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A case study of a waste dump design for oxidised material in a Western Australian mine

AJ Beer *AMC Consultants, Australia*

Abstract

This paper uses a design review for an in-pit waste dump in partly to fully oxidised material as a case study to discuss the generalised processes adopted in geotechnical design (or validation of a mining design) for waste dumps. The example used is for a West Australian open pit nickel mine in an area of moderate rainfall, with the mining above the natural groundwater table. Issues addressed in detail include methods for material characterisation (laboratory testing, or empirical relationships available in the literature, back-analysis), factors influencing the stability of different parts of the dump (dump base, main dump body and tip face), rationale behind selecting the appropriate shear strength model types for modelling the dump material, simulation of runoff for surface-water management design, effects of loading the tip head by vehicles operating nearby, influence of water, foundation conditions and their assessment and practical considerations for dump operation. The role of back-analysis and assessment of tip face angles in selecting appropriate material properties for modelling is also described.

Keywords: *waste dump design, material characterisation, slope design principles, operational considerations for waste dumps*

1 Introduction

In-pit waste dumps are an increasingly common solution to several of the issues surrounding waste rock dump location and design in Australia. Permitting issues are reduced, as additional land does not need to be used, and the issue of backfilling pit voids on completion of mining activities is reduced or eliminated. Haul distances for the waste material can also often be greatly reduced by this strategy. The risk of dump failure in the long-term is also greatly reduced, as the dump is largely or fully contained by the pit void. These advantages must, however, be considered carefully against the possibility of sterilisation of any future ore reserves. For flat, shallow orebodies that do not extend to depth, they may be a good solution.

The case study described here arises from work to validate the design of in-pit dumps for a nickel laterite mine in Western Australia. The project brief was to assess the suitability of the current and final in-pit waste dump designs, determine appropriate mechanical properties for the waste for future design work and assess the existing dump drainage, making recommendations for any required changes. A 2D limit equilibrium analysis was to be used for the stability modelling. The current dump design uses 12 m lifts, separated by 15 m wide berms, with a design batter face angle of 33°, giving an inter-ramp angle of 21°.

In the absence of laboratory test data on the mechanical properties of the waste material, it was necessary to make assumptions based on published data, experience and examination of the material involved. Back-analysis of existing slopes was also used to help assess suitable values for the strength properties.

2 Mine setting

The mine is situated on a topographic high, in an area where the natural surface elevation ranges from 150 m above sea level (ASL) to around 230 m ASL. The footprint of the pit in relation to topography is shown in Figure 1.

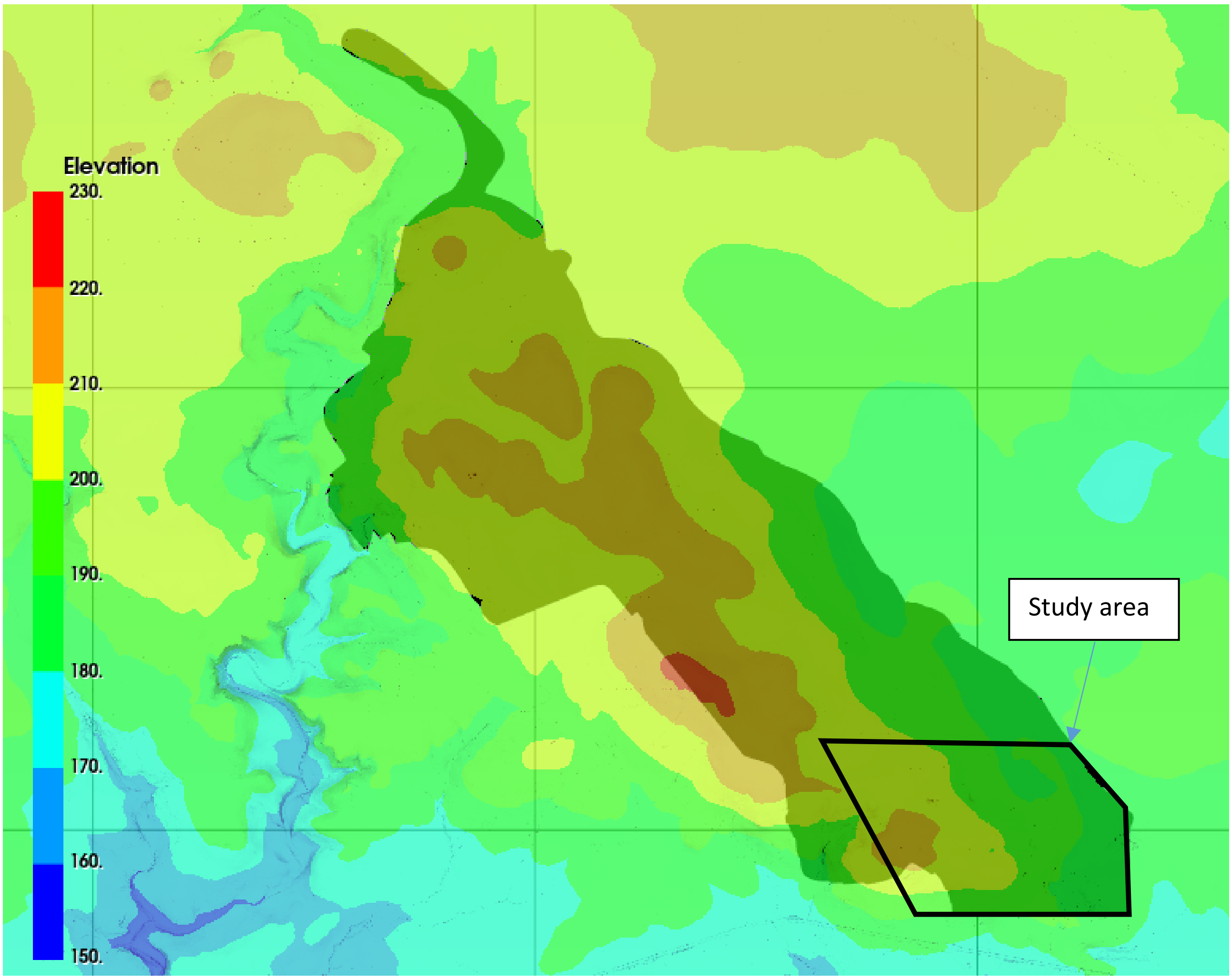

Figure 1 Topography of mining area, with open pit outline shaded. Grid is 2 × 2 km

The mine is in an area of moderate rainfall (around 430 mm average per year), with intense rainfall events (>100 mm in 24 hours) being extremely rare. Erosion from intense rainfall is therefore not expected to occur. The water table lies below the maximum planned depth (around 70 m below surface) of the mine; thus, any water accumulating within the dumps as a result of rainfall is likely to be ephemeral.

The fresh rock geology consists of a differentiated ultramafic complex, overlain by weathered zones derived from this host rock. The weathered zones contain the mineralisation. Fresh rock is not encountered within the current pit, and the final pit design does not intersect fresh rock. An east–west geological cross-section through the study area is shown in Figure 2.

