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A technical note on the nature of uncertainty in geotechnical engineering

De la nature des incertitudes en géotechnique

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ABSTRACT: This paper presents a commentary on the nature of uncertainty in geotechnical engineering and the reliance in current practice on engineering judgement and belief in the robustness of the systems employed. Uncertainty in geotechnical engineering stems from variability in materials, spatial uncertainty in the ground, limits on methods of investigation and testing and limits of understanding of how actions are applied and how structures respond. Effective ground engineering requires uncertainties and risks to be recognized early in the project and addressed within a holistic design process with a full and clear reporting structure. Codes and standards are essential to controlling uncertainty. Quantification of design reliability may not be possible other than subjectively unless a quantitative process involving a probabilistic model (structured Bayesian framework) is employed (Engineering Judgement). Independent technical assessment is helpful in ensuring system compatibility and achieving successful project outcomes.

RÉSUMÉ: Cet article traite de la nature des incertitudes en géotechnique, et de la dépendance des pratiques actuelles au jugement d'ingénieur, associé à la confiance dans la robustesse des règles appliquées. Les incertitudes en géotechnique découlent de la variabilité des matériaux, de l'hétérogénéité spatiale du sol, des limites des méthodes de reconnaissances, et des limites de notre compréhension des actions du sol et de la réponse des structures. Une bonne intégration des problématiques géotechniques dans un projet nécessite d'avoir identifié les incertitudes et les risques suffisamment en amont, et de les traiter à l'aide d'une démarche holistique, associée à une procédure de suivi clairement définie. Codes et normes sont essentiels dans la maitrise de ces incertitudes. Quantifier la fiabilité d'une conception ne peut être que subjectif, hormis lorsque le dimensionnement intègre un modèle probabiliste (de type bayésien) dans le cadre d'une expertise spécifique. Une revue technique indépendante peut également aider à assurer l'adéquation des méthodes de dimensionnement aux enjeux et aux risques, et ainsi fiabiliser l'aboutissement du projet.

KEYWORDS: Uncertainty. Holistic design. Management of risk.

1 INTRODUCTION.

Uncertainty in geotechnical engineering is quite different from uncertainty in structural engineering. In structural engineering the materials used are manufactured and installed in a specified way and rejected if they fail to meet acceptance criteria, and the structural configuration is under the control of the designer.

However, in geotechnical engineering, the engineer is dealing with natural materials (soil and rock) where the properties and the spatial distribution are often difficult to determine and indeed can never be known completely. Also, geotechnical materials generally exhibit complex mechanical behavior (constitutive relationships) and may not follow simplified models of elasticity or plasticity. Complex geometries often occur and there is the added complication of water being present in the system, or partial saturation.

Geotechnical Codes of Practice seek to address these uncertainties by adopting design principles formulated to suit specific situations, and applying various forms of safety or performance factors to both actions and materials, generally following deterministic models. However, many situations in engineering practice are different from idealized conditions and require adaptation of methodologies and development of project specific models. This requires geotechnical expertise involving engineering judgement, and which should be applied within a systematic framework which can be subjected to technical audit and validation throughout the project stages. Thus, geotechnical design needs to be respectful of uncertainty and to incorporate suitable conservatisms.

Geotechnical engineering involves a potentially higher level of uncertainty than in structural engineering and relies heavily on this engineering judgement. It may not be possible to quantify the risk associated with the solution developed other than subjectively (poor, standard, high, very high) based on belief in the reliability of the approach taken. This can be informed by a margins assessment to identify where conservatisms (or not) have been included in the design.

However, formal quantification of risk requires quantitative risk assessment involving a probabilistic model (structured Bayesian framework) which represents all the various events and elements which could give rise to risk exposure, with likelihoods assigned to each, and so can quantify system reliability. This is referred to as "expert judgement" (see below).

Traditional "good practice" is not bounded by a rigorous mathematical structure of this kind. However, it should be undertaken within a logical and documented system

Boyd has proposed a staged approach requiring answers to four questions:

1. "What have we got?" - (site investigations)
2. "How does it behave if we do something to it?" - (analysis)
3. "What do we do?" - (design)
4. "Did we have what we thought we had and did it behave as we thought it would?" - (construction supervision and monitoring)

Question 4 implies use of the Observational Method (e.g. Patel et al) as a way of verifying the design or requiring modification if necessary. All projects require a fallback at question 4 even if this is to stop and re-think.

