INFLUENCE OF SITE INVESTIGATION BOREHOLE PATTERN AND AREA ON PILE FOUNDATION PERFORMANCE

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ABSTRACT

Site investigations are the largest element of technical and financial risk in civil engineering works, with insufficient testing often causing cost over-runs, construction delays, foundation failure and over-design. However, there is little research on where best to place boreholes with respect to the foundation. Typically, if the structure location is known, then boreholes are placed at the centre, or otherwise at the corners, although some studies indicate that there may be benefit to randomising the sampling location. This study aims to determine the best of a series of sampling schemes, where each scheme involves varying degrees of randomness, as well as to examine the effect of investigation area relative to the building footprint.

The optimal sampling scheme is determined from Monte Carlo analysis, where a random, variable, single layer, 3D virtual soil is generated. From this, it is possible to carry out a variety of virtual site investigations, determine true foundation performance, and determine the magnitude of structural damage resulting from insufficient investigation. Total cost, calculated from a combination of construction, investigation, and failure costs, is used as the objective function to be minimised.

1 INTRODUCTION

Site investigations are an essential part of civil engineering works, as they allow for the determination of subsoil material properties. As soil profiles are spatially variable in nature, resulting from varying geological and environmental processes, it is important to test a range of multiple locations. There are many reported cases where insufficient testing has led to cost over-runs (Boeckmann and Loehr, 2016), construction delays (Jaksa, 2000), foundation failure (Moh, 2004) and overdesign (Clayton, 2001). Clearly, there is great benefit to conducting a site investigation of satisfactory scope. However, there is little guidance on what the components of such a scope would consist of (Crisp et al., 2018). This study aims to investigate the influence of borehole location on the performance of the resulting foundation.

The work in this study is undertaken with Monte Carlo analysis, based on a framework originally proposed by Jaksa et al. (2003), and later elaborated and improved upon by Crisp et al. (2018). Within each realisation, a virtual soil is generated using random field theory (Vanmarcke, 1983), where each soil can be represented entirely by three statistical, spatial parameters. These include the two moments of the lognormal distribution; the mean and the standard deviation, where the latter is often normalised by the mean to produce the coefficient of variation (COV). The lognormal distribution is chosen as it has been found to adequately represent soil properties, and is commonly used in this line of study due to its simplicity and non-negative nature (Fenton and Griffiths, 2008). The third parameter is the scale of fluctuation (SOF) which represents the correlation length, not unlike the range parameter in geostatistics. Alternatively, the SOF can be described as the distance within which properties are expected to be correlated.

As all details of the soil are known, it is possible to replicate, in a virtual manner, the full process of planning, construction, and performance of infrastructure. This is achieved by simulating site investigations, designing resulting foundations, determining the true performance of those foundations (through 3D linear-elastic finite element analysis, FEA), and calculating potential damage to the superstructure through foundation failure. By assigning costs to each of these components (construction, soil testing, failure), an objective function is assembled in terms of the total, combined cost. This represents an ideal optimisation problem, as the optimal investigation is that with the lowest total cost, incorporating all components as described above, and the optimisation implicitly reflects both economic and risk-based factors.

Currently, there has been little research on the effect of borehole configuration, including explicit benefits of randomizing locations. Ferguson (1992) has suggested that some degree of randomness in borehole location may be beneficial, although this is in the context of detecting localized contamination hotspots, as opposed to foundation design where the properties over a large area are required. Goldsworthy et al. (2007a) compared varying degrees of borehole location randomness in the case of pad foundations, although simplified settlement methods were used instead of the more accurate FEA, and so the true foundation performance may not be reliable. It was found that a stratified sampling pattern produced the cheapest total cost for pad foundations. However, it was noted that the decrease was modest, and Goldsworthy ultimately recommended a regular grid pattern largely out of practicality. These findings are supported by Crisp et al.

(2017), who compared a regular grid and stratified random patterns in a 2D, two-layer soil profile for pile design. It was found that while the average design error was reduced by up to 6% for the latter scheme, the variability of the design error was significantly higher. These results indicate that regular grid sampling pattern may be optimal, or sufficiently close to it. However, further research is required.

Greater focus has been given to optimising the location of a single borehole with respect to a foundation. Goldsworthy et al. (2007b) found that a centrally-located borehole was ideal in the case of a pad foundation group where a pad was present at the centre. In the case without a central pad (i.e with four pads), it was found that sampling near a pad location yielded best results, in terms of the lowest total cost. On the other hand, Arsyad et al. (2010) modelled the influence of a single borehole around a single pile foundation in an attempt to find a 'critical distance' between the two, beyond which the probabilities of under- and over-design became constant. As expected, this distance was a function of the SOF, and was found to be 5 m and 22m for a SOF of 1 m and 10 m respectively. Beyond a SOF of 10 m, the critical distance decreased, implying this SOF to be the worst case. These findings indicate that while boreholes should coincide with a foundation, ideally they should be within the influence range of all foundations at a site, and that this range is strongly influenced by the SOF.