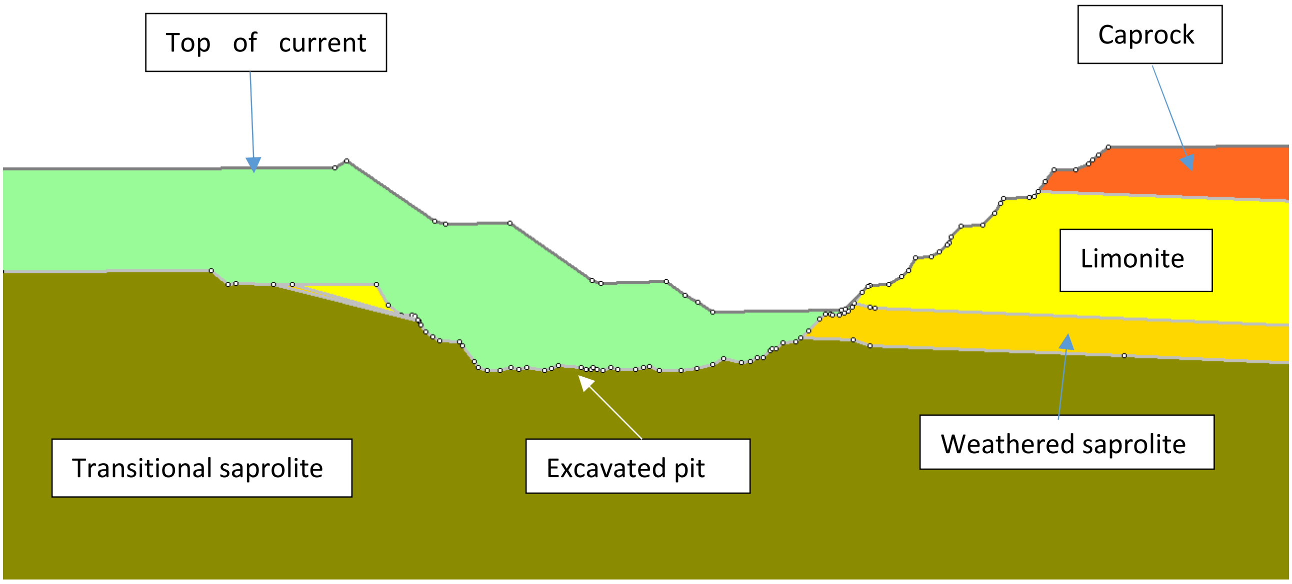

Figure 2 East–west cross-section through the study area

3 Geotechnical conditions of pit walls

Information on the geotechnical conditions of the in situ materials within the pit was taken from a previous study. No large-scale structural features that might affect the pit were identified during this study. Interpretation of drillcore logging did not show any identifiable structural patterns within the rock mass; however, it was noted that this might be due to insufficient data. No obvious major structures or structural patterns were noted during the author's site visit.

Rock mass strength parameters had been derived as part of the previous study from core logging data. The Hoek–Brown shear strength model was used for all units apart from the limonite clay (which occurs at the base of the limonite layer in Figure 2), for which a Mohr–Coulomb (M–C) shear strength model was used. These parameters were adopted for the modelling in this study, and they are shown in Table 1.

Table 1 Strength parameters used for modelling of in situ materials

Rock domain	Unit weight (kN/m^3)	Hoek–Brown parameters				Mohr–Coulomb parameters	
		σ_{ci} (MPa)	GSI	m_i	D	c (kPa)	ϕ (°)
Caprock	22	39	41	20	0.7	–	–
Limonite	21	41	42	9	0.7	–	–
Limonite clay	17	–	–	–	–	95	39
Weathered saprolite	22	15	56	15	0.7	–	–
Transitional saprolite	23	38	65	15	0.7	–	–

As previously noted, the pit is entirely above the water table. Thus, initial modelling scenarios did not include any water. A piezometric surface was added to some of the later modelled scenarios to test for sensitivity to water levels.

4 Waste material characterisation

4.1 Field observations

No work to establish shear strength parameters for waste material had previously been carried out for this mine, either by physical testing or by back-analysis. Additionally, no particle size distribution had been determined. The only classification made with regard to waste was based on its potential to contain fibrous material, in which case it was dumped in such a way that it would be completely encapsulated by non-fibrous material. Thus, it was not possible to determine where particular types of material had been deposited, and for modelling purposes the dumps have therefore been regarded as homogeneous. It was decided to use a physical examination of the waste material to assess 'first-pass' shear strength parameters, which could then be tested by comparison with published data, other shear strength models and back-analysis.

Once the pits have reached the base of the weathered saprolite material, the composition of the waste material is not anticipated to change significantly, as the different in situ layers do not change in thickness significantly across the deposit. Observations of stockpiles of waste material by the author during the site visit suggested that the dump material consisted of gravel to boulder-sized particles contained within a sand-sized matrix (Figure 3). The sand-sized fraction was sufficiently dominant to form a matrix supporting the larger-sized fraction material.

Figure 3 Typical waste material

In the author's experience, it has been standard practice to model sand-sized material using an M–C shear-strength model. Ranges of values for friction angle of granular materials are given by Terzaghi & Peck (1967); for materials with little or no clay-sized fraction, the cohesion is usually taken conservatively as 0 kPa. The batter faces of the already constructed parts of the dump have as-surveyed angles of between

33° and 35°. This suggests that adopting the 'standard' shear-strength model for sandy material, with a cohesion of 0 kPa and a friction angle of 33° (the lowest observed angle of repose), would be an appropriate and conservative approach for modelling the waste material.

4.2 Comparison of strength model types for waste rock

Literature searches, combined with a straw poll of practitioners in the mining industry, indicate that there are three main types of shear strength model in use for characterising waste rock in mining and quarrying.

The first type of strength model is the M–C model that was adopted as a 'first-pass' model for the material in this study. This model assumes that the effective friction angle of the granular material remains constant with increasing normal stress, whereas triaxial testing indicates that the friction angle of such material decreases with increasing normal stress. The M–C shear strength model is given by Equation 1.

$$\tau = c + \sigma_n \tan\phi \qquad (1)$$

where:

τ = shear strength.

σ_n = normal stress.

Φ = effective friction angle.

The second type is a power function, based on work undertaken by Leps (1970). Leps fitted straight lines to data from the triaxial testing results of different types of waste rock material to obtain upper and lower limits on friction angles of tested material, plotting the normal stress on a logarithmic scale. In this way, he was able to describe the way in which friction angle decreases with increasing normal stress in granular material. This model has been developed by several authors, and these relationships have been expressed in terms of shear strength and normal stress in the CSIRO publication *Guidelines for mine waste dump and stockpile design* (*Guidelines*) (Hawley & Cunning 2017). Hawley and Cunning have incorporated more-recent data into the work of Leps and derived power functions to enable shear-normal strength functions to be plotted for the range of rockfill from strong, well-graded materials to weak, poorly graded materials. The power functions are of the form shown in Equation 2.

$$\tau = a\,\sigma_n^{b} \qquad (2)$$

where:

τ = shear strength.

σ_n = normal stress.

a and b = constants.

To obtain the actual shear-normal function for a particular material, it would be necessary to undertake a program of triaxial testing with samples of that material, as this model is simply a type of mathematical function used to fit a curved line to experimental data. Alternatively, one of the example functions plotted in the CSIRO *Guidelines* may be used as an approximation of the type of material being modelled. This model will be referred to as the 'Leps model' in the rest of this paper.

The third type of strength model is an empirical relationship relating friction angle to three parameters: equivalent strength (S), equivalent roughness (R), and basic friction angle (ϕ_b). This relationship was developed by Barton & Kjærnsli (1981), and it has been discussed by several authors (e.g. Linero-Molina et al. 2021; Dwumfour et al. 2020). The full relationship is given by Equation 3.

$$\tau = \sigma_n \tan(\phi_b + R\log_{10}(S/\sigma_n)) \qquad (3)$$

where:

τ = shear strength.

σ_n = normal stress.

ϕ_b = basic friction angle.

R = equivalent roughness.

S = equivalent strength.

R is an empirical quantity estimated from the shape and angularity of the particles, together with the porosity of the compacted material. S is also an empirical quantity estimated from the 50% passing size (d_{50}) in mm and the uniaxial compressive strength (UCS) of the particle material. The estimation is done using charts given by Barton & Kjærnsli (1981). ϕ_b, the basic friction angle, is obtained from tilt tests on sawn blocks of the material and is normally within the range 25° to 35 (Barton & Kjærnsli 1981).

Although no testing data were available (as previously mentioned), a comparison was undertaken of the three different shear strength criteria, using estimated parameters to investigate the differences in predicted shear strengths arising from the three models. Two curves were plotted for the Leps model, one being the lower bound line from Hawley & Cunning (2017) and the other being the lower quartile line. The resulting shear-normal functions are shown in Figure 4.

