

# SEISMIC ANALYSIS FOR OPEN PIT MINES

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## ABSTRACT

Open pit mines are of a dramatically different scale and nature to most civil works, so seismic analysis techniques required for open pit mines are also very different to those for civil works. This paper demonstrates two important aspects of the seismic behaviour of open pit mines; site response effects resulting from large scale man-made and natural topographical features, and the effect of earthquake ground motion on seismic stability assessments for steep and high slopes. An understanding of the first aspect is a prerequisite for understanding the second aspect.

The effect of topographical features is generally to amplify ground motion at the crests of pit slopes and ridges, and up through spoil piles. These effects will alter response spectra for infrastructure design. Slip mass scale effects mean that, during an earthquake, the maximum average acceleration within a slip mass is less than the maximum surface acceleration. The combination of these two effects means that the appropriate value of acceleration for use in slope stability calculations is highly dependent on topography, and the size and location of the potential slip mass under consideration.

Seismic analysis techniques for open pit mines are not well established. Two case studies, one of an open pit slope, and one of a large ore spoil pile on a ridge, demonstrate that meaningful insights, based on sound engineering principles and consistent with the literature, can be obtained with the use of appropriate and thorough seismic analysis techniques. It is suggested that dynamic analysis is required to assess seismic behaviour at open pit mines.

## 1 INTRODUCTION

### 1.1 BACKGROUND

Open pit mines are of a dramatically different scale and nature to most civil works. The seismic analysis techniques required for open pit mines are also very different to those for civil works, and consequently in open pit mine engineering it is often inappropriate to adopt the seismic analysis procedures used for civil works, regardless of how well developed and widely used they are.

Aspects of the seismic behaviour of open pit mines that differ from those of civil works include site response effects resulting from large scale modification of topography, and the effect of earthquake ground motion on the stability of steep and high slopes. Unfortunately, because seismic analysis techniques for open pit mines are not well established, it is usually required to adapt existing techniques and/or work from first principles to properly assess these effects.

### 1.2 PURPOSE

This paper does not seek to provide comprehensive coverage of, or solutions to, all issues related to seismic analysis for open pit mines. Rather, the aim of this paper is to discuss some important aspects of seismic analysis for open pit mines that would typically be encountered in practice, namely site response effects and slope stability. General methodologies and approaches for typical problems are also discussed.

Two case studies are used to demonstrate important points, one of a pit slope, and one of a large ore spoil pile on a ridge. Although these case studies are based on project work undertaken for actual open pit mines by the author, they are presented as generic examples because they are typical of many open pit mines. Tailings dams are outside the scope of this paper; they are extensively covered in the literature and have their own unique set of design approaches.

### 1.3 RELEVANCE OF EARTHQUAKE ENGINEERING TO OPEN PIT MINES

The author acknowledges that in Australia, relatively low levels of seismic hazard mean that the effects of earthquakes on open pit mines are not usually a significant issue in design. Furthermore, seismic considerations are usually less important than other design considerations, given the semi-permanent nature of open pit mine and spoil pile slopes and their inherent level of risk even under static conditions. However, there are occasions

for Australian mines where earthquake performance is of significant practical importance, such as situations with:

- Higher consequence slopes where ensuring stability under all conditions is critical;
- Unusual or unfavourable geology or geometry for which no precedent or experience exists;
- Mine slopes which are part of, or interact with, permanent works that are required to serve a purpose post-mining;
- Infrastructure adjacent to mine slopes that may be at risk due to seismic slope instability and
- Infrastructure that is designed to resist earthquakes and is located adjacent to mine works, the seismic hazard for which may be affected by large-scale changes in topography due to the mine works.

In addition, a considerable amount of work, undertaken locally, is for overseas mines in seismically active areas. In such situations, seismic considerations may be an integral part of the mine design process.

## **2 SITE RESPONSE AND TOPOGRAPHICAL EFFECTS**

### **2.1 INTRODUCTION**

Site response is the behaviour of earthquake ground motion as it is transmitted through a site and manifests at the ground surface. Site response is a fundamental part of seismic analysis, and forms the basis for all other seismic analysis including slope stability. However, because site response is often codified or provided directly to engineers by seismologists, it is not often considered in great detail in routine engineering analysis.

