A framework for quantifying the reliability of geotechnical investigations

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ABSTRACT: It has long been recognized that, in civil engineering and building projects, the largest element of financial and technical risk often lies in the ground. Indeed, structural foundation failure, construction over-runs and delays can often be attributed to inadequate and/or inappropriate site investigations. Unfortunately, geotechnical engineers have, at their disposal, limited guidance when deciding upon a scope of a site investigation. Almost exclusively, the scope of such investigations is not governed by what is needed to characterize appropriately the subsurface conditions but, rather, how much the client is willing to spend on a geotechnical investigation. What is urgently needed is a series of guidelines that link the scope of a site investigation with the probability that the foundation will be under-designed – resulting in some form of failure, or be over-designed – resulting in more funds being spent on the foundation than would have otherwise been necessary had a more appropriate site investigation been carried out. This paper proposes a framework for developing such a series of guidelines, which is based on Monte Carlo simulation. The guidelines, when developed, will enable geotechnical engineers to quantify the effectiveness of one site investigation program with another, with respect to the probability of failure and over-design. As a result, the geotechnical engineer will be able to discuss, with the client, the ramifications and cost-effectiveness of several geotechnical investigation scenarios.

1 INTRODUCTION

Several studies have been published over the last 30 years or so that clearly demonstrate that, in civil engineering and building projects, the largest element of financial and technical risk usually lies in the ground (National Research Council 1984, Institution of Civil Engineers 1991, Littlejohn et al. 1994, Whyte 1995). Indeed, structural foundation failure can often be attributed to inadequate and/or inappropriate site investigations (Nordlund and Deere 1970, ASFE 1996). These international studies have demonstrated that most geotechnical investigations are inadequate because, in the vast majority of cases, too few resources are committed to the investigation and, as a result, its scope is inadequate. Expenditure on geotechnical investigations varies considerably, sometimes as low as between 0.025% and 0.3% of the total project cost. In addition, these studies have demonstrated that low levels of investigation result in large uncertainties, which often result in unforeseen additional construction and/or repair costs. Furthermore, inadequate geotechnical investigations usually force the geotechnical engineer to reduce the risk of failure by over-designing the foundation, thereby increasing the cost of the project. In most projects, this 'cost of over-design' is rarely, if ever, quantified.

Jaksa (2000) presented a case involving a $AUD24 million project where a $AUD10,000 geotechnical investigation in a highly variable soil profile resulted in a foundation failure involving $AUD170,000 cost over-runs and a delay of one month. In the US, an analysis of 89 underground projects concluded that, in more than 85% of cases, the level of geotechnical investigation was too low for adequate characterization of site conditions, leading to claims and cost overruns (National Research Council 1984). It is clear that over the last 30 years geotechnical investigation prices have been driven down, with the scope often being governed by minimum cost and time of completion (Institution of Civil Engineers 1991). As a consequence, the Institution of Civil Engineers concluded that: "*You pay for a site investigation whether you have one or not*."

However, the cost of a site investigation is only part of the story. It is the quality of the investigation that is paramount (Littlejohn et al. 1994). Furthermore, several studies have shown that ground engineering risk is one of the largest elements of technical and financial risk in civil engineering and building projects. This is due to the fact that the engineering properties of soil and rock often exhibit significant variability from one point to another, that is, *spatial variability*.

A good geotechnical investigation involves a program of borehole drilling, material sampling and laboratory and/or in situ testing. The number, depth and locations of these boreholes, samples and tests is defined qualitatively by the geometry of the structure, the loads imposed by the structure and the anticipated subsurface profile. Whilst some guidance is available for planning the scope of a geotechnical investigation (e.g. Lowe and Zaccheo 1991, Bowles 1996), in general, the extent is based on engineering judgement and, hence, is determined subjectively.

Recently, Parsons and Frost (2002) proposed a methodology by which a geotechnical engineer can assess the effectiveness (or *thoroughness*, as defined by the authors) of the current site investigation program. The methodology is based on geostatistics and geographical information systems.

At present, however, a geotechnical engineer is unable to assess quantitatively the benefits and disadvantages of one program when compared to another. For example, a typical site investigation for a multi-story building could consist of (i) 4 boreholes to 30 meters with triaxial samples and tests at 1.5 meter intervals, or (ii) one borehole to 30 m with 4 cone penetration tests (CPTs) to 30 m. Many other combinations, which include other laboratory and in situ tests, may also be appropriate for a particular site. Whilst it is relatively straightforward to determine and compare the relative costs of carrying out these investigations, there is currently no means available for determining the most appropriate geotechnical investigation to quantify (i) the risk of foundation failure, (ii) the cost of over-design, and (iii) construction delays and cost over-runs. This paper proposes a framework for improving the effectiveness of geotechnical investigations by quantifying and minimizing these three parameters.