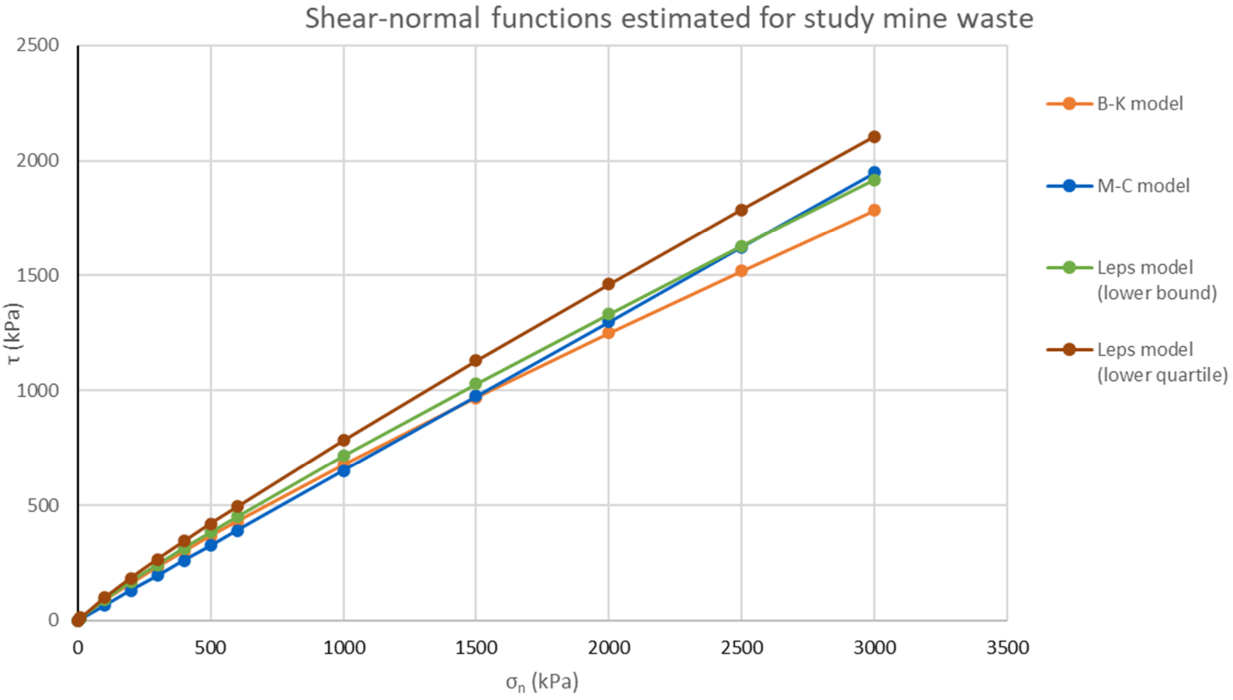

Figure 4 Comparison of shear-normal functions for the study mine waste

The parameters adopted for plotting the shear-normal functions in Figure 4 are listed below, together with brief notes on why these particular values were adopted. The functions used are those in Equations 1 to 3.

M–C model

c = 1 kPa

ϕ = 33

B–K model

ϕ_b = 25° (lower limit of the 'normal' range from Barton & Kjærnsli [1981]).

R = 7 (partly angular and 20% porosity – the value used by the mine engineers to estimate density).

S = 20 MPa (UCS of upper limonite and caprock; the dominant materials is 40 MPa, d_{50} estimated as 5 mm).

Leps model (i)

This is the lower bound function from Hawley & Cunning (2017).

Leps model (ii)

This is the lower quartile function from Hawley & Cunning (2017).

The reason for the adoption of a 1 kPa cohesion for the M–C model is described in the next section. The B–K parameters were probably the most difficult to estimate. What are assessed to be conservative values have been adopted for these: the lower limit for basic friction angle, a moderately angular shape and a relatively coarse 50% passing size of 5 mm.

The results in Figure 4 suggest that the lower quartile Leps curve is more optimistic than the other models. The lower bound Leps model and the M–C model match fairly closely at the scale of the plot; although, the M–C model is more conservative up to a normal stress of 2,500 kPa. The B–K model matches the M–C model well at low normal stresses but becomes more conservative at normal stresses above 1,500 kPa.

Thus for low normal stress, the M–C strength model represents the most conservative case of the three different model types. With a maximum design depth of 75 m, the maximum possible normal stress at the base of the waste dump is calculated to be 1,100 kPa. In the modelling undertaken, the actual maximum stress was 320 kPa for the 'final' dump, as the maximum dump thickness will not be reached until full backfilling of the pit (where the toe of the dump will be supported by the pit wall) is being undertaken. The current progress of the backfilling with respect to the pit can be seen in Figure 2. As a result of this, it was decided to use the M–C strength model for the dump stability analyses.

5 Back-analysis and dump stability modelling

5.1 Back-analysis

Back-analysis of some lower dump faces was undertaken to attempt to derive a cohesion value to account for their higher face angles than the 'friction-only' M–C shear strength model would account for. (The B–K and Leps models vary friction angle with normal stress so that a cohesion value is not required.) The 2D Rocscience limit equilibrium software SLIDE2® was used for this back-analysis and all dump stability analyses. As no information was available detailing the deposition history of any of the dumps, it had to be assumed that the material was homogeneous. For this situation, a circular failure surface model would generate the lowest Factors of Safety (FoSs), so this option was selected. The 'grid search' method was used to generate potential failure surfaces.

Three sections where the batter face had different heights were selected and the profiles obtained from survey pickup. Batter face angles varied from 37° to 39°. Using a friction angle of 33°, the cohesion was varied from 0 kPa to 3 kPa for each section. The results of one of the modelled sections is shown in Figure 5.

The results of the back-analysis showed that for the various sections a cohesion of 1 kPa gave FOSs very close to 1. This value was therefore adopted for the modelling going forward.

