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Earthquakes are Exciting for Coal Miners too

John V Simmons[1,2] (*john.simmons@sgrs.au*)

1. *Sherwood Geotechnical and Research Services, Peregian Beach Qld 4573*
2. *The University of Newcastle, Callaghan NSW 2308*

Abstract

Earthquakes remain exciting to but greatly misunderstood by the mining community. Open cut coal mines regularly undertake blasting and monitor the effects on slopes. Earthquake analogies to blast vibration loadings are often discussed but rarely investigated other than observations that blasts will displace rocks but earthquakes do not displace many rocks at all. While most coal mines are located in areas of low seismic hazard, the random timing of earthquake loadings means that risk reduction measures applying to personnel and equipment are limited in scope. This paper outlines the typical approach taken to earthquake risk management for coal mine slopes, in contrast to the more informed approach applied to coal mine tailings dams. Simplistic stability screening is generally used, while rigid-block movement analysis is rarely used, and both are of untested reliability. Coupled dynamic modelling is the most rarely used last resort. Rockfall-based risk reduction measures are probably adequate in most situations, but this paper is a plea for a more informed discussion and perhaps some welcome initiatives for improved understanding of how best to model earthquake load action effects for pit slopes.

Keywords: slope stability; rockfall; pseudo-static loads; screening; risk reduction measures

1 Introduction

Open cut coal mining involves excavation and waste dumping at scales that dwarf other engineered structures. Current excavated slope depths range from less than 100 m to about 300 m, with plans to go deeper. Current dumped slope heights range up to 350 m height. Slopes are designed to be stable based on a body of geotechnical knowledge that has evolved from observations, limited-scale materials testing, and back-analyses of full-scale instabilities.

Geotechnical practitioners at open cut mine sites typically have primary geological rather than engineering training with minimal exposure to earthquake engineering principles and practices even after specialised study. Earthquakes at mine sites are typically rarely felt and much less exciting than large-scale production blasting. The requirement to "design for earthquake" is typically imposed by site safety and health administrative procedures in response to regulatory requirements, but the existence of AS 1170.4 or any alternative is not widely recognised. The regulatory requirements are well-meant but not explicit regarding details. In the event of an earthquake-related incident involving significant damage or loss this is potentially likely to result in a lawyers' picnic.

Geotechnical slope "design for earthquake" ranges widely from dismissal based on lived experience as the primary response to the simplest alternative involving reliance on a simplified screening approach.

2 Seismic Hazards at Coal Mines

2.1 Black Coal and Brown Coal

Australia's geological evolution has generated widespread coal deposits that can be subdivided into two classes: black coals of sub-bituminous and higher rank from Palaeozoic and Mesozoic deposits primarily in Queensland and New South Wales, and brown coals (lignites) of Cenozoic age primarily in Victoria. The black coal deposits have been subjected to multiple tectonic processes, buried deeply and subsequently uplifted and eroded, and located in areas of relative seismic inactivity . The brown coal deposits tend to be thick with mild tectonic history, but interbedded with clays and gravels and subjected to high groundwater pressures. The Latrobe Valley lignite deposits are located within one of the more seismically active areas of Australia. Both coal types are mined at large-scale, but the black coal and brown coal industries are driven by different economics and share very little technical knowledge except at the output end of electricity generation.

2.2 Design Considerations

Open cut coal mining takes place where it is most economic to dig a big hole from surface rather than to tunnel to access coal resources, and this corresponds to Class B_e or (less often) Class C_e sites. Coal mine workers vastly outnumber geotechnical practitioners, therefore it is most likely that questions regarding any differences between blasting and earthquake load action effects on slope hazards and risks will arise from people with minimal technical background.

Based on lived experience to date, coal mine slopes have a demonstrably low consequence of failure corresponding to AS 1170.0 Importance Level 1. However, in the event of an arbitrarily timed earthquake-induced rock or dump slope collapse there is potential for multiple fatalities corresponding to Importance Level 2. Geotechnical specialists should thus be mindful that AS 1170.4 Table 2.1 implies that a minimum level of earthquake loading should be assessed and appropriate design conditions documented.

