Measuring the Risk of Geotechnical Site Investigations

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Abstract

The site investigation phase of any geotechnical design plays a vital role, where inadequate characterization of the subsurface conditions may contribute to either a significantly over designed solution that is not cost-effective, or an under design, which may lead to potential failures. Although it is intuitive to expect that the financial risk of a design will reduce as the site investigation scope increases (i.e. additional sampling), it is not known to what degree the risk is reduced, nor whether other uncertainties have an impact on this relationship. As such, this paper discusses research to measure the impact of varying the scope of a site investigation, on the financial risk of a foundation design project. The financial risk is defined as the total cost, which includes costs associated with undertaking the site investigation, constructing the foundation and superstructure, and any works required to rehabilitate a foundation failure. The analysis is numerically based, where a foundation design simulation model is incorporated into a Monte Carlo framework, in order to generate expected costs, and a measure of the financial risk. Results indicate that the risk of a foundation design is considerably reduced as the scope of a site investigation increases. However, results also indicate that there is an optimal site investigation expenditure, which leads to the least financial risk, and where additional sampling becomes redundant.

Introduction

It is well understood that a detailed site investigation, consisting of many samples and refined testing methods, yields a better representation of the underlying soil conditions. However, is it really worth spending additional money to retrieve additional samples, or use better testing methods? Until now, this decision has typically been made based on project budget and time restrictions, and at the discretion of the geotechnical engineer (Jaksa et al. 2005). However, Baecher and Christian (2003) suggested that a more quantitative method of planning geotechnical site characterization activities is required.

Past research dealing with recommended site investigation strategies has expressed the cost of the investigation as a percentage of the total project cost (Clayton et al. 1982; National Research Council 1984; Peacock and Whyte 1988; Site Investigation Steering Group 1993; Jaksa 2000). However, Littlejohn et al. (1994) believed that the scope of the best site investigation should take into account the uncertainty and inherent risk associated with the site and the project. Furthermore, the Site Investigation Steering Group (1993) believed that an improved site investigation strategy may not necessarily incur an additional cost. Instead, current site investigative methods could be refined to yield designs with a lower risk of failure or cost overrun.

Clayton (2001) suggested that a risk-based approach to improving the site investigation strategy for geotechnical application is required. As such, the authors have developed a framework to quantify the risk, measured in terms of total project cost, of site investigation strategies with varying scope. Using these results, engineers will be able to tailor a site investigation strategy to minimize the financial risk of a project, or at least be aware of the risks associated with limited site investigations.

Methodology

The framework for the method discussed and used in this paper was initially proposed by Jaksa et al. (2003). The basis for the framework is the generation of a simulated soil, where all properties are known at all locations. This offers the condition of complete knowledge of the soil, which is not attainable when using real soil sites. Furthermore, a simulated soil allows a numerical sampling technique, where properties are sampled at discrete locations around the site. This process is similar to a site investigation, where boreholes are located at various points at a site.

Using the information gained from the simulated site investigation, a foundation can be designed using one of many different foundation design or response models. However, because this design is based on the results of the sampling process, or simulated site investigation, there is a possibility that it is over designed (sampled properties were too conservative) or under designed (sampled properties were not conservative enough). As such, when the design is analyzed using the complete knowledge of the soil, where all soil properties are included into the analysis, results indicate whether it is adequate or not, which in turn yields conclusions about the scope of the site investigation. In this paper, this process is repeated 1000 times in a Monte Carlo framework to generate probabilities and an expected total cost of the design.

Simulating a Soil

The soil properties within the site are generated using Local Average Subdivision (LAS), as developed by Fenton and Vanmarcke (1990). This numerical technique yields properties in 3-dimensional space that conform to a target normal distribution and correlation structure. However, mechanical soil properties are typically non-negative. Therefore, Fenton (1999) suggested the use of the lognormal distribution, and a transformation of the generated properties from a normal to lognormal variant.

The target distribution and correlation structure are defined by the coefficient of variation (COV) and scale of fluctuation (SOF), respectively. The COV is a measure of the property variability, defined as the standard deviation divided by the mean, while the SOF is loosely defined as the distance at which properties become uncorrelated (Vanmarcke 1977). In addition to defining the correlation structure by the SOF, the relationship between two soil properties is also dependent on how the correlation between them varies for increasing separation distance. Fenton (1999) suggested that an exponentially decaying correlation structure most appropriately models the relationship between increasing separation distance and property correlation. Furthermore, the analysis in this paper is based on simulated soils with an isotropic correlation structure, where the SOF is the same in all directions. Although it is common that soils show greater correlation in the horizontal direction, due to the formation processes like sedimentation and weathering, Goldsworthy (2006) found that changes in the vertical correlation distance had little impact on the effectiveness of site investigation scope.

