Influence of Site Investigations on the Design of Pad Footings

J S Goldsworthy
BE(Hons)
Doctoral Student, School of Civil and Environmental Engineering, University of Adelaide, Australia
M B Jaksa
BE(Hons) PhD, M.I.E.Aust, CPEng
Senior Lecturer, School of Civil and Environmental Engineering, University of Adelaide, Australia
G A Fenton
BEng, MEng, MA, PhD, PEng
Professor, Department of Engineering Mathematics, Dalhousie University, Canada
W S Kaggwa
BSc(Eng), MEngSc, PhD, M.I.E.Aust
Senior Lecturer, School of Civil and Environmental Engineering, University of Adelaide, Australia
D V Griffiths
BSc, MS, PhD, DSc, CEng, PEng
Professor, Department of Engineering, Colorado School of Mines, USA
H G Poulos
AM, BE, PhD, DScEng, F.I.E.Aust, FASCE, FAA
Senior Principal, Coffey Geosciences Pty. Ltd. & Emeritus Professor, Department of Civil Engineering, University of Sydney, Australia
Y L Kuo
BE
Doctoral Student, School of Civil and Environmental Engineering, University of Adelaide, Australia

Summary: The reliability of foundations is greatly influenced by uncertainties associated with the geotechnical model on which their design is based. In turn, the geotechnical model is derived from a site investigation whose scope is largely dictated by financial constraints, rather than the variability of the ground. This paper seeks to quantify the influence of the scope of site investigations on the design of pad footings. This is achieved by simulating geotechnical profiles, where the soil properties vary from location to location in a random yet continuous and realistic fashion. The simulated soil profiles are generated using random field theory, which makes use of three statistical parameters: the mean, variance and the scale of fluctuation – which is a measure of the randomness of the geotechnical property in question. The methodology involves generating a geotechnical profile by simulating a 3D random field to know soil properties at each point in detail. A site investigation is then simulated by sampling from the 3D random field. By using the sampled values, a pad footing is designed to conform to a serviceability criterion, as would be achieved in practice. A benchmark design is also undertaken making use of the complete knowledge of the soil profile. This design is achieved using a numerical process involving a 3D finite element analysis. Both designs are undertaken on numerous different simulated soil profiles in a Monte Carlo analysis. A comparison of the two designs provides failure and over-design probabilities for a series of site investigation plans. It was observed that the probability of failure and over-design decreased with an increasing site investigation scope, as expected. The results provide information to estimate the relative benefit of conducting various scopes of site investigations.

INTRODUCTION

Geotechnical site investigations are used to assist geotechnical engineers to interpret the subsurface conditions for design purposes (Bowles, 1997). Although such investigations are used in nearly all civil engineering projects, there are currently limited techniques to quantify the effectiveness of one investigation compared with another (Jaksa et al., 2003). Generally, the scope of a site investigation is based on the budget and time constraints placed on the investigation and the experience and judgement of the consulting geotechnical engineer (Jaksa et al., 2003). However, one of the major causes of structural failure is due to inadequate site investigation resulting in unknown or unexpected soil conditions (Temple and Stukhart, 1987). Such failures can cause structural failures, construction delays, cost overruns, large claims and human injury (Temple and Stukhart, 1987). The research presented in this paper seeks to quantify the effectiveness of various combinations of numbers and locations of geotechnical tests (herein referred to as the scope) which make up a site investigation. The results of such research will assist geotechnical engineers to design and plan site investigations on a rational basis, rather than conforming to cost and time constraints. The methodology involves analysing results from a Monte Carlo analysis of foundation designs achieved by traditional design methods using data obtained from a site investigation and a numerical procedure using the complete knowledge of the soil profile and finite element analysis (Jaksa et al., 2003). Although it is not feasible nor practical to obtain complete knowledge of a site in real terms, a simulated site, using statistical methods allows all properties to be known in detail. The framework for such analysis is given by Jaksa et al. (2003).

