Observations on the Observational Method

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ABSTRACT
Major contributions to the development of the observational design method in geotechnical engineering are reviewed. These contributions are discussed in regard of the duality of uncertainties related to knowledge based (epistemic) uncertainties and those related to the natural ground variability (aleatoric). Some common concerns related to the proper use of the observational method are discussed. It is shown that the use of the observational method is feasible only for cases where it can be anticipated that epistemic uncertainties might decrease as more observational data become available during construction. Among these, three cases of the possible development of the upper and lower bounds, and the most probable anticipated value of the ground parameter governing design, are illustrated and discussed. These cases made it possible to draw some conclusions on the suitability of the use of the observational design method regarding the serviceability and the ultimate (failure) limit states in view of ductile and brittle material behaviour.

Keywords: observational method, uncertainty, design, safety, limit states

1 INTRODUCTION

Construction of a large civil structure is a complex engineering endeavour requiring careful and extensive technical and financial planning involving rational optimisation of various possible solutions to frequently conflicting objectives, requirements and environmental conditions. Not always well known and understood natural ground conditions are often the cause of large cost and time overruns, or fortunately less often, construction failures. Therefore, dealing with geotechnical risk, created by construction in natural ground, attracts great interest among geotechnical engineers.

In contrast with structural or mechanical engineers, geotechnical engineers deal with subsurface materials that nature provides, and they have limited knowledge about their conditions and resistances despite time consuming and costly field and laboratory investigations they undertake. This limited knowledge leads to uncertainties in planned construction activities. To deal with these uncertainties, the geotechnical engineer must establish bounds on possible ground behaviour for which he can design a sufficiently safe and economical structure.

The process of decisions by which the geometry and type of man made structures and construction processes are determined is called design. There are basically two design approaches found in present day geotechnical practice. The first and prevailing one is the conventional approach where the design is more or less finalized prior to commencement of the construction process. Due to uncertainties in natural ground conditions, such a design is based on conservative (some would argue most pessimistic or most unfavourable) interpretation of available ground data. In this conventional design approach monitoring and observations during the construction process may be provided but only as a means to verify the assumptions about ground conditions made in the design and to check that the structural behaviour is within the acceptable limits predicted by design calculations. If unexpected ground conditions are found, or if the actual structural behaviour falls outside acceptable limits, an emergency situation occurs, which requires actions usually not provided for in the design.

The second design approach is the use of the observational method. It was developed from the need to avoid highly conservative assumptions about ground properties in geotechnical design when faced with unavoidable uncertainties of natural ground conditions. It was used more intuitively than formally by many engineers in the past but was recognized as a design approach by Terzaghi (Terzaghi and Peck 1967) as the observational procedure. The formal ingredients and name of this method were laid down by Peck in his Rankine lecture (Peck 1969). In this approach the construction process may start with a design based on more optimistic assessment of natural ground conditions than in the conventional approach. At the same time, carefully planned measures for detecting possible differences between assumed and actual ground conditions are provided in the design, as well as carefully planned provisions for actions to be carried out in the event that significant differences do occur. By this approach the design process is extended into the construction phase. It takes advantage of observations and data gathered during construction to adapt the design to actual ground conditions in an orderly and planned way. It may be characterized as a learn-as-you-go approach and it was successfully applied in practice by many designers of tunnels, excavations, foundations, ground treatment works, embankments, waste disposal structures etc. (for an extensive review see Nicholson et al. 1999 and Allagnat 2005).

The success of Terzaghi's learn-as-you-go approach to the observational method, and particularly its formalization by Peck drew much attention by the geotechnical community. Many case histories adopting this method and several important contributions to its improvement were published. However, it also raised questions about its limitations and proper use. A whole variety of opinions emerged, from the one that the method is an element of a quality control system, to the one that it allows for less intensive site investigations, up to the view that it stimulates the introduction of innovations and that it is one of the most powerful weapons in the civil engineering arsenal. According to Powderham (1998), starting with a more optimistic initial design may tend to create concerns about the safety, which could inappropriately be associated with uncomfortably low safety margins. This circumstance has discouraged a wider use of this method.

Concerns about the limitations and the proper use of the observational method deserve further clarification. This is attempted in the paper by invoking the nature of uncertainties and their related probabilities, as well as by recognizing the role of risk management.