In terms of multiple boreholes relative to foundation locations, existing research is minimal. Goldsworthy et al. (2004) studied the effect of varying the location of a constantly-sized investigation area around a pad foundation. It was found, unsurprisingly, that the best results in terms of probability of failure and overdesign were obtained when the investigation area overlays the foundation location centrally, such that the foundation footprint is entirely contained within the area's boundary. This central preference is as opposed to a foundation at least partially located outside of the investigation plan. Furthermore, Goldsworthy (2006) noted that besides the aforementioned single borehole case, the number of boreholes was the dominant factor in investigation performance, and that the exact locations of these boreholes were of secondary relevance. These results imply that in the case of multiple boreholes, investigation performance is not sensitive to borehole configuration.

To date, no research has compared the effect of random sampling on the performance of pile foundations in 3D, or with any foundations using the accurate FEA settlement model. Furthermore, no study has analysed the influence of varying the size of the investigation area relative to the foundation footprint. This study therefore examines the influence of borehole pattern, area and number in a variety of soil profiles. The two aims are as follows:

1. To investigate potential benefits of using random borehole locations, though a variety of sampling schemes with different inherent degrees of location randomness; and
2. To determine the effect of changing the size of the investigation area, centred around the foundation.

The outcome of this research is key insight into the relationship between total cost and the number of boreholes, for a variety of soil conditions and borehole configurations. The degree of sensitivity between these variables and total cost, as well as any identifiable universally optimal cases, will inform practicing engineers to plan their investigations more effectively.

2 METHODOLOGY

2.1 OVERVIEW

The results in this study were processed from a reusable database of pile and site investigation performance information that can be adapted to many different structural and soil configurations, as described in this section. The database was generated using the methodology described by Crisp et al. (2018), and the authors refer readers to that report for verification and a detailed account of the procedures adopted in the present paper. The basis of this framework is the generation of normalized pile settlement functions in terms of pile length, which are developed in two stages. The first stage involves determining the settlement corresponding to specific pile lengths using linear-elastic FEA. Secondly, a continuous curve (i.e. the settlement function) is produced through Akima interpolation (Akima, 1970), which has been found to be the most appropriate interpolation method for this case.

The functions are normalized due to being in terms of unit soil stiffness and applied load. Due to the linear-elastic nature of the analysis, the functions can be scaled linearly with load and soil stiffness, as well as the piles being designed to an arbitrary settlement tolerance, hence its reusable nature. As such, this pile function database can be used by other researchers for a wide variety of structure and foundation configurations, as well as soil stiffness and design redundancy. The latter facilitates reliability based design research to be conducted. Note that this pile performance database was generated using the Phoenix supercomputer at the University of Adelaide (University of Adelaide, 2018). The database itself would have taken 30 years to generate, despite the heavy optimisation implemented, had Phoenix's parallel capabilities not been utilised.

The determination of site investigation quality requires two sets of pile settlement functions, which are differentiated by the soil properties used as input to the settlement model. Firstly, curves can be generated for the true performance of foundations by using the appropriate soil properties mapped from the complete and original virtual soil, thus representing complete knowledge of the site (CK functions). Secondly, settlement curves corresponding to various site investigations can be generated by mapping the soil model derived from the corresponding site investigation (SI functions). Once the functions are obtained, determining the quality of an investigation then becomes a simple 2-step process, as illustrated in Figure 1. Firstly, pile length is designed to a specific settlement tolerance using the SI functions. Secondly, these lengths are converted to true settlement through use of the CK functions. These curves are generated in a Monte Carlo simulation with 8,000 realisations, meaning there are 8,000 sets of the same curves derived from different random soils, such that the average (expected) total cost across the realisations is computed. The relationship between total cost and site investigation effort can be determined through plots of the two variables.

2.2 COST CALCULATIONS

Damage occurs to the superstructure in cases of excessive differential settlement, as determined from the true performance, and a corresponding cost penalty is applied. These failure costs were interpreted from a series of differential settlement thresholds for various magnitudes of failure, as suggested by in Day (1999), and correlated with repair costs given by Rawlinsons (2016). The remaining costs for construction and soil testing were derived through a combination of Rawlinsons (2016) and personal correspondences. The described 6-storey super-structure is $6,157,750, while the piles cost $200 / m. The cost of building damage (C) in terms of differential settlement (δ), is governed by the following equation: $C = 1.024 \times 10^9\,\delta - 3.056 \times 10^6$, where C is constrained with a minimum of $0, and a maximum of $6,534,400, which corresponds to demolishing and rebuilding the superstructure. Finally, site investigation costs are calculated per metre of testing. Two test types are considered; the cone penetration test (CPT) and standard penetration test (SPT), which cost $156 and $77 per metre, respectively.

The resulting problem then becomes that of optimisation, where cost is to be minimized. This is a trade-off, as foundation failure decreases as the investigation effort increases. Conversely, the investigation cost increases at the same time. Theoretically, the foundation construction costs should also decrease with increased investigation, because practising engineers typically compensate for poor investigations with increased design redundancy (overdesign). However, such design redundancy is not accounted for in this study, nor is it recommended in lieu of sufficient investigation, as the optimal degree of redundancy is not known at this time.

