Improved contracting practices and ground risk management using geostatistics

Tunneling projects face uncertainty in terms of the differences between simplified models described in tender documents and the reality of full-scale construction. It is not easy to document intrinsic geological variability and stratigraphy, the spatial variation in geotechnical parameters, the differences between laboratory sampling and testing and in situ behavior, ground water variations, rock mass quality variations, and the existence of anomalies, such as boulders or voids.

There are considerable pressures on drafters of geotechnical interpretative documents, such as geotechnical baseline reports (GBRs), to get it 'right,' and this can lead to ambiguous representations and give rise to disputes should those topics identified turn out to be more adverse than originally assumed.

In fact, they can be counterproductive to the owner's interests given the widely accepted doctrine of 'contra proferentum,' a rule of contract interpretation that states an ambiguous contract term should be construed against the drafter of the contract.

Most interpretations of project geology are deterministic in that they derive a single interpretation. There is no measure of accuracy or bias. The uncertainty in the interpretation is seldom quantified in a meaningful manner, and this can lead to overconfidence in the model (especially if presented in colorful 3D).

This article presents a framework for how geotechnical uncertainty can be quantified using geostatistics, and translation into practical tools for ground risk management throughout planning, procurement and construction, and enable a more objective basis for interpretation. The sources and types of uncertainty, the impact these uncertainties can have on construction risks, and approaches for managing risks associated with uncertainty are described.

The approach, if adopted, should give more clarity to the degree of uncertainty present to enable resources to either reduce the uncertainty or mitigate the risk as necessary. Clear communication of risks is vital to achieving a common understanding, and to enable proper risk management.

Tunneling projects that go wrong are usually the result of key risks not being anticipated and priced at tender; they start wrong. Relying on geotechnical interpretations and baselines without considering uncertainties in and variations from the interpretation/baseline can lead to the project team (owner, designer and contractor) being unprepared. Therefore, assessing and quantifying the range of uncertainty in ground properties and behavior will help to inform the project team of what to anticipate, and through such risk awareness, minimize commercial losses.

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Geotechnical uncertainty in tunneling

Geotechnical uncertainty types and sources. Uncertainties related to subsurface conditions generally fall under into two categories (Phoon and Kulhawy, 1999; Baecher and Christian, 2003):

- Natural or aleatory variability – The inherent spatial and temporal randomness in geologic materials. In principle, this cannot be reduced; however, the degree of variability can be estimated more accurately by collecting more data.
- Knowledge or epistemic uncertainty – Includes: (i) statistical estimation and site characterization uncertainty, (ii) model uncertainty and (iii) parameter (or measurement) uncertainty. This type of uncertainty is related to the lack of sufficient information.

While it is generally accepted that these uncertainties will exist, too seldomly are they properly quantified and their implications on risks assessed for a project. Inadequate assessment of subsurface variability and uncertainty on a project basis can lead to critical errors in geological and geotechnical interpretations.

Impact of uncertainties on tunnel construction risks. The lack of a proper understanding of the associated uncertainty in geotechnical interpretations is considered one of the main reasons behind commercial losses, and even catastrophic geotechnical failures. A study of 110 geotechnical failure case studies by Tonks et al. (2017) identified the top two main causes of those failures as selected construction means/methods and poor geotechnical interpretation (Fig. 1).

