A Simple Method of Estimating Ground Model Reliability for Linear Infrastructure Projects

Darren Paul

Abstract

The ground model is fundamental to any engineering project with ground structure interaction. Linear infrastructure projects have many forms of ground interaction and ground models are essential. All ground models are hypothetical. Interpolation or extrapolation from known data is required in order to form a prediction of the ground characteristics at any particular location. There is therefore inherent uncertainty in every ground model. The reliability of the ground model may be considered to be a function of (1) the accuracy or reliability of the data on which it based; (2) the quantity of data or ground information available; (3) the geological complexity of the ground from which the data has been obtained and (4) the complexity of the ground response to changes induced by the project. This paper presents a method of assessing ground model reliability for linear infrastructure projects based on an assessment of these four key factors. This method has been applied to three linear infrastructure projects in Australia, which are discussed.

Keywords

Ground models • Geological uncertainty
Geological reliability • Linear infrastructure

1 Introduction

Ground models are required over the full course of planning, design and construction of linear infrastructure projects. The typical progression of a ground engineering project would see the level of detail and certainty of the ground model increase over the course of the project as the ground model develops in parallel with the project and design development. The uncertainty within the ground model would then generally reduce in parallel with the progression of the project. A challenge facing any geotechnical engineering project is in identifying how much uncertainty can be tolerated at any stage of the project. An assessment of the uncertainty in the ground model and its associated risks informs the investigation that needs to be undertaken over the course of the project and what risks must be accommodated in design.

Amongst other things, the usefulness of ground information used as input for developing a ground model depends on:

- the reliability that can be placed on the ground information;
- the quantity of information and its location or relevance to the project for which it is being assessed;
- the geological complexity and variability of the ground at the location of interest, and;
- the susceptibility of the project to ground conditions.

Assessing how much investigation should be undertaken at various stages throughout the project, requires an assessment of how much ground model uncertainty can be tolerated. A method is set out below which seeks to qualify the uncertainty associated with a ground model for linear infrastructure projects which can be applied throughout its various stages. The method proposed follows the process as set out in Fig. 1. Two key streams are considered: the available ground information (left column on Fig. 1) and the ground complexity (right column on Fig. 1). An assessment of each is undertaken and then qualitatively combined in order to assess ground model reliability.

This paper describes a qualitative process to assess ground model uncertainty which is similar to and draws inspiration from qualitative systems used to assess risk, for example the RTA system of slope risk assessment, Stewart et al. (2002). Each step of the qualitative process is described in this paper. The numbered headings may be cross referenced to the numbers shown in the flow chart in Fig. 1.

D. Paul (✉)
Golder Associates, Melbourne, Australia
e-mail: dpaul@golder.com.au

A. Shakoor and K. Cato (eds.), *IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018—Volume 2*, https://doi.org/10.1007/978-3-319-93127-2_2