Designing a Foundation

Using the soil properties from the simulated soil, a pad foundation is designed for a settlement criterion only. Although it is typical that a design considers both ultimate and serviceability limit states, computation times associated with non-linear analyses to investigate an ultimate limit state are prohibitive.

The foundation designed in this paper consists of 9 pad footings, arranged in a grid pattern within a 20 m × 20 m area. The footings are spaced at 8 m intervals in both plan directions, as shown in Figure 1. The foundation region of 20 m × 20 m is centered on a 50 m × 50 m site, with an assumed depth of 30 m. Footing loads are representative of a 5-storey structure supporting a 5 kPa dead load and 3 kPa live load. No load factoring is considered, as it is peripheral to the analysis and not normally included in a settlement design.

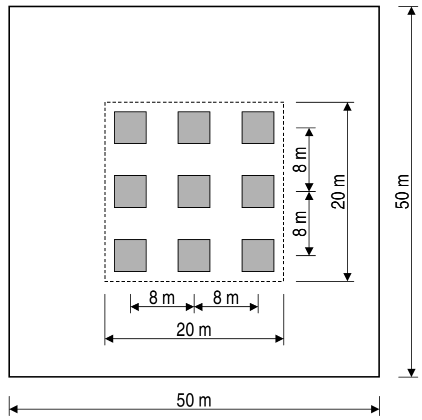


Figure 1. Schematic of the 9-pad footing foundation system

Footings are designed so that settlement does not exceed 25 mm, and differential settlement does not exceed 0.0025 m / m. Footing settlement is estimated using Schmertmann's method (1970). Time dependent and embedment effects are not considered. Elastic modulus values with a target mean of 30,000 kPa are generated as part of the soil simulation discussed earlier. These elastic modulus values are used in the Schmertmann equation after uncertainties due to measurement and transformation model errors have been added, as discussed later.

The initial phase of the design involves estimating the settlement of a small footing, with a size of 0.5 m × 0.5 m. If the settlement of this footing exceeds the maximum settlement of 25 mm, the footing size is increased by 0.1 m in one direction, yielding a new footing size of 0.6 m × 0.5 m. The analysis is repeated, and if the footing settlement still exceeds the limit, the size is again increased by 0.1 m in the other plan direction, yielding a footing size of 0.6 m × 0.6 m. This iterative process is repeated until all footings conform to the settlement criteria discussed above.

In order to represent a typical foundation design, only sampled soil properties are considered when estimating the settlement of a footing. Sampled properties are selected at locations arranged within the 20 m × 20 m foundation region shown in Figure 1. Sampling patterns considered in this paper are shown in Figure 2(a) for a regular grid pattern (RG), and Figure 2(b) for a stratified random pattern (SR). The stratified random pattern involves dividing the 20 m × 20 m foundation region into a discrete number of segments and randomly selecting a sampling location within that region. At each sampling location multiple soil samples are obtained by recording properties at different depths. The vertical sampling rate depends on the type of geotechnical test being investigated, as discussed later.

When a sampling plan consists of more than one sampling location, it is necessary to combine the soil properties from each location into one set of properties for use with the Schmertmann settlement equation. Essentially this is selecting characteristic values to represent the sampling undertaken. Many different means of combining properties exist. Five common techniques are investigated in this paper; standard arithmetic average (SA), geometric average (GA), harmonic average (HA), inverse distance weighted (ID) and 1st quartile method (1Q). These are considered reduction techniques and have been treated by Goldsworthy et al. (2005) and Goldsworthy (2006).