Uncertainties may invoke hazards, i.e. events with the potential for consequences. Uncertainties may also be associated with probabilities. They enable the use of powerful analytical tools provided by the theory of probability, statistics and the theory of reliability. The combination of the quantified measure of the consequence of an event, with the probability of its occurrence, is known as risk. The combination is often replaced by the product, when risk becomes the statistical expectation of the consequence of an event, or expectation of the cost incurred by the consequence, when the later is expressed by monetary means.

Risks may be studied by the risk analysis and managed by the risk management. The risk management, widely used for some time by the financial community and more recently by some other engineering fields, is now gaining more and more acceptance by geotechnical engineers (see e.g. Clayton 2001). The risk in engineering may be limited to acceptable or agreed levels by the appropriate design measures, so that the risk management enters the engineering design. Recognizing, evaluating and managing risk are the core of the observational method.

It is worth recognizing that the observational method assumes that the changes of the design are possible, that it deals with uncertainties in the ground conditions and that its implementation incurs cost in addition to the cost of the conventional design. When design changes are not possible or not feasible, the method is not applicable. Where there are no uncertainties in ground conditions, or if they are negligible, if such cases exist at all, the use of this method is uneconomical.

2 DUALITY OF UNCERTAINTIES

The probability is usually used as a standard way to quantify uncertainty. However, it is important to recognize the dual nature of uncertainty, as emphasized and discussed in details by Beacher and Christian (2003) and Christian (2004).

Two types of uncertainties may be recognized: the aleatoric[1] uncertainty, or uncertainty based on natural variability of a property, and epistemic[2] uncertainty, or uncertainty originating from the lack of knowledge, or from the insufficient knowledge of a property, or from the consequence

[1] After the Latin word aleator - gambler
[2] After the Greek word episteme - knowledge

of these. The two types of uncertainties play an important role also in geotechnical engineering. The aleatoric uncertainty mostly deals with the space or time variability of a certain ground property in a more or less homogeneous ground layer, and is thus associated with randomness The epistemic uncertainty deals with the lack of knowledge in site characterization, the inadequacy of the mathematical model used in design, or the precision to which model parameters can be estimated. Thus, some refer to the first uncertainty as objective, because it rests in the field, and to the second as subjective, because it rests in our minds.

While the epistemic or knowledge based uncertainty may be reduced by a more extensive ground investigation program, such a program would not do much for the aleatoric or natural based uncertainty. On the other hand, investigating the natural variability of a property, for example the shear strength, in an assumed homogeneous soil layer may not be of much help if we fail to recognize, for instance, the existence of a thin weak soil layer, which might govern the failure mode of the geotechnical structure.

Both types of uncertainties may be associated with probabilities. While the aleatoric probability may be evaluated from the frequencies of field or laboratory investigation results, the epistemic probability is usually evaluated by subjective judgments based on experience.

Since both types of uncertainties are quantified by probabilities, it is important to know the type of uncertainty the probability represents if a proper interpretation of the analysis is sought. Furthermore, it should also be emphasized that the division or even the distinction between the two types of uncertainties may be somewhat blurred and may depend on the conceptual model which represents the natural ground conditions.

In this paper, the attention is drawn to the dual character of uncertainties related to natural ground conditions. Recognizing this duality may have an important influence on clarifying some ambiguities about the use of the observational method. The major contributions to the development of this method are, thus, revisited in the following paragraphs and discussed in the light of this duality.

3 MAJOR CONTRIBUTIONS TO THE DEVELOPMENT OF THE OBSERVATIONAL METHOD

3.1 *Peck's ingredients of the observational method*

As already stated, Peck (1969) coined the name and formalized the observational method by identifying its following eight ingredients: (*a*) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail; (*b*) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions; (*c*) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions; (*d*) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis; (*e*) Calculation of the values of same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions; (*f*) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis; (*g*) Measurement of quantities to be observed and evaluated on actual conditions; and (*h*) Modification of design to suit actual conditions.

At the same time, Peck discussed the advantages and limitations of the observational method by presenting instructive case histories. Their close inspection reveals that the uncertainties he dealt with were mostly knowledge based or epistemic. He also stressed that the full value of the method cannot be realized unless the engineer is thoroughly familiar with his problem and has the authority to act quickly upon his decisions and conclusions.