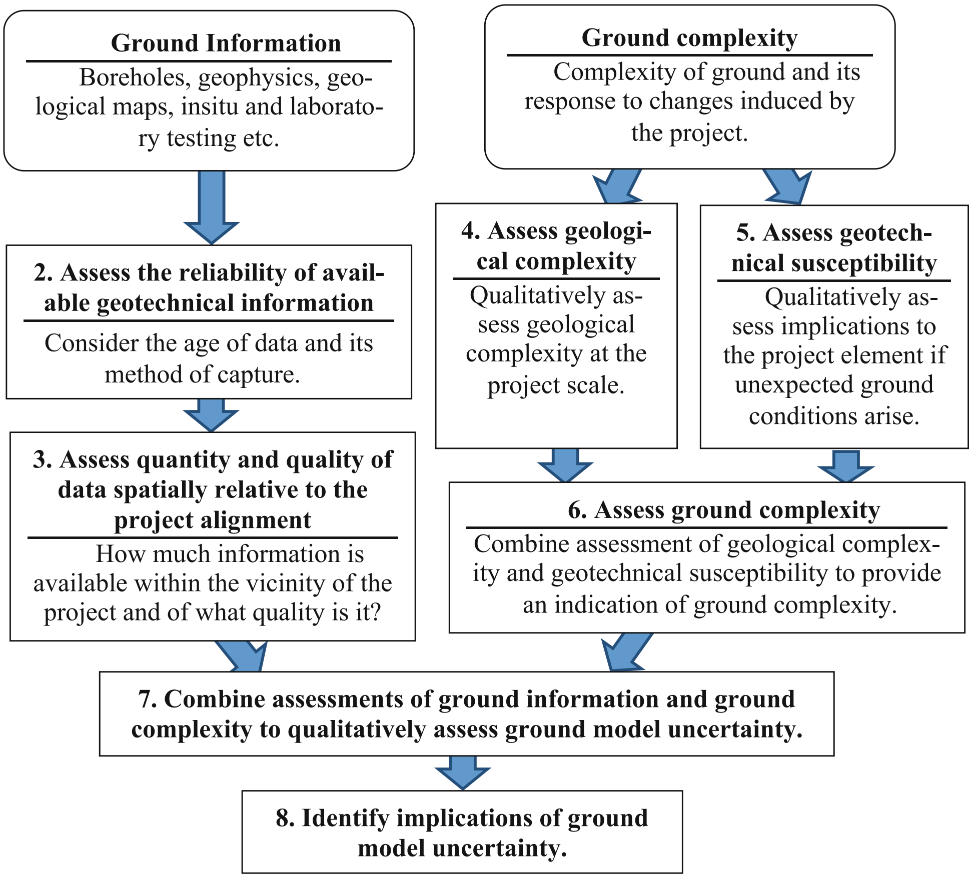


Fig. 1 Flow chart indicating steps in assessing ground model uncertainty. Numbered steps may be cross referenced to headings in this paper

2 Assess the Reliability of Available Geotechnical Information

The ground model at the concept or feasibility stage of a project is likely to be based on a desk study and informed by existing information that is unlikely to have been acquired specifically for the project. It may have been acquired to inform geotechnical aspects of other projects or for entirely unrelated, non-geotechnical purposes and therefore have varying relevance. For urban infrastructure projects for which the method set out in this paper was developed, the available information was predominantly historical borehole information and a method of assessing the quality of borehole information is set out here. Notwithstanding this, the methods set out here for boreholes could be adapted for map information, CPT, geophysics or any other relevant information.

In order to assess the reliability of boreholes, a semi-qualitative assessment can be made on a borehole by borehole basis. The method suggested here uses a similar approach to that used in rock mass classification systems such as RMR (Bieniawski 1989). Various attributes of the borehole are assessed and score is allocated for each attribute as indicated in Table 1. The scores for each attribute are then summed with the score allocated to a borehole reliability category, 1–5. Although development of the borehole reliability score is semi-quantitative, it is important to note that the overall system presented here is qualitative and that the borehole reliability score is used to provide a qualitative input (borehole ranking) to the system. The attributes considered for boreholes are set out below.

Drilling Method—Boreholes with core drilling including an assessment of rock defects are more reliable than boreholes using washbore or hammer techniques.

Survey—Boreholes with recent ground survey are considered more accurate than those without survey and allow more reliable positioning in ground models.

Sampling Frequency—The greater the sampling frequency in the borehole, the more reliable the soil or rock description is considered to be.

Age—There is greater uncertainty around the provenance of older borehole logs.

Depth—Shallow boreholes are generally considered less relevant than deep boreholes, particularly for tunnel projects.

Installation—Boreholes with groundwater wells installed and groundwater measurements are considered more useful than boreholes without well installations.

Table 1 Categories used to assess borehole reliability score

Borehole attribute	Category	Score
Drilling method	Washbore and coring	5
	Washbore or hammer only	2
Survey	Survey to modern coordinate system inc. RL	5
	Survey to modern coordinate system, RL estimated from topographical information OR Survey to modern coordinate system inc. RL	4
	Survey to modern coordinate system, RL estimated from topographical information OR No survey—georeferenced from site plan	3
	Converted from historical datum OR No survey—located using georeferenced aerial imagery and topographical information	2
Sampling frequency	<1.5m	10
	>1.5–3 m	6
	>3 m	2
Age	<5 years	5
	>5 to <10 years	4
	>10 to <20 years	3
	>20 years	2
Depth	>25 m	10
	>10 to <25 m	6
	>5 to <10 m	2
	<5 m	1
Installation	Piezometer or well installation	3
	No installation	0
In situ testing	SPT and packer, or pressuremeter testing	5
	SPT only	3
	No in situ testing	0

In situ Testing—Boreholes with in situ testing including SPTs, packer testing or pressuremeter testing provide information on engineering properties of the ground.

Note that the above criteria have been developed with a focus on urban tunneling projects but could be readily adapted to other forms of linear infrastructure projects or other types of projects.

The process of selecting suitable numbers for each category was one of trial and error. A borehole reliability assessment was undertaken for approximately 1000 boreholes and the scores assigned to each category varied until the output was considered reasonable. Judgement was exercised in undertaking this trial and error process. If required, it is a relatively simple process to vary the categories and numbers to include project or location specific attributes and weightings.

