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The use of random limit equilibrium models to enable the selection of equivalent shear strength parameters in spatially variable heterogenous weak rock masses from the Pilbara basin

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Abstract

Heterogenous weak rock masses, catalogued as either detrital material or channel iron ore deposits, can typically be found in the uppermost stratigraphic layer of Pilbara iron deposits. Due to the nature of their formation, their composition and strength properties can be highly variable within a deposit. This raises the question of whether a single, statistically selected strength design parameter has the potential to properly represent the multi-parameter scenario most likely to be encountered in a weak rock mass slope failure, as it intersects materials that are spatially variable.

The following paper provides a statistical comparative analysis of heterogeneous models built with a random spatial distribution (30 with a positive distribution and 30 with a uniform distribution) and models built with a homogeneous single design value. To accomplish this, limit equilibrium stability analyses were undertaken using Slide2®. Both types of models were set with Hoek and Brown shear strength criteria, and the uniaxial compressive strength (UCS) parameter, ranging from extremely weak rock to extremely strong rock, was selected as a benchmark for the two types of models.

The comparison was made over the 60 models mentioned above by replicating the resulting slip surface and the Factor of Safety (FoS) of the heterogeneous models in the homogeneous models. Then, homogeneous models were back analysed to obtain the corresponding UCS for the FoS being analysed in each model. Finally, the back analysed homogeneous UCS was compared with a weighted UCS from heterogeneous models obtained by measuring the length of the slip surfaces that intersect every material zone. Additionally, the same routine was applied to site-specific data of channel iron deposits.

The results of this analysis clearly show that despite the variability of strength parameters that might be present in this type of material, it is appropriate to use a single design value for this material when potential rock mass failures are analysed. Although, the results show that a 50th or 65th percentile for UCS can be related to the slip surface with a minimum FoS, this paper does not attempt to propose the use of these statistical values in practice because the models presented here do not follow any spatially random variability rules, such as correlation distance as formulated in Slide2.

Keywords: *random limit equilibrium models, UCS selection, spatially variable models, detritals*

1 Introduction

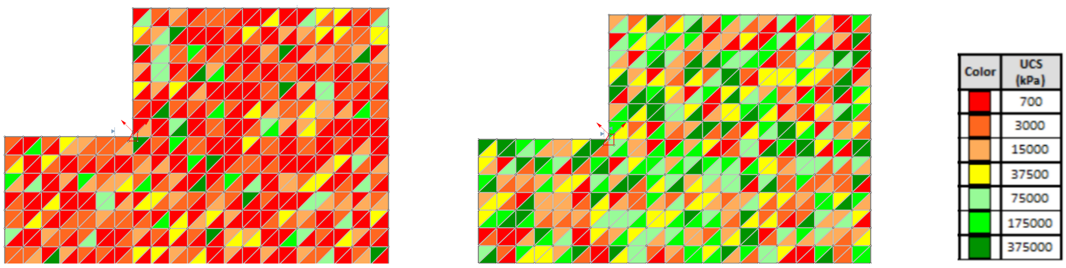
Detrital deposits are found commonly as layers of variable thickness in Pilbara iron deposits. They were formed as alluvial and/or colluvial deposits stripped from Marra Mamba or Brockman parent rocks. Detritals were subjected to cycles of deposition and erosion, each of those related to weathering, alteration and cementation processes. As a result, detrital materials have highly variable strength properties. Processes such as concretisation, mineral replacement, oxidation, reduction etc. also impact their conformation (Morris 1994) and consequently their strength properties. Figure 1 shows a core log of detrital material where it is noticeable that strength properties vary significantly over a short distance.

Figure 1 Detrital core from an iron ore deposit, 8 m apart in depth

Spatial variability of detritals or soils in general has been found hard to predict by practitioners (Sung-Chi & Nelson 2006). This causes uncertainty in material characterisation for geotechnical assessments. To achieve a better understanding on how spatial property distribution impacts slope stability, and to improve strength parameter selection criteria, a probabilistic approach has been taken.