Out of the eight ingredients of the observational method, the establishment of the initial design based on the most probable ground conditions drew most concerns. These concerns arise from the circumstance that when unfavourable conditions are encountered during construction, and they have a rather high probability of occurrence of 0.5 (because the initial design is based on most probable ground conditions, which have an occurrence probability of 0.5), contingency measures have to be introduced to rectify the design. This leads to cost and time overruns, while in the meantime the safety margin may decrease and the risk increase. This situation would certainly not be favoured by many of the parties involved in the project.

3.2 *Powderham on initial design and progressive modification*

Powderham (1994, 1998, 2002) recognized that the safety issues are essential and that a high degree of certainty in project performance and schedule is generally required in modern construction practice, which is led by teams rather than individuals. He further developed the observational method by advocating a more conservative initial design (with a probability of being adequate larger than 0.5), which is then progressively modified in small and well controllable steps as more data and their trends become available by observations, most probably in the direction of saving costs rather than introducing contingency measures. This situation would certainly be more attractive to most parties involved. By this approach the level of risk may well be maintained or even decreased as construction proceeds.

In summary, Powderham's approach is to (*a*) commence construction with a design providing an acceptable level of risk to all parties, (*b*) maintain or decrease this level of risk, (*c*) progress construction in clearly defined phases, and (*d*) implement appropriate changes progressively and demonstrate acceptable performance trough observational feedback.

Although being more conservative than that proposed by Peck, the initial design proposed by Powderham may still be less conservative than the one in the conventional design approach, or, in terms of probabilities, the initial design may be based on more probable ground conditions than those for the conventional design approach. Powderham (1994) used the term "more probable" in the context of the observational method to denote conditions that are moderately conservative, without assigning them any specific probability value. As stressed by Powderham and Nicholson (1996), it often may be appropriate to start with a basically conventional design, and then to proceed applying the principles of the observational method through progressive modification.

Case histories presented by Powderham in his papers are very illustrative. He described the use of very elaborate decision making trees, with mechanisms for triggering design changes, resembling a traffic light system. He stresses the great importance of a very strong connection between design and construction teams including adequate book keeping, good communication among parties involved, and adequate contractual provisions between the client, the designer (or consultant) and the contractor. The ground and construction conditions related uncertainties he addressed were mostly knowledge based or epistemic, as indicated by the title of one of his papers (Powderham 2002).

3.3 *Muir Wood on tunnels and initial design*

In his critical paper on the New Austrian Tunnelling Method, Muir Wood (1987) proposed a simplified version of the observational method for use in tunnelling: (*a*) Devise a conceptual model, (*b*) Predict expected features for observations, (*c*) Observe and compare against (*b*), (*d*) Are differences between (*b*) and (*c*) explained by values of parameters, inadequacy of (*a*) or inappropriateness of (*a*)?, (*e*) Devise a revised conceptual model, (*f*) Repeat (*b*), (*c*), (*d*) and (*f*) as appropriate.

Muir Wood stressed that the adoption of the method in tunnelling must presuppose the ability to supplement the tunnel support, while the observational process is in progress, without the risk of collapse. It also must presuppose a general degree of confidence in the approach, which is expected to be based on comparable experience and on the analysis of the particular circumstance. It can again be argued that the above rules deal primarily with the knowledge based or epistemic uncertainty rather than with a simple statistical variability of natural ground conditions, or the aleatoric uncertainty.

In his book on tunnelling, Muir Wood (2000), warns about possible problems if the "most probable conditions", set up by Peck, are adopted in choosing the basis for the initial tunnel design. By performing a risk analysis under very simplified assumptions, he showed that the minimal expected construction costs for the initial design and the ground conditions to be encountered during excavation, are obtained with the minimum probability of being safe p, given by

$$p = 1 - \frac{1}{2k}, \qquad (1)$$

where k is the ratio between the unit cost of supplementary support, to be added when worse ground conditions are encountered, and the unit

