 5. Site investigation schemes examined**

more precisely, a vertical step size of 0·01 m is used, rather than the 0·5 m element size.

The optimal and traditionally (Schmertmann) designed footings are then compared as outlined previously. Typically, the process described above, for a single soil profile and 1000 realisations, takes approximately 150 h to converge to a solution on a supercomputer using eight simultaneous processors, with each processor handling single realisations in turn.

## RESULTS AND DISCUSSION

In order to illustrate the variability associated with different scales of fluctuation, Fig. 6 shows the results of the

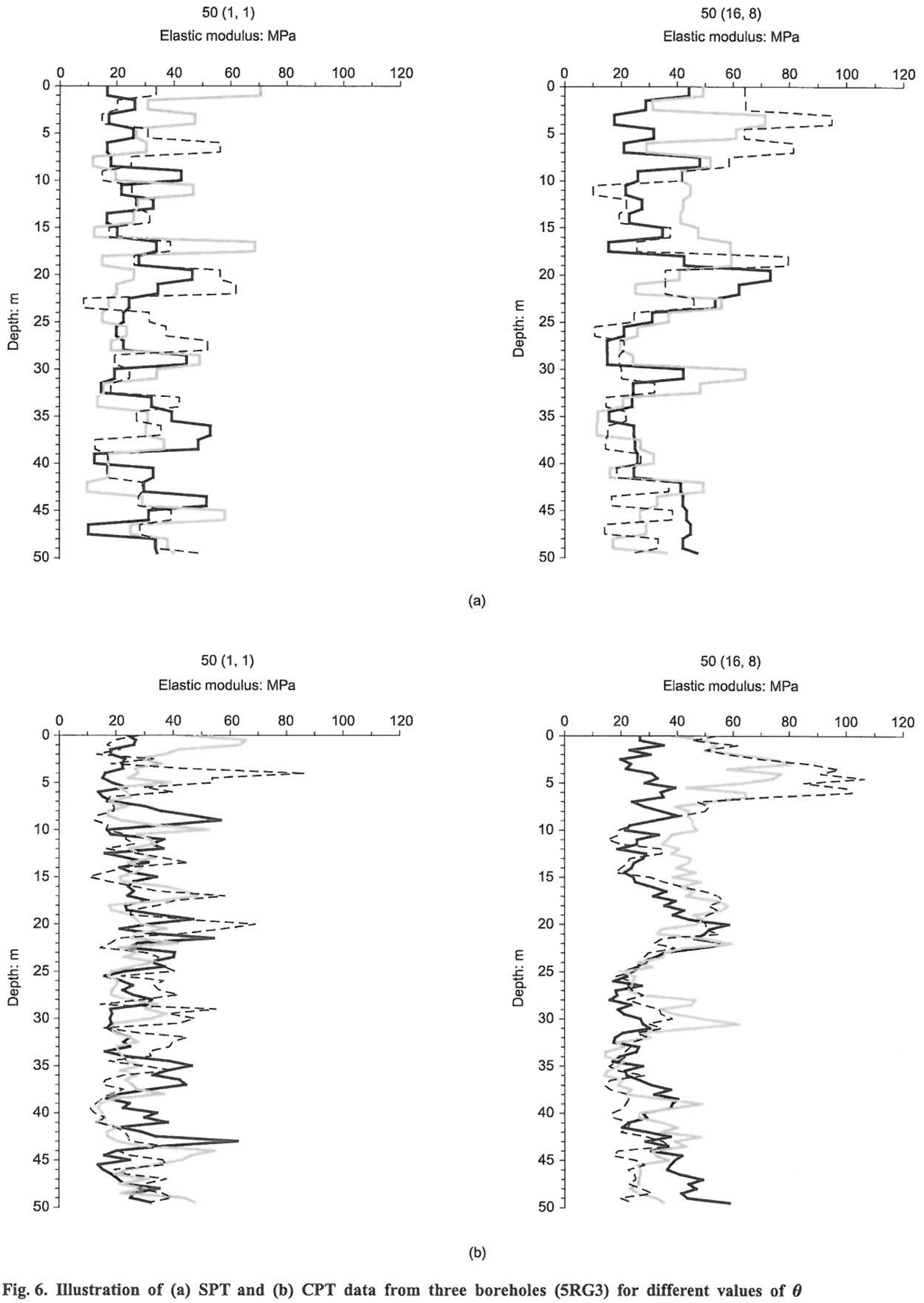


**Fig. 6. Illustration of (a) SPT and (b) CPT data from three boreholes (5RG3) for different values of $\theta$**

simulated site investigation associated with scheme 5RG3. Each plot shows the results, for a soil variability COV of 50%, of the three boreholes obtained from a single random field realisation. The left-hand plots refer to a realisation with $(\theta_H, \theta_V) = (1, 1)$ and the right-hand plots to $(\theta_H, \theta_V) = (16, 8)$. The upper two plots show the results of SPTs at 1·5 m vertical intervals and the lower two the results of 'continuous' CPTs, with data spaced at 0·5 m vertical intervals. Note that these results include testing errors of $COV_{SPT} = 50\%$ and $COV_{CPT} = 20\%$, as discussed above, which are superimposed on the variability of the soil profile itself, i.e. COV = 50%. It is evident from this figure, as explained previously, that small values of $\theta$ result in more erratic or rapid fluctuations.