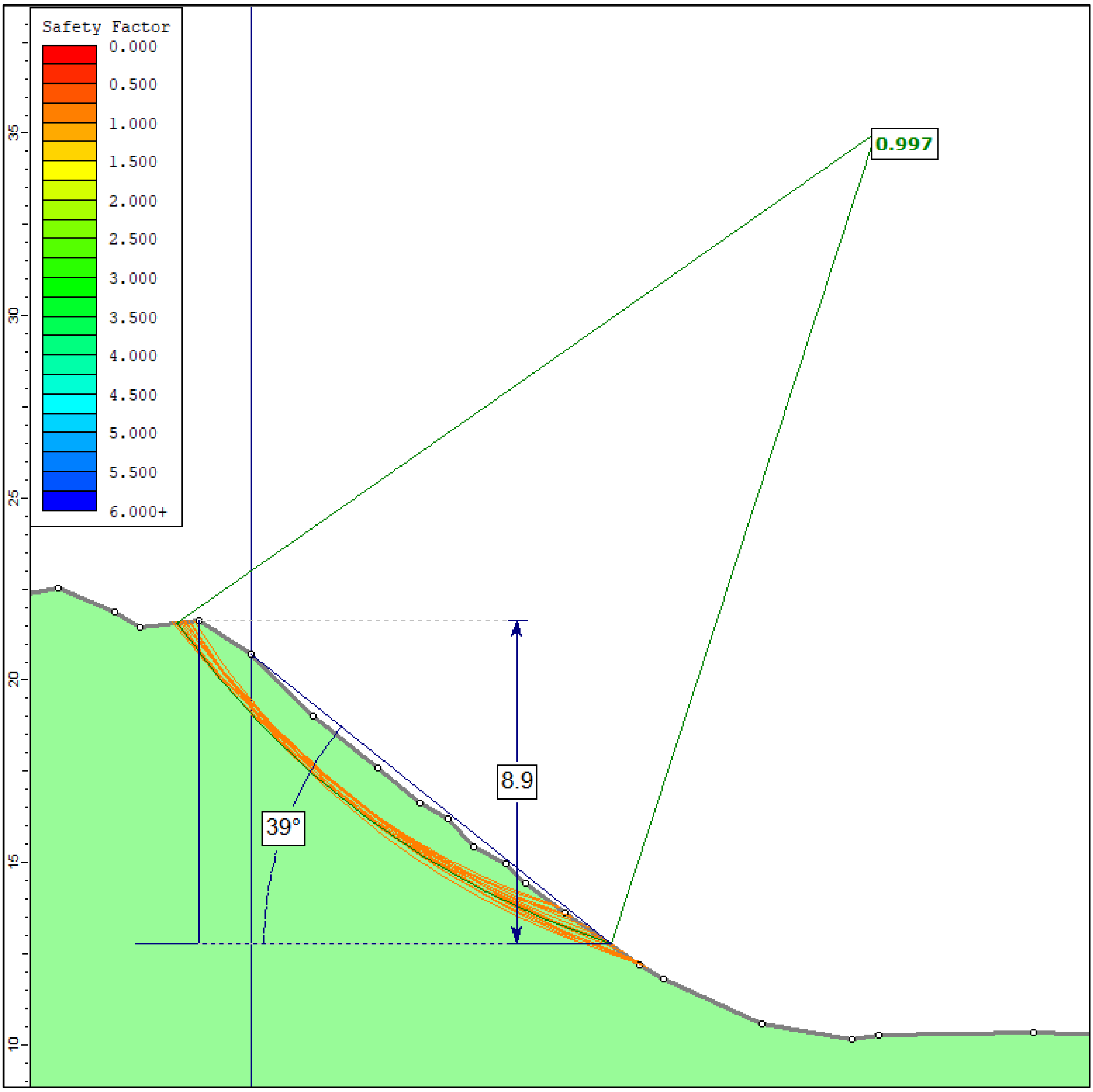

Figure 5 Example section used in back-analysis. Properties adopted c = 1 kPa and φ = 33°

5.2 Dump stability modelling

Dump stability modelling was undertaken to address the following issues identified by the mine engineers:

- An assessment of current stability.
- Effect of machinery working near the edge of the dumps.
- Effect of water on the dump stability.
- Stability of the final proposed design.
- Effect of increasing lift height to 15 m.

These models were run on an east–west section of the existing dump, as shown in Figure 6. The results of the modelling to address the issues listed above are shown in Figures 7 to 12. All of these analyses were undertaken using Section 1 in Figure 6.

A further model was run to assess the effect of incorporating the weak limonitic clay, which had not been mapped in sufficient detail to enable a DTM to be generated. This analysis was undertaken on Section 2, where the geometry of the base of the limonite saprolite (used as an assumed location for limonitic clay) was less favourable than that of Section 1. The results of this model are shown in Figure 13.

The results of the assessment for each of the dot points above, plus the effect of the presence of the limonitic clay layer are discussed in the following sub-sections.

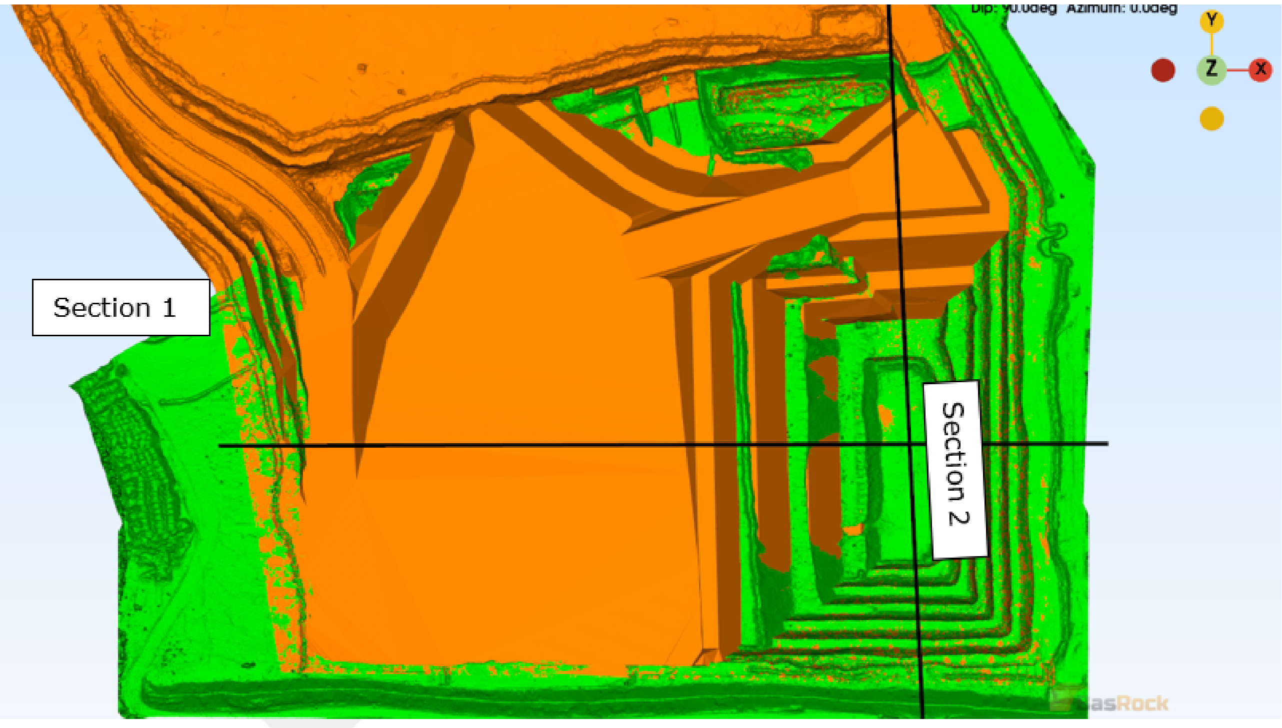

Figure 6 Location of modelled sections within the study area

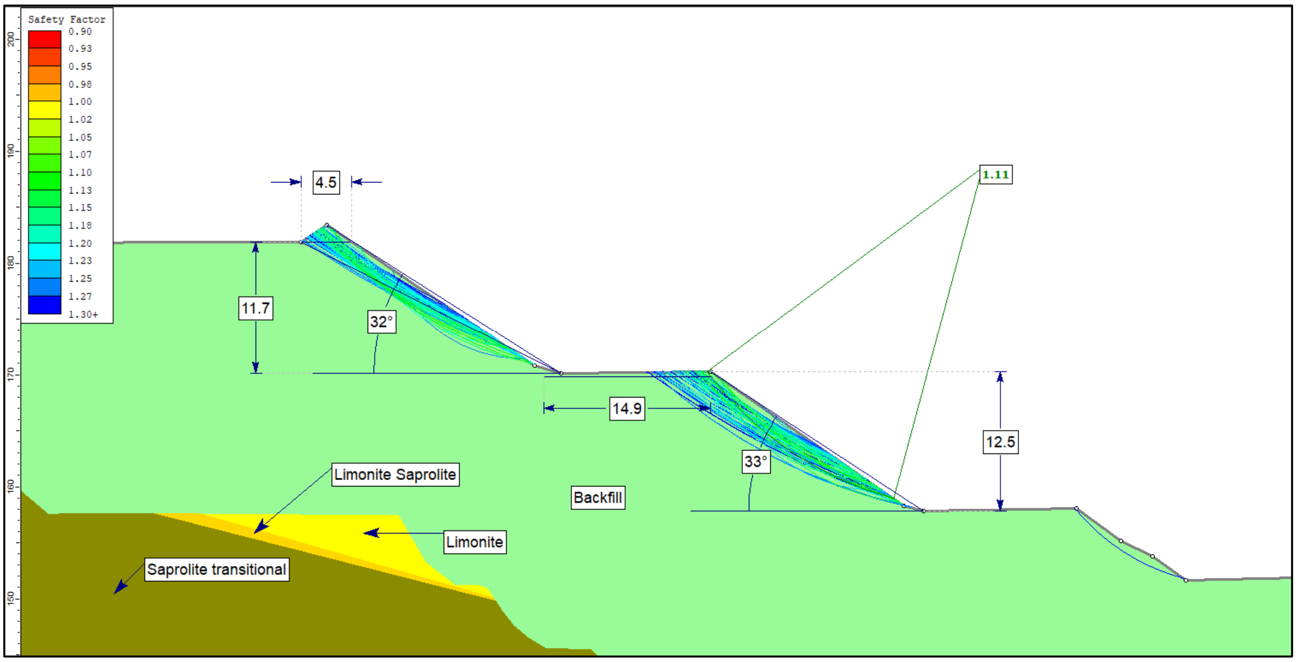

Figure 7 'Base case' model—existing dump profile. All surfaces with modelled FoS ≤ 1.3 are shown

