International Conference on Structural and Foundation Failures
August 2-4, 2004, Singapore

COST OF FOUNDATION FAILURES DUE TO LIMITED SITE INVESTIGATIONS

J. S. Goldsworthy, M. B. Jaksa and W. S. Kaggwa
School of Civil & Environmental Engineering, The University of Adelaide, Australia
jgoldswo@civeng.adelaide.edu.au, mjaksa@civeng.adelaide.edu.au,
wkaggwa@civeng.adelaide.edu.au

G. A. Fenton
Department Engineering Mathematics, Dalhousie University, Canada
gordon@random.engmath.dal.ca

D. V. Griffiths
Department of Engineering, Colorado School of Mines, USA
vaughan@finite.mines.edu

H.G. Poulos
Department of Civil Engineering, University of Sydney &
Coffey Geosciences Pty. Ltd., Sydney, Australia
harry_poulos@coffey.com.au

Abstract

One of the greatest causes of foundation failure is due to insufficient knowledge of ground conditions. Uncertainty in ground conditions can also cause significant cost overruns and time delays for both client and contractor. Site investigations aim to reduce the uncertainty of ground conditions by various combinations of field and laboratory testing. However, time and cost constraints, as well as the judgement and experience of the consulting geotechnical engineer, have traditionally governed the scope of such site investigations. Analyses have been undertaken to investigate the performance of various site investigation schemes with respect to the cost of the resulting pad foundation system and the probability of failure. Penalty costs are attributed to foundation designs that experience excessive settlement to enable direct comparisons with foundation designs that conform to the design criteria. Designs resulting from the site investigation data are compared to a benchmark design achieved by employing a 3-dimensional finite element analysis within a trial-and-error process. Many realisations are undertaken for varying soil types in a Monte Carlo analysis by generating 3-dimensional simulated soil profiles using random field theory. The results illustrate a decreasing trend of total foundation cost for an increasing site investigation scope. The results also show that the cost of a foundation, excluding the penalty cost of failure, designed using an increased amount of knowledge regarding the site, does not always result in a less expensive foundation. However, all results suggest that a site investigation scheme with limited testing will result in a more expensive foundation, when the cost of possible foundation failure is included.

Keywords: Foundation failure, random fields, costs, finite elements, reliability design, site investigation.

Introduction

Numerous studies have indicated the greatest element of risk in a building project lies within the uncertainties in ground conditions (Institution of Civil Engineers, 1991; Littlejohn *et al.*, 1994; National Research Council, 1984; Whyte, 1995). Furthermore, risks are significantly increased with inadequate geotechnical investigations resulting in unpredictable construction costs and programming (Collingwood, 2003). Consequently, a site investigation forms a vital part of a building design yet, in general the scope of such an investigation is constrained by financial and time considerations. In reference to such constraints, the Institution of Civil Engineers (1991) stated "*you pay for a site investigation whether you have one or not*", suggesting that a limited site investigation will either result in gross over-designs or a foundation design that may not meet the design criteria. Additionally, the National Research Council (1984) concluded in a study of 89 underground projects that the level of geotechnical investigation in 85% of the cases was inadequate for accurate characterisation. This inadequacy resulted in large cost overruns and time delays. Such inadequacies can also cause potential foundation failures costing clients and professionals time and money.

The research presented in this paper uses a model developed and implemented by the authors to quantify the risk of varying site investigation scopes with respect to the resulting foundation design and potential consequences of failure. The framework for this model has been introduced by Jaksa *et al.* (2003) and preliminary results have been published by Goldsworthy *et al.* (2004). In addition to the analyses published by Goldsworthy *et al.* (2004), costs of site investigation, building and foundation construction and potential failures have been attributed to the foundation design. This enables conclusions to be drawn regarding the risk of the site investigation scheme using a *total* cost approach.

Simulating Traditional and Optimal Foundation Designs

The model adopted to simulate a foundation design, as introduced by Jaksa *et al.* (2003), involves simulating 3-dimensional soil profiles to enable all soil properties to be known at all locations, which can never be achieved with real sites. The simulated soil profiles are generated to conform to random field theory (Vanmarcke, 1984), where the dominant statistics are the mean, variance and scale of fluctuation[1]. Using the knowledge of the soil profile, an optimal design is determined using a 3-dimensional finite element analysis. This design is compared with a design based on information obtained from a simulated site investigation, representing a traditional design procedure, which is heavily influenced by the quality and quantity of information obtained from the site investigation and provides the basis for the analyses presented. This paper focuses on foundation designs for serviceability and adopts the Schmertmann design model (Schmertmann, 1978) for the traditional design.