Stability models with positive skew (30 models) and uniform (30 models) distributions were generated. These models were developed by establishing random fields in which seven different materials were statistically distributed. The random fields are utilised to generate inputs for generic Slide2® models which contain triangular material cells in which material inputs are assigned spatially according to considered different strength distributions.

In this scope of work, the only variable under examination was the uniaxial compressive strength (UCS). The models constructed consider a vertical wall of 70 m high (typical thickness of these geological units). Figure 2 presents sample models built for positive skew and uniform distributions, with the considered UCS values provided by BHP Iron Ore in kPa units.



(a) (b) (c)

Figure 2 Sample models with spatial strength distribution: (a) Positive skew; (b) Uniform; (c) Colour strength legend

2 Modelling assumptions and limitations

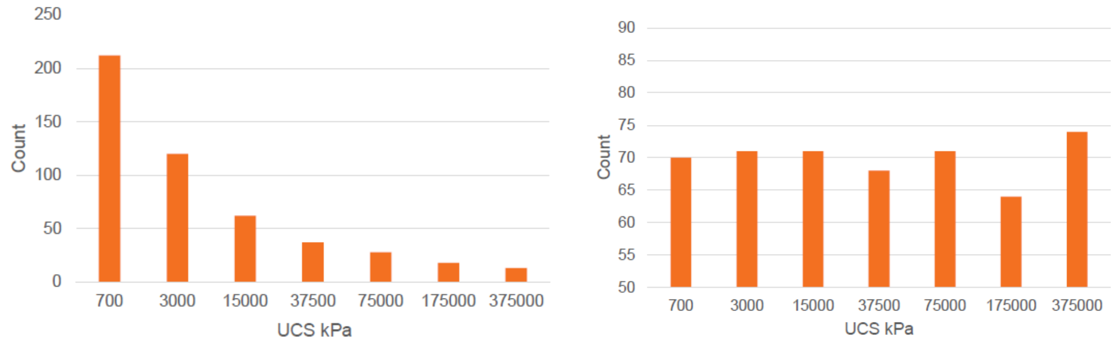
1. Limit equilibrium (LE) analysis is preferred in this modelling exercise as this is the main tool used at BHP's Western Australia Iron Ore sites to assess the Factor of Safety (FoS).
2. Although LE analysis has limitations in capturing strain softening issues, this does not invalidate the conclusions around the statistical analysis used here. In addition, it has been shown by (Javankhoshdel et al. 2017) that the non-circular and circular random LE methods are in good correlation to the random finite element method.
3. Models were built using a deterministic approach which allows control over the resultant slip surfaces. This permits a direct comparison with homogeneous models. The range of FoS obtained by computing numerous models of each distribution, however, would most probably be similar to an FoS distribution achieved from probabilistic analyses using statistical distribution of material properties.

3 Statistical distributions

Within iron ore pits, it is a prevalent occurrence to encounter detrital data characterised by either a positively skewed or uniform distribution. As a result, both distribution types were employed in the development of random models. Statistical parameters for the analysis of the 60 models are presented in Table 1, while Figure 3 visually represents an instance of a positively skewed distribution and a uniform distribution through a bar graph.

Table 1 Summary of UCS results from modelling

UCS random values (kPa)	Models	Number of models	Median of UCS percentile 50 kPa	Median of UCS percentile 65 kPa
700 3,000 15,000 37,500 75,000 175,000 375,000	Positive skewed	30	1,490	2,935
	Uniform	30	26,441	57,861



(a) (b)

Figure 3 UCS statistical distribution. (a) Positive skewed; (b) Uniform

4 Stability analyses for heterogeneous and homogeneous models

Stability analyses were undertaken using Slide2 software, which is a 2D LE slope stability program for assessing circular or non-circular failure surfaces in terms of the FoS using vertical slice methods. GLE/Morgenstern-Price and Bishop methods were used in these assessments.

Appropriate slip surface with a minimum FoS was identified for each heterogeneously distributed model. A weighted UCS value for the identified slip surface was then calculated for each scenario. The weighted UCS was obtained from heterogeneous models by measuring the length of the slip surfaces that intersect every material zone.