2.3 FOUNDATION AND STRUCTURE

The present analysis investigates a 4-pile foundation arranged in a grid pattern, where the centre-centre pile spacing is 20 m. Relative to the borehole locations, the piles are placed as demonstrated in Figure 4(a). The foundation supports a 6-storey, 20 × 20 m structure as seen in Figure 2. Each floor is subject to 3 kPa of live load and 5 kPa of dead load, with no load factoring applied as engineers do not typically use safety factors in settlement calculations. This weight results in a total load of 19,200 kN, distributed equally among the piles.

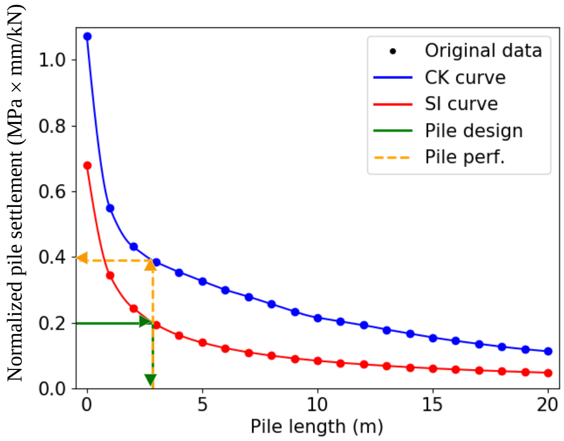


Figure 1: Example pile design and performance process.

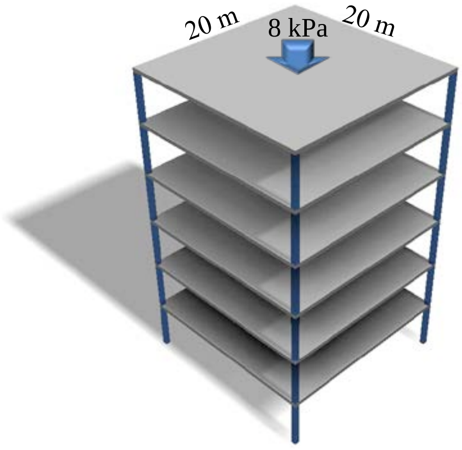


Figure 2: Structure used in this analysis.

The pile radius is set at 0.5 m, where length is the design variable, which is set to vary between 0 m and 20 m in depth. Due to the nature of the settlement model discussed later, the pile is assumed to be a square prism of cross sectional area 0.5 m by 0.5 m. The piles are designed according to a settlement tolerance of 50 mm, which corresponds to a differential settlement of 0.0025 m/m. The resulting average pile length is approximately 8 m.

2.4 GENERATION OF VIRTUAL SOIL PROFILE

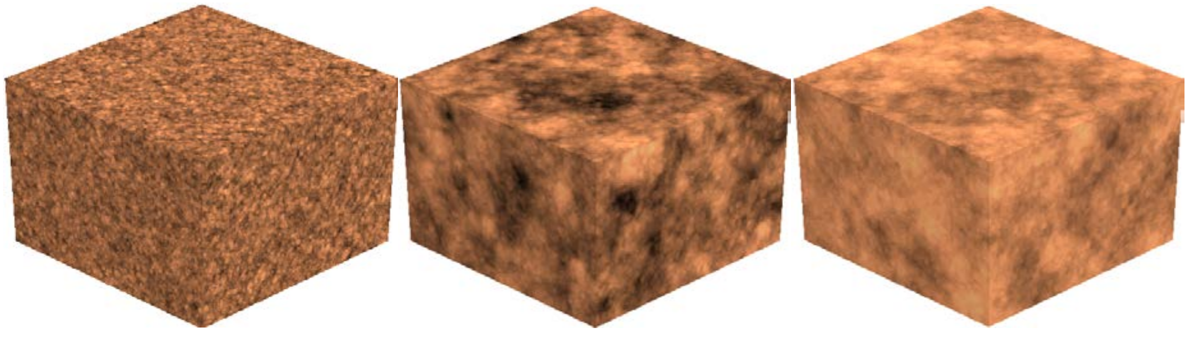
The random fields used to represent virtual soils are generated with the local average subdivision (LAS) method (Fenton and Vanmarcke, 1990), as it is noted as being relatively fast and accurate. Field dimensions are inherently restricted to sizes of $a2^b$ elements, where a and b are integers, however smaller fields of arbitrary size can easily be extracted if desired. As such, the field used in this study is of size 240 × 240 × 160 elements, randomly extracted from an original field of 320 × 320 × 192 elements. The soil elements are cubes of length 0.25 m, resulting in the working field being 60 m by 60 m by 40 m in the x, y and z directions respectively. The generated random field represents Young’s modulus (E), while Poisson’s ratio (v) is held constant at 0.3. An example of the influence of COV and SOF on a virtual soil can be seen in Figure 3.

Local average subdivision at its simplest works by generating an initial field of a single element, specified as having the desired mean soil property. Subsequently, a number of subdivisions occur, where the number of elements in each dimension are doubled, resulting in eight new elements within the volume of a previous-stage (parent) element. At each subdivision, new elements are randomly generated according to a lognormal distribution according to two constraints:

1. The elements are correlated in 3D space according to an exponential Markov correlation model.
2. A group of elements generated within the volume of a parent element has an average value equal to that of the parent element. As such, the global average is maintained while allowing local variability.