In the context of this paper, the key characteristic of site response is the response spectrum. A response spectrum describes the maximum response of a single degree of freedom oscillator to a particular input motion, as a function of the natural period of the system (Kramer, 1996). The most common form in engineering applications, an acceleration response spectrum, is a plot of spectral acceleration (the maximum acceleration experienced by a single degree of freedom oscillator at any time during a particular earthquake) versus period (of the oscillator). It indicates how systems with different dynamic properties would respond to the same earthquake. Peak Ground Acceleration (PGA), a commonly used measure of the intensity of an earthquake, can be obtained directly from the acceleration response spectrum of the ground surface, because PGA is the spectral acceleration at a period of zero (i.e. an infinitely stiff oscillator that moves exactly the same as the ground surface). For slope response analysis without the additional requirement for earthquake-resistant design of structures, the use of Fast Fourier Transforms can be a quicker and simpler way to process and understand the frequency content of ground motion (depending on the approach taken and software being used).

### **2.2 EFFECTS OF NATURAL AND MAN-MADE TOPOGRAPHY ON SITE RESPONSE**

Using well proven techniques it is relatively simple to assess the response of a flat site. However, a flat site is often only an idealisation of reality, especially in engineering practice, and flat ground is often altered by the presence of topographical features such as hills, mountains, ridges, depressions, valleys etc. It has long been recognised that topography has a significant effect on site response, and that the response characteristics of sites with major topographical features are very different to those of flat sites.

The effects of natural topography on ground motion were first studied in detail in the late 1960s and 1970s. Studies have involved observations and analysis of records from seismographs located on different topographical features, and numerical analysis. Some results of these studies are summarised in Table 1. However, the exact effects of topography and methods to assess its effects for engineering purposes are still not well understood, and are seldom considered in practice.

Based on the effects of natural topography on site response, it is not unreasonable to conclude that large-scale man-made alterations to topography would also alter site response. Open pit mines of several kilometres in plan extent and over 500 m in depth are becoming increasingly common. These dimensions are much larger than the minimum size of topographical features that have been observed to alter site response.

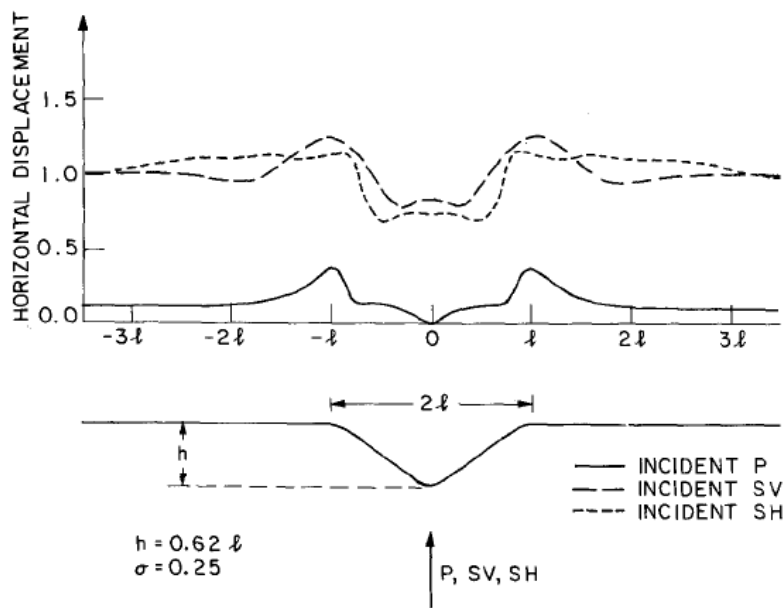


Figure 1: Spatial distribution of amplitude of synthesised horizontal displacements for P, SV, and SH waves vertically incident on a depression (Bouchon, 1973)

### 2.3 IMPLICATIONS OF MODIFICATION OF SITE RESPONSE BY MINE WORKS

An understanding of how site response is modified by topography (natural or man-made or both) is a prerequisite for any meaningful seismic stability analysis of large open pit mine works. This is discussed later in the paper.

It must also be recognised that the effects of topography on site response can be important even if stability is not at issue. Robust earthquake-resistant design of infrastructure depends on a good estimate of the site response, including any effects of topography on spectral acceleration (i.e. essentially an estimate of how the maximum acceleration experienced by an oscillating structure at the site is affected by topography). In routine civil design, these estimates are usually prescribed by design codes or obtained from site specific seismic hazard studies, and are typically only applicable to flat ground. If infrastructure is located in close proximity to a large topographical feature such as a pit slope, it is likely that the feature would cause site response to differ from the response of a flat site. Therefore, appropriate earthquake-resistant design of infrastructure on top of or in close proximity to large scale topographical features such as those present at an open pit mine would depend on an appropriate assessment of topographical effects on site response.