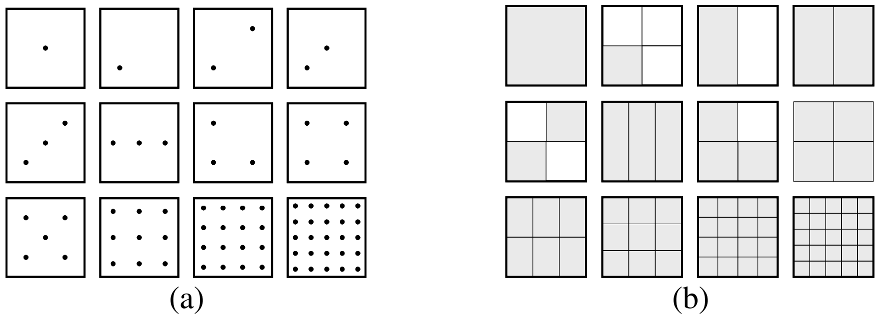


Figure 2. Sampling locations for the (a) regular grid (RG) and (b) stratified random (SR) patterns

Different types of geotechnical tests are also modeled in this framework. In this case, the standard penetration test (SPT), cone penetration test (CPT), triaxial test (TT), and flat-plate dilatometer test (DMT) are simulated using different degrees of uncertainty and vertical sampling rates. The degree of uncertainty for each test type is separated into three categories: bias, random and transformation model errors. Test uncertainties are modeled using a coefficient of variation value, as shown in Table 1. The COV values in Table 1 are based on the relative uncertainties of each test type, as discussed by Orchant et al. (1988). The means of incorporating each source of uncertainty (bias, random and transformation model error) was developed by Goldsworthy (2006) and involves multiplying the elastic modulus values sampled directly from the simulated soil by three lognormally-distributed random variables, each with a mean of one and a COV as given in Table 1.

Table 1. Coefficient of variation values representing measurement and transformation model errors.

Test Type	Measurement		Transformation Model
	Bias	Random	
SPT	20%	40%	25%
CPT	15%	20%	15%
TT	20%	20%	0%
DMT	15%	15%	10%

The simulation method also distinguishes between the vertical sampling rates for each different test type. For example, the SPT and DMT are examples of discrete sampling methods, where samples are taken at discrete depth intervals. As such, the SPT and DMT are both assumed to obtain soil properties at 1.5 m intervals. On the other hand, the CPT is an example of a relatively continuous sampling method, and is modeled to sample values at 0.5 m depth intervals. The TT, which is a laboratory test, is modeled to retrieve soil data at 15 m intervals. As such, only 2 properties per sampling location are considered using the TT.

Analyzing the Design

The foundation design that is based solely on sampled information may be considerably over or under designed. This is because sampling does not necessarily capture the soil condition. Therefore, this design is analyzed using complete knowledge of the soil. Originally, Jaksa et al. (2003) envisaged this process would use a numerically exhaustive analysis tool like the finite element method. However, after initial simulation runs, Goldsworthy (2006) observed that results were heavily influenced by a relatively coarse mesh required to keep computational times manageable. Hence, Goldsworthy (2006) proposed the use of the Schmertmann settlement model, and an influence region of properties, to represent the analysis of the design incorporating complete knowledge of the soil.

The analysis of the design based on the sampled information provides an indication whether the sampling yielded a conservative characterization (over design) or an under conservative estimate (under design). Similar results have been used by Goldsworthy (2006) to demonstrate the probability of over and under design. However, in this case, the results of the analysis are used to attribute rehabilitation costs in the event that the footing is under designed.

Assigning Costs

The total cost of the foundation design is defined as the costs associated with the site investigation, construction of the foundation and superstructure (5 storey, 20 m × 20 m building) and any potential rehabilitation costs associated with a foundation failure. Costs assigned to the site investigation are based on typical geotechnical investigation rates in Adelaide, Australia, and are given by Goldsworthy (2006). Costs for the construction of the foundation and the building were obtained from Rawlinsons (2004) and are discussed in more detail by Goldsworthy (2006).

Rehabilitation costs associated with a potential foundation failure are based on a severity category, where a minor failure requires limited rehabilitation works, and a major failure requires extensive works. Foundation designs are considered to require minor or major rehabilitation works when a footing has a displacement greater than a specified settlement limit. Using the costs for rehabilitation and a specific settlement limit for each rehabilitation category, a relationship between rehabilitation cost and settlement is developed, as discussed by Goldsworthy (2006). This relationship is used to assign rehabilitation costs to the design. The rehabilitation cost ratio is a ratio of the costs associated with the rehabilitation of the footing to the initial construction cost of the project.