2 PROPOSED FRAMEWORK

Elementary statistical theory suggests that, as the variability of a subsurface profile increases, so too should the extent of the geotechnical investigation that is needed to characterize appropriately its geotechnical properties, without reducing the overall reliability of the building. Furthermore, the scope of site investigations is dependent on the proposed structure (its footprint area, magnitude and distribution of loading, and its flexibility) and the proposed foundation – whether it be a pad, raft, or pile system.

In order to determine the adequacy of a geotechnical investigation, one must know, with minimal error, the properties of the site's entire subsurface profile. In reality, one can never completely know the geotechnical characteristics of a site, as to do so would mean that the entire soil and rock mass would need to be destructively tested; thereby eliminating the site. Accordingly, virtual or simulated soil profiles, based on the characteristics of real sites, are needed.

The Monte Carlo technique (Rubinstein 1981) has been used successfully for decades to carry out statistical and probabilistic analyses. One of the main benefits of the Monte Carlo technique is that it provides the probability of achieving some outcome. For example, Ferguson (1992) used the Monte Carlo technique, in conjunction with subsurface simulation, to determine the most appropriate borehole sampling pattern for detecting an anomaly beneath a site. An anomaly might be a void, an unknown buried structure or a contamination hotspot. Ferguson (1992) was able to demonstrate that a herringbone grid pattern consistently outperformed random or square-grid patterns. In addition, he developed a series of probability charts that enable a site investigation planner to determine the minimum number of boreholes needed to intercept an anomaly with a given probability of success, or level of confidence. Such a tool is invaluable in the assessment of contaminated sites and his work has since been adopted in a number of codes of practice (e.g. Standards Australia 1997, AS 4482.1).

The framework proposed in this paper is based on the Monte Carlo technique and is summarized in flowchart form in Figure 1. The overall philosophy of the framework consists of simulating an entire site. Because the site has been simulated and is exhaustive, it is known *completely*. A foundation is designed using this complete knowledge of the site. This is the most appropriate and optimal foundation for the site ($F_{\text{Opt.}}$).

As mentioned above, in reality one can never know a site completely. Geotechnical engineers only ever sample and test a very small fraction of the site. In order to simulate a geotechnical investigation, the complete site simulation is used and discrete samples are taken from it – the nature of the samples being dependent on the type of geotechnical test being simulated. This limited knowledge is then used, with numerical modeling, again to design a foundation for the site and structural constraints ($F_{\text{Inv.}}$). This foundation is greatly influenced by the scope of the investigation. A thorough and extensive investigation will imply that accurate knowledge of the site and, hence, $F_{\text{Inv.}}$ will closely approximate $F_{\text{Opt.}}$ However, as the scope of the investigation becomes more limited, $F_{\text{Inv.}}$ will diverge from $F_{\text{Opt.}}$ It will either be under-designed, which result in damage and subsequent rehabilita-