---

[1] Scale of Fluctuation (θ) – measure of the distance of separation at which two samples are considered reasonably correlated (Vanmarcke, 1984)

Design Scenario

The results presented in this paper are based on a foundation system consisting of 4 equally loaded pad footings founded on soils with 6 different statistical characteristics, as shown in Table 1. Risk and reliability analyses are undertaken for each soil type to investigate the sensitivity of the soil properties. The soil types are distinguished by the naming convention shown in Table 1, where the number represents the coefficient of variation, COV (standard deviation/mean) and the R, M and C represent a random, medium or continuous profile, respectively. The random, medium or continuous nature of the profile is determined by the scale of fluctuation, where a small scale of fluctuation represents a randomly varying field, while a larger scale of fluctuation represents a continuously varying profile, that is, where properties vary more slowly with respect to distance. The Poisson's ratio of the field has been assumed constant, leading only to the Young's Modulus being represented by the 3-dimensional random field.

Table 1. Soil profile properties

No	**Young's Modulus (*E*)**					ν
	Mean MPa	**COV (%)**	**Scale of Fluctuation, θ**			
			X	Y	Z	
20R	60	20	1	1	1	0.3
20M	60	20	4	4	2	0.3
20C	60	20	8	8	4	0.3
50R	60	50	1	1	1	0.3
50M	60	50	4	4	2	0.3
50C	60	50	16	16	8	0.3

The loads subjected to the footings are representative of a 3 storey concrete framed building with an approximated dead load of 5 kPa and a live load of 3 kPa. The geometrical layout of scenario is shown in Figure 1. All footings are considered rigid and the point loads are maintained central to the footing.

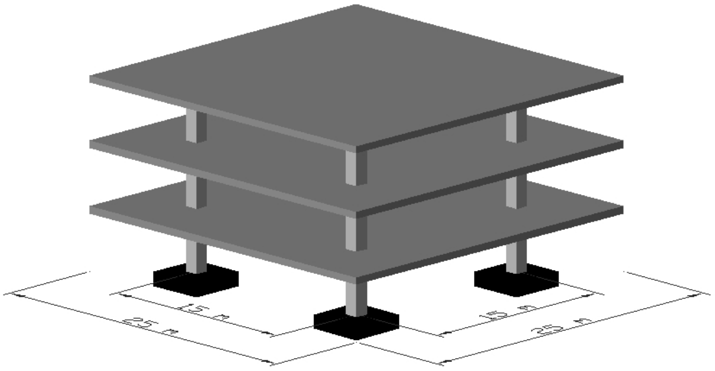


Figure 1. Layout of foundation system

Six varying site investigation strategies have been investigated consisting of up to 8 tests, as shown in Figure 2. Samples are taken at 1.5 metre depth intervals, mimicking the sampling of a standard penetration test (SPT) scheme. In this paper, no test uncertainty has been included, rendering the testing technique more of a sampling procedure. Future studies will investigate the use of other test types and will incorporate the effects of test and measurement errors. The naming convention used in Figure 2 represents the number of the site investigation strategy, the test pattern type ("RG" – regular grid) and the number of tests in the strategy. The effect of varying test patterns is being currently investigated and will be published in the future.

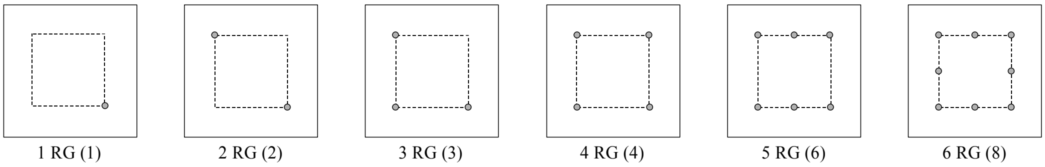


Figure 2. Site investigation schemes

The *Total* Cost of a Site Investigation

To measure accurately the risk of a site investigation scope, it is necessary to attribute the costs resulting from the decisions made regarding such an investigation. Firstly, the cost of the site investigation is included, as well as the cost of the foundation construction designed from the results of the investigation. This provides the direct cost of the site investigation. However, for an accurate comparison with all site investigation scopes, it is necessary to attribute costs of potential failures. The costs associated with the site investigation have been based on commonly used unit prices where cost of a standard penetration test is approximately \$45 per metre test depth and an additional \$25 per test (note that Australian dollars are used throughout this paper).