AS 1170.4 Table 2.1 was prepared for structural engineering applications so guidance regarding an appropriate minimum value of (k_pZ) for slopes is a matter of interpretation. In practice, the appropriate map from AS 1170.4 Figure 3.2 is consulted and in most locations a pga of typically 0.08g is adopted without further questioning. As discussed below, there is little awareness of alternative approaches related to tailings dam design.

2.3 Practical Operational Considerations

Excavated or dumped slope instability is relatively rare, but the consequences can be wide-ranging and recovery very costly. Risk reduction measures are primarily at design-level, requiring input and verification from geotechnical stability assessment based on a geological and geotechnical model. Implementation in accordance with design must be monitored.

Rockfalls in open cut coal mines happen on a regular basis despite adequate design and implementation and for a wide range of reasons. Operational risk reduction measures range from administrative rules regarding "drop zones", physical windrows to demarcate exclusion zones for unprotected personnel and to trap displaced materials, to falling object protection systems (FOPS) for plant and equipment.

Risk reduction measures are often summarised in TARPs (Trigger Action Response Plans). Most triggers are based on movement observations with time histories. Earthquake loadings occur immediately and without warning, so effective risk reduction measures rely upon design-level slope stability and rockfall trajectory analysis. Assessment, interpretation, and communication of stability and rockfall matters are the primary role of site geotechnical practitioners. When coal mine workers experience earthquakes there are usually questions asked about slope stability.

2.4 Contrast with Coal Mines Tailings Dam Design

The majority of coal mines have coal handling and preparation plants that generate carbonaceous waste streams including gravelly rejects and clay-silt mixtures in slurried form (tailings). Design and construction of tailings storage facilities includes mandatory consideration of earthquake load action effects and potential liquefaction of materials including foundations, embankments, and stored tailings. Designs are usually carried out by dam design specialists with appropriate geotechnical knowledge, skills, and experience. It is routine for such designs to be based on pga levels for maximum credible and design basis earthquakes determined at different annual exceedance probabilities from site-specific seismic hazard assessments.

Geotechnical design for tailings dams typically commences with limit equilibrium stability pseudo-static screening analyses, described below. Depending on the screening outcomes, it may be necessary to undertake either simplified block-sliding or fully dynamic deformation modelling to determine acceptability of a design. Irrespective of the screening outcomes, identification and specification of materials are required to resist or limit liquefaction potential.

Typically, coal mine geotechnical practitioners have minimal involvement with and limited awareness of the earthquake design processes that are applied to tailings dams, and usually have little experience or even awareness of deformation modelling.

3 Geotechnical Earthquake Analysis for Pit Slopes

Geotechnical earthquake engineering evolved in parallel during the 1920’s to 1970’s formative period of the soil and rock mechanics disciplines, and with particular applications to large dams. At this time also the ground deformations from devastating earthquakes were being interpreted for development of design tools. The introduction of digital computers into engineering practice enabled all of these developments to be integrated into current design procedures that require specialised training.

3.1 Rigid-Block Deformation Modelling

Newmark (1965) described a rigid-block methodology by which the inelastic deformation of a dam structure subjected to earthquake loading could be predicted. This method is based on adopting a strong-motion acceleration-time record and calculating the directional incremental movement for the portions of the accelerogram where shear sliding of the idealised rigid block could occur based on the adopted strength characteristics. The calculation involves the energy balance between block movement and shear dissipation. When first introduced this methodology challenged available computing facilities, but it was demonstrated to predict observed seismically induced dam movements reasonably well.

Currently the Newmark method, enhanced to include more model detail and later advances in strength characterisation, is available for routine use by geotechnical practitioners. However, it is not widely applied other than for dam design, and even then it requires careful time-consuming modelling.

