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Case Study: Using limiting equilibrium analysis in landslide risk assessments

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ABSTRACT

Many regulatory bodies (e.g Councils) relate slope stability performance criteria to a Factor of Safety (typically 1.5). Frequently the input parameters for such analyses are selected in a subjective manner following relatively expensive subsurface investigation and laboratory testing. Subsurface investigation works, logging and laboratory testing works are all undertaken following specific procedures and standards. No such standards exist when it comes to modelling parameter selection and analysis. This paper addresses this issue and provides a methodology for linking limiting equilibrium analysis results to landslide risk assessments.

Keywords: Parameter selection, Factor of Safety, probalistic analysis, geomorphological mapping, risk assessment

1 INTRODUCTION

The Australian Geomechanics Society (AGS) Guidelines (2007) adopt a risk based approach to landslide assessments with no direct linkage to the commonly adopted limiting equilibrium approach.

This paper, through a case study, aims to address three issues, namely;

1. Provision of a robust and logical procedure for adopting limiting equilibrium modelling input parameters. The aim here is to remove (or include) some of the subjective interpretation associated with modelling input parameters so that two, or more, practitioners can readily agree on an appropriate range for analysis.
2. Presentation of an approach to probabilistic limiting equilibrium analysis.
3. Finally, a methodology for linking limiting equilibrium analysis results to landslide risk assessments.

Due to client confidentiality issues the site for the case study provided is ‘generic’ but based on ground conditions found in some parts of the Sunshine Coast (Queensland) where landslides are common.

The landslides on the Sunshine Coast are typically slow moving rotational or translational failures and examples are shown on Plates 1 and 2 below. The soil strength parameters used in the case study are from actual shear box test results taken from a database held by the authors.

Plate 1 – Landslide on residential land

Plate 2 – Landslide on rural road

2 SUNSHINE COAST 'CASE' HISTORY

2.1 The Site

The site covers an area of about 1 hectare (100m x 100m) where a six lot subdivision is proposed (ref Figure 1). Site investigation has identified a profile of basaltic colluvium over fissured Tertiary Sediments (highly plastic clays) which in turn overly Late Triassic-Jurassic variably weathered sandstone. Groundwater was found close to the interface between the tertiary clays and underlying sandstone. Springs were noted in the lower part of the site.

The ground conditions are described further in the following sections

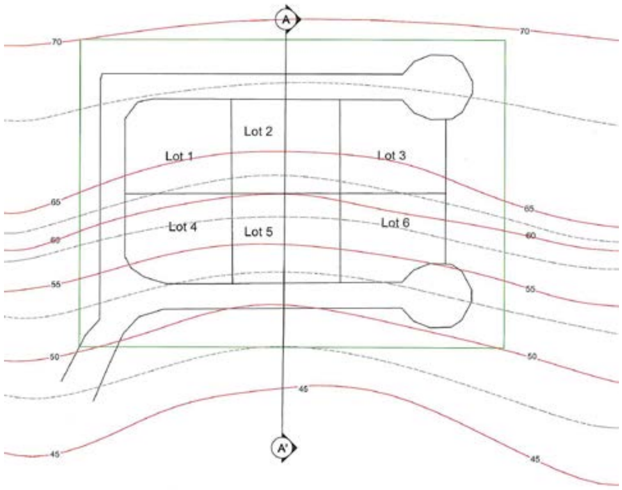


Figure 1 – Site Plan

2.2 Development of the geotechnical model

Based on the site investigation results (boreholes & test pits) and geomorphological mapping a block model was developed for the site as shown in Figure 2. The western boundary of the block model (Section A-A' on Figure 1) has been taken through the centre of Lots 2 and 5 to show the deepest soil profile. Four shear box tests were carried out, two in the colluvium and another two in the Tertiary Clays. Parameter selection for limiting equilibrium analysis is discussed in Section 2.3 below.