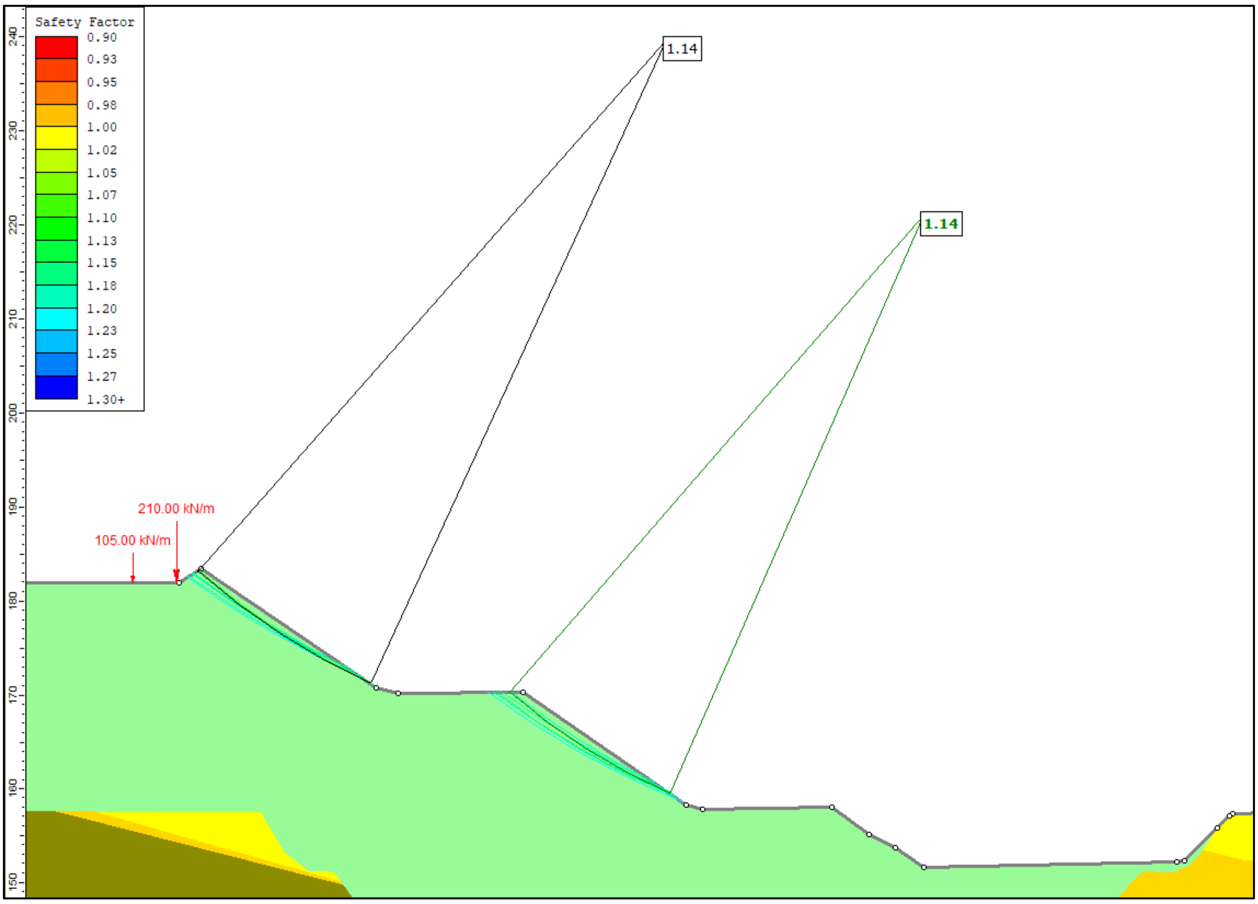

Figure 8 'Base case' model—with truck loading. All surfaces with modelled FoS ≤ 1.2 are shown

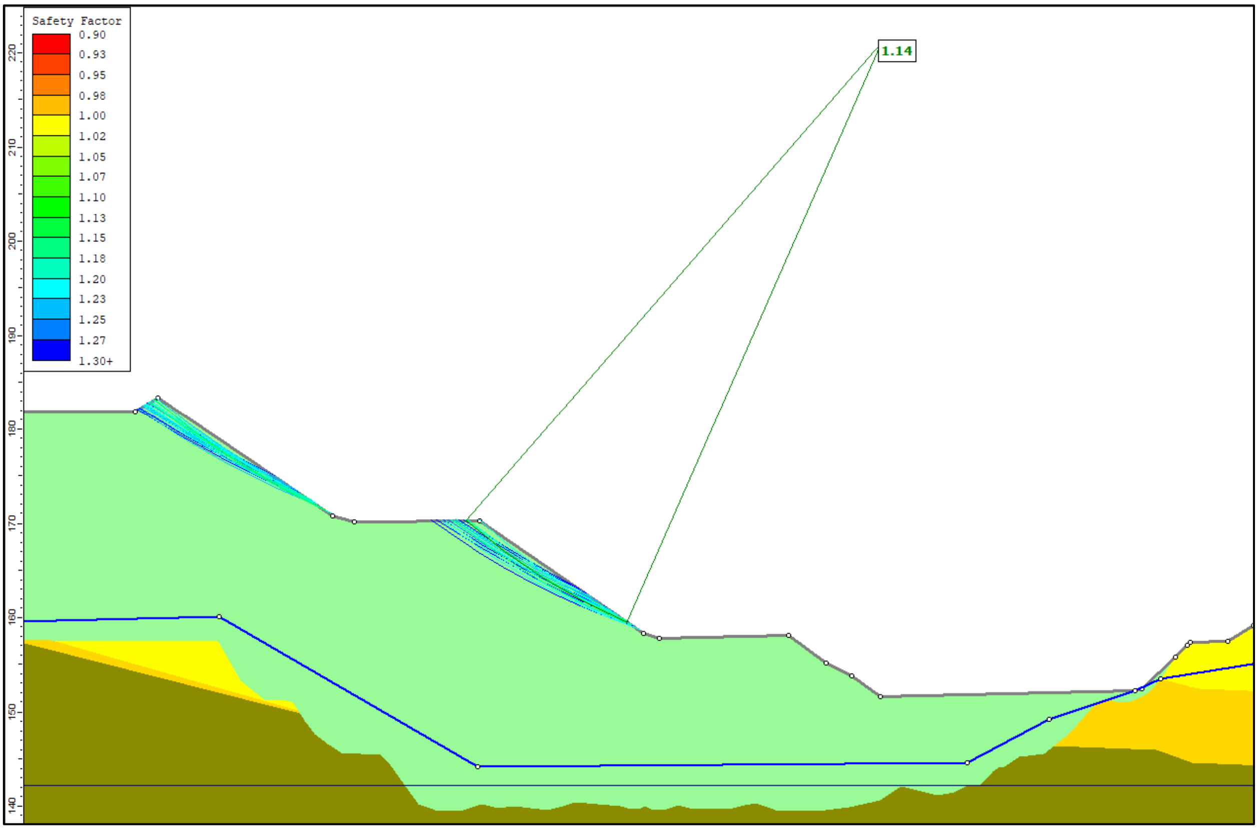

Figure 9 Water table 2 m above mined surface. All surfaces with modelled FoS ≤ 1.3 are shown