This study involves the use of a single-layer heterogeneous soil profile, following the assumptions of second order stationarity (weak stationarity). With this assumption, the soil mean is constant and the correlation between two points depends only on their lag (i.e. separation distance) and not their locations (Brockwell and Davis, 2013). This is used so that the results can be generalised to a wider range of soils, as opposed to soil profiles that have specific, complex multi-layer stratigraphy. However, as a result of this simplifying assumption, any recommendations given in this study, as to the ideal number of boreholes should be taken as a minimum, as more complex geology would require more extensive investigation. Further details on LAS are given by Fenton and Griffiths (2008), along with the corresponding Fortran code for the generation of random fields.

For the soil parameters used in the present study, a mean Young’s modulus of 60 MPa was chosen, corresponding to hard clay or dense sand. SOFs of 1, 2, 4, 8, 16 and 24 m were assessed, along with COVs of 20, 40 and 80%.



(a) (b) (c)

Figure 3: Example soils generated using LAS, with parameters (a) COV 80%, SOF 1 m; (b) COV 80%, SOF 16 m; (c) COV 20%, SOF 16 m.

2.5 SETTLEMENT MODEL

The settlement model used in this study is a 3D linear-elastic FEA Fortran subroutine adapted from Program 5.6 by Smith et al. (2013). The mesh is comprised of 8-node brick elements, where nodes at the bottom are fixed in the vertical direction, representing infinitely-stiff bedrock. Similarly, nodes on the sides of the mesh are laterally restrained so as not to move out of plane. The subroutine uses an iterative, pre-conditioned, conjugate gradient solver in lieu of assembling and solving the global stiffness matrix in order to greatly reduce RAM usage.

The foundation is modelled as a series of rigid piles which are restrained against rotation and lateral movement, and are assumed to be perfectly bonded to the surrounding soil. Each pile is modelled separately in an individual, isolated mesh. While this isolation does not account for pile group settlement effects, it serves to greatly reduce the number of mesh elements as the required soil volume is reduced, resulting in a significant increase in computational speed. The number of FEA elements is further reduced by increasing the size of elements that are located some distance from the pile. While this results in a discrepancy between the FEA elements and LAS soil elements, direct mapping can be achieved by evaluating the geometric average of the LAS elements within each FEA element volume.

The mesh itself is 20.5 × 20.5 × 40 m in the *x*, *y* and *z* dimensions respectively, with the pile located centrally. Around the pile at the mesh centre, at the highest resolution, the elements are cubes of length 0.5 m. The mesh dimensions are based on the maximum possible design of 20 m, where 20 m is the minimum distance between any point of the pile and the mesh boundary. This spacing is sufficient to negate the influence of the mesh boundary on settlement results, when compared to the theoretical semi-infinite soil mass represented by the model.

On the surface, these assumptions, along with those of linear-elastic material mechanics, may not appear to be an accurate representation of the complex mechanical behaviour found in soil. Note that Crisp et al. (2018) devotes significant space to demonstrating the suitability of this model. However, the greatest factor is simply that of practicality; Monte Carlo simulation, combined with hundreds of combinations of variables, requires millions of FEA simulations to be carried out. As such, the relatively computationally-efficient model described here is required for results to be generated within a practical timeframe.

2.6 SITE INVESTIGATION

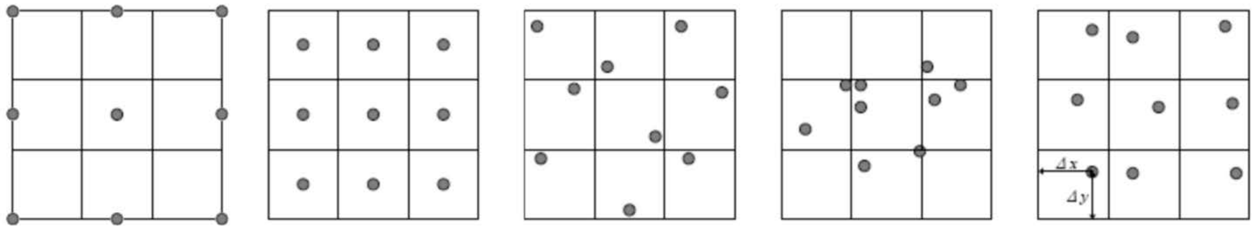
The site investigation is conducted with both the SPTs and CPTs to a depth of 20 m. Testing is undertaken by extracting values of Young's modulus from the complete knowledge random field at appropriate locations, followed by the application of random errors. The two tests therefore differ in three areas; cost (described previously), sampling interval and accuracy. Sampling by the SPT and CPT are respectively undertaken at discrete 1.5 m vertical intervals and continuously. In terms of the discrete random field, this sampling rate corresponds to every 6 elements and every consecutive element with depth, respectively.

In terms of testing inaccuracy, three sets of unit-mean, lognormal random errors are applied to the sampled values. These sets represent inherent randomness associated with borehole drilling, sample testing, and parameter conversion. In the case of the CPT, these are comprised of 20% random bias per borehole (based on the mean), 15% random error per sample, and 15% global bias (based on the mean), respectively, and applied in that order. The SPT errors follow the same process, with the above values replaced by 25%, 20% and 40%. As such, in terms of exclusively determining Young's modulus of a soil, the SPT is theoretically inferior to the CPT in each category of cost, quantity of data and accuracy. Following the application of errors, a representative soil model is assembled in order to design the pile. The model uses a single, constant soil stiffness which is determined by taking the 1st quartile of all sample values from the investigation.