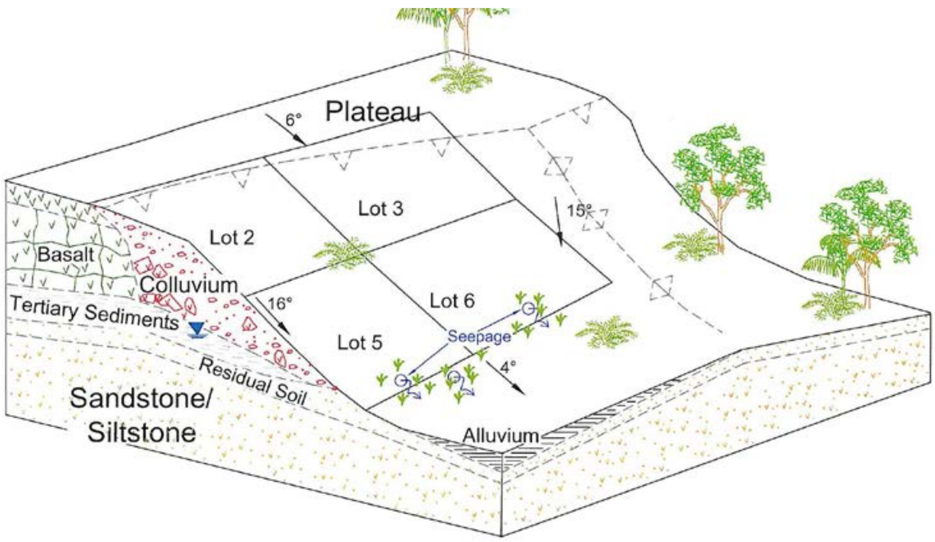


Figure 2 – Site geomorphological block model

Section A-A' was adopted for limiting equilibrium analysis as this is the area with the deepest soil profile and it is also likely to have the highest groundwater conditions due to the concave nature of the topography.

2.3 Selection of input parameters

With a local knowledge of landslide mechanisms the critical parameters (as assessed by the authors) are the shear strength parameters for the colluvium and the Tertiary clays, together with the groundwater level.

Two sets of shear box results were available from the site investigation together with another four sets of results in similar materials from nearby sites. The results are presented in Table 1 below.

Material Type	Cohesion (c' (kPa))						Friction Angle (Φ' (degrees)					
Colluvium	2*	2*	5	5	6	4	24*	27*	24	23	23	27
Tertiary Sediments	3*	0*	1	0	1	0	17*	18*	18	19	20	18

Note: * Denotes results of testing from site materials. Values without * from similar sites.

Table 1 – Available shear strength parameters

Using this data the following range of shear strength parameters were adopted for the analysis.

Material Type	Cohesion (c' (kPa))				Friction Angle (Φ' (degrees)			
Colluvium	Distribution	Min.	Mode	Max.	Distribution	Min.	Mode	Max.
	Triangular	2	4	6	Triangular	23	25	27
Tertiary Sediments	Distribution	Min.	Mode	Max.	Distribution	Min.	Mode	Max.
	Triangular	0	1	3	Triangular	16	18	20

Table 2 – Modelled distribution of shear strength parameters

Monitoring of standpipes in the site investigation boreholes over the wet season showed that groundwater levels rose about 2 m above dry season levels. Groundwater levels remained elevated for relatively short periods of time (days) following periods of significant (>25 mm in 24 hours) or prolonged rainfall. To model the variability in the groundwater level the piezometric line was input at the highest levels observed over the wet season. A triangular probability distribution was then applied to a range of 2 m below, to 2 m above the input level.

2.4 Probabilistic limiting equilibrium analysis

Probabilistic limiting equilibrium analysis may be carried out using the range of input parameters given above, a probability density function and a monte carlo simulation approach. For this case study a triangular distribution was adopted for the variable input parameters and the results are presented below in Table 3 and Figure 3.