Costs for the construction of the building and foundation have been suggested by Rawlinsons (2002), which provides base unit prices for construction in Australia. Unit prices from the Adelaide area have been adopted to maintain consistency and are given in Table 2. These prices are specified as a floor area rate per storey of the building including the foundation. For the purposes of this research, a fully serviced office building is the nominated structure. Rawlinsons (2002) suggests the foundation cost for a typical building, with costs as given in Table 2, is approximately 1.5% of the total construction cost. Hence, to separate the foundation cost from the overall building cost the prices have been reduced by 1.5%. The resulting building costs are given in Figure 3 as a cost per plan area of the building per storey.

The results given in Figure 3 show a strong trend with the regression line given by Equation (1), where y is the cost of the building per square metre of plan area and x is the number of storeys. The cost of the foundation construction has also been adopted from unit prices suggested by Rawlinsons (2002) and determined to be \$380 per cubic metre including excavation, formwork, reinforcing, concreting and finishing.

$$y = 2200x \tag{1}$$

Table 2. Building costs for Adelaide, Australia (including foundation)

Building – Structure and Finishings	**Cost ($ / m^2)**
Administration	
2-3 Storey	1410-1510
3-10 Storey	1625-1725
Office – Fully Serviced	
Single Storey	900-1000
Two Storey	1025-1125
Three Storey	1155-1280
4 –7 Storey	1250-1400
7-20 Storey	1665-1815
21-35 Storey	2045-2245
36-50 Storey	2215-2465

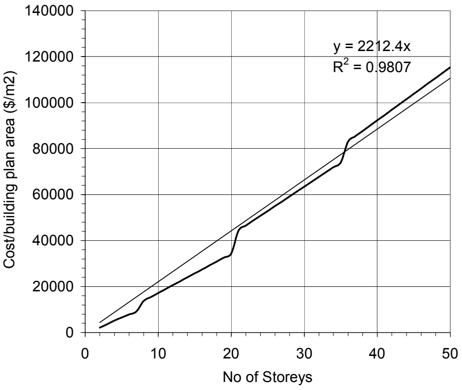


Figure 3. Cost of building construction (per plan area) less foundation construction cost for varying storeys

To determine the potential failure cost, a failure severity scheme is used in three categories; minor retrofit; major retrofit and demolish & rebuild. The rehabilitation costs for each failure severity have also been determined using unit rates suggested by Rawlinsons (2002). Table 3 summarises the rates adopted for each of the failure severity categories, while Figure 4 graphically presents the penalty cost ratio (defined as the retrofit cost divided by the total building cost) for varying building heights.

Table 3. Summary of failure severities and attributed costs.

Failure Severity	**Failure Description**	**Unit Rate Description (Rawlinsons, 2002)**
Minor	Some cracking evident from excessive settlement – requires patching and repainting	Minor refurbishment works divided by 2 (not include plumbing etc…)
Major	Major cracking and structural failures – requires significant patching, structural retrofitting and foundation underpinning	Major refurbishment works + Foundation underpinning
Demolish & Rebuild	Building can no longer be used for intended purpose – requires complete demolition and rebuild	Demolish costs + Rebuild costs as per Table 2

In order to determine continuous functions for the analyses described later, the penalty ratios are plotted against building heights, as shown in Figure 4. It is apparent from this figure that the minor retrofit and demolish and rebuild failure severities show little variation for increasing building height, which allows a constant penalty ratio to be used for both situations. On the otherhand, the major retrofit shows a decreasing penalty ratio for increasing building height until a constant is achieved. This is a result of the constant foundation underpinning costs, which is independent of building height. Consequently, an exponentially decaying function is adopted, as shown in Figure 4.

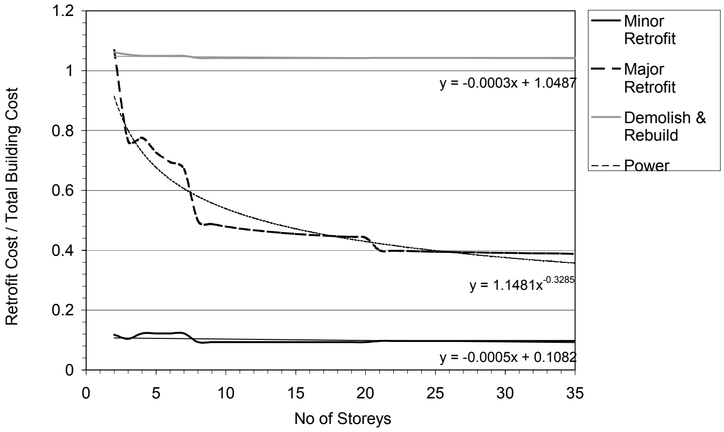


Figure 4. Cost Ratio of Minor Retrofit, Major Retrofit and Demolish & Rebuild for varying number of building storeys