SIMULATING A SOIL PROFILE

There are currently numerous accepted methods to simulate realistic spatially variable soils. Many of the more recent methods involve using statistics to manipulate random numbers to represent the soil property. Random field theory (Vanmarcke, 1977) uses a spatial correlation distance termed the *scale of fluctuation* as a measure of the distance at which two points are reasonably correlated. Fenton and Vanmarcke (1990) introduced the Local Average Subdivision (LAS) method to generate a three-dimensional random field based on a nominated correlation structure. The method is best described as a top-down averaging method, which generates a new random series to comply with local and global averaging as well as cross boundary correlations of the previous series. Fields generated by the LAS method provide a good estimation of correlations with small-scale fluctuations represented by a small scale of fluctuation. This is sufficient when dealing with soil profiles as discussed by Jaksa and Fenton (2002) in their investigation of over 200 cone penetration tests in the Adelaide parklands. Jaksa and Fenton (2002) showed, although soils show long scale fluctuations it is not an exclusive property of soil and simulation using small-scale fluctuations is reasonable. A common correlation model used to simulate small-scale fluctuations in soils is the Markov model (Fenton, 1990), which generates an exponentially decaying correlation. To ensure non-negative soil properties are generated, random numbers are selected from a lognormal distribution.

The research presented in this paper investigates footing design for serviceability or settlement, which is a function of two soil properties: Young's modulus and Poisson's ratio (Bowles, 1997). It has been assumed that Poisson's ratio is constant, leading only to varying Young's Modulus properties in both vertical and horizontal directions, which are simulated by a random field. This paper presents the results of four different soil types with underlying Young's Modulus statistics as shown in Table 1. Although the soil properties vary in each realisation of the Monte Carlo analysis, the global statistics conform to values in Table 1. To ensure the random field generator achieves reasonable simulations, a statistical analysis is undertaken on the generated field. Table 2 provides comparison of the target and generated means and standard deviations for each soil type after numerous realisations of the Monte Carlo analysis. For convenience, each soil type is expressed in terms of a code, where the number identifies the COV and the letter "C" or "R" refers to a relatively continuous (homogeneous) or random (heterogeneous) profile.

Table 1. Statistical Properties of Young's Modulus Representing Different Soil Types.

Soil Type	Mean (kPa)	Std Dev (kPa)	COV %	Scale of Fluctuation (m)		
				X	Y	Z
5C	10000	500	5	4.0	4.0	2.0
5R	10000	500	5	1.0	1.0	1.0
30C	10000	3000	30	4.0	4.0	2.0
30R	10000	3000	30	1.0	1.0	1.0
X, Y – horizontal directions; Z – vertical direction						

Table 2. Comparison of Target and Generated Statistics of Each Soil Type.

Type	Mean (kPa)			Standard Deviation (kPa)		
	Target	Generated	% Diff	Target	Generated	% Diff
5C	10000	9997.09	0.0	500	418.53	16.3
5R	10000	10000.30	0.0	500	490.85	1.8
30C	10000	9992.58	0.1	3000	2938.73	2.0
30R	10000	9874.16	1.3	3000	2463.06	17.9

DESIGN BASED ON A LIMITED SITE INVESTIGATION

The major uncertainty in the design procedure is in the quality of the site investigation. This uncertainty is due to the inherent variability within a soil deposit and because limited spatial testing is performed. Typically, site investigations are designed to minimise the impact of spatial variability by locating tests systematically around the site.

Site Investigation

There are numerous accepted testing methods to provide details about the subsurface condition with respect to a foundation design for serviceability. Common methods include the standard penetration test (SPT), cone penetration test and dilatometer test (Bowles, 1997). The research presented in this paper will simulate a test similar to an SPT where values are obtained at discrete locations through the soil medium. In this paper, no attempt has been made to account for test measurement error, however, it will be included in future work. Hence, the results do not demonstrate the effectiveness of the SPT.

The varying scope of a site investigation provides the most useful information. Due to the variability of soil, the scope has a direct influence on the representation of the subsurface conditions. Typically, a larger scope provides a better representation of the soil. By varying the scope, a different representation of the site is obtained, influenced by the spatial variability of the soil. Figure 1 illustrates the various site investigation scopes simulated. Tests are undertaken within a site investigation area indicated by the dashed line in Figure 1. The site investigation area is a nominal 5 m × 5 m size and represents a testing area nominated prior to foundation design. The influence of the location of the testing area is also investigated by offsetting it from the centre of the proposed footing location. This resembles a true footing design as the site investigation is rarely centred about each and every footing in a given design. Figure 2 presents the relative locations of the site investigation areas investigated in this paper, with respect to the entire site and the proposed footing location.