3.2 Pseudostatic Screening

As the Newmark method became more widely used for dam engineering, it became the subject of debates regarding two issues:

1. For any given location, what would be an appropriate accelerogram to adopt for design, given that it should be scaled to reflect the design pga (determined by an unspecified method)?
2. In many circumstances the predicted result was negligible movement, so would it be possible to simply “screen-out” the cases where rigid-block modelling would not be necessary?

The first issue remains a design issue that can be addressed in many ways, preferably with advice from seismologists and engineering geologists with experience of seismic events. The libraries of accelerograms typically available in geotechnical stability analysis codes are selected with such advice but are sourced from large magnitude plate boundary earthquakes.

The second issue was the subject of detailed review by the US Army Corps of Engineers, based on applying a lateral acceleration to the earth structure as a “pseudo-static” load. Hynes-Griffin and Franklin (1984) published the details and outcomes of this review, which is now known as the Pseudostatic Screening method. Key recommendations were:

- Carry out a conventional pseudostatic stability analysis using a horizontal seismic coefficient of 0.5 pga determined by an unspecified process;
- Determine appropriate dynamic strengths for earthquake cyclic loads, and factor these by 0.8;
- If the computed Pseudostatic Factor of Safety is 1.0 or greater, the likelihood of significant deformation is too low to warrant dynamic analysis.

There were some important caveats: the method is not applicable to earthquakes of magnitude 8.0 or greater, not applicable to liquefiable materials; and not applicable to structures vulnerable to small deformations. While the magnitude caveat is unlikely to be an issue in Australia, the liquefaction and vulnerability caveats require appropriate consideration.

As experience with the pseudostatic screening approach accumulated and there were improvements in laboratory test procedures and computational capabilities, further questioning of the methodology arose. These applied particularly to the determination of dynamic strengths and to a more nuanced approach to the factoring of pga, and are well summarised in Jibson (2011). The US Geological Survey, with primary concern for seismically induced landslides, developed the publicly available code SLAMMER (Jibson et al, 2013) which now forms the basis for the Newmark and pseudostatic analysis modules in current commercially available slope stability codes. Slide2 (RocScience, 2023a) is the code utilised for the analyses described in this paper.

3.3 Dynamic Deformation Modelling

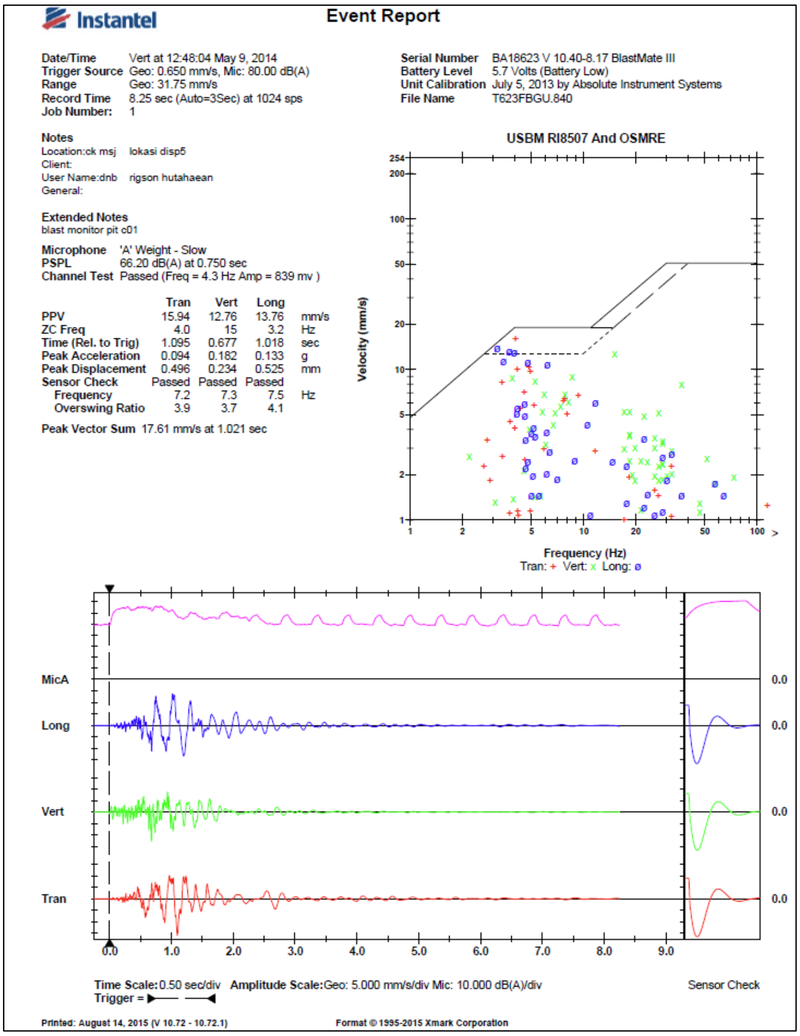
Dynamic deformation modelling is required where the consequence assessment warrants evaluation of stability under seismic loading and the slope design does not pass the pseudostatic screening process. Currently dynamic deformation modelling can be undertaken using a variety of computational methodologies in either two- or three-dimensions. RS2 (RocScience, 2023b) is the general-purpose finite element analysis-based code used by the author, while FLAC3D (Itasca International, 2023) is a widely used finite difference analysis-based code. It is worthwhile noting that, despite any claims by vendors, all such codes are technically equivalent and their ultimate value rests with the manner in which they are applied.