The settlement limits for each failure severity category have been determined on a differential settlement basis. The differential settlements which cause cracking damage of varying severity have been suggested by Day (1999) and are shown in Table 4 for the failure severity categories introduced earlier. Although the damage categories do not explicitly match the failure severity adopted in this paper, the description of damage suggested by Day (1999) match the rehabilitation descriptions shown in Table 3. The total settlement limits, also shown in Table 4, have been determined by using ratios of the differential settlement limits. The resulting relationship of rehabilitation cost ratio for maximum settlement is shown in Figure 5. The rehabilitation cost ratio is a function of the minor retrofit, major retrofit and demolish & rebuild cost ratios, illustrated in Figure 4 and varies with building height.

Table 4. Settlement and differential settlement of foundations for each failure severity

Failure Severity	**Limits**	
	Settlement	**Diff Settlement**
No Damage	25 mm	0.025
Minor	60 mm	0.006
Major	100 mm	0.010
Demolish & Rebuild	130 mm	0.013

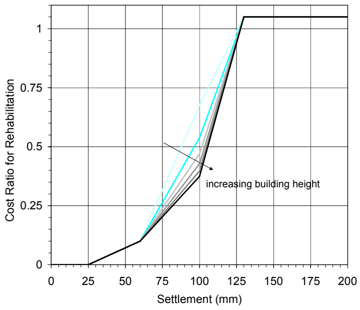


Figure 5. Cost ratio versus foundation settlement for varying building heights

The actual settlement of the foundation system, designed using a traditional design technique, is found by a finite element analysis using the complete knowledge of the soil profile. This provides absolute settlements for each footing in the system and differential settlements between footings. Should these settlements exceed the allowable, the penalty cost related to that settlement is applied. In the case where two or more footings exceed the allowable settlement, the worst failure condition is used to determine the cost rehabilitation ratio.

Risk and Reliability of Site Investigations

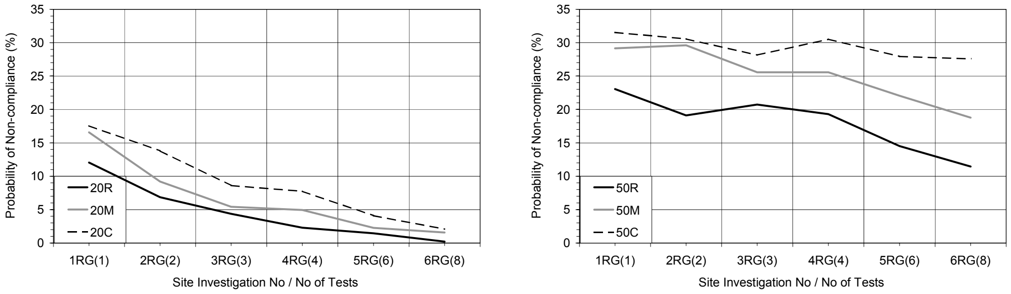
The results obtained from the model allow two distinct analyses to be undertaken. Reliability analyses measure the performance of each site investigation strategy as a function of failure and overdesign probability. Using such analyses, conclusions are drawn regarding the conservatism of the design model, the uncertainty and bias in the design model and the effectiveness of one site investigation plan compared with another to obtain a suitable design. Reliability analyses of this form have been published by Goldsworthy *et al.* (2004) and Goldsworthy and Jaksa (2004) for a single pad footing and a system of 9 pad footings, respectively.

A risk analysis has also been undertaken, made possible by the inclusion of consequences in the form of foundation costs. The risk analysis enables direct and meaningful comparisons of site investigation performance for the soil profile and loading situation detailed earlier. Together with the reliability analysis, the risk analysis provides a comprehensive perspective of the effectiveness of site investigation schemes and their resulting consequences.