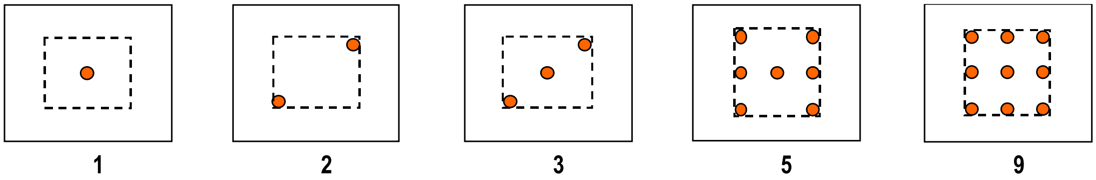


Figure 1. Layout and Number of Tests in Each Site Investigation Plan.

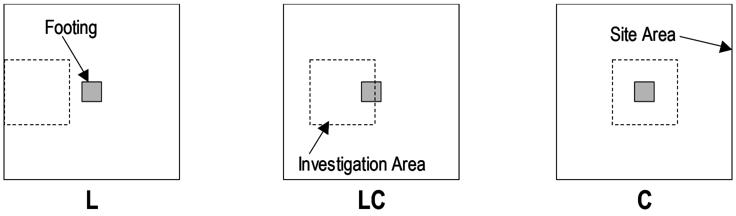


Figure 2. Location and Designation of Site Investigation Areas with Respect to Entire Site and Proposed Footing.

Footing Design

The elastic settlement of a footing is a function of the geometrical properties, applied load, Young's Modulus and Poisson's ratio (Bowles, 1997; Craig, 1997). Typical design relationships use these variables to predict the total settlement of a pad footing. One of the more common methods is Schmertmann's method (Schmertmann, 1978) based on linear elastic deformations (Craig, 1997). Although the assumption of linear elastic behaviour is not strictly valid, settlements are typically calculated for much smaller applied loads than would cause soil failure (Small, 2001). Schmertmann's method uses two correction factors C_1 and C_2 to account for the depth of the footing (embedment) and creep, which may occur during the design life of the project. It is common that the correction factor for creep is taken as unity (Craig, 1997), while the embedment factor for this research is also assumed equal to one, as the proposed footing is located at the surface. The strain influence factor I_z weights the contribution of the strength of the soil using an idealised distribution to a depth equal to twice the least plan dimension of the footing (Schmertmann, 1978).

To target the smallest, most efficient footing, the design process commences with the smallest possible footing. The settlement is estimated using Schmertmann's method and is compared with a maximum allowable settlement of 25 mm. If the footing settlement is greater than the allowable settlement a larger footing size is obtained by increasing the size by one metre in the x direction. If the footing still does not meet the settlement criteria, the size is increased by one metre in the y direction. This process is continued until the footing settlement is less than the allowable settlement. These steps ensure the footing is central about the applied point load and also conforms to the discretisation restrictions placed on the design with complete knowledge, discussed later. However, this will not result in a footing design that exactly meets the design criteria. Instead, the footing that causes the largest settlement, which remains less than the maximum allowable settlement, is taken as the converged solution.

DESIGN BASED ON COMPLETE KNOWLEDGE OF SOIL PROFILE

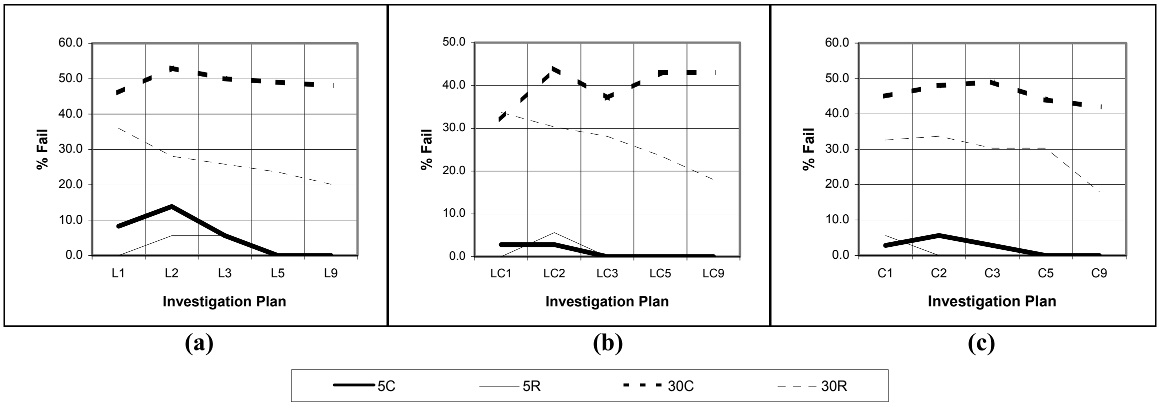
The design based on complete knowledge of the soil profile is only possible due to the simulation of the soil profile. The most common numerical method to analyse the effect of external forces or loads is the finite element method (Cook et al., 1989). Although this is not a design tool, it can be incorporated into a trial-and-error procedure to converge to the best possible solution. The calculations for the finite element analysis are undertaken using the conjugant gradient method to remove the need to assemble the global stiffness matrix (Smith and Griffiths, 1998). Although this causes an iterative procedure to achieve a result, it does reduce the necessary memory requirements of assembling a global stiffness matrix.