Two sets of analyses are conducted in order to quantify the effect of sampling pattern and site investigation area relative to the building footprint. Five sets of borehole numbers are analysed per investigation: 1, 4, 9, 16 and 25. Furthermore, both the SPT and CPT have been evaluated for each scenario. Details for the specific analyses are given in the following sub-sections.

2.6.1 Analysis of Sampling Pattern

Five kinds of sampling schemes are considered in the first analysis, with varying degrees of randomness, as shown in Figure 4 for a nine-borehole case. The first two are the random grid (RG) and equivalent grid (EG). With the RG



(a) (b) (c) (d) (e)

Figure 4: Five different sampling patterns: (a) regular grid; (b) equivalent grid; (c) stratified random; (d) simple random and (e) stratified systematic unaligned (after Ferguson (1992)).

scheme, boreholes are spaced equally across the full building footprint, whereas EG has equally spaced boreholes such that the area represented by each borehole within the footprint is equal. The stratified random (SR) pattern adopts a borehole located randomly in each of the equal-sized cells. The stratified systematic unaligned (SU) pattern (Ferguson, 1992) has the boreholes in each row share an x-coordinate relative to its cell, and similarly the boreholes in each column share a relative y-coordinate. Finally, there is the simple random (RN) pattern, which adopts boreholes placed entirely randomly across the full building footprint, on the condition that they do not coincide.

2.6.2 Analysis of Investigation Area

The second analysis involves the influence of the investigation area on foundation performance. A series of investigation areas, centred around the foundation, have been analysed using the RG sampling scheme. The areas range from larger than the building footprint to smaller, and are squares of the following lengths: 1.25, 10, 14, 18, 20, 22, 26, 30, 40, 60 m. They can be seen in plan view in Figure 5.

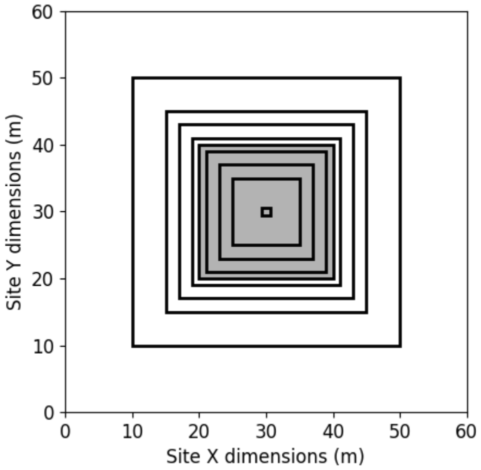


Figure 5: Investigation areas relative to the foundation footprint (shown in grey).

3 RESULTS AND DISCUSSION

3.1 INFLUENCE OF SAMPLING PATTERN

The results of the five sampling schemes and five borehole sets are shown below in Figure 6 for soils with a COV of 40% (low) and 80% (high), as well as SOFs of 1 (low), 8 (medium), and 24 (high) m. Lower COV values are not shown below, as they follow the trend of Figure 6(a) where all costs coincide for their respective test types, and a single borehole is recommended. This convergence of results for low COV is due to a lack of foundation failure. The exceptional foundation performance in such cases is due to a combination of the relative uniformity of the soil precluding differential movement, and the conservative nature of the 1st quartile reduction method.

It can be seen from all components of Figure 6 that there is strong consistency in the shape of the cost curves across the different borehole patterns, within each test case. In particular, the cost curves essentially overlap in all cases except with the high COV in combination with a medium or high SOF, as seen in Figure 6(a-d) in comparison to Figure 6(e-f). This overlap in low variability soils implies that some degree of the benefit of additional sampling is from the reduction of sampling error derived from having a larger number of samples. This is as opposed to the benefit of knowing the properties of a larger proportion of the soil volume. In turn, this suggests that site investigation performance is not as sensitive to borehole location, in a majority of soil cases, as speculation may have suggested.

In the high COV, medium-high SOF soil cases, where a difference is noted between the sampling patterns, the regular grid scheme is consistently the best in terms of cost, contrary to previous studies. The improvement is particularly noticeable in soils with higher SOFs, and in the cases of 4 and 9 boreholes. These cases can be explained by considering two points. Firstly, with the high SOF, the 4 piles are likely to be located in distinct pockets of different soil stiffness. Secondly, the corner boreholes of the regular grid scheme coincide with the piles at the corners of the building, therefore providing insight into the properties of these pockets. From Figure 6(f) it can be seen that the savings from using the regular grid pattern over random sampling can be as high as $60,000 and $100,000 for the SPT and CPT respectively. From Figure 6(e), the savings of both tests can be as high as $30,000. These notable differences could be explained by a random sampling pattern having the possibility of positioning multiple boreholes in close proximity of each other. This would weight that sampled region more heavily as opposed to the soil as a whole, in detriment to the site investigation performance.