The reliability scores are then assigned to a category in accordance with Table 2 which can then be used as input to the qualitative assessment. Similar to the parameters used to develop the reliability score, the category ranges have been developed through a trial and error process and can be tailored to the specific project and location. The implications of this borehole reliability ranking to future investigation and ground model development are set out in Table 2.

Boreholes ranked 1–3 would generally be used to inform ground model development, supplemented by boreholes with a lower ranking. Figure 2 provides an indication of the borehole reliability spatially along part a project assessed using the methods set out above.

3 Assess Quantity and Quality of Data Spatially Relative to the Project Alignment

To assess information quality and quantity, the borehole reliability ranking can be used in conjunction with an assessment of the density of boreholes relative to the proposed project alignment. Table 3 provides an example

Table 2 Borehole reliability ranking

Borehole reliability score	Borehole reliability ranking	Implications
>34	1	Good, detailed information, known provenance, can be relied upon without need to undertake further investigation
29–34	2	Good information, but information needs to be supplemented or verified through further investigation
23–28	3	Information reliable, but shallow or lacking in detail. Supplemental investigation needed
16–22	4	Provides some useful information, but insufficient detail or uncertain provenance. Not to be relied upon. New investigation needed
<16	5	Minimal or no useful information, not to be relied upon. New investigation needed

Fig. 2 Example of borehole reliability plotted on portion of linear infrastructure project

Table 3 Borehole information quality and quantity

Very poor	No intrusive investigation, or boreholes more than 100 m from the alignment, existing information limited to geological maps
Poor	Boreholes 50–100 m from the alignment
Fair	One or more boreholes within 50 m of the alignment, along a 100 m length. Borehole reliability ranking low, typically 4 or 5, some 3
Good	Up to 5 boreholes within 50 m of the alignment, along a 100 m length. Boreholes have a high borehole reliability ranking, 1 or 2
Very good	More than 5 boreholes within 50 m of the alignment. Boreholes have a high reliability ranking, 1 or 2

of how this was undertaken for an urban tunneling project in Melbourne, Australia where the assessment was undertaken over 100 m intervals along the proposed tunnel alignment.

4 Assess Geological Complexity

Geological complexity refers to ground characteristics with complexity related to aspects such as variability of lithology, complexity of structure, stress field and tectonic history. It might also be described as the degree of ground homogeneity at the scale of the project.

Table 4 presents a guideline for the assessment of geotechnical and geological complexity which was developed for an urban tunneling project in Melbourne.

For example, the geological complexity of normally to slightly overconsolidated Holocene sediment may be ‘simple’ because its depositional history and stress history are known and its engineering properties are relatively predictable. Conversely, a metamorphic rock mass with multiple phases of deformation and weathering would be

Table 4 Assessment of geological complexity at scale of tunneling project

Very simple	Single material type, no deformation, regular or repeatable structure, no discernible weathering
Simple	Single material type, no deformation, predictable structure, some chemical or mechanical weathering
Intermediate	Multiple material types, single phase deformation, somewhat predictable structure, chemical and mechanical weathering
Complex	Multiple material types, single phase of deformation with unpredictable structures, multiple phases of chemical and mechanical weathering
Very complex	Many different lithologies, complex structure with multiple phases of deformation and metamorphism with complicated structure, multiple episodes of chemical and mechanical weathering

'complex'. Note that geological complexity should be assessed at a scale relative to the projects zone of influence.

5 Assess Geotechnical Susceptibility

Geotechnical susceptibility refers to the susceptibility of the project or project element to ground uncertainty.

Table 5 presents a guideline for the assessment of geotechnical susceptibility which was used to qualitatively assess an urban tunnelling project in Melbourne.

Table 6 presents an example of the geotechnical susceptibility that might be estimated for various elements of an urban metro project.

6 Combine Assessments of Geological Complexity and Geotechnical Susceptibility to Assess Ground Complexity

The assessments of geological complexity are combined to arrive at an overall estimate of ground complexity. Table 7 provides a matrix which combines geological complexity and ground susceptibility. This matrix is biased towards geotechnical susceptibility. For example complex geological complexity and intermediate geotechnical susceptibility combines to intermediate.