Figures 6 and 7 illustrate the probability of the foundation design derived from site investigation data being overdesigned or not complying with the design criteria. An overdesign, for the purposes of this study, is defined as the foundation design resulting from the site investigation data being larger than the optimal design derived from complete knowledge of the soil profile. Conversely, when the design using the site investigation data is smaller than the optimal design, it is deemed not to comply. The results presented in Figures 6 and 7 do not represent the magnitude of foundation overdesign or underdesign. These values are shown in Figure 8, which is a measure of the difference between the foundation area derived from the traditional design models and the optimal design.

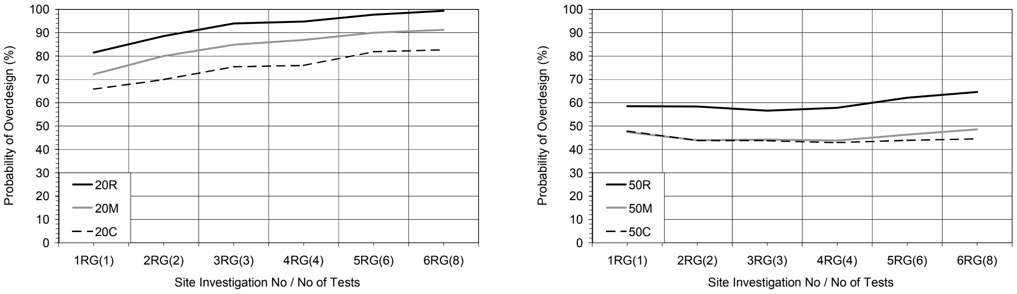
The relationship evident in Figure 6 suggests that there is a significantly lower probability of designing a foundation, which does not meet the design criteria when a site investigation of larger scope is adopted. This is particularly apparent when the foundation is located on a soil of low COV (Figure 6(a)). This indicates that a greater amount of information about the site will result in a foundation design that is less likely to fail. However, the probability of overdesign (Figure 7) shows a slight upward trend for site investigations of increasing scope. This contradicts the results shown by Goldsworthy *et al.* (2004) and Goldsworthy and Jaksa (2004) where it was apparent that the probability of non-conformance increases for increasing site investigation scope and the probability of overdesign reduces. This tends to suggest that these trends, which also include inherent design model errors (Goldsworthy and Jaksa, 2004), are a function of the soil statistics and the loading conditions. As discussed by Goldsworthy and Jaksa (2004), this seemingly unusual trend in the probability of overdesign is better explained by examining the difference in the foundation area compared with the optimal design, as shown in Figure 8.

As illustrated in Figure 8, the magnitude of overdesign is much larger than the magnitude of underdesign for foundations on both low and high variability soils, suggesting the Schmertmann design model is inherently conservative. This conclusion is in agreement with the results presented by Goldsworthy and Jaksa (2004), where



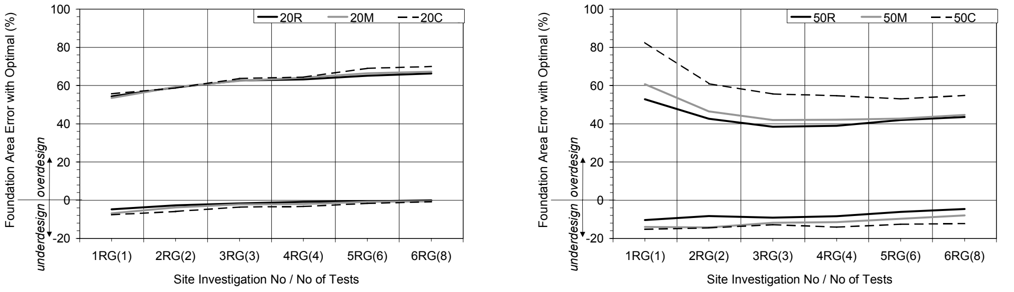
(a) (b)

Figure 6. Probability of non-compliance for foundation designs on soil profiles with (a) low variability (COV = 20%) and (b) high variability (COV = 50%)



(a) (b)

Figure 7. Probability of overdesign for foundation designs on soil profiles with (a) low variability (COV = 20%) and (b) high variability (COV = 50%)



(a) (b)

Figure 8. Foundation design area difference with optimal design for soil profiles of (a) low variability (COV = 20%) and (b) high variability (COV = 50%)