The advantage of dynamic deformation modelling is that the stress-strain-strength behaviour of materials under seismic loading can be more realistically modelled, provided that the input data specifications are realistic. There is an abundant geotechnical literature regarding such matters, but such analyses are normally undertaken by geotechnical specialists and very rarely undertaken by minesite practitioners.

3.4 Analogy with Blast Vibration Monitoring

Large-scale blasting is a feature of the open cut coal mining industry. Blasts are typically monitored visually using drones and physically using geophones and microphones to collect data for compliance with authorised environmental criteria. The data that is routinely collected is rarely reviewed unless there is a non-compliant or otherwise unsatisfactory blasting outcome. Blasts are usually designed to achieve optimal fragmentation and cheapest cost in a compliant manner.

Figure 1 is an example of such a monitoring report, from which it may be noted that lateral pga is in excess of 0.08g with a vertical pga that is comparable in magnitude. From a mining engineers' perspective, such pga levels are typically ignored as the noise level and peak particle velocities are of most direct interest and accountability.



Instantel **Event Report**

Date/Time Vert at 12:48:04 May 9, 2014
Trigger Source Geo: 0.650 mm/s, Mic: 80.00 dB(A)
Range Geo: 31.75 mm/s
Record Time 8.25 sec (Auto=3Sec) at 1024 sps
Job Number: 1

Serial Number BA18623 V 10.40-8.17 BlastMate III
Battery Level 5.7 Volts (Battery Low)
Unit Calibration July 5, 2013 by Absolute Instrument Systems
File Name T623FBGU.840

Notes
Location:ck msj lokasi disp5
Client:
User Name:dnb rigson hutahaean
General:

Extended Notes
blast monitor pit c01

Microphone 'A' Weight - Slow
PSPL 66.20 dB(A) at 0.750 sec
Channel Test Passed (Freq = 4.3 Hz Amp = 839 mv)

	Tran	Vert	Long	
PPV	15.94	12.76	13.76	mm/s
ZC Freq	4.0	15	3.2	Hz
Time (Rel. to Trig)	1.095	0.677	1.018	sec
Peak Acceleration	0.094	0.182	0.133	g
Peak Displacement	0.496	0.234	0.525	mm
Sensor Check	Passed	Passed	Passed	
Frequency	7.2	7.3	7.5	Hz
Overswing Ratio	3.9	3.7	4.1	