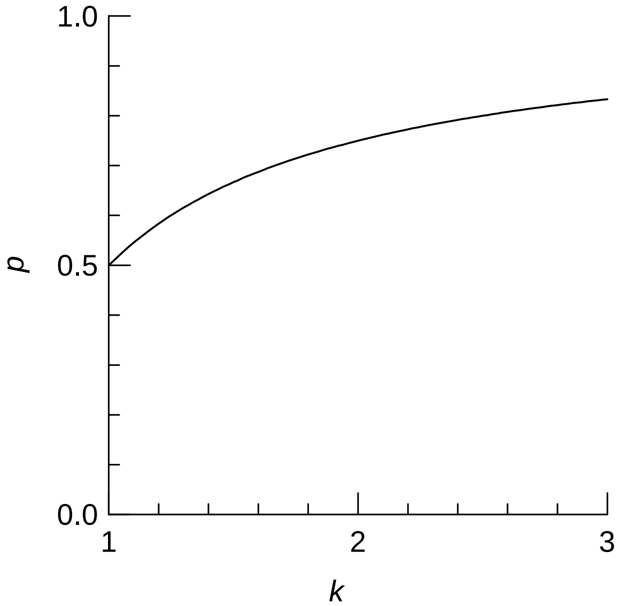

Figure 1 Required minimum probability (p), that an initial tunnel design is safe for ground conditions encountered during construction, as a function of the relative unit cost (k), if minimum construction costs are to be achieved (Equation 1; after Muir Wood 2000).

cost of the same support if deployed as planned by the initial design. Because the unit cost of instalments of supports, provided for in the initial design, and being part of the construction routine, are lower than the unit cost for the same work, when performed out of sequence as a contingency action, k in equation (1) will always be larger than one and, therefore, p will always be larger than 0.5, the value of probability for the most probable ground conditions. Equation (1) is graphically depicted in Figure 1. The probability $p = 0.5$, for the relative unit cost $k = 1$, relates to the "most probable" ground conditions quoted by Peck in one of his eight ingredients of the observational method.

The preceding analysis is in principle equally applicable to geotechnical design of all geotechnical structures, not only to tunnels. It shows that, apart from concerns for safety, there exist economical needs for a more conservative initial design than the one based on the most probable ground conditions. The problem with this, as well as with other similar, but less simplified risk analyses, is to assign probabilities to particular ground conditions to be encountered during construction with any degree of precision, in the case when the related uncertainties are knowledge based or epistemic. On the other hand, this analysis shows that the Powderham proposal for a more conservative initial design is substantiated by the risk analysis under the requirement of minimizing construction costs.

3.4 *Eurocode 7 requirements*

Eurocode 7 (e.g. BSI 2004), the new European geotechnical design code, addresses the observational method only briefly. But never the less its description is interesting and therefore cited here (Clause 2.7):

(1) When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as "the observational method", in which the design is reviewed during construction.

(2)P The following requirements shall be met before construction is started:
- acceptable limits of behaviour shall be established;
- the range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits;
- a plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully;
- the response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system;
- a plan of contingency actions shall be devised, which may be adapted if the monitoring reveals behaviour outside acceptable limits.

(3)P During construction, the monitoring shall be carried out as planned.

(4)P The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put into operation if the limits of behaviour are exceeded.

(5)P Monitoring equipment shall either be replaced or extended if it fails to supply reliable data of appropriate type or in sufficient quantity.

The first paragraph of Eurocode's 7 clause 2.7 explicitly states that the observational method is a viable alternative to conventional design when the geotechnical engineer is confronted with knowledge based uncertainties of ground behaviour. However, as stated by Frank et al. (2004), it leaves open the manner in which safety is introduced in the supporting calculations. Same authors advise not to use the method when collapse can occur without prior warning, as may be the case for brittle ground or ground-structure systems.

4 DISSCUSSION

As stated before, apart from the great success in geotechnical practice, the application of the observational method also raised concerns. Some of the more common concerns are as follows:

– Starting construction with the design based on the most probable ground conditions may in due course endanger the safety;
– What are the safety margins to be used in the design based on the observational method, with reference to the serviceability and ultimate limit states, as well as with temporary works?
– Brittle ground or structural behaviour may exclude the use of the observational method;
– Is the observational method a substitute for thorough ground investigation works?
– Legal matters, contractual and quality assurance restraints might hinder the application of this method.