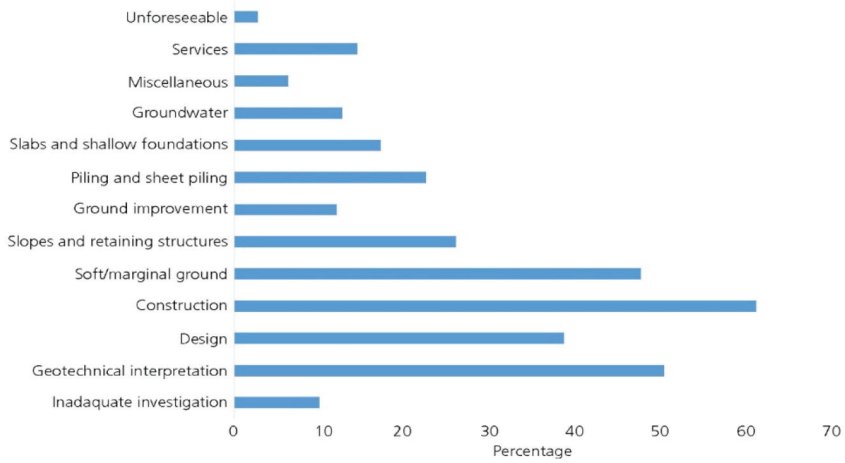
Several case studies of geotechnical challenges or failures in tunnel construction linked, partially or entirely, to inadequate geotechnical interpretation can be referenced. For example, the Lausanne M2 metro experienced a sinkhole collapse when ground conditions were found to deviate significantly from the initial interpretation (Fig. 2). Relying on a single deterministic interpretation of the subsurface geology, without any representation or quantification of interpretation uncertainty, gave a misguided belief that the excavated tunnel would encounter full-face Molasse. However, a mixed face condition with Moraine deposits in the upper half of the tunnel was encountered, causing face instability when the contractor was not prepared for this condition.

It is often said "that the client pays for sufficient site investigation, whether it does one or not," and with limitations of access and with typically less than 1 percent of the ground investigated for a tunneling works project, there is often severe limitations on the data available for interpretation, and a high degree of uncertainty associated with the interpretation of ground conditions that follow. The significance of this uncertainty is usually unknown, as it is not quantified nor communicated in advance of an adverse event.

Therefore, it is recommended to quantify the uncertainty of the conditions from site investigations to determine a measure of the sufficiency of the ground investigation along the alignment. This can also make clear the need for more site investigation. Such an approach of quantifying uncertainty should be valuable to any client organization that is committed to the efficient management of risk in underground construction, and in determining and allocating resources to manage such uncertainty.

FIG. 1

Main geotechnical issues (percentage identified in 110 cases) (Tonks et al., 2017).



Communicating the risk. The degree to which the parties to a contract understand the project risks at the time of forming the contract is considered a fundamental success factor for any tunnel project. This understanding is essential so that:

- Risks (not just geotechnical risks) are clearly allocated; and
- Financial provisions are made accordingly, and
- The parties understand the basis for changed conditions (from reference conditions created by the GBR baselines) should they arise and thereby minimize the potential for disputes.

Therefore, it is most important to define the basis of geotechnical forseeability (along with the communication of other project risks) and provide mechanisms within the contract such as a differing site conditions clause to vary the contract. These concepts are widely accepted (even

FIG. 2

Initial interpretation (left) and revised interpretation with addition of post-accident boreholes (right) (modified from Saousa and Einstein, 2021).