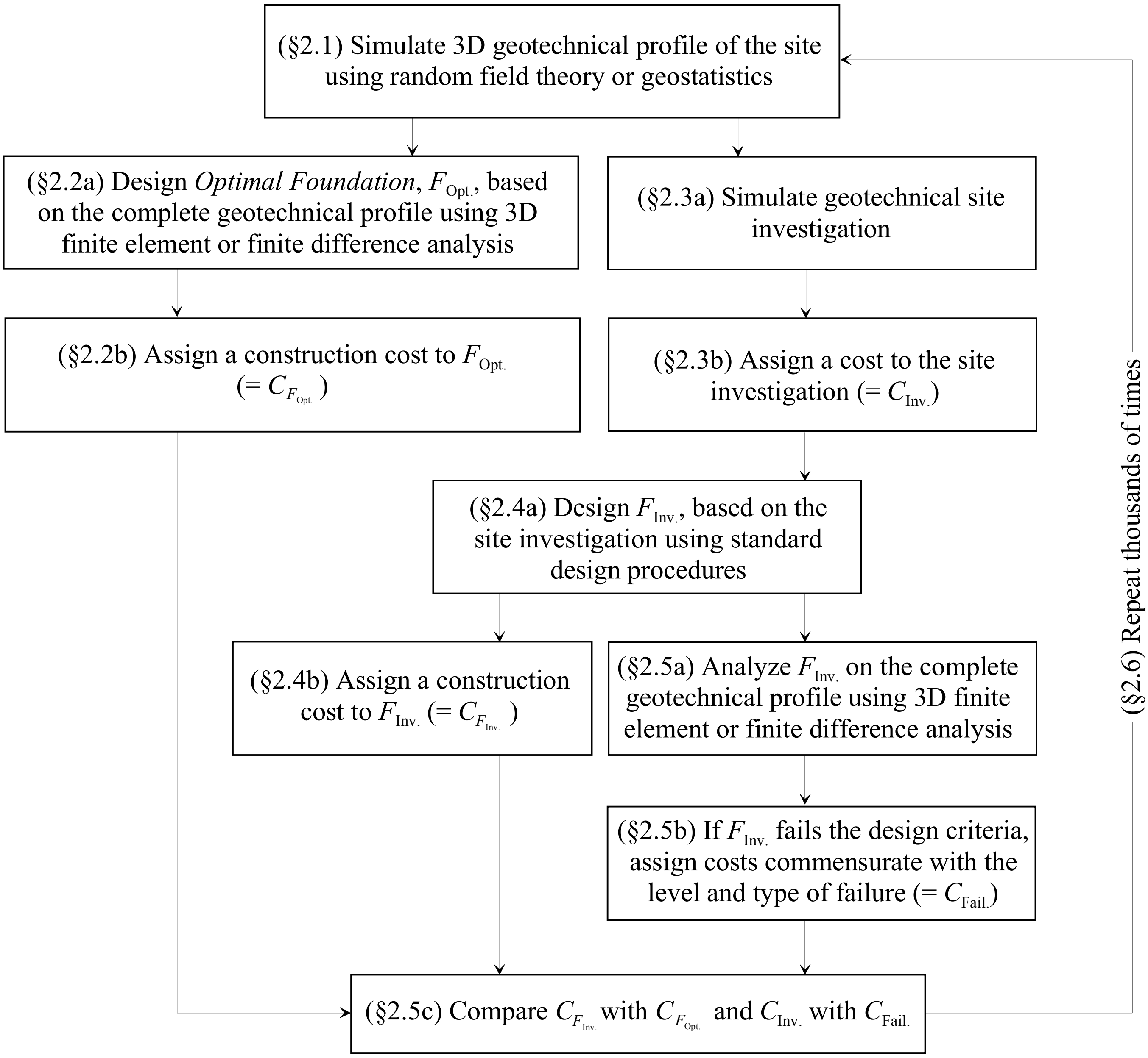

Figure 1. Framework expressed in flowchart form.

tion, or be over-designed, resulting in construction costs over and above those that would have been incurred had a more extensive investigation been performed. By assigning costs to each of these, performing Monte Carlo simulation, and comparing these costs, it is possible to quantify the reliability of a site investigation. By investigating several different site investigation programs, soil profiles and parameters as detailed below, it is possible to develop guidelines for planning and costing effective site investigations and relating these to their probabilities of failure and over-design.

The individual steps involved in the framework, and shown in Figure 1, are described more fully in the sub-sections that follow.

2.1 *Simulation of geotechnical profile*

It has been observed by many researchers (e.g. Agterberg 1970, Vanmarcke 1977a; Fenton 1990; Jaksa et al. 1993, Jaksa 1995; Fenton and Vanmarcke 1998) that the properties of soils and rock are randomly distributed in a spatial sense, but exhibit spatial continuity; that is, values at adjacent locations are more correlated than those separated by larger distances. *Random field theory* (Vanmarcke 1983) and *geostatistics* (Journel and Huijbregts 1978) provide mathematical frameworks whereby spatially correlated properties can be conditionally simulated. The parameters which quantify the extent of spatial variability are: (1) the mean, μ; (2) the standard deviation, σ; and (3) the scale of fluctuation, δ_v, which accounts for the distance within which the soil property, v, shows relatively strong correlation, or persistence, from point-to-point (Vanmarcke 1977a, 1983). A soil with highly random spatial variation would exhibit a small value of δ_v (in the order of millimeters), whereas a strongly correlated soil would exhibit a large δ_v, that is, of the order of several meters.

The first two parameters describing spatial variability (μ and σ) are available from numerous publications (e.g. Lumb 1966, Li and White 1987, Jaksa 1995, Jaksa et al. 1996, 1999). Furthermore, much work has already been done in quantifying δ_v for a range of different soil types (e.g. Vanmarcke 1977b, Fenton and Vanmarcke 1991, Wickremesinghe and Campanella 1993, Jaksa 1995, Jaksa et al. 1993, 1997, 1999, Cafaro et al. 1999). It is proposed that unconditional simulations be performed, using published values of μ, σ and δ_v to generate a variety of virtual soil profiles – from single-layer to multiple-layers; random to correlated; horizontal to sloping and undulating layer surfaces; and combinations thereof. By specifying different values of δ_v in the horizontal and vertical directions, it is possible to simulate soil profiles that exhibit spatial behavior similar to natural deposits.