Table 5 Assessment geotechnical susceptibility

Very low susceptibility	Construction and structure proposed has a low susceptibility to uncertain or unexpected ground conditions. No significant consequences if unexpected ground conditions are encountered
Low susceptibility	Proposed design and construction has some susceptibility to unexpected ground conditions, but these can likely be mitigated or managed through design or pre-planned contingency
Intermediate susceptibility	Proposed design and construction is susceptible to unexpected ground conditions. There are expected to be implications if unexpected ground conditions are encountered during construction which may require design changes, remedial measures or delays during construction
High susceptibility	Proposed design and construction is susceptible to unexpected ground conditions with significant implications including project delays and cost overruns if unexpected ground conditions are encountered
Very high susceptibility	Proposed design and construction highly susceptible to ground variation or unexpected ground conditions with major implications if unexpected ground conditions are encountered. Project delays, cost overruns, health and safety risks and reputational damage likely if unexpected ground conditions are encountered

Table 6 Estimated geotechnical susceptibility of various elements

Very low susceptibility	Shallow surface excavation Lightly loaded footings Lightly loaded pavements and track
Low susceptibility	Unsupported surface batter slopes
Intermediate susceptibility	Retained excavation TBM tunnels
High susceptibility	Deep retained excavation TBM tunnels close to existing underground assets with potential interaction effects or mixed face conditions
Very high susceptibility	Large span underground excavation (caverns) Deep retained excavation in close proximity to existing movement sensitive structures

Table 7 Tool to assist in estimating ground complexity based on geological complexity and geotechnical susceptibility

Geological complexity	Geotechnical susceptibility				
	Very low	Low	Intermediate	High	Very high
Very simple	Very simple	Simple	Simple	Intermediate	Intermediate
Simple	Very simple	Simple	Intermediate	Intermediate	Complex
Intermediate	Simple	Simple	Intermediate	Complex	Complex
Complex	Simple	Intermediate	Intermediate	Complex	Very complex
Very complex	Intermediate	Intermediate	Complex	Complex	Very complex

7 Combine Assessments of Ground Information and Ground Complexity to Qualitatively Assess Ground Model Uncertainty

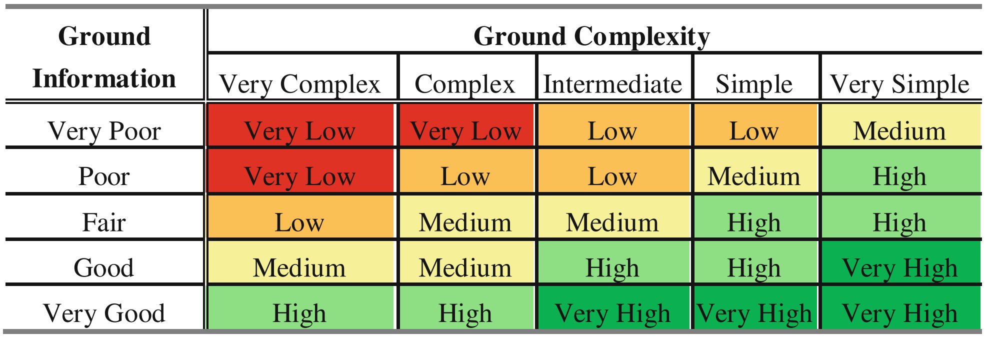
The assessments of ground information (step 3) and ground complexity (step 6) are combined using the matrix in Table 8, to arrive at an overall ground model reliability ranking. An example of how the ground model reliability may be communicated on a ground model, in this case a simple cross section, is presented in Fig. 3. The ground model uncertainty was superimposed over the ground model at project feasibility stage using desktop information.

8 Identify Implications of Ground Model Uncertainty

An indication of the implications of the estimated ground model reliability score is provided in Table 9.

This approach informs an assessment of where further investigation might be expected to provide the most value and can be refined multiple times as the project progresses and additional information becomes available.

Table 8 Ground model reliability rating



Ground Information	Ground Complexity				
	Very Complex	Complex	Intermediate	Simple	Very Simple
Very Poor	Very Low	Very Low	Low	Low	Medium
Poor	Very Low	Low	Low	Medium	High
Fair	Low	Medium	Medium	High	High
Good	Medium	Medium	High	High	Very High
Very Good	High	High	Very High	Very High	Very High