The Real Cost of Site Investigations

Four different costs are generated by the methodology described above: site investigation cost; construction cost; rehabilitation cost; and total cost. Each cost is an average of 1000 Monte Carlo realizations, where the process is repeated for the same soil conditions. In this case, the same soil condition is defined as a soil with the same COV and SOF. For each Monte Carlo realization, the soil is regenerated using the same COV and SOF. Soil types are distinguished by the COV and the SOF in parentheses (e.g. 50(4) represents a soil with a COV of 50% and a SOF of 4 m).

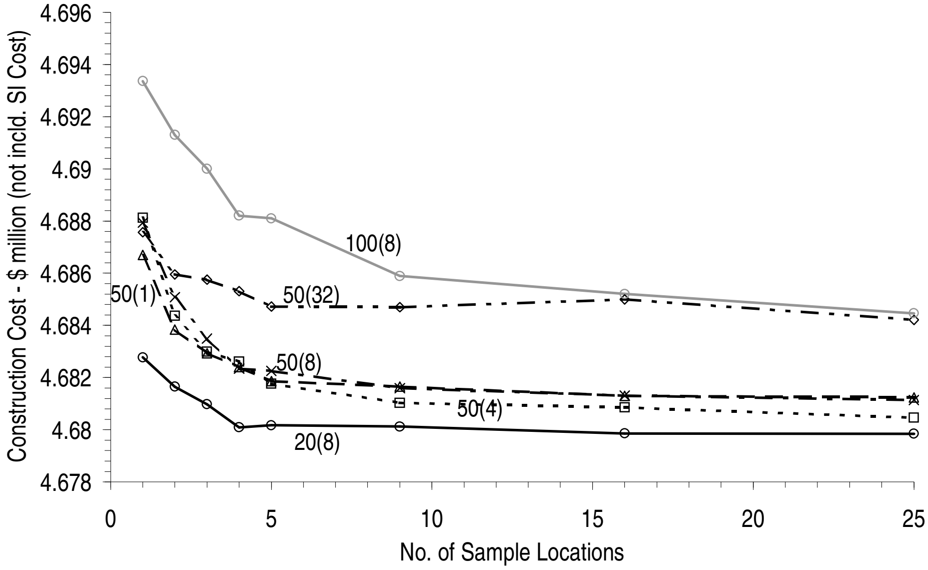
Results shown in Figure 3 illustrate the influence of increased sampling on the construction [Figure 3(a)] and rehabilitation [Figure 3(b)] cost for different soil types. In general, these results indicate that both the construction and rehabilitation cost reduce as sampling increases. For the construction cost, this typically infers that the conservatism in the foundation design is reduced as additional sampling is undertaken. However, the rehabilitation cost also reduces as sampling increases, which suggests that the foundation design is more conservative to avoid potential failures. However, it is important to note that these results are averages of 1000 Monte Carlo realizations and second order effects have an influence. Therefore, the reduction in construction cost is primarily driven by a declining conservatism, whereas the reduction in the rehabilitation costs is governed by a decreasing variability in the design.

Results presented in Figure 3 also allow conclusions regarding the impact of additional sampling for different soil types. For example, the reduction in construction cost for increased sampling appears to be greater when the soil COV is higher. However, it appears that the maximum decrease in construction cost, for increased sampling, occurs when the soil SOF is between 4 and 8 m. This situation purports a worst case SOF where the impact of additional sampling is greatest. Fenton and Griffiths (2005) have observed a similar worst case SOF when investigating the reliability of settlement estimates for two adjacent pad footings.