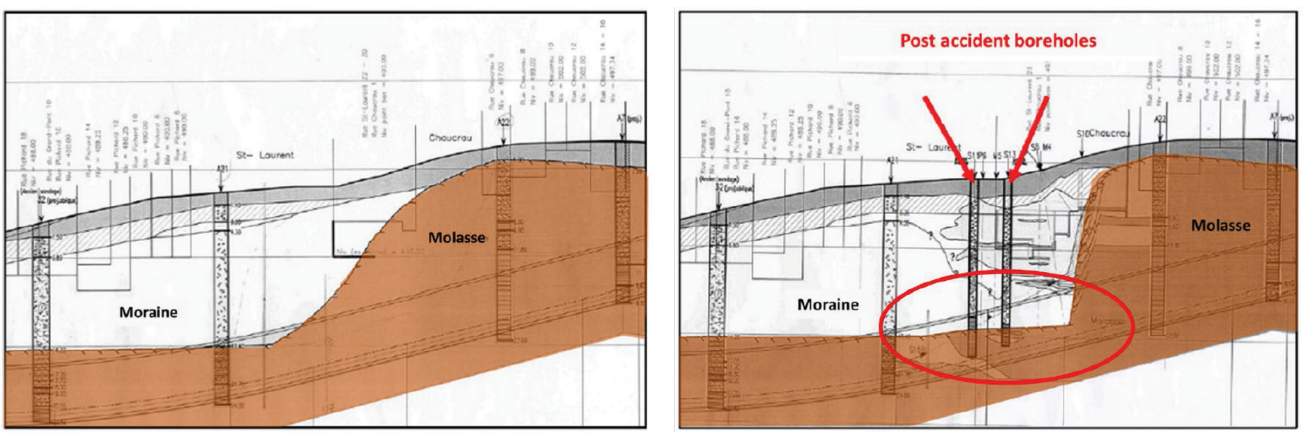
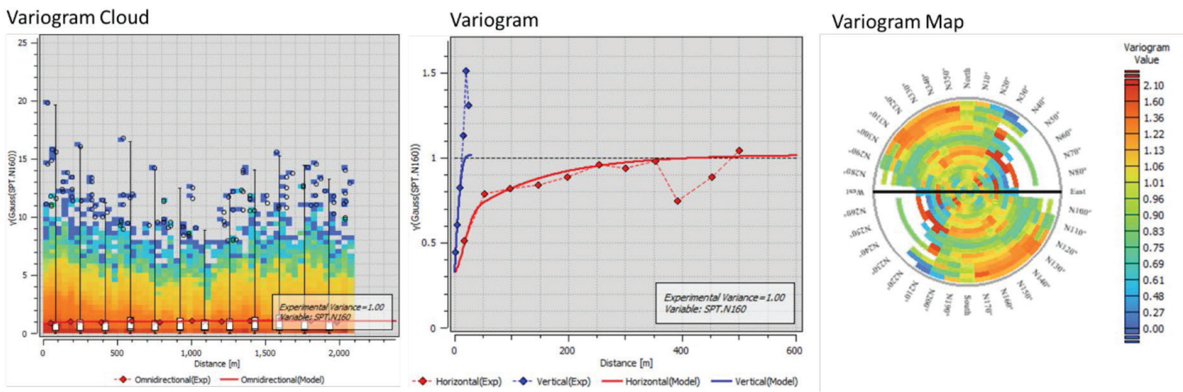


FIG. 3

Examples of visualizing the variogram, which describes the variability in the data as a function of distance and direction.



if practices may fall short) and have been the focus of industry since an Organisation for Economic Co-operation and Development conference held in Washington, D.C. in 1970 that led to the formation of the International Tunneling Association (ITA).

Quantifying uncertainties using geostatistical methods

This section introduces some approaches for quantifying uncertainty in geotechnical interpretations using geostatistical methods. Readers should refer to other references for a more detailed discussion of the theory and methods (e.g., Chilès and Delfiner, 2012; Pyrcz and Deutsch, 2014).

Overview of geostatistics. Geostatistics is a class of applied statistics used to analyze the spatial relationship of data to make predictions at unsampled locations. Widely adopted in industries such as natural resources, mining and hydrogeology, it is considered the best approach to model the spatial distribution and variability of geological and geotechnical properties. It provides a framework to integrate data from many sources (for example, geological interpretation, direct measurements and secondary measurements/information). The method is practical (consistent with the data), repeatable and can be easily updated with new information.

The spatial variability of geological and geotechnical properties is generally described by the variogram, which quantifies the degree of variability of the parameter as a function of distance and direction according to the data. A variogram is generated by computing the semivariance one-half the squared difference of all pairs of data.

Figure 3 presents example visualizations of the measure including the variogram cloud (semivariance of all data pairs versus distance), the variogram (mean semivariance versus distance) and variogram map (mean semivariance versus distance for specific direction angles).