*Finite element analyses used for complete site knowledge*

Figure 7 summarises the results of four analyses in terms of the mean total footing area (i.e. the sum of the areas of the nine footings averaged over the 1000 realisations) as a function of the number of boreholes. These traditional analyses are confined solely to the SPT. The legend identifying each of the four curves refers, first, to the soil variability COV, as a percentage, and second to the horizontal and vertical scales of fluctuation, respectively, in metres. Note that, for reasons that will be explained later, the results of the optimal footing design derived from 3D FEA are not shown on this plot. Instead, for each of the curves there is an associated dashed line, which refers to the result of the optimal footing design that is obtained if complete knowledge (CK) of the site is used in the application of Schmertmann's method. In this case, for each of the nine footings, the optimal footing is designed based on each element of soil within the region associated with each footing. The region adopted is 8 m × 8 m in plan (i.e. the centre-to-centre spacing of the footings) × 2*B* m in depth (*B* being the footing width), as is consistent with Schmertmann's method. (Although this region seems appropriate, future studies will investigate the significance of varying its extent.)

Figure 7 shows that, as expected, as the extent of the site investigation increases, the mean footing design area decreases, for both of the COVs presented. Perhaps surprisingly, the more continuous soil profiles [10 (16, 8) and 50 (16, 8)] yield greater variation, with increasing site investigation extent, than the more randomly fluctuating profiles [10 (1, 1) and 50 (1, 1)]. This is particularly apparent with the 50 (16, 8) case. (This will be discussed in greater detail later.) Furthermore, it can be seen in each case that, as a greater number of boreholes is adopted, the footings derived from the site investigation converge asymptotically towards those obtained from complete knowledge of the site (the dashed lines), as one would expect.

A similar behaviour is observed when one examines the standard deviation of the total footing area as a function c the extent of the site investigation, as shown in Fig. 8. Again, for larger numbers of boreholes, the standard deviation of the footings derived from the site investigation approaches that associated with the footings designed from complete knowledge of the site—again, as expected.

Figure 9 presents the results of the probabilities of over- and underdesign as a function of the number of boreholes. Overdesign is defined as the situation, for any realisation, where the total area of the nine footings derived from the site investigation data and Schmertmann's method exceeds the total footing area designed on the basis of complete knowledge of the site and 3D FEA. Underdesign is the reverse situation, where the total area of the nine footings derived from the site investigation data and Schmertmann's method falls below the total footing area designed on the basis of complete knowledge of the site and 3D FEA. Again, Fig. 9 suggests that the amount of overdesign decreases as the extent of the investigation increases. However, Fig. 9

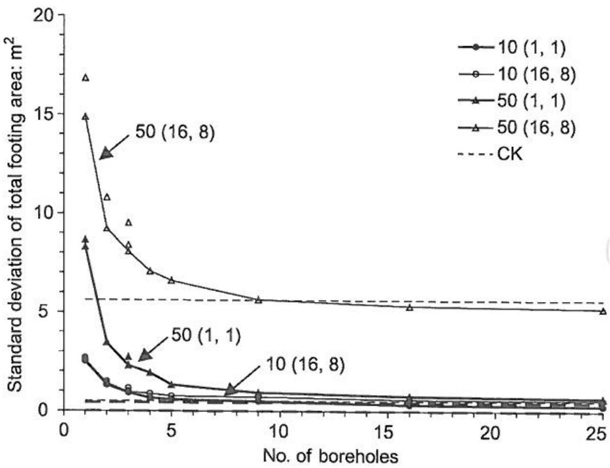


**Fig. 8. Standard deviation of footing size against extent of site investigation based on Schmertmann's method and SPTs**