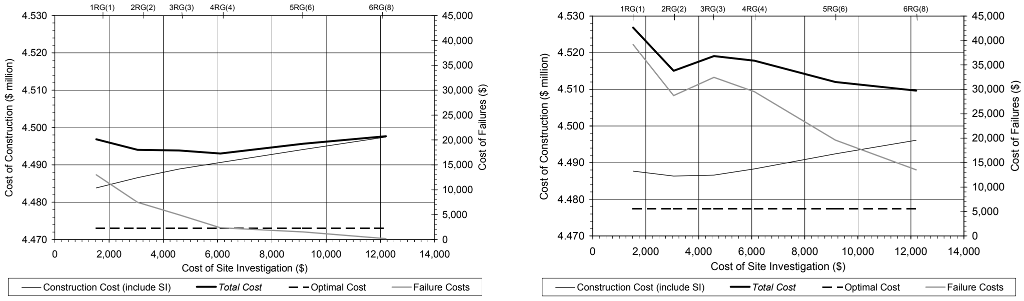
the magnitude of the overdesign error resulting from the Schmertmann model is greater than the magnitude of the underdesign error. However, it is apparent from Figure 8(a) for a foundation on a lower variability soil (COV = 20%), the magnitude of overdesign increases with an increasing site investigation scope. This is in contrast with the results for foundations on higher variability soils (COV = 50%), which suggests the magnitude of overdesign and underdesign both tend to zero (the optimal design) for increasing knowledge about the soil profile. This phenomenon appears to be driven by the large probability of overdesign for foundations on soil profiles with low variability soils presented in Figure 7(a). Therefore, it is concluded that an increased site investigation scope in soils with lower variability will not explicitly reduce the probability of foundation overdesign and may result in a larger foundation than required.

The risk analysis yielded the results displayed in Figures 9-11, which present the effect of increasing the scope of the site investigation in terms of cost. The site investigation scope itself, has also been defined in terms of cost, where an increasing cost of site investigation corresponds to a site investigation of larger scope. Figures 9-11 illustrate the results for foundations designed on soil profiles with both low (COV = 20%) and high (COV = 50%) variability and random, medium and continuous variations, respectively.

The increasing construction cost for increasing site investigation cost, evident in Figures 9-11, indicates that a site investigation of larger scope does not necessarily provide a less expensive foundation. However, this is negated by the significant reduction in failure costs for increasing site investigation scope, as indicated by the total cost. The total cost is defined as the sum of the construction cost (inclusive of foundation and superstructure construction and site investigation costs) and the failure or rehabilitation costs. This total cost reduction is also evident with foundations on soil profiles of low variability (COV = 20%), where it has been shown above that an increasing site investigation scope increases the probability of overdesign and the corresponding magnitude of overdesign (Figure 8). Yet, when the costs of potential foundation failure are applied, the total cost of the foundation reduces for increasing site investigation expenditure.

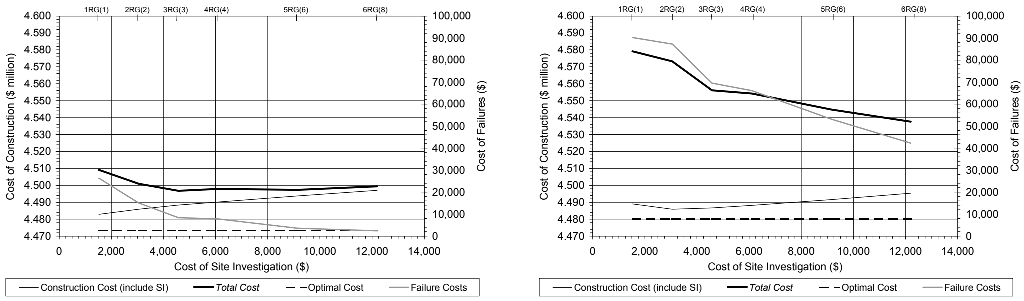
Figures 9-11 show that the total cost reduces for an increase in site investigation expenditure where the reduction is in the order of 3 or 4 times the additional expenditure for designs on soils with high variability (COV = 50%). It is also apparent that the trend is not monotonically decreasing. This maybe a result of the test locations in the site investigation plans shown in Figure 2, which suggests that an investigation into the sensitivity of test location using a similar methodology may be beneficial.