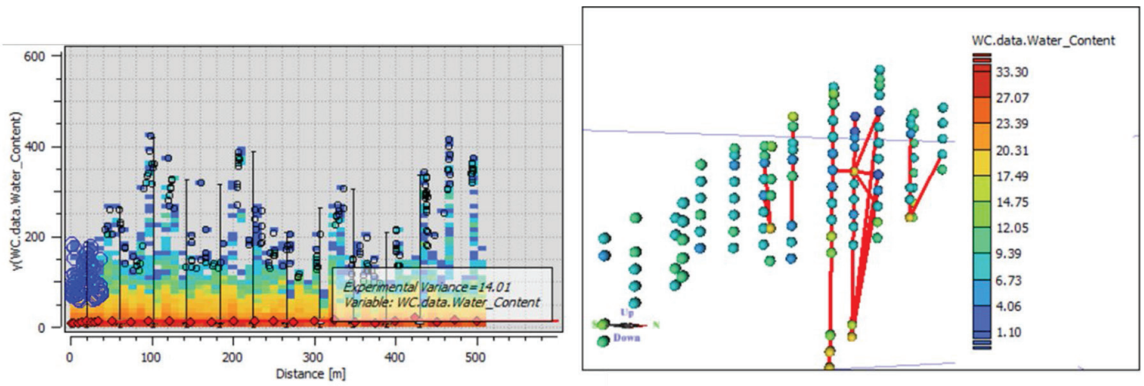
The variogram is used for estimating properties at unsampled locations. At any unsampled location, the variogram and nearby known data (referred to as conditioning data in geostatistics) are used to derive a distribution of estimated values at that location, using an interpolator function such as kriging. In a simulation framework, multiple equally probable realizations of subsurface parameters based on geostatistical and geological rules or constraints can be generated. This offers users information on subsurface conditions consistent with the known data, alleviating the geologist or engineer of having to determine a single interpretation of the model, which can often be difficult to rigorously defend against any other expert opinion.

Using geostatistics to address reporting/measurement uncertainty. Since the variogram is a measure of the difference between data points as a function of distance and direction, it can serve as a powerful tool to identify potential outliers in a spatial context with respect to nearby measurements. In Fig. 4, for example, the highest water content semivariance values at each (binned) distance are identified via the variogram cloud (highlighted in blue). These points are then further reviewed (for example, 3D visualization, laboratory testing records) to allow a more rigorous assessment of the data points: whether the geological data classification is correct or whether they should be removed as outliers, or otherwise described in the process of determining baselines. Such a method is useful to more effectively identify samples and parameter values that require further verification during the data review process.

When constructing the variogram to model parameter variability, measurement errors can be incorporated such that the model reflects the uncertainty associated with the error. The semivariance value at a distance of 0 is referred to as the nugget of the variogram and reflects the microscale variability and measurement error of the parameter. This is an intuitive and effective way of incorporating measurement error into the geostatistical models to assess its impact on interpretation uncertainty.

There are several geostatistical tools available to perform exploratory data analysis and address parameter measurement/reporting uncertainty. These are useful for not only assessing the uncertainty in the sampled data, but also for accounting for uncertainty in the simulation

FIG. 4



Use of variogram techniques to identify spatial outliers of reported geotechnical parameters.

process to develop the subsurface models of geological/geotechnical conditions. Furthermore, the exploratory data analysis undertaken can reveal outliers and/or anomalies that should be disclosed in the geotechnical data reports and considered when establishing baselines.

Quantifying uncertainty at unsampled locations. Geostatistical methods are useful for estimating geology and geotechnical parameters at unsampled locations. In a simulation framework, multiple equally probable realizations of the estimation can be generated. Each of these equally probable realizations conform to the input data (for example, borehole data) and spatial correlation model (for example, the variogram). Other constraints, or geological rules, such as contacts, ranges and faulting can also be included in the simulation process.

From the multiple realizations, uncertainty can be quantified spatially at each simulated location based on the variability in estimates across all realizations. For example, the uncertainty in transition boundaries such as sand/clay interface or intact rockhead surface is quantified by the height/width of the 90 percent (or other percentile) confidence interval (Fig. 5). This can be incorporated into baseline statements such as: 'The uncertainty in the rockhead surface elevation interpretation ranges from 0-15 m (0-50 ft), depending on the chainage location (provide table of +/- variation from estimate).'

Generally, subsurface models of the spatial variability of geotechnical parameters are not developed for tunneling projects. However, there are several reasons why developing such a model would be advantageous. First, the distribution of geotechnical parameter values may differ on a local scale compared to the full-project scale. This local variation can be captured in a geostatistical model (Fig. 6).

Second, estimated geotechnical parameters at unsampled locations are dependent on the estimated geology. Geostatistics enables a framework where geology and geotechnical parameters can be simulated jointly such that the uncertainty in geology is carried forward to the uncertainty quantification of geotechnical parameters spatially.