Peak Vector Sum 17.61 mm/s at 1.021 sec

Time Scale:0.50 sec/div **Amplitude Scale:**Geo: 5.000 mm/s/div Mic: 10.000 dB(A)/div
Trigger = ▶—— ——◀

Printed: August 14, 2015 (V 10.72 - 10.72.1)
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Figure 1 Example of minesite blast vibration monitoring report

Other notable features of this example report include the detectable frequency range (typically greater than 2

Illustrative Example of Seismic Stability Analyses

To place some context on the above discussion, an example 265 m high dump slope was analysed for seismic stability for a pseudostatic horizontal acceleration of 0.08g. This dump would be constructed incrementally to a final (end of mining) profile ideally as steep as could be managed operationally by routine truck dumping, with 30 m tiphead lifts separated by 10 m wide benches for rockfall management purposes. Shear strengths for the spoil materials are reliably known, and the 5 m depth of the groundwater table during mining operations is empirical but backed by multiple lines of indirect evidence.

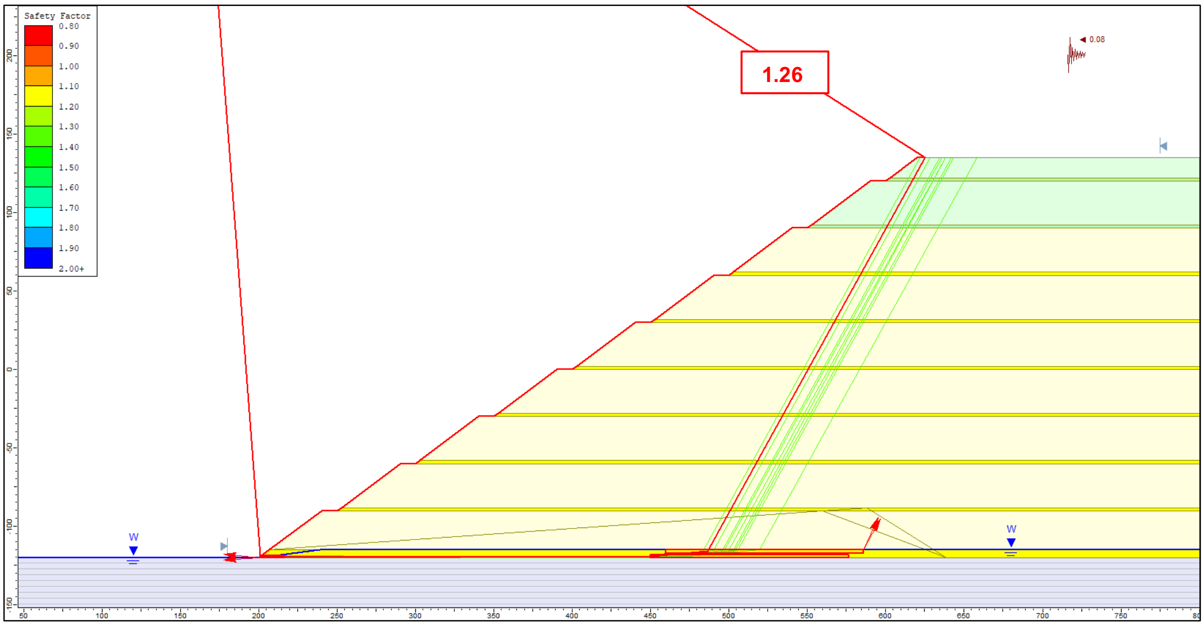

Figure 2 Critical stability condition FOS = 1.26 for 265 m height spoil dump operational condition with pga applied (green shapes are the 10 most critical mechanisms)

Without the effect of seismic loading the minimum computed limit equilibrium Factor of Safety (FOS, the factor by which all strengths have to be reduced to bring the slope to the point of instability), calculated using the Morgenstern-Price method for vertical slices, was 1.60 (not illustrated). Figure 2 shows the critical potential instability mechanism when the pseudostatic horizontal acceleration was introduced, with the minimum computed FOS reduced to 1.36.