Despite the above points, the random sampling patterns tend to converge with the regular grid scheme for a very small or large number of boreholes. The latter case occurs despite the regular grid scheme having 4 boreholes positioned in the corners. This is because the site investigation begins to weight the interior of the building more heavily due to the higher number of internal boreholes, where the soil content may be different to that in proximity to the piles. Furthermore, the random sampling schemes tend to resemble an approximate grid pattern as the number of boreholes becomes large, resulting in a greater likelihood of sampling evenly across the building footprint. In the case of a single borehole, the improvement of a centrally-located borehole is not as high as suggested by Goldsworthy et al. (2007b), although this is because there is no central pile. Therefore, the single borehole in the regular grid case is at the maximum possible distance from each pile, explaining its poor performance. Nevertheless, the regular grid sampling scheme is the recommended pattern for this study, and all results from this point onwards will refer to this scheme.

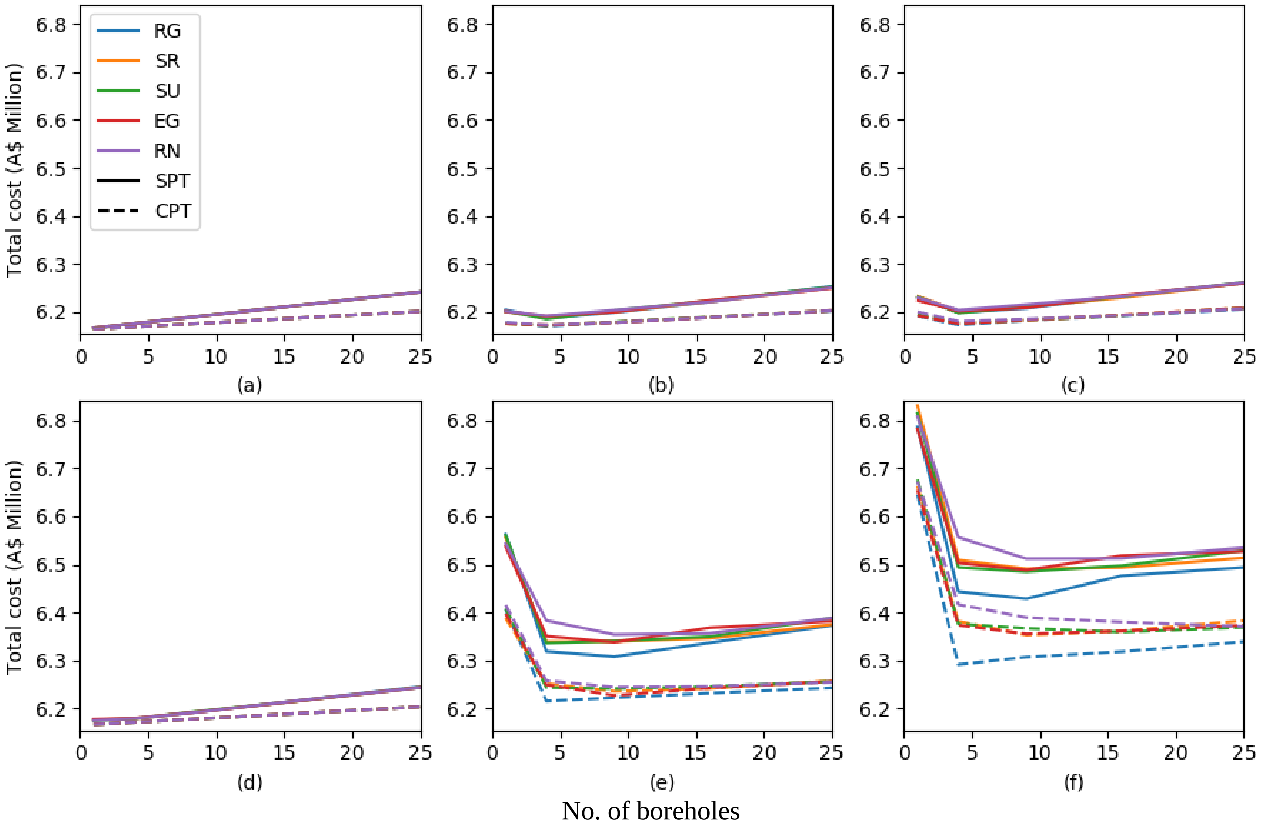


Figure 6: Total cost for the 5 borehole schemes with 1-25 boreholes, in a soil with a SOF of (a) 1 m; (b) 8 m; (c) 24 m and COV of 40%, as well as a SOF of (d) 1 m; (e) 8 m; (f) 24 m and COV of 80%.

In terms of the optimal number of boreholes based on minimum cost, the recommendation varies with both the variability of the soil, and the test type used. In the case of low SOF, a single borehole is sufficient, regardless of test type and COV. This is because the foundation is unlikely to fail as mentioned previously, and because the rapid fluctuation of soil properties with depth ensures that the full distribution of properties is sampled by a single borehole. For low COV, but medium and high SOF soils, a more thorough investigation of 4 boreholes is required, producing savings over a single borehole of $30,000 and $20,000 for the SPT and CPT respectively. These results reinforce that performing a more thorough site investigation than the minimum can indeed produce net savings, despite the higher initial investment. These savings are due to a combination of cheaper foundation design and, more importantly, reduced risk of potential damage.