Translating uncertainty to ground risk management

Quantified metrics of uncertainty in geotechnical interpretations can be used for the assessment and management of risks including clogging, cutter-tool wear, groundwater inrush, and face instability (Fig. 7). This would be advantageous for assessing the spatial variation

FIG. 5

Simulating multiple equally probable transition surfaces to derive confidence intervals of the true transition location.

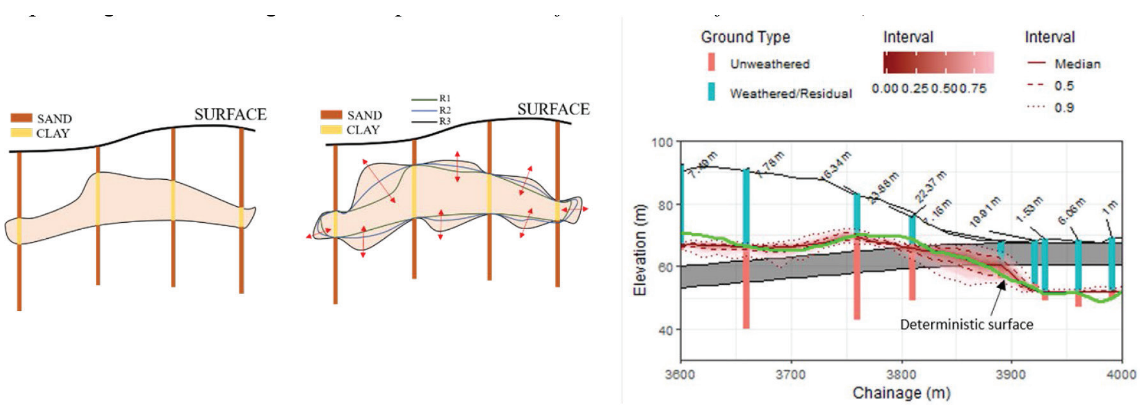
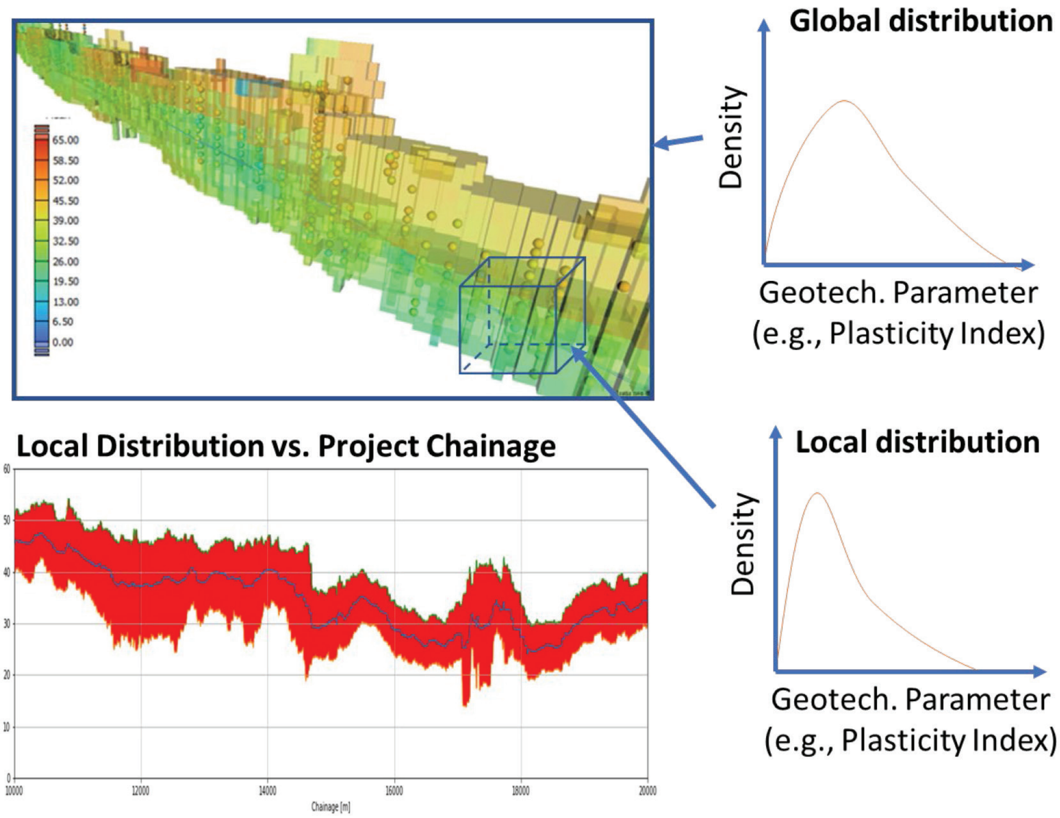