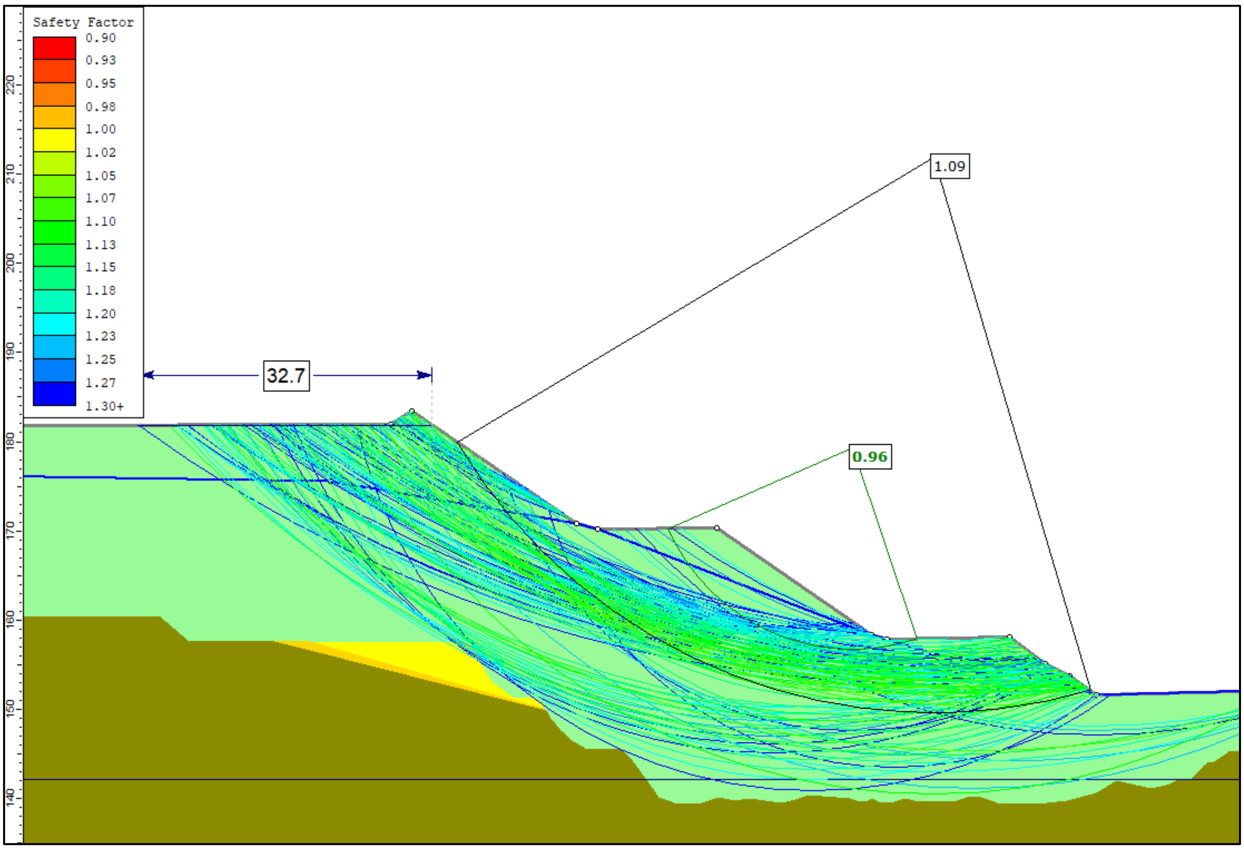

Figure 10 Very high water table. All surfaces with modelled FoS ≤ 1.3 are shown. The lowest FoS surface for an inter-ramp scale failure is also shown