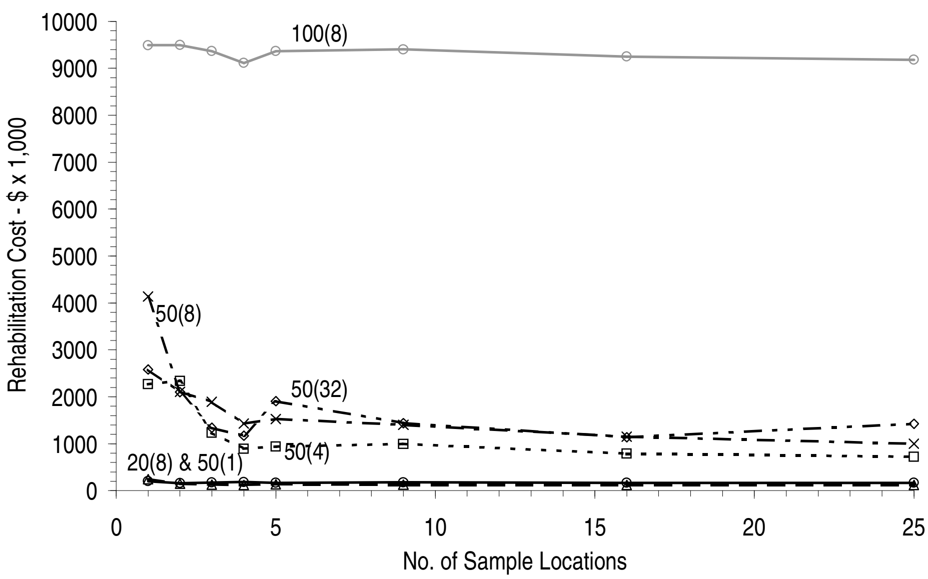
The relationship between rehabilitation cost and sampling for different soil types is not as evident as for the construction cost. However, it does appear that, in general, the greatest reduction in rehabilitation cost occurs when the soil SOF is 8 m. Again this infers a worst case SOF. However, the results in Figure 3(b) also suggest that the decrease in rehabilitation cost, for increased sampling, occurs when the soil COV is 50%. This condition exists because the rehabilitation cost is driven by the variability in the foundation design, and when the soil COV is 50%, the uncertainties in the soil properties, sampling locations, test types and reduction techniques yield a highly variable design. Therefore, for the design situation presented, a soil with a COV of 50% and SOF of 8 m provides a limiting case, where additional sampling is most effective. Such a condition is useful to engineers because the spatial statistics of a soil are rarely known without extensive investigation.

In the following results, which illustrate the impact of different sampling strategies on the total cost, the site investigation cost is expressed as a percentage of the construction cost. This is to be consistent with previous research regarding the recommended site investigation expenditure discussed earlier. Results demonstrate the impact of additional site investigation expenditure on the total cost for different soil types (Figure 4), sampling patterns (Figure 5), reduction techniques (Figure 6) and geotechnical test types (Figure 7).

The results shown in Figure 4 are similar to those in Figure 3(b) for the rehabilitation costs alone. This suggests that the rehabilitation costs have a large influence on the total cost. Therefore, foundation designs should be targeted towards minimizing the rehabilitation costs, even if this infers a larger construction cost.



(a)



(b)

Figure 3. Expected cost of (a) construction and (b) rehabilitation of a design based on using a CPT, RG sampling pattern, and the SA reduction technique

With regard to the effect of different site investigation strategies on the total cost of the foundation design, the results in Figure 5 suggest that the RG and SR sampling patterns are very similar. In fact, these two sampling patterns show almost the same relationship between increased sampling and total cost. However, there are notable differences between the reduction techniques, as shown in Figure 6. In this case, it appears that the 1Q method yields the lowest total cost, or least financial risk. On the other hand, the ID method produces the highest total cost and does not show the same smooth relationship for increased site investigation expenditure. This is because the ID method is based on a weighting system, where sampling locations closer to the footings take precedence over locations further away. However, in the limiting case, where a sample location coincides with the footing, the ID method only considers the soil properties from that location. This means that the other sample locations have no influence and, as such, there is no averaging to reduce the variability of the property. This condition yields a highly variable design, which, as shown earlier, produces a high rehabilitation cost and, in turn, a high total cost. Therefore, the ID is not recommended for this form of site characterization, unless soil properties from all sampling locations are considered.