Soils with a high COV and medium-high SOF are the most interesting case, as significant gains can be obtained through sufficient sampling, and because there is a divergence in the optimal number of boreholes for each test. For example, the benefit of conducting 4 boreholes over one in Figure 6(f) is $350,000 for both tests. An additional saving, in the order of $15,000, can be gained with the SPT by conducting 9 boreholes. It should be noted that $15,000 is the edge of the Monte

Carlo analysis error margin, meaning that this additional saving over 4 boreholes cannot be stated with complete confidence. However, there is certainly no detriment to conducting 9 boreholes, with the SPT, over 4 in terms of total cost.

Furthermore, it can be seen that the CPT is always cheaper than the SPT for a given number of boreholes. This is due to both the higher quantity of information being collected by its continuous sampling, as well as the lower magnitude of errors associated with the test, with the latter point being the dominant factor. It can also be seen that the CPT is cheapest overall in all soil cases, and that 4 boreholes with this test yields better results than any number of SPT samples for the reasons discussed above. As such, the recommended investigation for the majority of soils is 4 CPTs; one at each of the pile locations if possible.

3.2 INFLUENCE OF INVESTIGATION AREA

The following section discusses the implications of changing the size of an investigation area with respect to the foundation footprint. The results are given in Figure 7 for different numbers of boreholes in soils with a COV of 80%, and a SOF of 1 m, 8 m and 24 m. The performance of the site investigations does not appear to be highly sensitive to the site investigation size in high COV. As such, lower COV values correspond to negligible sensitivity, and so are not included in the analysis. This insensitivity is most prominent in low SOF soils, where the total cost is constant with investigation width. Medium SOF soils correspond to minor sensitivity. However, assuming that the investigation width is greater than or equal to the width of the building, the difference in cost is negligible. These results indicate that, in all soil cases except high SOF and high COV, the performance of a site investigation is largely independent of the investigation width.

The reasons for this investigation width insensitivity were given in the previous section in the context of lack of sensitivity to a specific borehole location due to the relative uniformity of the soil, and the need to overcome sampling error with additional samples. This insensitivity can also be explained by understanding how the soil around piles contributes to the settlement. For example, if a borehole is drilled at a fixed radius from a pile, the accuracy of that borehole should be constant regardless of its location. Therefore, it would not matter whether this borehole was drilled inside or outside of the building footprint. In other words, the soil around the outside of the building also contributes to settlement, so it is logical to sample this region.

On the other hand, for high SOF soils, there appears to be a unique optimal investigation area for each number of boreholes, the width of which is equal to or greater than the width of the building. This optimal width increases as the number of boreholes increases, which implies that the benefit is due to a particular borehole spacing. As seen in Figure 7(b-d) the optimal widths for the SPT are roughly 24 m, 30 m and 40 m respectively for the cases of 9, 16 and 25 boreholes configured in a regular grid. These values correspond to an optimal borehole spacing of approximately 10 m. It should be noted that this 10 m value is roughly half the distance of both the footing spacing and the SOF, indicating that there may be a relationship between either of these variables and the optimal borehole spacing. On the other hand, it may simply be a coincidence, given that the optimal widths for the CPT are in the order of 25–30 m in the same soils. In either case, the consistency of the optimal 10 m spacing is notable, and requires further research. The exception to the above recommendations is the 4-borehole case, which has an optimal spacing of 20 m for both tests, as seen in Figure 7(a). This outlier is due to the boreholes being positioned exactly at the pile locations. As such, this result reinforces that each borehole should always coincide with a pile if the numbers of both are equal, at least in high SOF soils.

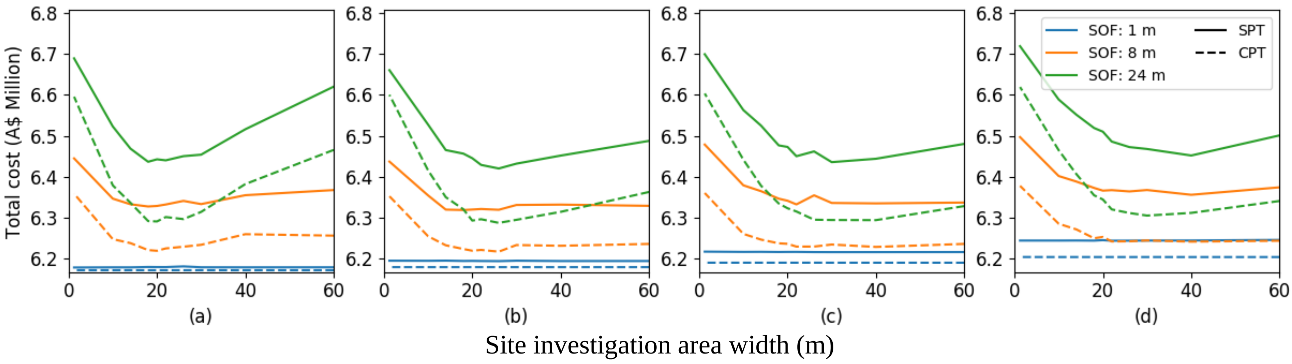


Figure 7: Comparison of investigation areas and SOFs with (a) 4; (b) 9; (c) 16; and 25 boreholes and COV of 80%.