For each heterogeneous model scenario, a homogeneous single material model was set with an identical slip surface as per the heterogeneous stochastic model for comparison purposes. These homogeneous models were run with sensitivity analysis tools to obtain a homogeneous equivalent single UCS value to achieve the same FoS identified in the corresponding heterogeneous analysis. The process of identifying equivalent UCS values from the sensitivity analysis of homogeneous models is presented in Figure 4.

Figure 4 shows sample model results for the heterogeneous and corresponding homogeneous analyses with interpreted UCS values. Figure 5 shows how the UCS corresponding homogeneous case value was obtained from sensitive analysis.

The weighted UCS results from heterogeneous models are compared with the homogeneous results to examine how an adopted single value relates to a more realistic heterogeneous scenario.

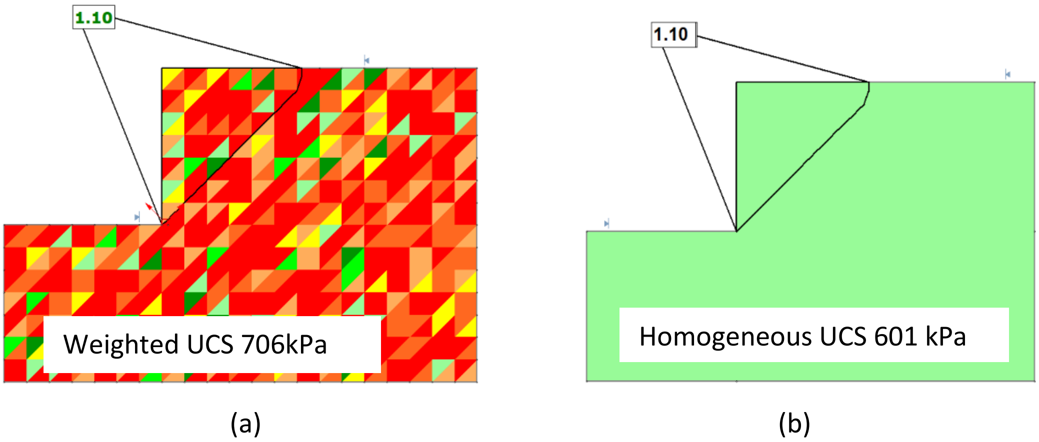


Figure 4 Sample model results with interpreted UCS values. (a) Weighted heterogeneous UCS; (b) Homogeneous UCS