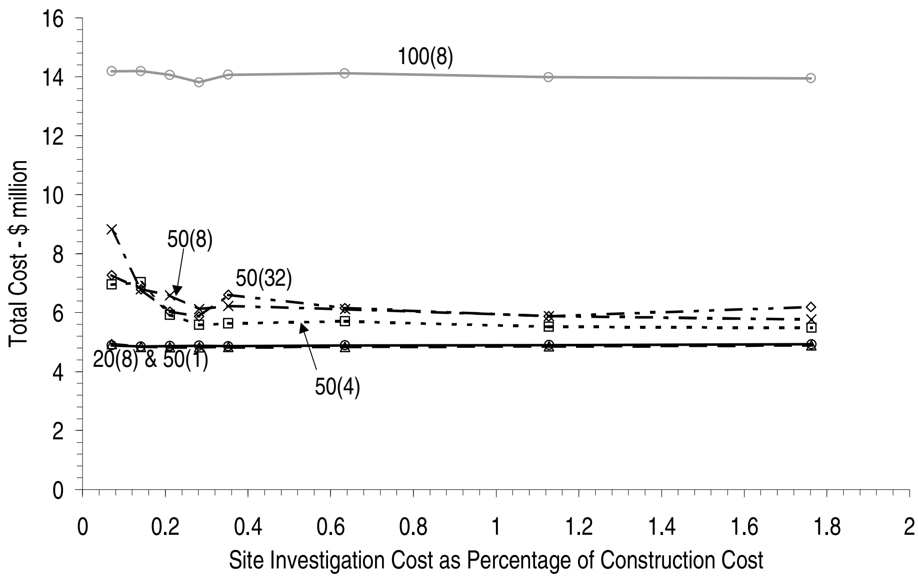


Figure 4. Expected total costs for increased site investigation expenditure for different soil types

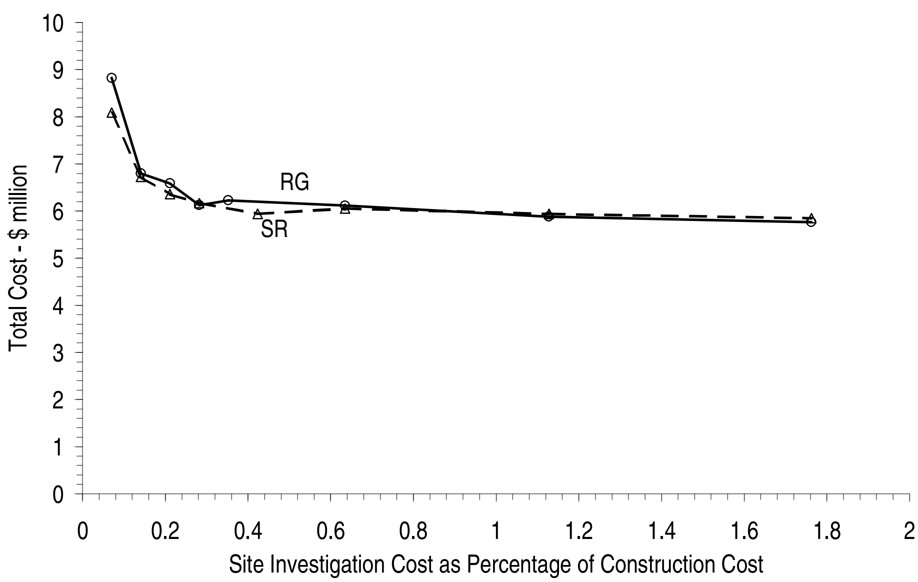


Figure 5. Expected total costs for increased site investigation expenditure for different sampling patterns

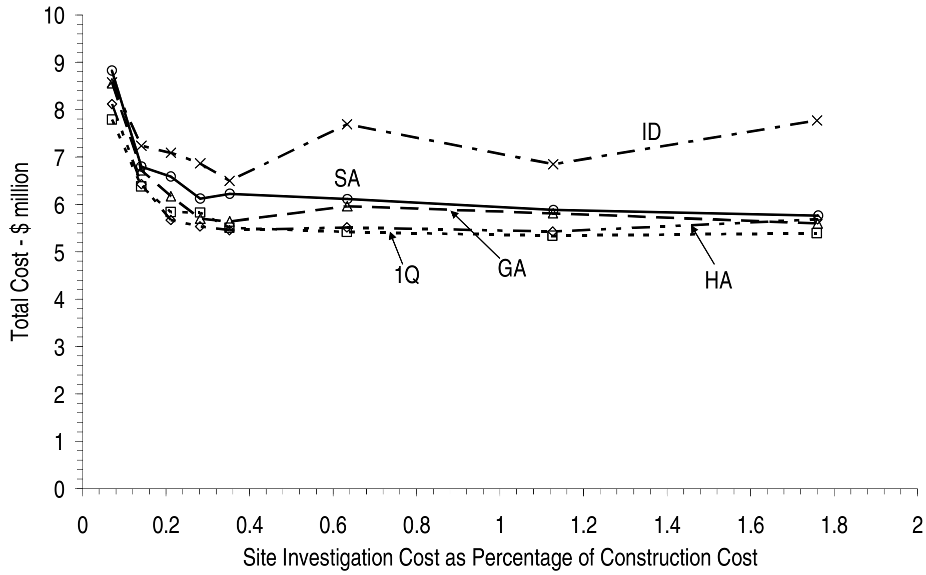


Figure 6. Expected total costs for increased site investigation expenditure for different reduction techniques