Each simulation, for example, consists of a 3D grid of points, with each point being assigned a series of geotechnical design parameters depending on the constitutive soil model adopted. For example, for an elasto-plastic model, the unit weight, γ, internal angle of friction, ϕ, dilation angle, ψ, cohesion, c, elastic modulus, E, and Poisson's ratio, ν, are required. As an example, a site for a (10 m × 10 m) multi-story building might be 50 m × 50 m in plan, by 30 m in depth. If the data are simulated at horizontal and vertical intervals of 0.5 m, the entire grid will consist of 600,000 points; each point being assigned specific values of the geotechnical parameters. The simulation is relatively straight-forward to perform, as simulation models involving a number of different techniques, including the *turning bands method*, *local area subdivision* (LAS) (Fenton and Vanmarcke 1990, Fenton 1994), *lower-upper decomposition*, *sequential Gaussian elimination*, and *sequential indicator simulation*, are available (Deutsch and Journel 1992).

It should be noted that it is standard practice in finite element modeling for the mesh boundaries to be set at least five times the loaded area, in order to ensure that boundary effects do not influence the results (Desai and Abel, 1972). However, the element size further away from the loaded area is usually larger than elements near the loaded area. In addition, techniques such as local area subdivision (LAS) simplify the task of generating finite elements from the random field (Paice et al. 1996). Furthermore, by using LAS, one can economize the number of elements, in order to develop a parsimonious model, whilst maintaining the inherent correlation structure of the soil profile.

2.2 *Design of optimal foundation based on simulated geotechnical profile*

With the relatively complete subsurface profile having been simulated, the geotechnical properties of the entire site are known in detail. It is then possible to design the 'optimal' foundation (pad, raft or pile), $F_{\text{Opt.}}$, for this site to meet a set of design criteria. In order to do so, the properties of the site will then be used as input for numerical analysis. A 3D finite element or finite difference model can be used for this purpose. The numerical analyses will yield a set of foundation dimensions that satisfy the ultimate and serviceability criteria imposed by the design. Using appropriate unit rates (e.g. Rawlinsons 2000), a construction cost will be assigned to this optimal foundation. This *Optimal Cost*, $C_{F_{\text{Opt.}}}$, will be used later for comparison purposes.

2.3 *Simulation of geotechnical investigation*

Since a geotechnical engineer never knows the subsurface properties of a site with complete certainty, some degree of error is always involved because of statistical uncertainty. It is proposed to simulate the design process adopted by a geotechnical engineer by performing a virtual geotechnical investigation. A foundation is then designed based on the results of the investigation and interpretation of the data. It is essential for the successful adoption of the proposed framework by the geotechnical engineering profession that the investigation and the design process mimic closely that used in current practice, particularly the range of quality and quantity of testing.

The simulated geotechnical investigation is best explained by means of an example. The investigation for a multi-story building on a medium-sized site, might involve say 4 boreholes to a depth of 30 meters, with either: samples taken at 1.5 m vertical intervals for subsequent triaxial testing in the laboratory, if in a clay layer; or in situ standard penetration tests (SPTs) at the same spacing, if in a sand or gravel layer. The boreholes may be located in the corners of the building, or in some other arrangement. To simulate such an investigation, four pseudo-boreholes would be taken along four separate vertical grid lines of the 50 × 50 × 30 m representation of the site. The building might occupy an area of 30 × 30 m of this site, the location of which would be fixed in relation to the site. Each Monte Carlo iteration would involve a new soil simulation and a subsequent geotechnical investigation. Where a triaxial test or SPT is to be performed at a specific depth, the value at the relevant location within the 50 × 50 × 30 m grid will be assigned as the test result. A CPT can be simulated by adopting an entire vertical transect, as would be the case in this type of continuous in situ test.

However, prior to assigning the value at the grid node to the test result, measurement error is added, as all measurement incorporates some degree of error. For example, laboratory testing involves sample disturbance and measurement errors, with the results being test specific. In situ testing, whilst minimizing sample disturbance, involves some degree of model uncertainty, which arises from the difficulties in modeling the complex behavior of the test device within the soil mass (Wroth 1984). In order to include sampling, measurement and model errors, published values of correlations among tests, and coefficients of variation are applied to the simulated and sampled values (Lee et al. 1983, Orchant et al. 1988, Jaksa et al. 1997).