FIG. 6

Assessment of the local variation and uncertainty of a geotechnical parameter. Outputs of the geostatistical model can be used to derive confidence intervals around an estimated parameter magnitude versus project chainage.



in such types of risks, which is not conveyed in typical risk registers. The uncertainty in geological/geotechnical conditions can be directly carried forward to the risk metric and provide a common basis for understanding the risk between the owner and contractor.

Currently, many risk registers are qualitatively assessed and rely on subjective engineering judgement and experience. In a geostatistics-based approach, levels of risk in the risk register can be improved with the inclusion of quantified uncertainty to allow objective comparison. Mitigations can also be developed to reduce the risk to an acceptable level in accordance with the adopted risk criteria established by the owner in terms of contractual risk allocation, and by the contractor for internal enterprise risk management.

Proposed framework

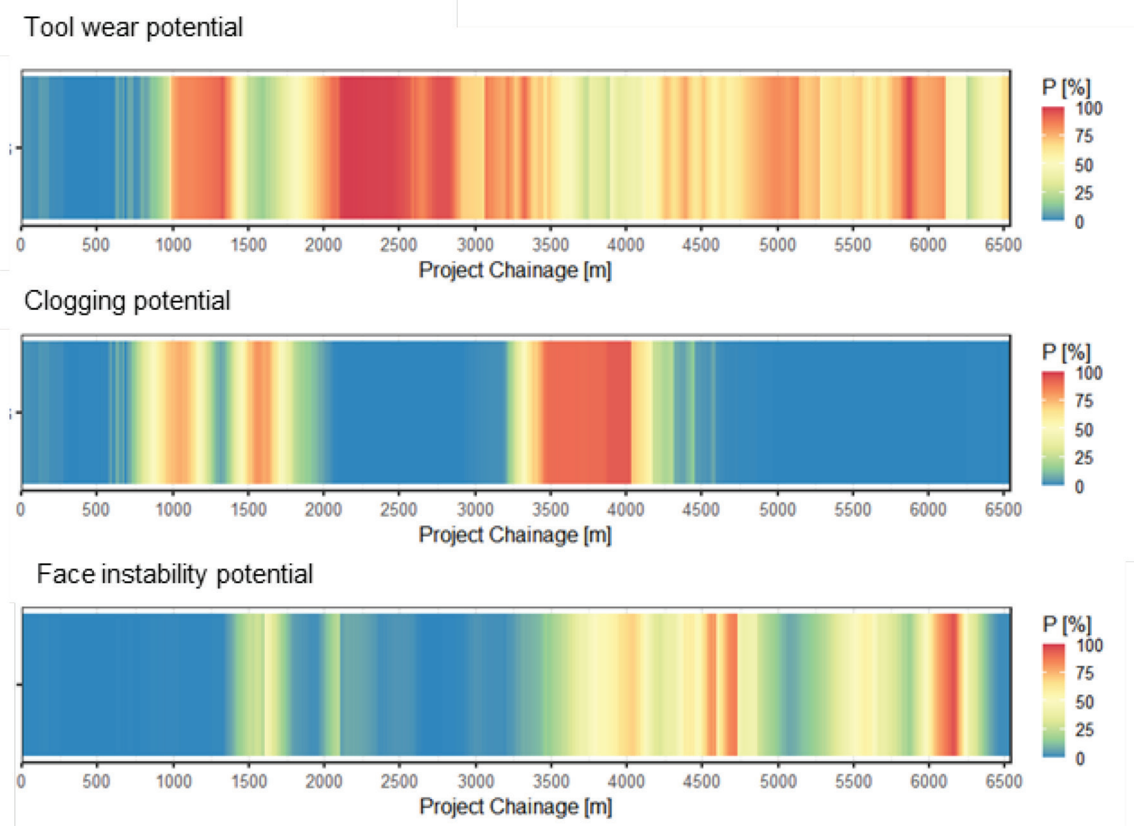
A geostatistics-based approach for quantifying uncertainty can be implemented at all stages of the project: planning and GBR preparation, bidding at tender, procurement and GBR negotiations, and construction. Figure 8 presents a general framework for this approach at each stage of a project.