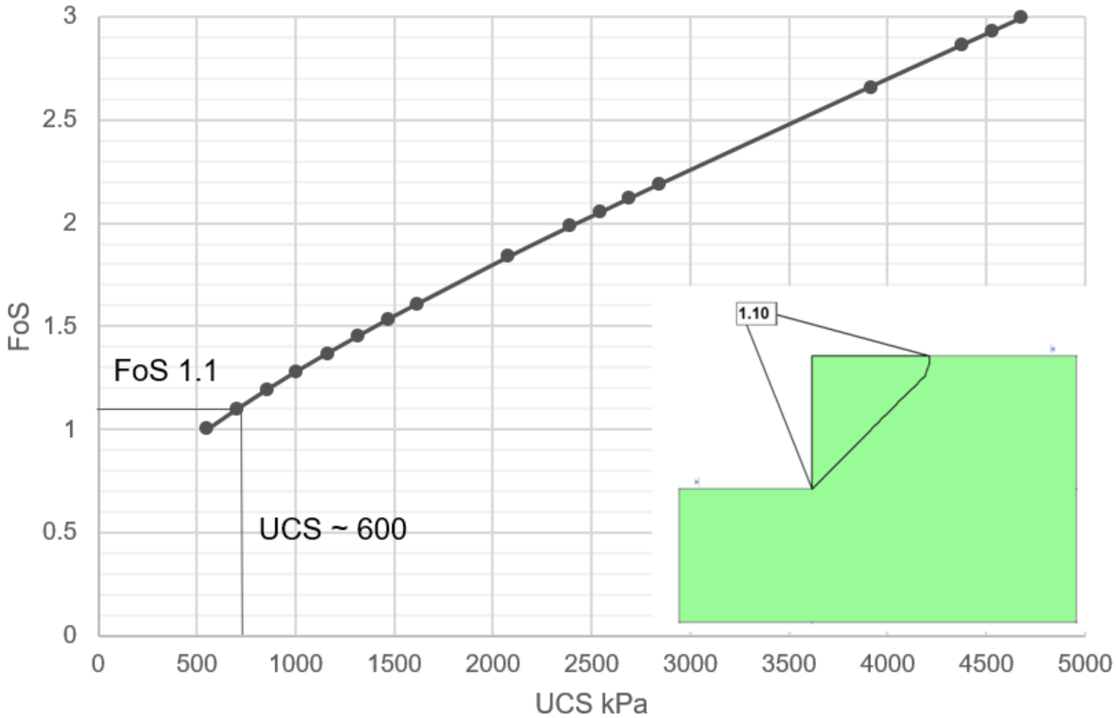


Figure 5 UCS obtained from sensitivity analysis

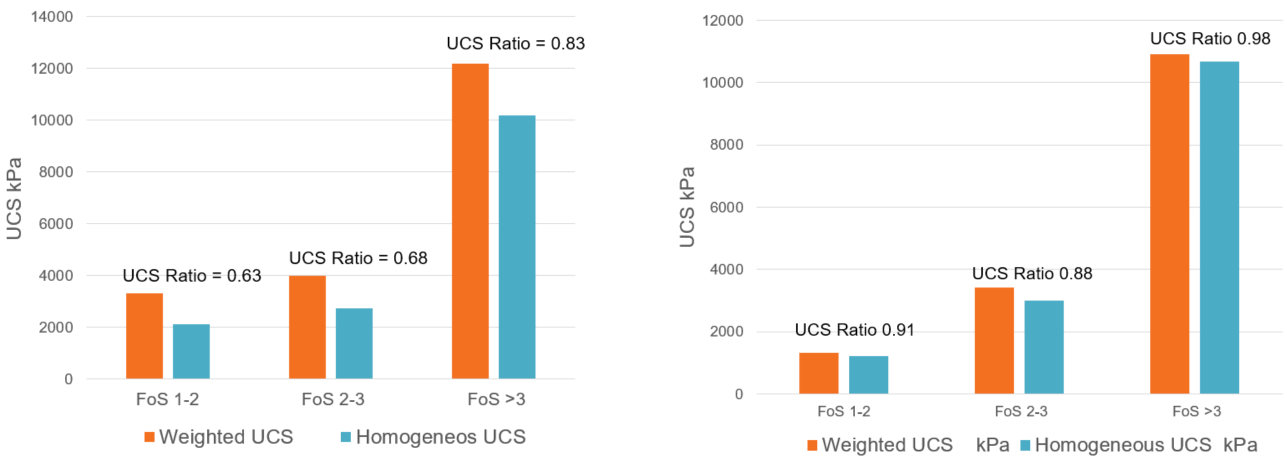
5 Results

A summary of UCS results obtained from heterogenous and homogeneous models with circular and non-circular slip surface search is presented in Table 2. In addition, the data is presented in column graphs organised by FoS ranges in Figures 6 and 7.