Similarly with the design based on a limited site investigation, this process begins with an initial footing size. The settlement for this footing size is analysed using the finite element method. If the settlement is greater than the prescribed allowable settlement, the footing size is increased in the same manner as the design based on a limited site investigation. The discretisation of the soil mass to satisfy the finite element mesh enforces a limitation on the convergence to the best possible design solution. The minimum increase in footing dimension must be equal to the element size to conform to the finite element method. The speed of the finite element analysis of a three dimensional field (64 × 64 × 32 = 131,072 elements) has limited the scope of the results for this paper. The design process using the finite element method has been optimised to reduce computational time by using an initial footing size. The initial footing size is determined prior to any finite element analysis and provides a best-estimate starting point. This reduces the number of times a finite element analysis has to be undertaken and therefore the required computational time.

PARAMETRIC STUDY

The effectiveness of the soil investigation plans illustrated in Figure 1 are analysed by comparing the designs using the site investigation data alone and a design using the complete knowledge of the soil profile. The iterative process, synonymous with a Monte Carlo simulation enables a probability of failure and over-design to be achieved for a single soil type and site investigation plan. The simulation is deemed to have converged when a difference of less than 0.005 m^2 of the designed footing area is achieved. At this point, it should be noted that, although the soil properties are randomly obtained in each realisation, they still conform to the underlying statistics (mean, COV and scale of fluctuation) detailed in Table 1.

For the purposes of the research presented in this paper, foundation failure is defined as the occurrences of a footing area achieved using the site investigation data being less than the area obtained using the complete knowledge. Conversely an over-designed foundation occurs when the design using the site investigation data results in a larger footing than the design using the complete knowledge of the site. Figure 3 and Figure 4 present the relationships between the failure and over-design probabilities for each site investigation plan respectively.

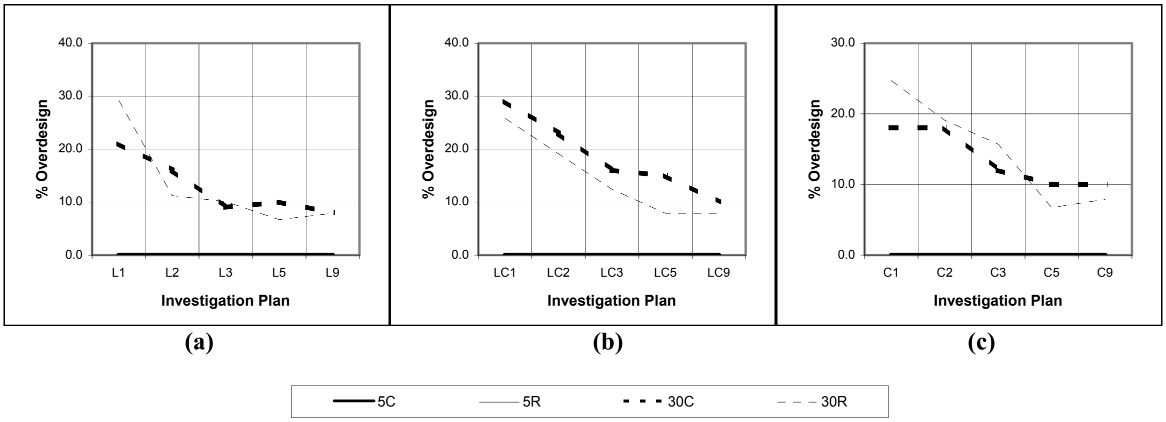


(a) **(b)** **(c)**

Figure 3. Failure Probabilities for Site Investigation Plans located (a) Left, (b) Left of Centre and (c) Centre.