Under this framework, the following risk management principles are suggested for the purpose of drafting better geotechnical baselines and GBRs:

- The owner should be liable for ground risks and differing site conditions, unless they are allocated by the GBR baselines.
- Baselines should be measurable or quantifiable during construction, and these methods of measurement or observation should also be defined under the baselines. It is important that the methodology to quantify the baseline parameters or observations is clearly stated in the originally agreed baselines. This is recommended to avoid possible disputes about how to establish if a baseline has been exceeded.
- Geotechnical baselines are the basis of foreseeability, and not a basis for design, per se. This is often confused and can give rise to disputes. The GBR should describe the anticipated subsurface conditions and the likely ground behavior for a given design and construction methodology for the purposes of establishing the commercial risks allocated with using baseline statements. To also provide a design basis, many more parameters need to be defined, and these can end up in artful interpretations of the data and unnecessary argument.
- GBR baselines should also define limits of geotechnical properties, and behavior noting that

FIG. 7

Example of quantified risk versus chainage.



geotechnical behavior or response baselines are influenced by works and methods, particularly the timing of installation, and the strength and stiffness characteristics of the support.

- Baselines that deviate from the GDR dataset should be explained, as well as the reasoning behind the difference. Data ranges should not be presented without a baseline because otherwise, there is no baseline — one may as well revert (and it is not recommended) to full-risk transfer approaches and not increase the ambiguity in the GBR.
- The owner can incorporate measures of uncertainty as part of the baseline definition process to report the relative quality and limitations of the subsurface data along the alignment. The quantified uncertainty in geological and geotechnical interpretations from the geostatistical interpretation of data can be reported with confidence intervals (for example, see rockhead surface example in Fig. 5).
- Not all geotechnical parameters that can be derived need to be baselined. However, for the purposes of risk management transparency, the reasoning behind this should be stated.
- Give plenty of time for tender interaction regarding the GBR. It is recommended to define forward-priced variations during the tender stage (for foreseeable scenarios outside of the baseline limits) and then agree the monitoring/response mechanisms that trigger the variation. This should focus all parties on project risk management at an early stage and improve the administration of any events as they are planned and costed in advance.

With the increasing adoption of digitalization in tunnel construction, the delivery of geotechnical baseline and data reports should also move toward a digital format (as opposed to conventional PDF). Some benefits to adopting digitalization for GBR and GDR delivery are:

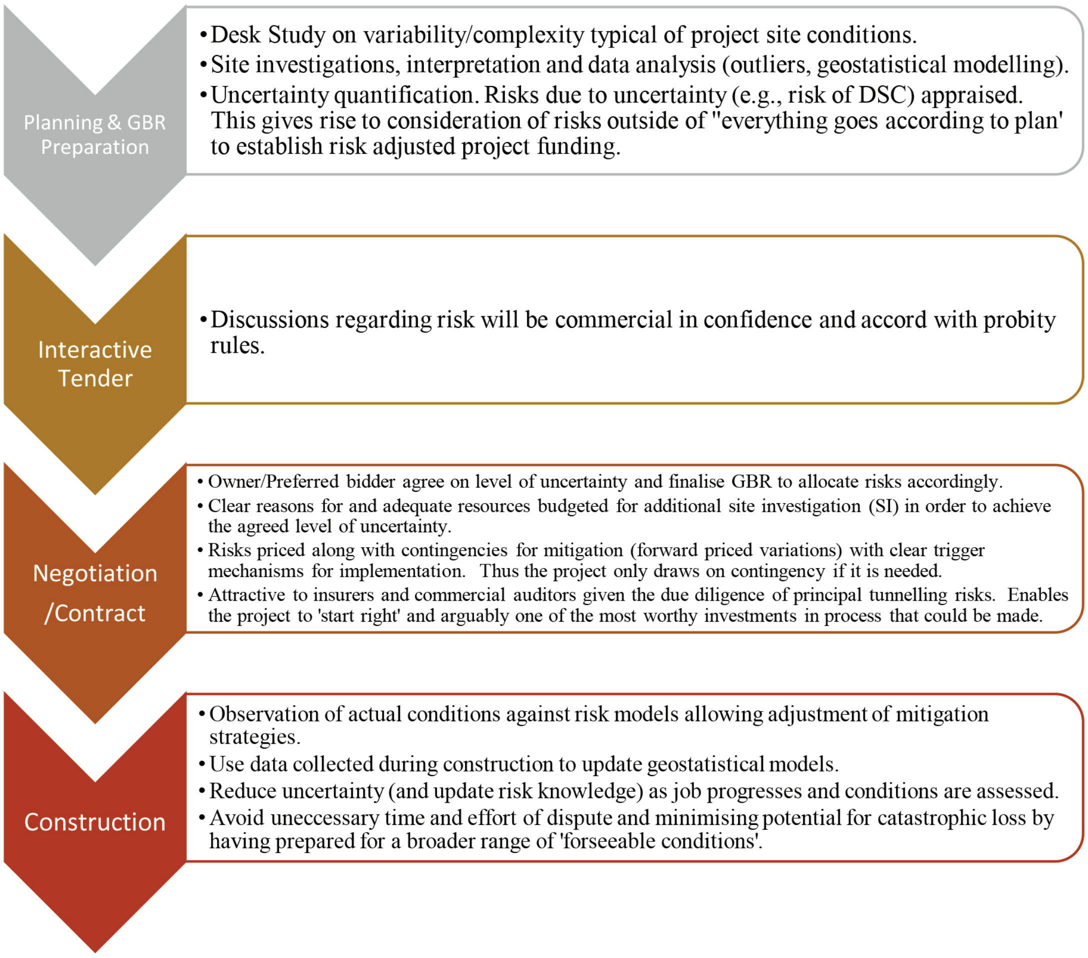
- Immediate access to the data so bidding parties can quickly begin analysis.
- Clear communication of georeferenced risks including geotechnical, sensitive structures, environmental, etc.
- BIM integration.
- The GIS-based GBR can be extended to use after the award for risk management; incorporate instrumentation and monitoring data, construction records and design, etc.

Conclusions

Usually when projects suffer commercial losses it is because key aspects of risk have not been anticipated and priced at the tender, but have been accepted due to an

FIG. 8

Proposed framework for applying geostatistical analysis for geotechnical baseline reports and risk mitigation.



attractively low (or sufficiently low) price. As a result of such underresourcing, the project team (owner, contractor and designer) may be unprepared for situations they encounter.

Insurers have an increasingly difficult role to play as what is technically possible encompasses a broader range of increasingly extreme geotechnical environments with ever-increasing potential for calamity. It is often overlooked that insurers also seek sustainable commercial returns, and so if claims are too large, then market coverage must be reduced (for the next job) and/or insurance costs must rise.

In this way, improved visibility of risk management (that precipitated the ITIG Guide in 2011), helps industry stakeholders and partners.

A focus on effective risk management may enable projects to differentiate themselves, and a mature and sophisticated risk management approach should be reflected in the number and quality of tenderers. By moving away from purely deterministic geotechnical interpretations and emphasizing uncertainty quantification, all parties will be better informed and prepared.

This article presents a methodology for improving the management of geotechnical risk using well-established techniques. When the methods are applied in a systematic way, the uncertainty (adequacy) associated with the preconstruction geotechnical model used to define forseeability (via the GBR) for a tunneling contract can be determined. This should enable a project team (owner, contractor and designer) to commence the project with sufficient resources and the knowledge that anything unforeseen can be efficiently and equitably dealt with. ■

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