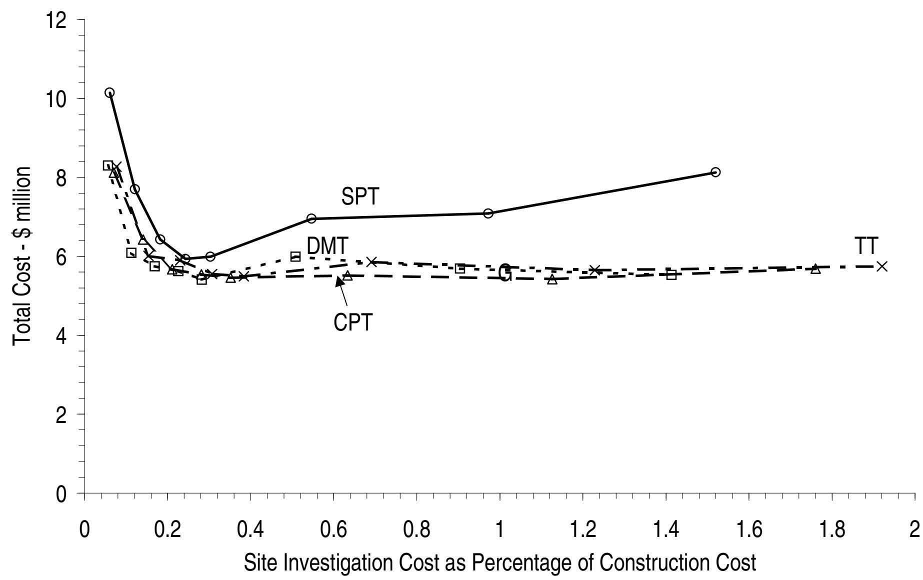


Figure 7. Expected total costs for increased site investigation expenditure for different test types

Finally, Figure 7 indicates that the CPT produces a foundation design with the least total cost or financial risk. However, the relationship between total cost and increased site investigation expenditure for the SPT warrants further attention. Firstly, the SPT yields designs with a much higher total cost than the other test types. This is partly expected due to the assumed high uncertainty associated with the SPT. However, there is a distinct minimum total cost for the SPT that is not evident with the other test types. The increase in total cost after the minimum for the SPT is most likely due to the high transformation model uncertainties associated with, and assigned to, the SPT. Unlike random errors, which average out when sampling increases, the bias and transformation model error remain, regardless the degree of sampling. However, it is important to note that the optimal site investigation expenditure, which produces the lowest total cost, is similar for all test types, suggesting that the same investigative effort (in terms of the number of sampling locations) is required for each of the test types examined.

It appears that, in most of the cases presented, the optimal site investigation expenditure is approximately 0.2% to 0.3% of the construction cost and includes the CPT using the regular grid (RG) sampling pattern and the 1st quartile (1Q) reduction technique. Additionally, the results indicate that an increased expenditure from 0.1% to 0.3% reduces the total cost of the design from over $8 million to just under $6 million. This is a considerable saving for an increased site investigation expenditure of approximately $20,000.

Conclusions and Recommendations

The results in this paper have clearly demonstrated that the financial risk of a foundation design is considerably reduced by increased site investigation expenditure. However, there appears to be an optimal site investigation expenditure, where the total cost of the foundation design is a minimum. Furthermore, results have shown that different methods of characterization lead to varying degrees of risk exposure. Therefore, it is not only the extent of the investigation that needs careful consideration, but also the type of geotechnical test used, and the method used to select characteristic values.

The results of this form of research will, in the future, assist geotechnical engineers to assess their designs based on the level of investigative effort. This research also provides clear supporting evidence that additional site investigation expenditure is beneficial to a project in the long term. Finally, the form of investigation, including the type of geotechnical test used and the means of selecting a characteristic value are both shown to have an influence on the risk of the foundation design.

It should be noted that the results presented in this paper are based on a single layer, statistically homogeneous soil, which is free from defects or other irregularities. In reality, the ground is typically highly variable and consists of complex layering. As such, the results presented in this paper should be considered an absolute minimum site investigative effort, and any site should be carefully reviewed before using recommendations presented.

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