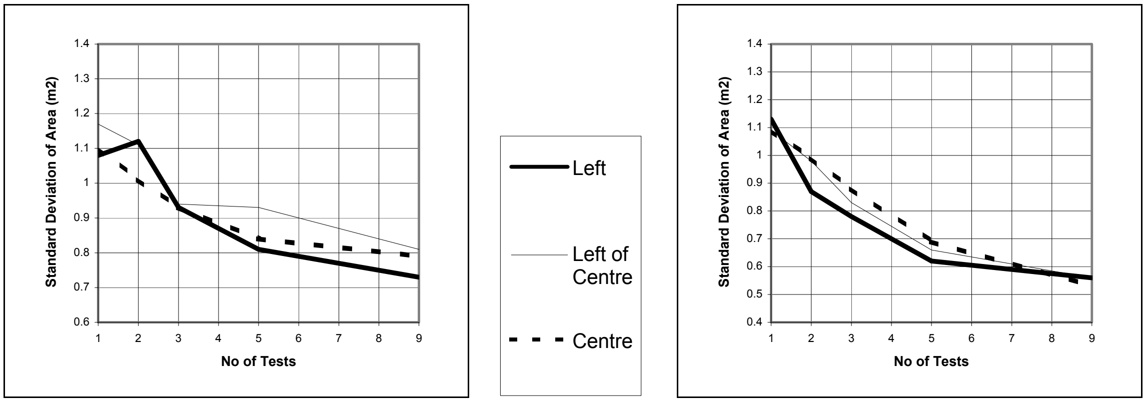
The soil type represented by the field with a COV for 30% and scale of fluctuation of 1 m, 1 m, 1 m shows a clear trend of failure probability decreasing with increased testing (Figure 3). This suggests that, as the number of tests increases, less uncertainty is achieved with respect to the soil profile resulting in a more appropriate design. This trend is not, however, explicitly evident for the other soils simulated by fields with lower COV or larger scales of fluctuation. These fields show greater continuity and hence the increased testing does not exclusively provide additional information regarding the soil profile. Rather, the additional testing provides similar information to the previous testing regime. It is also evident that the foundation designs on soils simulated by a random field with low COV (5C & 5R) have a relatively low probability of failure. This is due to the site being continuous and the influence of the spatial variability of the site not being as great on the effectiveness of the investigation plan. The probabilities of failure (Figure 3) for foundations located on the soils represented by a field with a high COV (30C & 30R) are noticeably large. This would tend to suggest the design based on the site investigation data is under-conservative for highly variable soils and provides foundation designs, which generate larger settlements than desired. Unusually, the soil represented by the field with high COV and large scale of fluctuation (30C) shows higher failure probability than the more random field with lower scale of fluctuation (30R). It was expected that the more random field would provide the higher failure probability due to the increased uncertainty due to the site investigation. This unexpected trend may be the result of larger weak zones in the soil as the continuous nature generates areas of soil with similar properties.

The trend of reduced probability for additional testing is also shown in Figure 4 for the probability of over-design. Similarly, the field with 30% COV and small scale of fluctuation (30R) showed the largest trend with the probability of over-design decreasing with additional tests. However, unlike the probability of failure, the probability of over-design decreased with additional testing for the field with a higher scale of fluctuation (30C), or a more continuous field. This suggests an increased number of tests does not explicitly reduce the probability of failure but does reduce the probability of over-design and, consequently, improves the probability of achieving the best design. However, this does not hold for soils represented by fields with low COV (5C & 5R). There appeared to be a zero probability of over-design for these soils which maybe due to differences in the design procedures or the limitation on the design methods regarding the discretisation of the field. The over-design trends (Figure 4) shown for soils with high COV (30C & 30R) may be the result of an increased confidence in the design when a site investigation of greater scope is used. Figure 5 shows the reducing standard deviation of the footing design (area) with increasing number of tests. These relationships suggest the footing design is less variable when there are an increased number of tests in the site investigation, as expected.