For operational purposes, and with the available level of confidence in the geotechnical model, the design acceptance criterion would be 1.20, in other words a 20% margin in strength over the condition where instability would be triggered.

In context, very few earthfill or rockfill dams are constructed to such heights, and if so, are very carefully compacted. However, dams are water retaining structures subjected to significant seepage forces which have to be accommodated safely by the slope profile design. For this example, the planned post-mining landform might comprise minimal reconfiguration of the slope profile but accommodate the effects of runoff and seepage water that would accumulate in the final void. Accumulation might take decades or centuries, and it would be inevitable that the water table within the spoil dump would effectively equilibrate to the void water level.

Figure 3 shows the critical potential instability mechanism for a final void water level 120 m above the pit floor. When the pseudostatic horizontal acceleration is added, the minimum computed FOS is reduced to 1.04, due to the reduction in shear strength that is known to occur under saturated conditions.

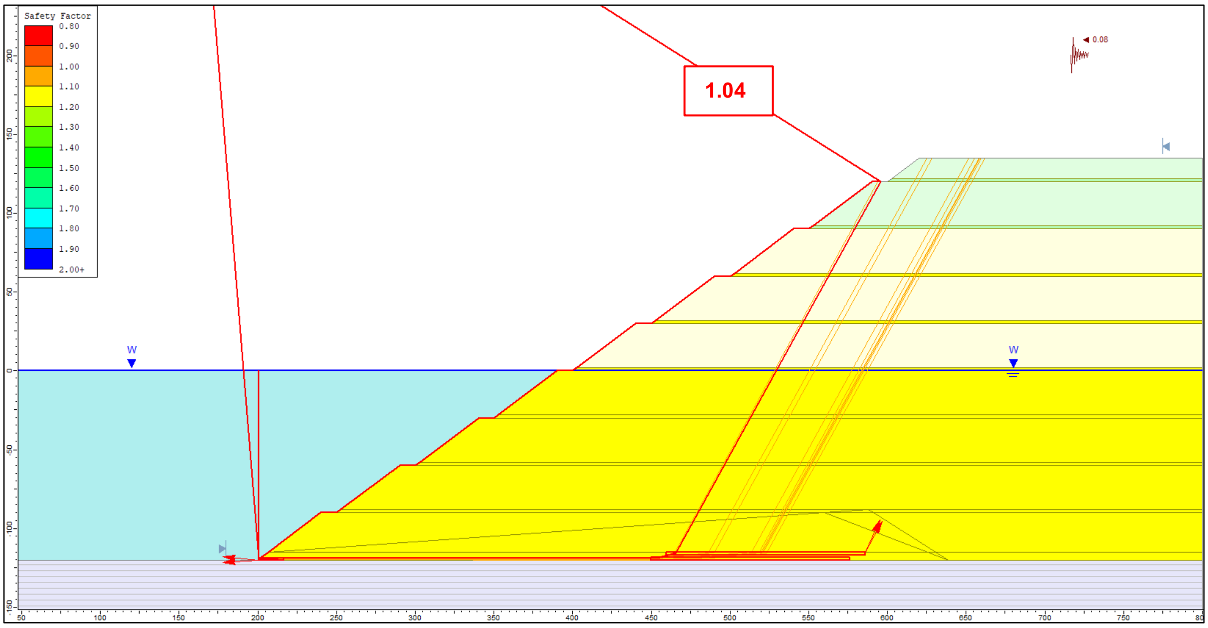

Figure 3   Critical stability condition FOS = 1.04 for 265 m height spoil dump worst-case void water level condition with pga applied (orange shapes are the 10 most critical mechanisms)