Subsequent sections of this paper discuss the nature of uncertainty and resulting risk.

2 UNCERTAINTY

The nature of uncertainty can be divided into two main categories; aleatory and epistemic.

- Aleatory uncertainty is due to true randomness. Roulette may be considered an example of such a process. In geotechnical engineering though, true randomness rarely applies because each situation is a function of the geological history and processes that have taken place, and real materials usually show complex behavior which is difficult to measure accurately.

- Epistemic category is where uncertainties exist (and may resemble randomness) because we do not know or understand enough about the situation and underlying processes and because of limitations on what can be measured. Epistemic uncertainty dominates in geotechnical engineering.

Many situations allow simplifications by grouping together of information, and with statistical analysis it may be possible to derive averages and valid ranges of values (stochastic methods). Usually, deterministic analysis is used to analyze and understand a problem, and presumes that certain parameters derived from investigations will apply, and that the analysis methodology properly reflects the behavior of the system. Banding analysis by varying parameters within credible ranges allows understanding of how uncertainties effect the outcome. Understanding a problem in this way can lead on to deciding on what is best to do to avoid or account for inherent uncertainties.

Also, a combination of semi-deterministic and stochastic processes (such as banding analysis across various possible configurations and ranges of properties and Monte Carlo simulations) can give an indication of system reliability. If we could get full geological information and full knowledge of material behavior it would be possible in principle to undertake an accurate deterministic analysis to obtain a certain outcome.

However, uncertainties in ground conditions abound and are related both to lack of knowledge about materials and about their spatial distribution. Investigations are made to gather site data but are necessarily constrained by what is possible and practicable. Uncertainties are related to the number of measuring points, the relevance of investigation methods, the relevance of measuring points, the precision and accuracy of the data collected and the actual variability of the ground.

A further level of uncertainty is introduced when data is analyzed and models are fitted in both deterministic and stochastic analysis and as a basis for design. This involves predicting how materials would behave if subjected to actions (analysis) and then deciding what to do (options analysis and decision making). Assumptions made in interpretation and synthesis add to the uncertainties.

Thus, uncertainty is related to the degree of belief in the methodology employed, what conditions apply, how the system will behave, and then deciding on what is the optimum choice of solution.

The probability of success for traditional design (utilizing engineering judgement, see below) will reflect empirical evidence embodied in codes of practice, and individual experience. It is thus a measure of confidence in an uncertain outcome and may not be quantifiable other than subjectively. In effect, we seek to understand uncertainties to get a basis for good engineering decisions, and not to describe a reality which, fundamentally, cannot be fully described.

3 GEOLOGY RULES!

Knowledge of the geology is crucial to understanding what materials are present in the ground, for planning site investigations and developing geotechnical interpretations. Understanding depositional mechanisms and geological processes is key to explaining soil layering, buried channels, over-consolidation and countless other phenomena encountered. Everything that follows in design development including the ground model and geotechnical design parameters depends on adequate understanding of the geology. This should be an iterative process built up as new information is gathered by the investigation. It adds logic and explanation to belief in the geotechnical conclusions.

4 METHODS OF INVESTIGATION

Different techniques may be used to investigate the ground from simple trial pits to detailed borings, sophisticated sampling, in-situ testing, geophysics and laboratory testing. The level of investigation necessary depends on the nature of the ground and the scale of the project and should be designed to manage uncertainty and reduce project risk.

Usually investigation will be undertaken in stages commencing with a desk study, including geological enquiries and investigation of local precedent, and preferably including a site visit. This would seek to identify likely ground conditions and potential uncertainties and indicate the scope of investigation required. The investigations themselves may be done in stages to build up a picture of ground conditions, with greater detail being added at each stage, giving increased knowledge and reduced uncertainty. This is often done in parallel with conceptual design, tailoring successive stages of investigation to the evolving design and any changing design requirements. It is useful to involve independent technical assessors in this iterative process which ensures continuity to later stages.