It may be the case that an engineer wishes to investigate a larger area than that of the building footprint. This could theoretically allow for the identification of a stable, stiff region of soil within that area for the building location, resulting in cheaper foundations and a net saving. As discussed in this section, this strategy appears reasonable in all soils with a low and medium SOF, where the performance of the site investigation is relatively insensitive to its width. However, deviating from the recommended investigation widths mentioned above for high SOF soils results in an increased total cost. In the case of 9 or more boreholes, as seen in Figure 7(b-d), the cost increases linearly with width from the optimal case in each subplot, to a net additional cost of roughly $50,000 at a width of 60 m for both tests. However, note that this cost corresponds to a high COV of 80%, and is therefore conservatively large.

Based on these results, an engineer could choose to investigate a larger area in high SOF soils if it is felt that the foundation construction savings would offset the increased investigation cost. The exception to the above recommendations is the case where the number of boreholes and piles is equal, in which case the boreholes should be located adjacent to the piles. Considering that the optimal investigation width increases with the number of boreholes, it can be concluded that investigating a wider area is not only allowed, but is encouraged, should the number of boreholes be sufficiently high. This recommendation is particularly true considering that there is no notable difference in cost between the different numbers of boreholes in a high SOF soil. This insensitivity indicates that the cost of additional sampling is largely offset from improved investigation performance, as seen in Figure 6(e-f).

4 CONCLUSIONS

A comparison of several different borehole patterns has shown that the regular grid sampling scheme consistently produces the lowest average total project cost compared with alternative patterns which incorporate random locations. In the case of high COV and high SOF, the difference in cost between these patterns can be as high as $100,000. On the other hand, there are several cases where site investigation performance is not affected by borehole pattern. In soils with a low COV or SOF, the soils appear relatively uniform at a macro scale, meaning that the specific locations of boreholes becomes less important. The results also converge as the number of boreholes increases, due to the increased probability of the random borehole locations resembling a random grid. This insensitivity in the majority of cases means that engineers can be flexible in where they place boreholes in a site investigation, although a regular grid scheme should be utilised where possible.

Regarding the ideal number of boreholes and choice of test, it was found that 4 CPTs, one at each of the pile locations was optimal. This is as opposed to the SPT, which had a higher cost overall, and required up to 9 boreholes to be optimal. The SPT’s inferior performance was due partly to the smaller number of samples taken, but the primary factor is the significantly higher sampling error. The exception to this 4 CPT recommendation is in the case of low SOF soils, where it could be argued that one CPT is best. However, these types of soils are not particularly common, and the undertaking of 3 additional boreholes requires negligible additional cost. Therefore, 4 CPTs are recommended for all soil cases, and can lead to a savings of up to $350,000 over a single CPT due to improved foundation designs and a reduced likelihood of failure. In the case where CPTs are not available or impractical, 4 SPTs could generally be substituted. This SPT recommendation carries additional risk, with a loss of up to $15,000 compared to the true optimum depending on the nature of the soil, however this value is at the Monte Carlo error margin, and is therefore deemed negligible.

Regarding the variation of site investigation area, it was found that in all soils with a low or medium SOF, the investigation performance was insensitive to its width, for reasons given above. This indicates that an engineer may confidently investigate a larger area if desired, without repercussions, which is useful if the building location is to be chosen based on site investigation results. In terms of high SOF soils, it was concluded that the optimal borehole spacing for the SPT is approximately 10 m, meaning that the optimal width increases with the number of boreholes. On the other hand, the CPT did not exhibit a consistent optimal borehole spacing, instead showing a more modest increase in optimal width as the number of boreholes increases, in the order of 25-30 m. Deviating from the optimal investigation width, in general, results in a linear increase of cost as width increases.

It is speculated that the optimal investigation width will decrease as the number of piles increases. This is because the soil within the building footprint becomes more important as the pile density increases, as that central soil contributes to the settlement of multiple piles. Therefore one would need to sample closer to, or possibly within, the building footprint. It is also anticipated that higher numbers of piles will require a more thorough investigation since the soil properties must be known at a larger number of locations. As such, future studies should investigate the impact of alternate pile configurations.

While these results generally indicate that modest investigation is required in the majority of soils, it is important to remember this only applies to single layer, somewhat simplistic, soils. In reality, soils are comprised of multiple distinct layers, often with complex geology. Such soils would require additional investigation to delineate the layer boundaries, and so the recommendations given by this study should be taken as a minimum. It is also expected that the presence of layers will produce an increased need to locate boreholes in close proximity to the piles, since it is important to know the depths of layer boundaries at the pile locations. Therefore, site investigation performance could become more sensitive to borehole location than the present study suggests. As such, future analysis should incorporate complex geology with multiple soil layers.

In conclusion, this paper has demonstrated that engineers can indeed expect to save hundreds of thousands of dollars across a project by implementing a satisfactory investigation, in contrast often to clients' desires to minimize site investigations in order to save money. This is the case for the relatively simple soils and small structure analysed in this study. It is anticipated that savings could be in the order of millions of dollars for complex, layered soils and larger projects, due to the optimisation of foundation design, but more importantly the decreased risk, that a thorough investigation provides.

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