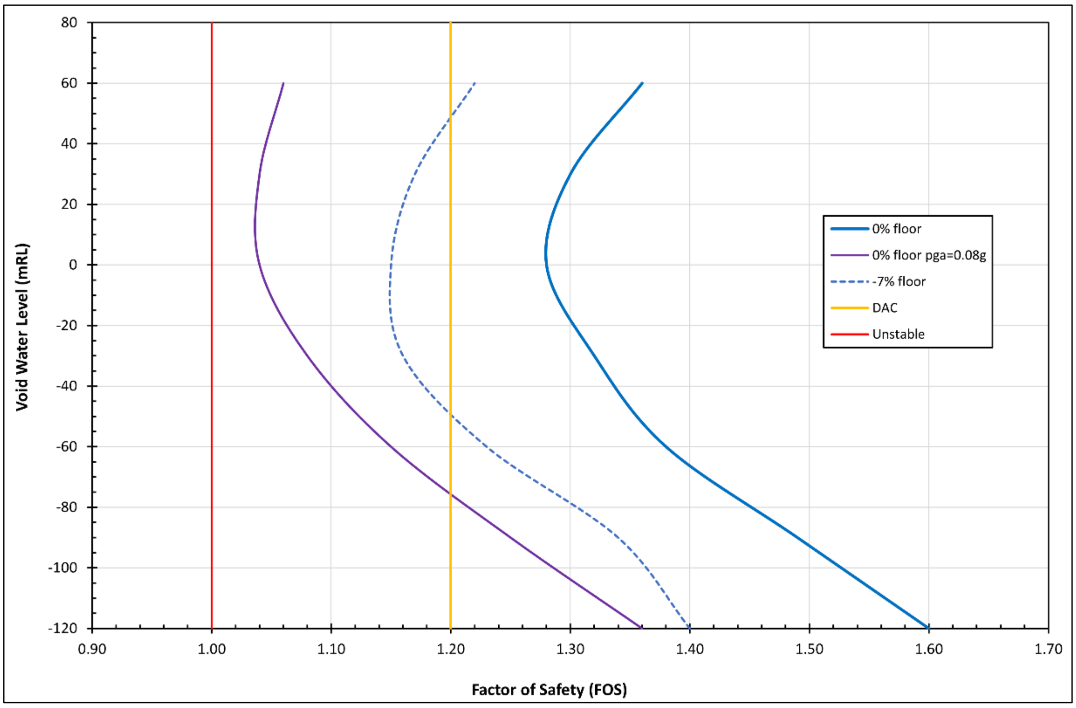

Figure 4   Example impact of pga on 265m height dump profile stability for variable void water level

Figure 4 is a summary of the effect of void water level on minimum computed FOS for three different conditions: 0% (flat) floor, 0% floor with pga = 0.08g, and -7% (-4°) floor. Clearly, with a flat floor there is a significant negative influence of water level rise, until the water is deep enough for the combination of water weight and buoyancy to improved stability. As expected, the additional seismic loading causes a significant reduction in FOS that is equivalent to roughly twice the effect of a floor with a commonly encountered adverse floor dip of 7%.