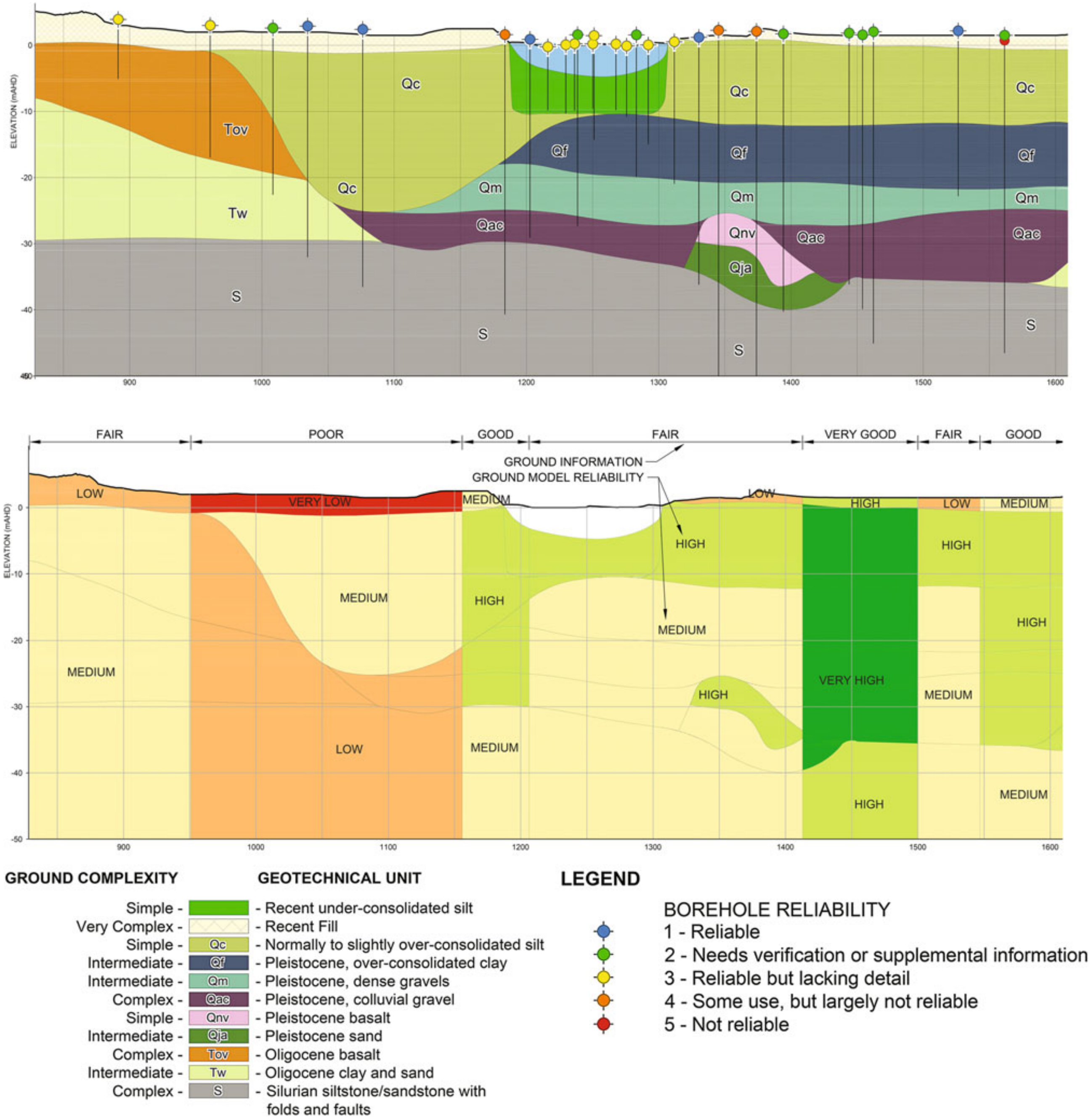


Fig. 3 Example of cross section presenting ground model reliability for a tunneling project. Ground complexity for each geotechnical unit and ground information are combined to indicate Ground Reliability (lower section)

Table 9 Implication of ground model reliability score

Very low (VL)	Available information insufficient given the geological complexity to develop a basic conceptual model. Indicative only.
Low (L)	Available information sufficient given the geological complexity to develop a basic conceptual ground model but not an observational model.
Medium (M)	Sufficient information given the geological complexity to develop an observational model. Significant residual uncertainty.
High (H)	Sufficient information given the geological complexity to develop an observational ground model. Some uncertainty remaining.
Very high (VH)	Able to develop detailed observational ground model. Sufficient information given the geological complexity to proceed with detailed design.

9 Conclusions

A method is set out here by which the reliability of a ground model may be assessed in a semi-quantitative manner. The methods described have been applied with success on three major tunneling projects in Melbourne, Australia. However, the methods described here are adaptable. The criteria and weightings assigned to criteria for borehole reliability assessment can be modified through a trial and error process and tailored to a specific project and geological setting.

Whilst the question of how much investigation is enough investigation cannot be answered directly using the technique described here, this method may inform identification of those areas where further investigation will add the most value.

References

Bieniawski, Z.T.: Engineering Rock Mass Classifications. Wiley, New York (1989)

Stewart, I.E., Baynes, F.J., Lee, I.K.: The RTA guide to slope risk analysis, version 3.1. Aust. Geomech. **37**(2) (2002)