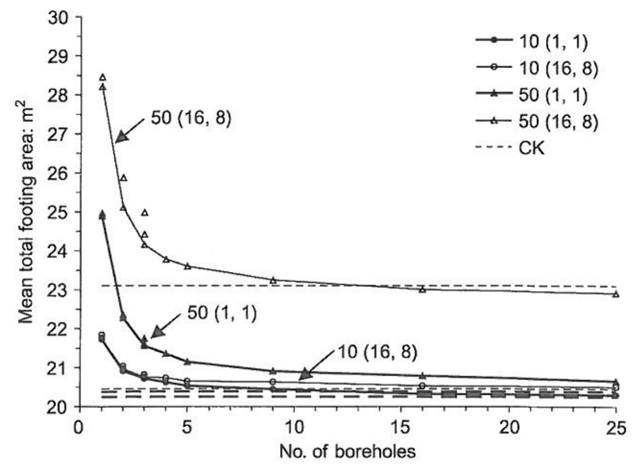


**Fig. 7. Mean footing size against extent of site investigation based on Schmertmann's method and SPTs**

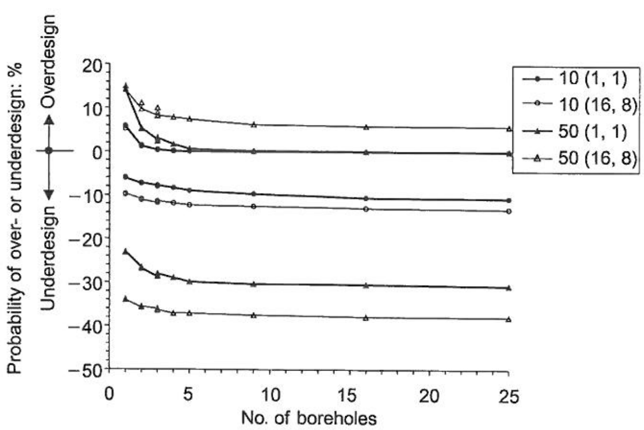


**Fig. 9. Probability of over- and underdesign for footing designed using SPT data and Schmertmann's method (when compared with footings designed using complete knowledge and FEA)**

also shows that the probability of underdesign increases as the extent of the investigation increases. This is contrary to what one would expect, but can be explained by the process adopted. As the optimal footing is based on a 3D FEA of the complete site, and the traditional footing design is based on the Schmertmann method, Fig. 9 includes model uncertainty, as explained earlier, which is the error between the finite element and Schmertmann techniques. For example, the mean optimal footing for the 50 (16, 8) case is 39·44 $m^2$, whereas if an optimal footing design was performed with knowledge of the entire site, using Schmertmann's method rather than 3D FEA, the mean optimal footing size would have been 23·10 $m^2$. As a result, even with complete knowledge of the site, the traditional design will always differ from the optimal footing obtained using 3D FEA, in this case by 16·34 $m^2$. To complicate matters further, the results presented in Fig. 9 are likely to be influenced, to some degree, by the adoption of the minimum footing size of 2·25 $m^2$ for the finite element analyses, as described previously.

For each of the cases examined, this discrepancy with respect to the mean and standard deviation of the total footing areas (i.e. the sum of the nine footing areas examined over the ensemble of 1000 realisations) is given in Table 1. This table demonstrates that, as the COV and $\theta$ increase, so too do the mean and standard deviations of the total footing area. In order to explain such behaviour, one needs to examine the nature of variability in more detail. Imagine two soil profiles, one with a small scale of fluctuation, e.g. (1, 1), which exhibits rapid variability over small distances, and the other with a larger scale of fluctuation, e.g. (16, 8), which is more continuous and varies slowly with distance, as shown previously in Figs 2 and 6. It is common for the latter, continuous profile to include larger pockets of soft or stiff material (Fig. 2(b)). As footing settlement essentially involves averaging the properties of many elements of soil within its zone of influence, the variability of settlement-based footing designs increases as the scale of fluctuation increases. This is because footings founded on continuous profiles might be founded on large zones of soft or stiff material, as well as material of intermediate stiffness, hence resulting in a wider range of possible footing sizes when compared with rapidly fluctuating profiles where the zone of influence effectively averages out the variability.

*Schmertmann's method used for complete site knowledge*

In order to compare more appropriately the footing sizes obtained, the remainder of the paper will make use of a slightly modified procedure from that described above. Rather than designing the optimal footings using 3D FEA, they will be designed using Schmertmann's method, adopting the process described earlier. As 3D FEA is not used in these subsequent analyses, the incremental increases in footing area are no longer constrained by the finite element mesh of 0·5 m × 0·5 m, as shown previously in Fig. 4. Instead, each individual footing will be increased in width by 0·1 m (0·05 m either side of the footing's centre). This enables more precise footing areas to be established. In addition, the minimum footing size of 1·5 m × 1·5 m that was used previously in the FEAs to maintain reliable numerical estimates is no longer required.