Probabilistic Analysis	Result
Mean F of S	1.2
Reliability Index	1.68
P (Failure) (%)	6.95
Standard Dev.	0.117
Min F of S	0.82
Max F of S	1.47

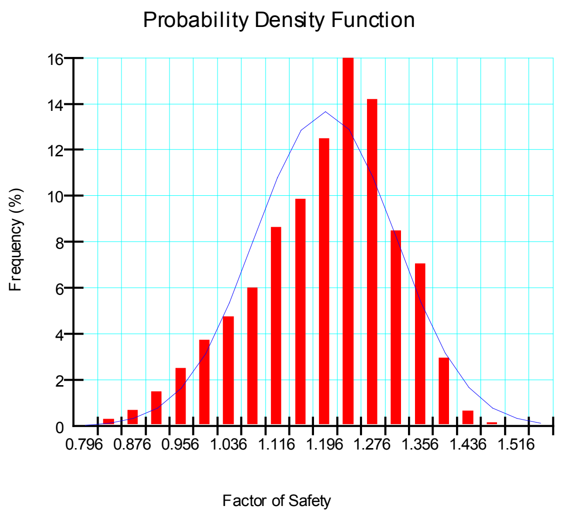
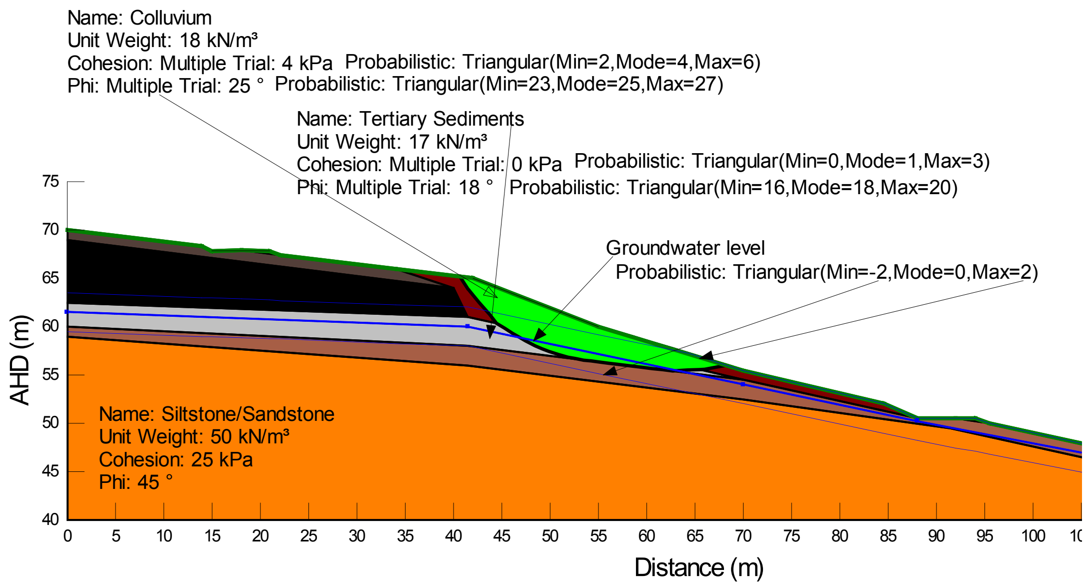


Table 3 – Results of Analysis



SECTION A-A'

Figure 3 – Results of analysis

2.5 Linking FOS to Risk Assessments

The acceptance criterion presented in the AGS guidelines (2007) are defined in terms of risk (i.e. very low risk is acceptable and low risk may be generally acceptable etc.). Risk is a combination of 'Likelihood' and 'Consequence'.

The AGS Guidelines present the following definitions of likelihood *(Qualitative Terminology for use in Assessing Risk to Property)*.