Different investigation techniques involve different degrees of applicability in different ground conditions. What works in one place might not work in another, and different technologies might have different precision. Interpretation should ensure continuity between results and compatibility with the geological understanding. Any unusual occurrences or anomalies should be assessed and accounted for.

Results should be presented in factual reports, summarizing geotechnical reports and interpretative reports (sometimes combined) and subject to review (such as by ITA). Clarity in reporting is essential to reduce uncertainty and increase confidence and belief in the outcomes.

5 PRECISION, ACCURACY AND BIAS

Measurement and testing is undertaken to quantify properties of the ground. Tests may be classification or index tests used to determine material type (Atterberg limit tests, gradation tests, slake durability, Los Angeles abrasion etc.) or physical tests where the results are related to a model of behavior and the test results analyzed to derive theoretical properties of the materials (constitutive relationships). This includes such as tri-axial tests, oedometer tests, insitu cone penetrometer, pressuremeter, insitu permeability tests etc., or indirect physical tests which derive properties by correlation (Point Load index, SPT etc.).

Precision relates to the repeatability and reproducibility of the test. That is, the same team doing the same test again in ostensibly the same conditions and getting the same results is a repeatable test, and others doing the same test and getting the same results is a reproducible test. High precision means that results would cluster together over a narrow range and low precision is when the results are widely spread. It is often difficult to separate lack of precision in the test from natural variability in the ground. Standardized test methods facilitate precision.

Averaging and deviation statistics are often applied to test results to determine average or representative values. “Rogue values”, that is values outside the main cluster of results, may be due to sampling or testing errors or a manifestation of material variability and macro features occurring at the scale of the test. If rogue values are to be omitted from analysis, this should be done explicitly and with due consideration that some important feature is not being overlooked.

Accuracy is a nebulous concept, and may relate to how well the test represents a theoretical behavior. “Accurate” values may be derived by back-fitting the test result to what is judged the most representative model. So, one type of test may be judged more accurate than another based on a judgement of how well the behavior fits with theory. However, real materials may show complex behavior and hence choice of constitutive relationship may only be an approximation and there is no "accurate" value.

As an example, consider attempting to derive an undrained strength profile in soft clay. Test profiles may be compiled from sets of boreholes in ostensibly the same stratum, by obtaining samples for tri-axial testing or by in-situ vane testing, in-situ penetrometer testing, SPTs etc. Similar trends may be identified in all sets of tests, but the derived values may differ (be offset from each other). Thus, deciding which is the "accurate" profile may not be possible from the data alone and would rely on which set of tests is judged the best fit with theory. The design itself may be based on a "characteristic" profile, "average" profile, "conservatively assessed" profile or whatever, by making an engineering judgement of the data.

Bias is a measure of how well the tests match with the assessed measure of accuracy. For instance, in the above example, tri-axial tests on large diameter samples may be assessed as best representing the behavior of the clay and judged the most "accurate". Penetrometer and in-situ vane tests may show a similar profile but may be offset somewhat. The degree of offset is a measure of bias and is often compensated for by factoring the sets of results.

6 EXPERT AND ENGINEERING JUDGEMENT

Skipp and Woo differentiate expert judgement from engineering judgement in that the former requires a quantitative process involving a probabilistic model (structured Bayesian framework) which represents all the various events which could give rise to risk exposure, and so to quantify system reliability. Technical knowledge in the subject area and high levels of informativeness and training of the individuals involved are prerequisites for either approach.

- Expert judgement plays a vital role in assessing and modelling the quality and reliability of systems and may be used where traditional "good practice" is unable to supply reliable (quantified) estimates of likelihood of outcome, particularly in areas with high reliability requirements because there are few data sets on failures. So, understanding the nature of uncertainties and potential weaknesses in design can be informed by expert judgement. Enumeration will invariably involve recourse to some subjectivity, and thus reliance on expert judgement itself reflects a degree of belief in the stochastic model and the underlying data. It follows that expert judgement should be formalized, explicit, and documented so that it can be identified and reviewed by others, and must be undertaken with openness and transparency.