(a) **(b)** **(c)**

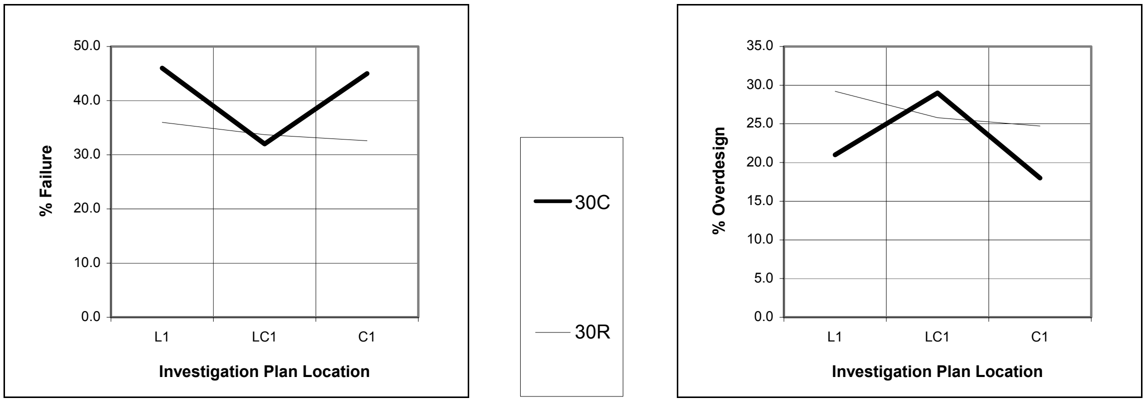
Figure 4. Over-design Probabilities for Site Investigation Plans Located (a) Left, (b) Left of Centre and (c) Centre.



(a) **(b)**

Figure 5. Standard Deviation of Designed Footing Area for Soils Represented by Fields (a) 30C and (b) 30R.

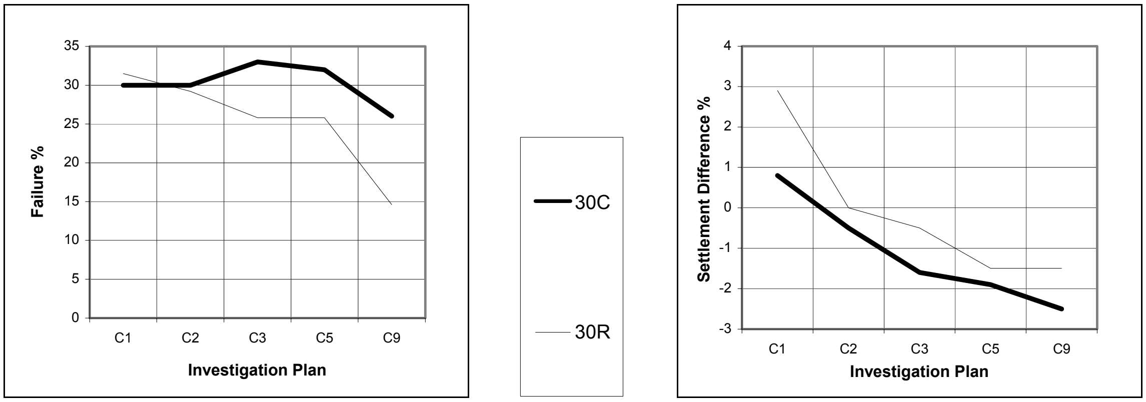
There is little difference between the location of the site investigation areas for fields with both high and low scale of fluctuations. Figure 6 shows the variation of failure and over-design probability for a single test from the three different site investigation locations indicated in Figure 2. Although there is little variation, there is an apparent trend for the field with the larger COV and lower scale of fluctuation (30R). This trend suggests the probability of failure and over-design decreases when the test is closer to the centre of the footing, as expected. This trend has a practical basis, as the best representation of the site will result from the site investigation plan being directly under the footing. However, the reduction in failure and over-design probabilities is low (less than 5%). This would suggest the location of the site investigation plan does not influence the effectiveness of the plan as much as the number of tests. However, these results must be viewed with concern as only three separate investigation plans were analysed and in each case, a test is located near to the footing.



(a) **(b)**

Figure 6. (a) Failure and (b) Over-design Probabilities of Varying Single Test Location.