QUALITATIVE MEASURES OF LIKELIHOOD

Approximate Annual Probability		Implied Indicative Landslide Recurrence Interval		Description	Descriptor	Level
Indicative Value	Notional Boundary					
10^{-1}	5×10^{-2}	10 years	20 years	The event is expected to occur over the design life.	ALMOST CERTAIN	A
10^{-2}	5×10^{-3}	100 years	200 years	The event will probably occur under adverse conditions over the design life.	LIKELY	B
10^{-3}	5×10^{-4}	1000 years	2000 years	The event could occur under adverse conditions over the design life.	POSSIBLE	C
10^{-4}	5×10^{-5}	10,000 years	20,000 years	The event might occur under very adverse circumstances over the design life.	UNLIKELY	D
10^{-5}	5×10^{-6}	100,000 years	200,000 years	The event is conceivable but only under exceptional circumstances over the design life.	RARE	E
10^{-6}		1,000,000 years		The event is inconceivable or fanciful over the design life.	BARELY CREDIBLE	F

Note: (1) The table should be used from left to right; use Approximate Annual Probability or Description to assign Descriptor, not *vice versa*.

Table 4 - Qualitative Measures of Likelihood from AGS Guidelines

With respect to limit equilibrium analysis (deterministic or probabilistic), the results cannot be directly linked to the criterion presented in the AGS guidelines.

Limit equilibrium acceptance criteria is typically defined as FoS ≥ 1.5 (long term) and FoS ≥ 1.3 (short term). These are difficult to correlate to likelihood.

Probability values obtained from Monte Carlo simulation relate to event probability (i.e. probability of failure (P_f)) rather than annual probability. Event probability of 0.01 means that should we construct the slope 100 times with the range of input parameters selected then one of the 100 will fall down. This is different to the time element of annual probability. Event probability can be correlated to annual probability by considering the annual probability of a triggering event (e.g. 1 in 100 year rainfall event). However, this would require the derivation of a conceptual model connecting rainfall to groundwater level response

An alternative is to review the assessed probability of failure (P_f) as a cumulative frequency of the event over the design life. This is the inverse function of the method discussed in Section 5.4.2 (c) of the Practice Note Guidelines for Landslide Risk Management (2007.

In this instance, the calculated P_f is the cumulative probability of occurrence which gives:

$$P_f = 1 - (1-P)^Y$$

Where: P = Annual probability of event

Y = Design life

This can be solved for P by:

$$P = 1 - \sqrt[Y]{(1-P_f)}$$

Based on a probability of failure (P_f) from the analysis in this case study of 7%, the calculated annual probability of the landslide event for a 50 year design life would be 0.001 (i.e. '*Possible'* in accordance with the AGS guidelines (ref Table 4)).

To complete the risk analysis an assessment of the consequence of failure is necessary. This requires an estimate of the type and size of a potential failure. An understanding of the geomorphology, geology and likely failure mode together with the 2-dimensional output from SlopeW may be used to aid this assessment.

For this case study the critical slope failure is defined in 2 dimensions on Figure 3 above, and the aerial extent has then been inferred on Figure 4 below.

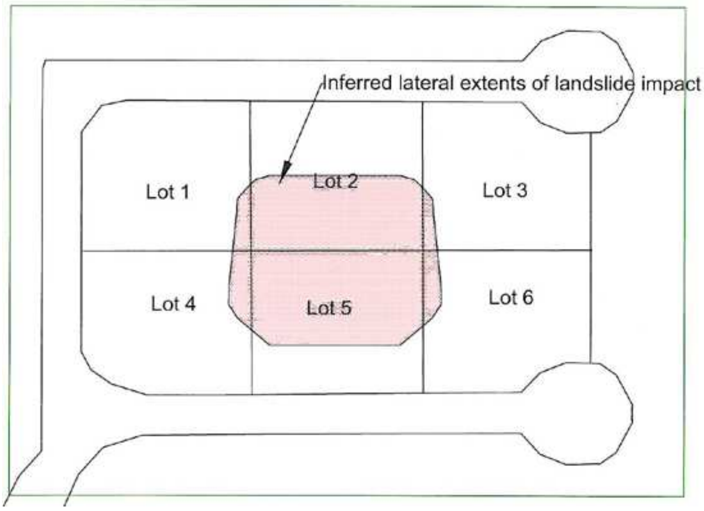


Figure 4 – Inferred aerial lateral extents of landslide

The AGS Guidelines present the following definitions of consequence *(Qualitative Terminology for use in Assessing Risk to Property)*.