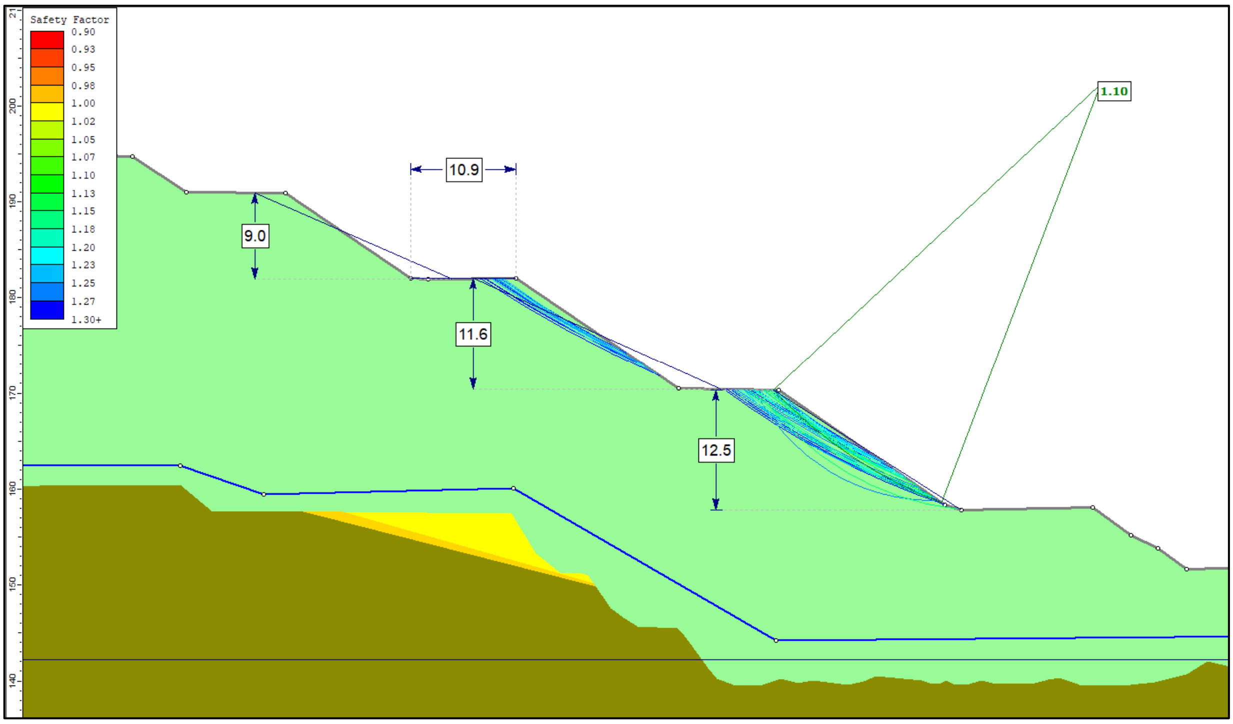

Figure 11 Final dump design; all surfaces with modelled FoS ≤ 1.3 are shown

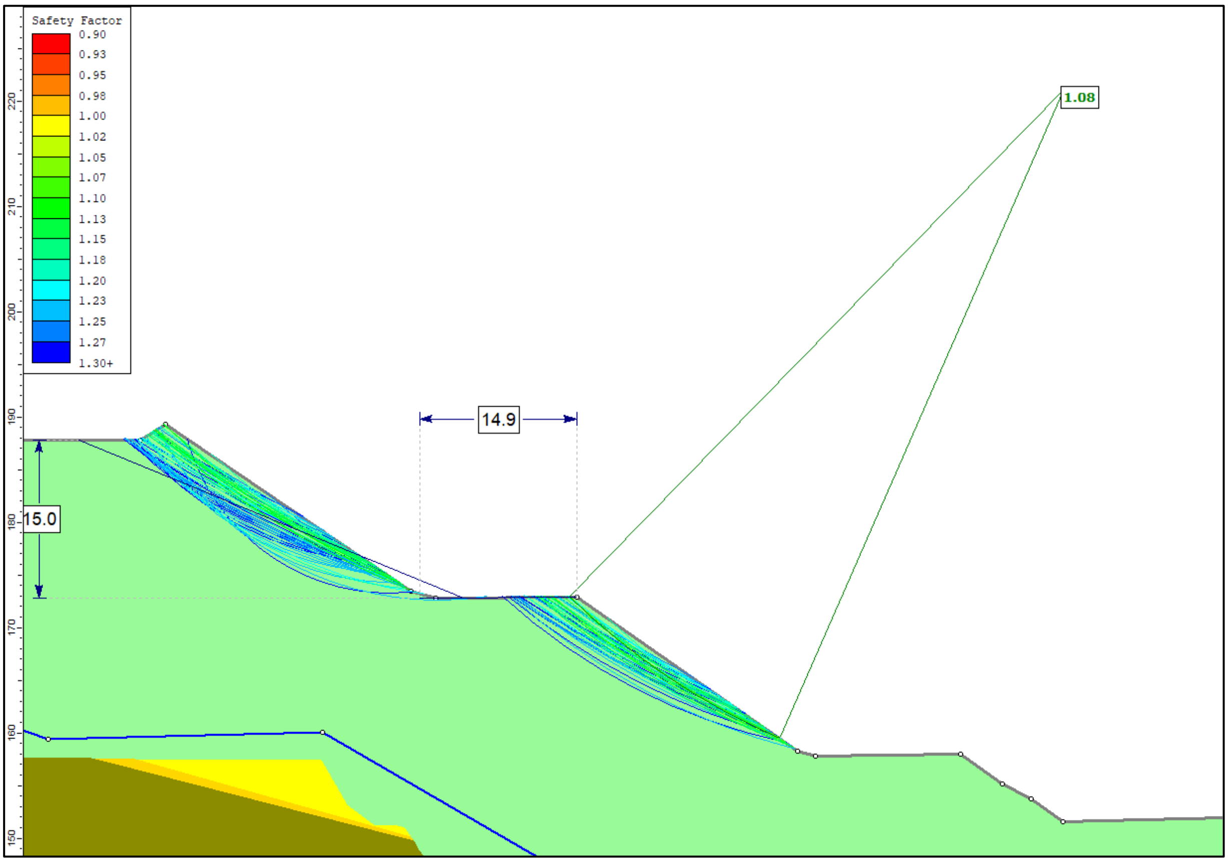

Figure 12 Dump design with 15 m lifts. All surfaces with modelled FoS ≤ 1.3 are shown

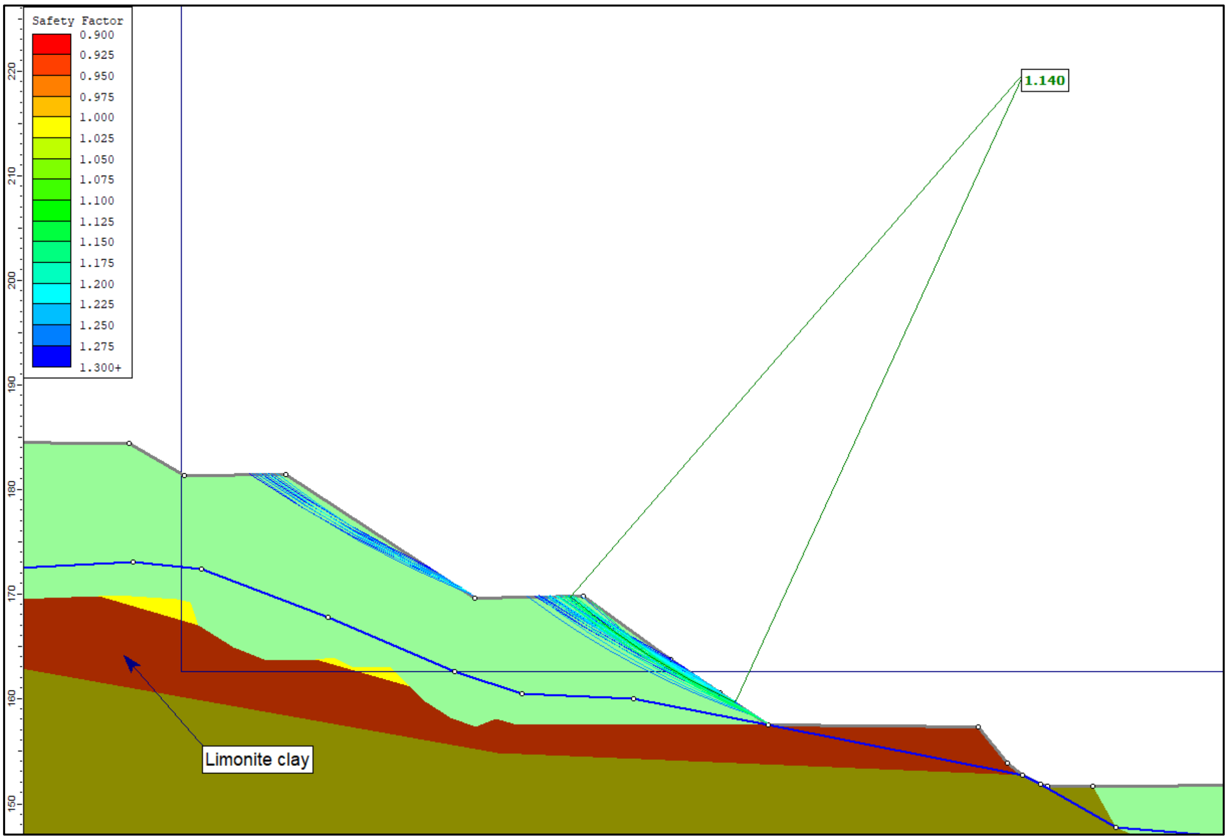

Figure 13 Section 2: effect of explicitly modelling weak clay layer. All surfaces with modelled FoS ≤ 1.3 are shown

5.2.1 *Assessment of current stability*

Using the M–C parameters described previously, the current dump is modelled to be stable in dry conditions. No surfaces with modelled FoS ≤ 1.3 break back more than 4.5 m from the pit crest (Figure 7).

5.2.2 *Effect of machinery working near the edge of the dumps*

The mine uses Cat 777 trucks for hauling and dumping. The forces applied by a loaded truck with its rear wheels touching the pit-edge windrow were simulated as shown in Figure 8. There is no change to the minimum Factor of Safety modelled, but a slight reduction in the FoS of surfaces that break back no further than the pit-edge windrow (from 1.3 to 1.2) resulted from the extra loading.

5.2.3 *Effect of water on the dump stability*

As previously mentioned, the mine is designed to be entirely above the water table, so the normal state of the dumps should be completely dry. However, some water infiltration during rain events is to be expected, particularly as the drainage assessment of the current dumps (see next section) suggests that water falling on the dumps will tend to infiltrate rather than runoff. Two scenarios of temporary water tables were modelled: a 2 m rise above the mined surface within the dump and a much higher rise (16 m above as-mined surface). The results of these two scenarios are shown in Figures 9 and 10.

The results indicate that a modest rise in water levels within the dump do not noticeably affect the modelled FoS, but a large rise could potentially cause large-scale failure, possibly extending across more than one batter. Failure surfaces with FoS ≤ 1.3 break back to almost 35 m behind the slope crest in this latter scenario.

5.2.4 *Stability of the final proposed design*

The final dump design is proposed to extend a further two full lifts (24 m total vertical height increase) above the current top of the waste dump (Figure 11). The modelling results suggest that this will not adversely affect stability.