In an attempt to resolve these concerns, Figures 2, 3 and 4 present three different simplified hypothetical cases, A, B and C, which show the change of anticipated values of a ground parameter, which governs the design, as the construction works proceed, and new observational data become available. Since the value of the parameter[3] (or its effect on the structure) is uncertain, it's anticipated upper and lower bounds are followed from the start to the end of the construction process. Their values at any moment are anticipated by using all available data and information up to that moment, including ground investigation and observations, and by using the chosen conceptual model, intuitive or statistical, which defines the upper, the lower and the most probable parameter values.

The range between the upper and the lower bounds represents the uncertainty; it covers the knowledge based component as well as the component related to the natural ground variability. It is assumed that the uncertainty decreases, due to the decrease of its knowledge based component, as the construction proceeds, and new observational data became available. The most probable value of the parameter falls somewhere between its upper and its lower bound.

The three cases depicted in Figures 2, 3 and 4 refer to three possible situations, depending on the gathered and interpreted information from observational data: Case A, where the lower bound and

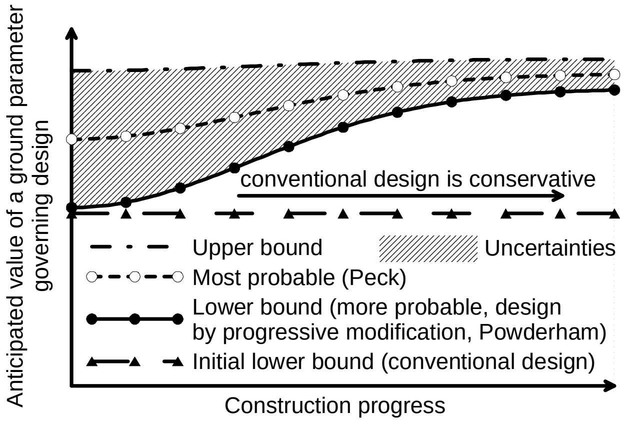

Figure 2 Case A: Both, the most probable and the lower bound anticipated ground parameter values increase with the construction progress

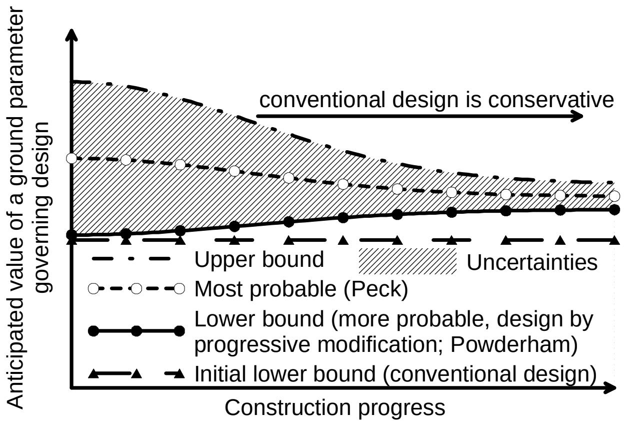

Figure 3 Case B: The lower bound of the anticipated ground parameter values increase, while the anticipated most probable values decrease with the construction progress

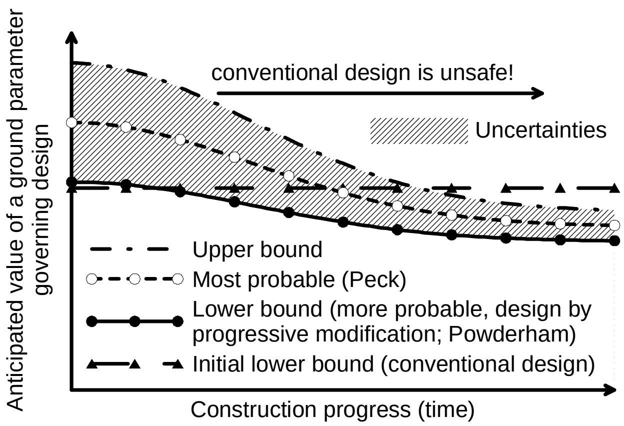

Figure 4 Case C: Both, the most probable and the lower bound anticipated ground parameter value decrease with the construction progress

[3] In this discussion the value of a governing parameter stays for its design value rather than for a value derived directly from specific laboratory or field tests.

the most probable values increase; case B, where the lower bound increases, but the most probable value decreases; and case C, where both values decrease. Which of the cases will occur is not known prior to the start of construction works.