Approximate Cost of Damage		Description	Descriptor	Level
Indicative Value	Notional Boundary			
200%	100%	Structure(s) completely destroyed and/or large scale damage requiring major engineering works for stabilisation. Could cause at least one adjacent property major consequence damage.	CATASTROPHIC	1
60%	40%	Extensive damage to most of structure, and/or extending beyond site boundaries requiring significant stabilisation works. Could cause at least one adjacent property medium consequence damage.	MAJOR	2
20%	10%	Moderate damage to some of structure, and/or significant part of site requiring large stabilisation works. Could cause at least one adjacent property minor consequence damage.	MEDIUM	3
5%	1%	Limited damage to part of structure, and/or part of site requiring some reinstatement stabilisation works.	MINOR	4
0.5%		Little damage. (Note for high probability event (Almost Certain), this category may be subdivided at a notional boundary of 0.1%. See Risk Matrix.)	INSIGNIFICANT	5

Notes: (2) The Approximate Cost of Damage is expressed as a percentage of market value, being the cost of the improved value of the unaffected property which includes the land plus the unaffected structures.

(3) The Approximate Cost is to be an estimate of the direct cost of the damage, such as the cost of reinstatement of the damaged portion of the property (land plus structures), stabilisation works required to render the site to tolerable risk level for the landslide which has occurred and professional design fees, and consequential costs such as legal fees, temporary accommodation. It does not include additional stabilisation works to address other landslides which may affect the property.

(4) The table should be used from left to right; use Approximate Cost of Damage or Description to assign Descriptor, not vice versa

Table 5 - Qualitative Terminology for use in Assessing Risk to Property from AGS Guidelines

Combining the Qualitative Measure of Consequence from the AGS Guidelines and the likelihood analysis described above (using the probabilistic capacity within SlopeW) a semi-quantitative analysis including limit equilibrium theory may be undertaken to assess Landslide Risk. The case study results show that the likelihood of failure is 'possible' and the resulting consequence would be 'major'. This results is a High Risk assessment for the site (using Table 6 below). Some form of preventative remedial works would therefore be required to reduce this risk rating to an acceptable level (Very Low to Low) to allow development to proceed.

QUALITATIVE RISK ANALYSIS MATRIX – LEVEL OF RISK TO PROPERTY

LIKELIHOOD		CONSEQUENCES TO PROPERTY (With Indicative Approximate Cost of Damage)				
	Indicative Value of Approximate Annual Probability	1: CATASTROPHIC 200%	2: MAJOR 60%	3: MEDIUM 20%	4: MINOR 5%	5: INSIGNIFICANT 0.5%
A – ALMOST CERTAIN	10^{-1}	VH	VH	VH	H	M or L (5)
B - LIKELY	10^{-2}	VH	VH	H	M	L
C - POSSIBLE	10^{-3}	VH	H	M	M	VL
D - UNLIKELY	10^{-4}	H	M	L	L	VL
E - RARE	10^{-5}	M	L	L	VL	VL
F - BARELY CREDIBLE	10^{-6}	L	VL	VL	VL	VL

Table 6 - Qualitative Risk Analysis Matrix – Level of Risk to Property from AGS Guidelines

3 CONCLUSION

This case history demonstrates how ground investigation and limit equilibrium analysis can be linked to a landslide risk assessment.

The author's note that the methodology presented is a design aid which can be used in combination with sound engineering judgement and experience to assess the likelihood of slope instability. The method requires cross validation with observations of failures of similar slopes and normal methods for assessing likelihood as presented by the AGS.

It is also acknowledged that a lack of data means this approach has limitations which must be recognised

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