Appropriate unit rates are used to determine the cost of the site investigation, $C_{\mathrm{Inv.}}$, which will be used in later comparisons.

2.4 *Design of foundation based on simulated investigation*

To simulate the design of a foundation, $F_{\mathrm{Inv.}}$, based on the results of a site investigation, it is first necessary to determine the parameters that are used in the design models. Sometimes these are the measured values, but in many situations, geotechnical engineers apply 'engineering judgement' to specify the geotechnical properties to be used in design. For example, the geotechnical engineer might adopt the mean of the measured values, the lowest value, or the tenth-percentile, among others. It is proposed to incorporate this 'engineering judgement' in the framework. Once the design parameters have been determined, they are input into the various foundation design models used in practice to satisfy the ultimate and serviceability criteria for the specified design loads. These models will yield a set of foundation dimensions and, when combined with appropriate unit rates, a construction cost will be assigned to this foundation. This cost, $C_{F_{\mathrm{Inv.}}}$, will be compared later with other costs.

2.5 *Analysis of $F_{\mathrm{Inv.}}$ on simulated geotechnical profile*

To ascertain whether the foundation designed in the previous step is appropriate, over-conservative or under-designed, it is analyzed using 3D finite element or finite difference analysis. This foundation, $F_{\mathrm{Inv.}}$, which was designed on the basis of the site investigation, is placed on the true and complete subsurface profile derived in §2.1. If the foundation fails to satisfy the originally specified ultimate and serviceability criteria, penalty costs are apportioned which are consistent with the consequences of failure, $C_{\mathrm{Fail.}}$. This implies that the scope of the site investigation was inadequate to characterize appropriately the site. $C_{\mathrm{Fail.}}$ is used to determine the consequences of failure as a result of inadequate site investigation, which are quantified by the investigation cost, $C_{\mathrm{Inv.}}$. If, on the other hand, $F_{\mathrm{Inv.}}$ satisfies the design criteria, $C_{F_{\mathrm{Inv.}}}$ will be compared with $C_{F_{\mathrm{Opt.}}}$ to determine the degree of over-conservatism inherent in the design. If $C_{F_{\mathrm{Inv.}}}$ is in reasonably close proximity to $C_{F_{\mathrm{Opt.}}}$, the site investigation will have been a success with respect to achieving optimal design.

2.6 *Repetition of process by performing thousands of iterations*

Consistent with the Monte Carlo technique, the locations of boreholes and samples will be varied and Steps 2.3 to 2.5 are repeated thousands of times in order to generate a probabilistic solution of the site, geotechnical investigation and design process. The minimum number of iterations required to ensure that the solution is statistically valid will need to be determined in each case.

2.7 *Parameters influencing the framework*

Many factors influence the effectiveness of a site investigation and it is proposed that the framework examine these and incorporate them in the subsequent guidelines. The factors include:

- Geotechnical characteristics of the site:
  - *Number of layers* – whether the subsurface profile consists of a single or multiple layers;
  - *Stratigraphy of layers* – whether the layers are horizontal and/or inclined, and whether lenses and/or other structural features are present in the profile;
  - *Variability of geotechnical properties* – whether the layers consist of properties that are spatially random or continuous; the degree of continuity being expressed in terms of the scale of fluctuation, δ_v.
- Response to external loads:
  - *Structure* – the magnitude and distribution of the structural loads, and the flexibility of the structure;
  - *Foundation type* – pad, raft or pile;
- Characteristics of the investigation:
  - *Scope of the geotechnical investigation* – the number, pattern and depth of boreholes, the frequency of sampling and laboratory testing, and the number and type of in situ tests;
  - *Measurement errors* – the errors inherent in the process of obtaining a measurement;
  - *Phases of the geotechnical investigation* – whether the investigation is carried out in a single stage or, as several authors suggest (Lowe and Zaccheo 1991, Bowles 1996, Jaksa 2000), in two stages; that is, a preliminary investigation followed by more detailed one; and
- Characteristics of the Monte Carlo simulation:

- *Number of iterations* – The number of iterations needed, in the Monte Carlo analyses, to achieve a stable solution.

3 CONCLUSIONS

This paper has proposed a framework for developing a series of guidelines that will allow site investigation planners to compare the effectiveness of various geotechnical investigation programs. The framework enables the probability of failure and over-design to be quantified for each geotechnical investigation program with respect to spatial variability, layering, the type of structure and foundation, the scope of the investigation, measurement errors and phasing of investigations. Research is currently underway to implement the framework and develop guidelines that can be used in routine geotechnical practice.

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