Figures 10 and 11 present the results for both SPT- and CPT-based site investigations, respectively, for COVs of 10% and 50% and scales of fluctuation of (1, 1) and (16, 8) obtained from 1000 realisations. (In comparison with the 3D FEAs, 1000 such realisations take approximately 2 h to converge to a solution on a single-processor desktop computer.) As can be seen from these two figures, the proportions of overdesign and underdesign generally decrease with a greater number of boreholes and as the COV decreases. In

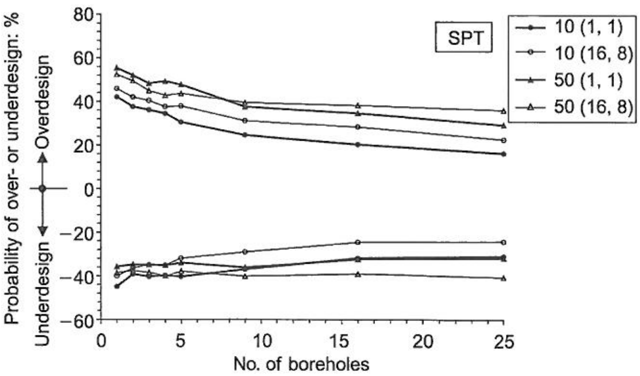


**Fig. 10. Probability of over- and underdesign for footings designed using SPT data and Schmertmann's method (when compared with footings designed using complete knowledge and Schmertmann's method)**

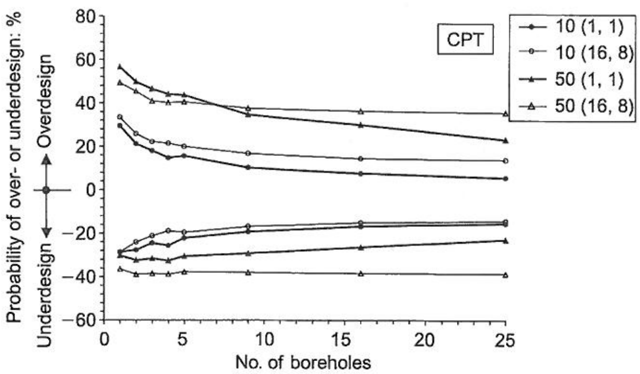


**Fig. 11. Probability of over- and underdesign for footings designed using CPT data and Schmertmann's method (when compared with footings designed using complete knowledge and Schmertmann's method)**

**Table 1. Means and standard deviations of total footing areas designed using Schmertmann's and finite element methods with complete knowledge of the site for different soil variabilities**

| Soil variability COV ($\theta_H$, $\theta_V$) | Mean: $m^2$ | | Standard deviation: $m^2$ | |
|---|---|---|---|---|
| | Schmertmann | Finite element | Schmertmann | Finite element |
| 10 (1, 1) | 20·25 | 21·76 | 0·00 | 0·18 |
| 10 (16, 8) | 20·45 | 22·87 | 0·51 | 1·92 |
| 50 (1, 1) | 20·39 | 26·70 | 0·43 | 1·84 |
| 50 (16, 8) | 23·10 | 39·44 | 5·62 | 25·52 |

highlight, particularly for 1RG1 and 8RG4, that a worst case appears to be associated with a horizontal scale of fluctuation of 8 m. This distance corresponds to the spacing of the columns: that is, the centre-to-centre spacing of the footings. Fenton & Griffiths (2004) investigated the differential settlement associated with two footings, and also found that the worst case $\theta$ was associated with the centre-to-centre spacing of the footings. This is a convenient observation, because, if the scale of fluctuation for a particular site is unknown, rather than needing to measure it—which can be very costly and time-consuming—one can assume a worst-case value equivalent to the centre-to-centre spacing of the footings.

Further analyses are needed before generic and comprehensive site investigation guidelines can be developed. Future studies should incorporate costs, other footing types, such as rafts, and other test types, including triaxial tests and the flat dilatometer test. In addition, sampling patterns and multi-layer profiles should also be investigated. Preliminary work on the relationship between the cost of foundation failures and the scope of site investigations has been published by the authors (Goldsworthy *et al.*, 2004). The long-term objective is to develop a series of guidelines that will enable geotechnical engineers to compare and discuss, with the client, the ramifications and cost-effectiveness of several geotechnical investigation scenarios. In this way the client will be better informed in relation to the risk of foundation failure and overdesign associated with the adopted site investigation, which, it is hoped, will lead to more reliable and cost-effective site investigations.

## CONCLUSIONS

Preliminary results have been presented describing the relationship between the extent of site investigations and the variability of a single-layer soil profile, based on a nine-pad footing system where only settlements have been considered. A framework proposed by Jaksa *et al.* (2003) has been implemented, and it has been observed that, not unexpectedly, the probability of underdesigning or overdesigning a footing decreases as the scope of the investigation increases. However, there will come a point where additional site investigation expenditure will not improve the reliability of the footing system, which will be highlighted when costs are included. A 'worst case' scale of fluctuation has been observed that coincides with the centre-to-centre spacing of the footings. Hence, if the scale of fluctuation for a particular site is unknown, one can assume a conservative value equal to the centre-to-centre spacing of the footings.

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