5.2.5 *Effect of increasing lift height to 15 m*

An alternative design that increases the height of each dump lift to 15 m while retaining 15 m wide berms (Figure 12) was assessed. This did not result in a significant change to the lowest modelled FoS, or significantly change the back-break surfaces with FoS ≤ 1.3. This is due to the fact that the lowest modelled FOSs are for single-batter slips, and the strength is modelled using the M–C criterion with a very low cohesion, making it relatively insensitive to scale changes.

5.2.6 *Effect of limonitic clay*

A model for the limonitic clay at the base of the limonite layer has not been developed; therefore, for the purposes of assessing the effect of this material on dump stability, the modelled shape for the limonite saprolite layer was used to represent this material. A different section (Section 2), where this layer is thicker and dips into the pit void beneath the dump was selected as a less favourable scenario for this modelling. The strength parameters derived for this material in the pit design study were used in the assessment. The results, shown in Figure 13, show no difference in modelled stability from the modelling for Section 1, even though the limonitic clay unit was modelled to be largely below a water table.

6 Drainage assessment

Water flow modelling was undertaken by using the Trajec3D package to simulate rainfall on and around the study area. The modelling enabled flow paths to be identified and areas with different flow characteristics to be determined. The modelling results are shown in Figure 14.

In general, the modelling suggested that water would NOT flow onto the dump from outside the pit; any rain falling outside the pit limits was modelled to either percolate down into the ground or flow away from the pit due to natural topography. The pit-edge windrows also assist in keeping water from flowing into the pit from outside.

Within the pit, the current pit void acts as a sump for any rain falling on the east side of the study area. The top of the waste dump within the pit is largely flat; some ponding areas were identified, as shown in Figure 14. More importantly, with the current geometry, there was no modelled flow off the top of the waste dump and into the pit void; all water falling onto the dump is expected to percolate into it.

This modelling identified areas where modifications to drainage and dump geometry were needed in order to improve runoff. With the pit being situated over a natural topographic high, it was only to be expected that rain falling outside the pit would tend to flow away from it. As water was already flowing into the remnant pit void, as shown in Figure 14, the logical solution would be to redesign the top of the dump with a suitable crossfall (3° to allow for drainage but not cause excessive erosion of the top of the dump). One single point of drainage into the pit void was suggested to the mine engineers so that any erosional damage would be localised. This would also allow for installation of liners if early observations suggested that erosion was an issue.

However, even if these drainage measures are implemented, some infiltration into the waste dump should be anticipated. In particular, periods of prolonged rain could result in significant amounts of water penetrating into the dump, with a subsequent rise in the groundwater table. Although the modelling has shown that the groundwater levels would need to be very high within the dump material to significantly affect stability, there is no way of measuring these levels at present. It would be possible to install standpipe piezometers within the dump to measure water levels, but drilling holes through unconsolidated material such as waste dumps is expensive. As filling of the pit void is currently planned to be complete within a maximum of two to three years, there would be a relatively large investment required for possibly little return. Thus, while failure due to groundwater levels appears to be a fairly remote possibility, it is likely that the groundwater levels within the waste dumps will remain unknown.

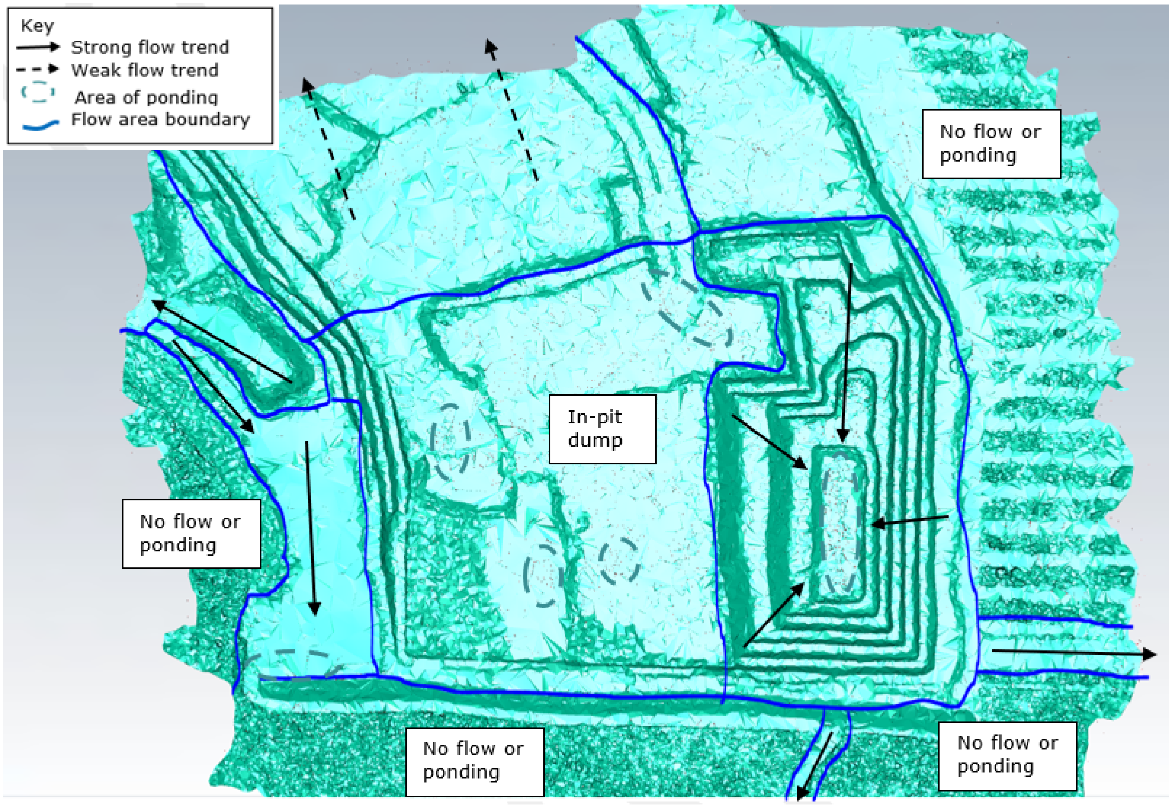

Figure 14 Results of rainfall simulation using Trajec3D for the study area. Arrows indicate flow directions

7 Conclusion

With regard to this particular example, the assessment and stability modelling identified no stability issues with either the current or the final dump design. The M–C shear strength model has been assessed as suitable for a dump of this size. There is uncertainty regarding the levels to which groundwater may rise in response to rain events within the waste dump. A wholesale dump redesign is not required; although, it would be prudent to regrade the top of the dump, both during construction and in the final landform, to allow rainfall to runoff rather than percolate into the dump. This would help to reduce, but not eliminate, water infiltration. It might also be prudent to limit access to the top of the waste dump to more than 35 m from the dump crest following large rainfall events.

More generally, the following points can be made:

- The M–C shear strength model compares well with the B–K model and Leps model for low normal stresses up to around 1.5 MPa. Above this, the M–C model may be overoptimistic compared with the B–K or Leps models. In this case study, the stresses were such that the M–C could be applied, but if the dumps were to be significantly increased in height, an alternative shear strength model should be used.
- The load applied by trucks dumping at the pit crest does not have a large effect on the FoS of the pit crest. This, however, assumes that the material forming the pit crest is easily compacted by the weight of previous trucks and ancillary equipment running over it. Some clay- and talc-rich materials do not compact easily, particularly when dry, and can have a very powdery consistency.
- Water within dumps can have a great effect on the FoS of the dump. In this instance, that is not the case, but particularly where there is a weak substrate, a relatively small rise in water level can lead to a significant decrease in stability. Water levels in dumps are problematic to assess, and all efforts should be made to prevent ponding if studies indicate that water levels will be an issue.
- Waste dumps that are constructed outside a pit may be built on materials that have not been well characterised. In this instance, the pit materials had been the subject of a ground investigation, which allowed strength properties to be adopted based on logging and testing results rather than guesswork. Foundation conditions are just as important as the characterisation of dump material itself, and areas for ex-pit dumps should always have a ground investigation carried out before dumping begins.

Acknowledgement

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