By Peck's approach to the observational method, the design follows the most probable value, whereas by Powderham's approach, the design follows the lower bound (or a value close to the lower bound). The conventional design does not rely on observational data and remains unchanged during construction. Therefore, it follows the initial value of the anticipated lower bound of the governing ground parameter.

The conventional design is safe, but uneconomical, for cases A and B. Case C is an engineer's nightmare since it may prove to be unsafe when the safety margin is small. All three cases may prove to be unsafe for Peck's approach when the safety margin is small, whereas Powderham's approach is always safe for cases A and B. It is also safe for case C, provided there is sufficient time to install the contingency measures. Therefore, Powderham's approach is better suited with respect to safety. Peck's approach would require a larger safety margin than Powderham's.

Regarding the safety margin, which should be used in the design based on Powderham's approach to the observational method, it may be argued that no stage in the construction process can be singled out. The safety margin should only take account of the current anticipated lower bound of the governing ground parameter, and the type of works, temporary or permanent, as in the case of the conventional design, where the precise value of the governing ground parameter is known in advance.

Regarding the differences between serviceability and ultimate (or failure) limit states, the answer to the question of suitability of the observational method lays in the types of data that can be observed and measured in situ. While we can measure displacements, rotations, strains, stresses and pore water pressures, and therefore control the serviceability limit states, the strength and strength related parameters (bearing capacity, pull out capacity etc.) can not be observed without induced failures. Therefore, it would generally be difficult, if not impossible, to modify an initially anticipated lower bound strength parameter (obtained from prior ground investigation works) as more observations became available during construction. If this is the case with a strength related ground parameter governing design, the observational method would be reduced to the conventional design. This is particularly the case for the brittle material behaviour. Following these arguments it can be concluded that the observational method is best suited to control the serviceability limit states when they govern design. It is applicable, but less suited, to control the ultimate (failure) limit states for ductile materials (where large deformations or the creep type behaviour would indicate the approach to failure), but not so for brittle materials (which might induce progressive failure and leave no time to apply contingency measures), because again, when properly used for brittle materials, it would be reduced to the conventional design approach. The latter case would be represented by the lower bound curves in Figures 2, 3 and 4, having a sudden vertical decrease.

The design in geotechnical engineering heavily relies on the proper and thorough ground investigation works. The observational method is no exception, because it induces large additional costs in comparison to the conventional design. A thorough analysis of cost, reliability and induced risks would theoretically give a balanced proportion between efforts to be undertaken for ground investigation works, and efforts for the implementation of the observational method, but its reliability seems dubious at present.

Legal matters, contractual and quality assurance constraints might indeed hinder the use of the observational method. However, if proper attention is given to those, and mutual interest exists between parties involved, there are available solutions, as described by Muir Wood (1990) and Powderham (1996).

5 CONCLUSIONS

The major contributions to the development of the observational design method in geotechnical engineering were reviewed and discussed. Dividing uncertainties into knowledge based (epistemic) and those related to the natural ground variability (aleatoric), it is possible to anticipate cases for which epistemic uncertainties might decrease as more observational data become available in due construction course. These are the cases suitable for the application of the observational method. Three such cases of the development of the upper and the lower bounds, and the most probable anticipated value of the ground parameter governing design, were illustrated. The analysis of these cases helped to clarify some common concerns related to the proper use of the observational method. The main conclusions from this analysis are:

– Peck's approach to the observational method, with the initial design based on the most probable ground conditions, is less safe (and would therefore require a greater safety margin) than Powderham's approach, by which the design progressively follows the anticipated lower bound values of the governing ground parameter, as more observational data become available; Peck's approach may also require more use of contingency measures;
– With Powderham's approach the required minimum safety margin may follow the current lower bound of the anticipated governing ground parameter;
– Powderham's approach would require the introduction of contingency measures only for cases where the conventional design approach would prove to be unsafe;

The observational method is best suited for designs that are governed by the serviceability limit states. It is applicable, but less suited, for designs governed by the ultimate (failure) limit states with ductile behaviour, and it is unsuitable for the ultimate limit states accompanied by brittle behaviour, when it is reduced to the conventional design method.

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