It is interesting to note that the total cost of the designs founded on the soils with lower variability (COV = 20%) show an optimal site investigation expenditure or scope. This is particularly evident in the analysis of the design on the low variability soil with random variations (SOF = {1,1,1}) as shown in Figure 9(a). For this particular design scenario, additional expenditure in the site investigation over $6,000 (4 SPTs) increases the total cost of the foundation. This phenomenon is not as pronounced for the soil profile with more continuous variations (SOF = {8,8,4}), as indicated by Figure 11(a). However, there appears to be little benefit in spending more than $9,000 (6 SPTs) on a site investigation for this situation. Conversely, the designs on the soil profiles with higher variability, do not reach an optimal site investigation expenditure or scope. This suggests that the optimal site investigation expenditure for the sites with a higher variability (COV = 50%) is greater than $12,000 and the total cost of the foundation will continue to reduce until this optimum is reached. As a measure of the effectiveness of the increased site investigation scope, Figure 12 plots the corresponding total foundation cost saving for the increased expenditure in site investigation.



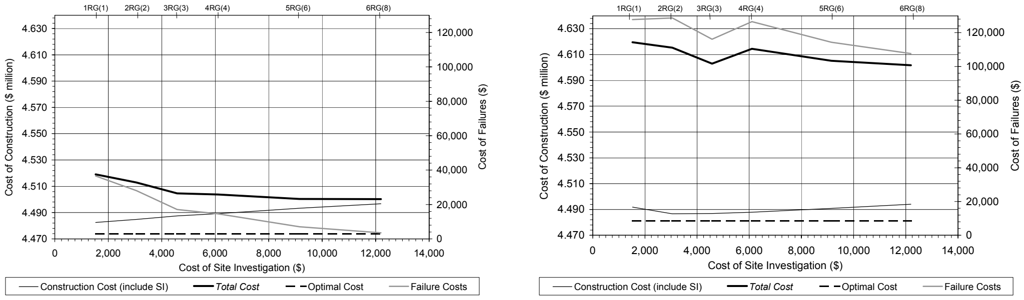
(a) (b)

Figure 9. Cost analysis for foundation design on soil profile with (a) low variability (COV = 20 %) and (b) high variability (COV = 50 %) and random variations (SOF = {1,1,1})



(a) (b)

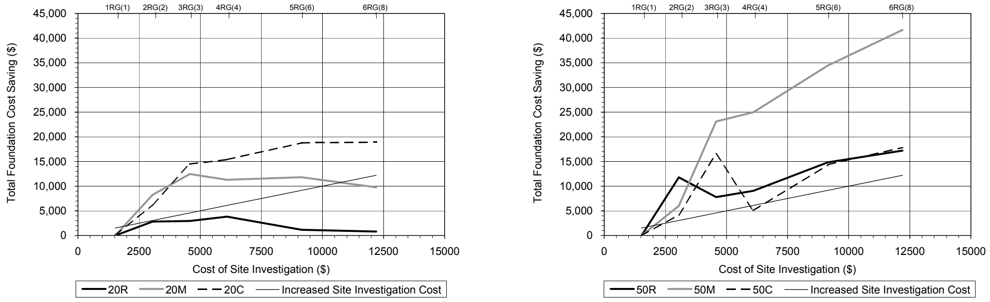
Figure 10. Cost analysis for foundation design on soil profile with (a) low variability (COV = 20 %) and (b) high variability (COV = 50 %) and medium variations (SOF = {4,4,2})



(a) (b)

Figure 11. Cost analysis for foundation design on soil profile with (a) low variability (COV = 20 %) and (b) high variability (COV = 50 %) and continuous variations (SOF = {8,8,4})

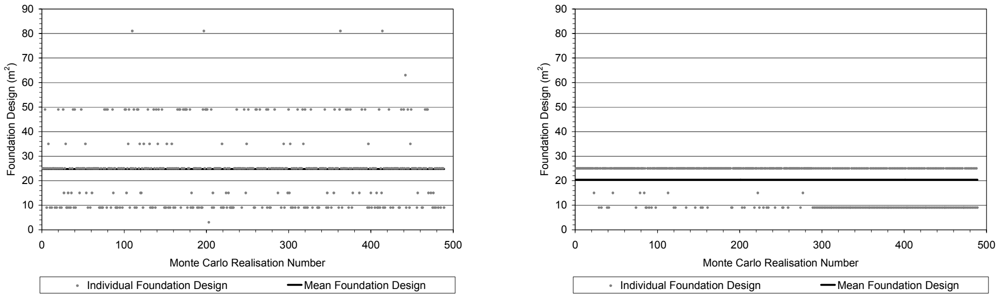
It is apparent from Figure 12 that in all design conditions considered, excluding the design on the soil profile with low variability and random variations (20R), an increased site investigation expenditure saves more than it costs. There is evidence of a significant benefit of increased site investigation expenditure for the design scenario on the soil profile with high variability and medium variations (50M). Interestingly, the benefit is comparably negligible for the design on the soil profile with high variability and continuous variations (50C). This tends to suggest the spacing of the tests, shown in Figure 2, is preferable for soils with properties exhibiting scales of fluctuations in the range of 4 metres rather than 8 metres. This aspect will be investigated in future studies.