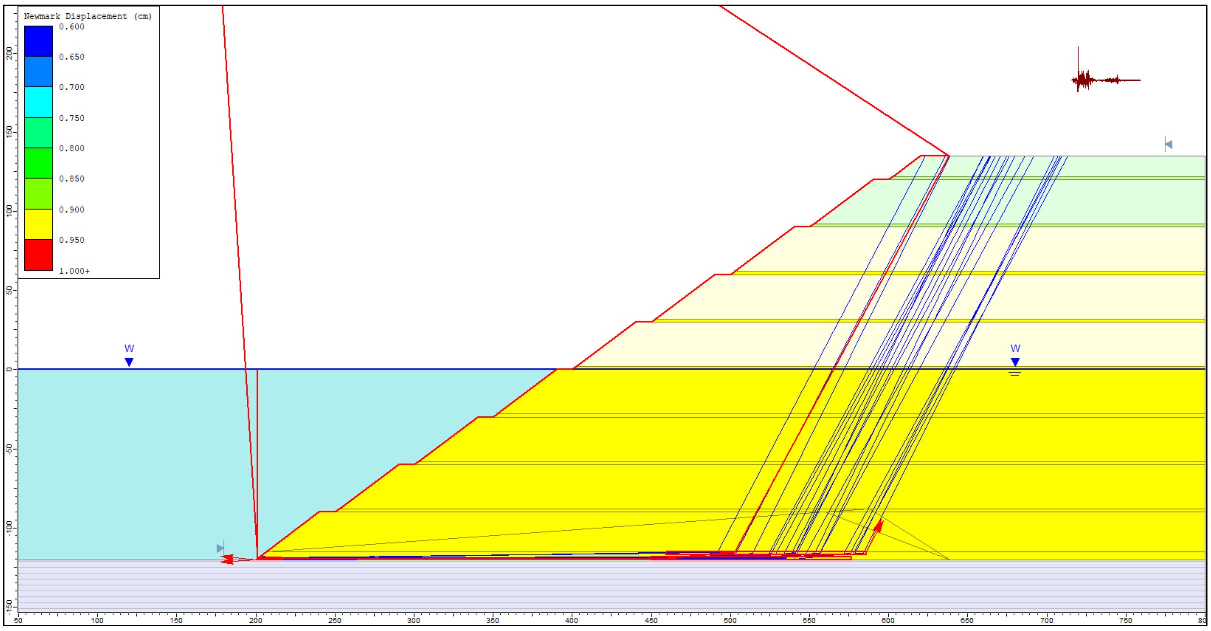

Figure 5 Example Newmark analysis of 265m height dump profile inelastic movement (20 most critical mechanism locations indicated, and inelastic deformation less than 0.1 m)

Figure 5 shows the outcome of a rudimentary Newmark analysis based on the Cape Mendicino (1970) earthquake accelerogram, one of the ten models supplied with Slide2. The pga from the accelerogram was crudely scaled to approximate a pga of 0.08g, and calculated inelastic deformation was less than 0.1 m. If the Hynes-Griffen and Franklin (1984) pseudostatic screening methodology had been followed, the Newmark analysis would not have been necessary. Alternatively, if this slope configuration had been treated as a tailings dam, then there would undoubtedly be a site-specific seismological assessment with more informed detail for seismic design.

5 Discussion

The intent of this paper is to highlight some of the very real uncertainties that seismic loading presents to the open cut coal mining industry. As an industry there is virtually no experience in testing the pseudostatic methodology against full-scale slopes subjected to damaging earthquakes and most mining geotechnical practitioners would regard this situation as more blessing than curse. Nevertheless, there are some underlying questions where guidance from the earthquake community could be very helpful to geotechnical practitioners who are charged with “design for earthquake”:

1. Should there be a widely available set of source model accelerograms suited to Australian intraplate conditions of low seismic risk (i. e. the “default” k_pZ of 0.08)? Clearly there is scope for the mining industry to be more aware of the processes adopted for seismic design of dams.
2. For really critical infrastructure adjacent to mine slopes, or for very long-term post mining slope designs, should geotechnical engineers be using the higher importance levels of AS 1170.4 Table 2.1 for pseudostatic screening, or would the uncertainties be better addressed with dynamic analyses instead? Again, the mining industry should be better aware of the processes adopted for seismic design of dams.

6 Acknowledgements

The author has been a specialist geotechnical practitioner and active researcher in coal mining geomechanics for over three decades, and this experience has included countless discussions

with technical and academic colleagues and coal mine workers regarding design for earthquake loading. This paper has provided the opportunity to air some of the uncertainties voiced by many colleagues whose questions, insights, and advice have been highly valued.

Fortunately, the author has also been influenced by and benefited from participation at some distance in the discussions that flow through the membership of the AEES. Although the subjects of structural and geotechnical engineering are very different, many of the design uncertainties are similar in character and the role of the AEES in fostering ongoing discussion is gratefully acknowledged.

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