The results given in Figures 3 to 6 related to a design using site investigation data with Schmertmann's method and a design using the complete knowledge of the soil and the finite element method. However, it is also useful to examine the results of designs undertaken using the same method (i.e. Schmertmann's or Finite Element) and compare the effects of using site investigation data or complete knowledge of the site. Figure 7 provides the results of such an analysis, where the comparison between the Schmertmann's methods is a failure probability and the comparison of the Finite Element Method is displayed as a difference in the footing settlement. The trends shown in both comparisons (Figure 7(a) and (b)) resemble the results of the analysis undertaken using the Schmertmann's method for the design with site investigation data and the Finite Element Method for the design using complete knowledge of the site (Figures 3-5). Similarly, as shown in Figure 7, the trend is more evident with the soil represented by a field with a high COV and low scale of fluctuation (30R). It is interesting to note that the failure probability is of a lower magnitude when Schmertmann's method is used for both designs compared with using the Finite Element Method for the complete knowledge design. This suggests there is an inherent difference or uncertainty between the design methods, which influences the results.



(a) **(b)**

Figure 7. (a) Failure Probability from Schmertmann's Method and (b) Settlement Difference from Finite Element Method Each Using Site Investigation Data and Complete Knowledge.

CONCLUSIONS AND RECOMMENDATIONS

The effectiveness of a site investigation plan and the ensuing design is not only influenced by the number and location of tests that make up the plan but also the nature of the variability of the underlying soil. It has been shown in the research presented in this paper that the reduction of failure and over-design probability for site investigations with additional tests is more evident for increasingly random soils. The research has also been able to quantify the reduction of failure probability due to the addition of 8 tests (15%). The probability of over-designing the foundation is also reduced by a similar magnitude for an equivalent increase in the number of tests. The influence of the site investigation plan location has also been reviewed and shows the best results when the plan overlays the proposed footing location, as one would expect. This research has made it possible to quantify the relative benefit of undertaking various site investigation plans for different types of soils.

This paper has introduced ongoing research currently being undertaken by the authors. This research aims to extend the methodologies introduced in this paper to various foundation types including multiple pad footings, raft footings and deep foundations. It will also extend the analysis to include numerous site investigation types and varying soil conditions. This will negate the requirement for the geotechnical professional to undertake time and resource consuming 3D finite element analyses as described in the paper. It is expected that this research will assist geotechnical engineers to rationally design site investigations, explicitly incorporating the relative risk of failure and over-design and accounting for uncertainties in soil variability, testing methods and design models.

ACKNOWLEDGMENTS

The research presented in this paper is supported by an Australian Research Council (ARC) Discovery-Projects grant. The support of the ARC is gratefully acknowledged.

REFERENCES

Bowles, J.E. (1997). *Foundation Analysis and Design, 5th ed.*, McGraw-Hill, Singapore.

Cook, R.D., Malkus, D.S. and Plesha, M.E. (1989). *Concepts and Applications of Finite Element Analysis, 3rd ed.*, John Wiley and Sons Inc, Toronto, Canada.

Craig, R.F. (1997). *Soil Mechanics, 6th ed.*, E & FN Spon, London, England.

Fenton, G.A. and Vanmarcke, E.H. (1990). "Simulation of random fields via local average subdivision," *Journal of Engineering Mechanics*, Vol. 116, No. 8, pp. 1733-1749.

Jaksa, M.B. and Fenton, G.A. (2002). "Assessment of fractal behaviour of soils," *Probabilistics in Geotechnics - Technical and Economic Risk Estimation*, Graz, Austria, pp.

Jaksa, M.B., Kaggwa, W.S., Fenton, G.A. and Poulos, H.G. (2003). "A framework for quantifying the reliability of geotechnical investigations," *9th International Conference on Statistics and Probability in Civil Engineering*, San Francisco, USA, (In Press).

Schmertmann, J.H. (1978). *Guidelines for Cone Penetration Test: Performance and Design,* Report No: FHWA-TS-78-209, US Dept of Transportation, Federal Highway Administration, Washington, USA.

Small, J.C. (2001). "Shallow Foundations, " In: *Geotechnical and Geoenvironmental Engineering Handbook, 1st ed.,* Ed: Rowe, R., Kluwer Academic Publishers, Boston, USA.

Smith, I.M. and Griffiths, D.V. (1998). *Programming the Finite Element Method, 3rd ed.*, John Wiley & Sons Ltd, West Sussex, England.

Temple, M.W.B. and Stukhart, G. (1987). "Cost effectiveness of geotechnical investigations," *Journal of Management in Engineering*, Vol. 3, No. 1, pp. 8-19.

Vanmarcke, E.H. (1977). "Probabilistic modelling of soil profiles," *Journal of the Geotechnical Engineering Division*, Vol. 103, No. GT11, pp. 1227-1246.