  A danger in quantitative risk assessments of this kind is that tendencies towards conservatisms can spiral leading to unrealistic outcomes and so there is a need to maintain consistency in the process.
- Traditional engineering judgement by contrast relies on engineering knowledge and experience, and seeks to compensate for possible shortcomings in knowledge of ground conditions, uncertainties in ground parameters, methods of analysis and decision making by following "good practice" and accepted standards. Engineering judgement usually involves deterministic design procedures often based on design codes and published design procedures (e.g. Eurocodes), and relies heavily on being able to recognize similarities between one situation and another, together with knowledge of what constitutes relevant precedent. Engineering expertise is important in setting a project in context and adopting strategies to avoid problems.

The lack of a rigorous mathematical structure means that quantifying system reliability may not be possible other than subjectively at a general level. Also, engineering judgements will vary from person to person and even if design outcomes are similar the arguments used may differ. For instance, adopting "conservative" estimates of soil parameters may accompany less conservative factors of safety, to achieve the same effect as using "best estimate" parameters and higher factors of safety. In any event, the arguments used to generate the geotechnical design should be articulated clearly in factual and interpretative reports, technical analysis reports, option studies, design substantiation reports and verification testing etc.

Peer review and independent technical assessment, using separate experts, are useful techniques for ensuring that good practice is employed and appropriate solutions are developed.

A "good design" is one that meets the necessary safety and serviceability standards under specified design level conditions but also avoids potential "cliff edge" effects, that is wherever possible the facility exhibits resilience beyond the design level event by allowing the onset of plastic deformation and some structural damage without sudden collapse, but preserving life and vital function.

7 INDEPENDENT TECHNICAL ASSESSMENT

Independent technical assessment (ITA) and peer review may be employed by various parties involved in a project to validate that the strategies and methodologies employed take account of uncertainty, and suitably protect their interest in the project, and to verify the design.

Designers routinely undertake internal design reviews as part of their quality assurance processes and may also commission reviews by external experts. Project owners may undertake or commission ITAs from experts or set up review panels to ensure that the project needs are achieved. Lenders or insurers may commission ITAs to be assured that their level of exposure is acceptable. Regulators may also undertake or commission reviews both to ensure compliance with safety and environmental requirements or to limit public exposure to risk.

The very presence of ITA requires a systematic and properly documented methodology that can be reviewed, and uncertainties identified, and so contributes to management of project risk. ITA should be considered part of the solution and not a burden which has to be endured. Review comments should be critical where necessary but make positive contributions and give guidance where possible.

8 BELIEF, RELIABILITY AND VALIDITY

Reliability may be expressed by repeatability and reproducibility and by consistency within the system. It may apply at the test level (by measures of precision), in analysis by comparison of outcome between different methodologies, and by concurrence of design decisions (ITA). Quantification of reliability would require a rigorous mathematical structure as in Expert Judgement.

Validity relates to how well the results and outcomes cover all the issues involved, correspond with established theory and knowledge and correspond with other valid measures and approaches such as empirical methods and simple precedent. In systems engineering terms (International Council On Systems Engineering, INCOSE), validation relates to ensuring you are building the right thing, and verification (question 4) that you are building it right.

Belief is thus a subjective judgement based on consistency, reliability and validity.

9 CONCLUSIONS

Uncertainty in geotechnical engineering design stems from variability in materials, spatial uncertainty in the ground, limits on methods of investigation and testing and limits of understanding of how actions are applied and how structures respond. Effective ground engineering requires uncertainties and risks to be recognized early in the project and addressed within a holistic design process with a full and clear reporting structure.

It follows that a principle of good ground engineering should be the ability to demonstrate that a robust solution can be put in place which can meet project objectives and cope with the uncertainties present, such as by using the "four questions" approach, and with verification at each stage of the design, construct and operate process. ITA is useful in achieving this.

If required, residual reliability may be estimated subjectively based on engineering judgement and belief in the methodology employed, but if this needs to be quantified, this would require a form of Expert Judgment involving formal quantified risk assessment methodologies.

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