(a) (b)

Figure 12. Total foundation cost saving for soil profiles with (a) low variability (COV = 20 %) and (b) high variability (COV = 50 %)

Figures 9-11 suggest a more expensive site investigation scheme will result in a more expensive foundation design, when the cost of potential failures is omitted. In fact, it appears that the increase in construction cost follows closely the increase in site investigation expenditure. This is due to the mean foundation design, averaged over several Monte Carlo realisations (500), being similar for all site investigation scopes. However, there are large variations in the design between the realisations when site investigations of smaller scope are used. This is illustrated in Figure 13, which plots the footing size, in m^2, for each realisation, where the spread of results is much larger when one test is used in the design as compared with 8 tests. Consequently, when a single design is chosen, there is a greater chance it will be closer to the optimal design when 8 tests are used rather than one test.



(a) (b)

Figure 13. Foundation design for each Monte Carlo repetition using a site investigation scope of (a) 1 RG (1) and (b) 6 RG (8)

Conclusions

The risk of a foundation failure is heavily dependent on the quantity and quality of information obtained from a geotechnical site investigation aimed at characterising the underlying soil conditions. This research has shown that by increasing the scope of the site investigation, the risk of foundation failure is significantly reduced, potentially saving clients and consultants large amounts of money. Using the methodology developed by the authors, it has been demonstrated that, for the loading and soil conditions considered, a slight increase of expenditure at the site investigation stage may result in a potential saving of up to 4 times the expenditure amount. It is anticipated that these results will assist geotechnical professionals to make decisions regarding the scope of a site investigation on a rational basis, incorporating the consequential risk of limited site investigations. They will also provide an avenue to promote the significance of a suitable site investigation to non-geotechnical professionals.

Acknowledgements

The research presented in this paper is part of an Australian Research Council Discovery Project. The support of the ARC is greatly acknowledged.

References

Collingwood, B. (2003), "Geotechnical Investigations for Piling Projects - The False Economy of a Cheap Site Investigation," *Australian Geomechanics*, **38**(1), 41-48.

Day, R. (1999), *Forensic Geotechnical and Foundation Engineering*, McGraw-Hill Companies Inc, USA.

Goldsworthy, J.S., and Jaksa, M.B. "Effect of Design Models and Test Numbers on the Design of Pad Foundations," *6th Australian Young Geotechnical Professionals Conference*, July 2004, in press.

Goldsworthy, J.S., Jaksa, M.B., Fenton, G.A., Kaggwa, W.S., Griffiths, D.V., Poulos, H.G., and Kuo, Y.L. "Influence of Site Investigations on the Design of Pad Footings," *9th Australia New Zealand Conference on Geomechanics*, 8-11 February, 2004, 282-288.

Institution of Civil Engineers (1991), *Inadequate Site Investigation*, Thomas-Telford, London, England.

Jaksa, M.B., Kaggwa, W.S., Fenton, G.A., and Poulos, H.G. "A framework for quantifying the reliability of geotechnical investigations," *9th International Conference on the Application of Statistics and Probability in Civil Engineering*, 1285-1291.

Littlejohn, G.S., Cole, K.W., and Mellors, T.W. (1994), "Without Site Investigation Ground is a Hazard," *Proceedings of the Institution on Engineers*, **102**, 72-78.

National Research Council (1984), "Geotechnical Site Investigations for Underground Projects," *US National Committee on Tunnelling Technology*, National Academy Press, Washington, USA.

Rawlinsons (2002), *Australian Construction Handbook 2002*, Rawlhouse Publishing Pty. Ltd., Perth, Australia.

Schmertmann, J.H. (1978), "Guidelines for Cone Penetration Test: Performance and Design." *FHWA-TS-78-209*, US Dept of Transportation, Federal Highway Administration, Washington, USA.

Vanmarcke, E.H. (1984), *Random Fields: Analysis and Synthesis*, The MIT Press, Cambridge, Massachusetts, USA.

Whyte, I.L. (1995), "The Financial Benefit from Site Investigation Strategy," *Ground Engineering*, **10**, 33-36.