Table 2 Summary of UCS results from modelling

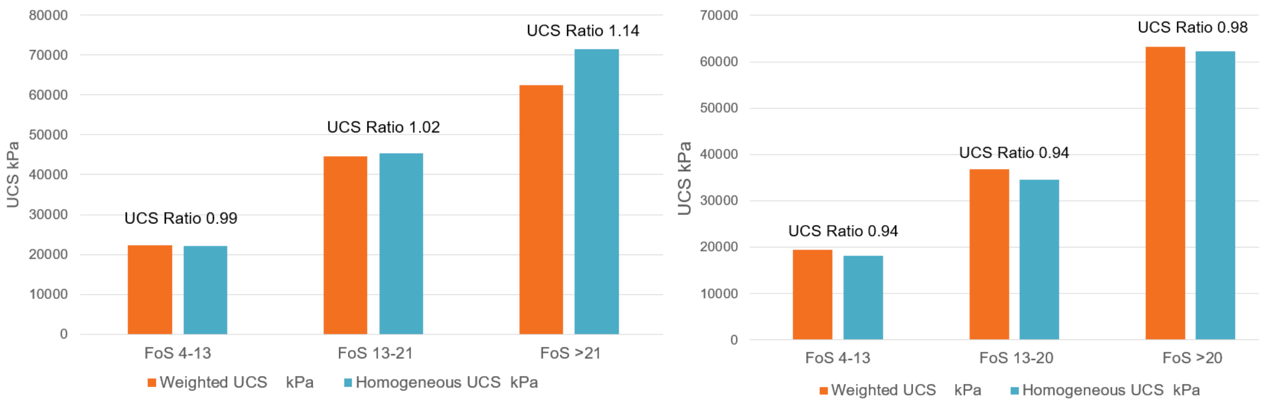
Model	Median of FoS results	Median of UCS for heterogeneous models (kPa)	Median of UCS for homogeneous models (kPa)	Ratio*
Positive skewed models circular	2.60	4,009	2,777	0.69
Uniform models circular	17.6	41,924	46,708	1.11
Positive skewed models non-circular	1.61	1,458	1,485	1.01
Uniform models non-circular	11.7	25,904	24,268	0.94

*Ratio between homogeneous UCS and weighted UCS



(a) (b)

Figure 6 Results for positive skewed models. (a) Circular search; (b) Non-circular search



(a) (b)

Figure 7 Results for uniform models. (a) Circular search; (b) Non-circular search

It can be noticed that for uniform models, higher FoS values were obtained. This is explained by the fact that high values of UCS were present in most of the models as they were uniformly distributed.

5.1 Additional modelling for site-specific data

Additionally, the same routine was executed for site-specific data of Yandi deposits. For those, positive skewed distribution with a non-circular search was applied.

For this analysis, five models were set with seven different materials ranging in UCS from 500–45,000 kPa. Then the same comparison was performed over weighted (heterogeneous) and homogeneous models. Table 3 shows the results for the site-specific exercise.

Table 3 Summary of results from the site-specific exercise

Model	Median of FoS results	Median of UCS for heterogeneous models (kPa)	Median of UCS for homogeneous models (kPa)	Ratio*
1	8.91	9,852	9,893	1.00
2	9.80	14,364	12,370	0.86
3	10.67	12,386	12,273	0.99
4	11.29	12,940	13,000	1.00
5	8.68	7,567	7,120	0.94

*Ratio between homogeneous UCS and weighted UCS

6 Conclusion

For the circular and non-circular searches, the following was found:

- Circular slip surface:
  - For positive skewed models, the homogeneous UCS obtained are lower than heterogenous weighted UCS.
  - For uniform models, the homogeneous UCS obtained are close to heterogenous weighted UCS.
- Non-circular slip surface:
  - For both positive skewed and uniform models, heterogenous weighted UCS and homogeneous UCS are well correlated.
- Non-circular slip surface site-specific data:
  - Heterogenous weighted UCS and homogeneous UCS are well correlated.

The findings of this study demonstrate that in the context of analysing potential slip surfaces in rock masses characterised by heterogeneous material distribution, the selection of a single UCS design value is a reasonable assumption. The analysis of random models reveals a correlation between the 50th or 65th percentile of UCS values and the occurrence of slip surfaces with minimal FoS. However, it is important to emphasise that the practical application of a 50^{th} percentile or 65^{th} percentile as a UCS design value is not advocated in this research. This limitation arises from the models employed in this study, which do not follow any spatially random variability rule, such as the correlation distance parameter as formulated in Slide2. Instead, the primary objective of this research is to contribute to the existing knowledge base by providing further justification for the selection of a single design UCS value in scenarios characterised by heterogeneous and spatially varied conditions.

It would be worth exploring how a 3D configuration impacts this conclusion. At first it would appear that the results should not be significantly different. However, this exercise needs to be computed to confirm this expectation. 3D block model-based tools may significantly reduce the computational time for such type of analysis.

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