As an example, Figure 1 presents the results of a numerical simulation by Bouchon (1973) of the effect of a triangular surface depression on surface motion. A surface depression is comparable to the geometry and nature of an open pit mine. The y-axis shows the synthesised horizontal displacement amplitude, normalised by the horizontal displacement amplitude for a flat ground case (synthesised means that results for different frequencies of harmonic input motion have been combined to represent a more complex but realistic ground motion). The x-axis shows the distance from the centre of the depression. The depression amplifies displacement by up to 25% at the depression crest, with the amplification effects extending back as far as three times the half width of the depression. Note that although these results consider displacement amplitude, all aspects of site response including spectral acceleration are also affected.

### 2.4 STUDIES OF TOPOGRAPHICAL EFFECTS REPORTED IN THE LITERATURE

The author is not aware of any information in the literature on the effects of open pit mine topography on site response. Information is available on the effects of natural topography on site response, although as noted earlier these effects are still not fully or well understood.

Table 1 summarises some topographical effects reported in the literature. Findings vary considerably between studies, perhaps highlighting the effects of variations in geology and complex three-dimensional topography, and the dependence of surface motion on source motion frequency. There is a wide variation in results presented, with a dependence on the type of topographical feature; the response of hills, mountains, and two-sided ridges are quite different to the response of depressions, valleys, and single sided ridges. Unfortunately, it appears that most literature relates to topographical peaks, the results of which may not be directly applicable to open pits.

Literature information on the response of depressions (e.g. Bouchon, 1973) and single sided ridges or slopes separating two level surfaces (e.g. Ashford *et al.*, 1997) is more limited but probably more relevant to open pit slopes.

Table 1: Summary of some case histories and other studies of topographical effects reported in the literature.

<i>Source</i>	<i>Methodology</i>	<i>Applicability</i>	<i>Topographical effect</i>
Davis & West, 1973	Field instrumentation installed to assess topographical effects of three mountain peaks on site response to aftershocks of the 9 February 1971 San Fernando earthquake and to a Nevada test site detonation.	Topographic prominences (mountain peaks).	Frequency dependent amplification (of pseudo-relative velocity spectra) as high as 30 times in the frequency domain.
Bouchon, 1973	Computational analysis of effects of topography on surface motion.	Symmetrical triangular depressions in an otherwise flat surface, with effects clear for depressions with slopes steeper than 1V:3H.	Amplification of surface displacement by up to 25% at the depression crest, with amplification effects extending back as far as three times the half width of the depression (see Figure 1).
Celebi, 1987	Analysis of spectral ratios of aftershocks of the 3 March 1985 Chile earthquake recorded at ridges.	Ridges within a ridge-canyon-hilltop topography of a large subdivision, including man-made modifications to topography (steep road cuttings).	Frequency dependent amplification of up to 30 times or more in the frequency domain, with amplification also dependent on geology.
Geli <i>et al.</i> , 1988	Computational analysis of topographical effects and comparison with other results available in the literature.	Peaks and ridges, incorporating complex geomorphology (topography) and geology (layering).	Generally consistent with previous studies, with predominant frequency (and wavelength) of amplification corresponding to mountain base width. Topographic effect difficult to isolate from surface layering and other geomorphological effects.
Ashford <i>et al.</i> , 1997	Computational analysis of effects of topography on surface motion by frequency domain parametric study.	Steep soil slopes represented by a stepped half-space (i.e. two different and semi-infinite flat ground levels separated by a steep slope).	Amplification of SH wave motion of up to 50% at slope crest, and 20% for distances beyond the crest of up to 4 times the slope height, depending on slope angle, and height of slope compared to seismic wavelength.
Eurocode 8, Informative Annex A	Unstated.	Slopes belonging to two-dimensional topographic irregularities such as long ridges and cliffs of height greater than about 30 m (see Section 2.4).	Amplification of the seismic action $\geq 1.2$ near the top of the topographical feature (see below).

The emphasis in existing studies has typically been on seismological aspects of the problem rather than engineering aspects. There is a notable absence of engineering tools; no clear guidelines or methodologies exist for assessing the effects of topography on site response for engineering applications.

Part 5 of the Eurocode 8 design code, dealing with geotechnical aspects of earthquake resistant design (CEN, 2003) is a design code that does provide guidance for assessing topographical effects. This guidance is provided in an informative annex and it is neither detailed nor prescriptive. It is limited in application to the stability of slopes. It states that topographical effects may be neglected for slope angles less than about 15 degrees, but recommends a specific study in the case of strongly irregular local topography. As a first approximation, for slopes belonging to two-dimensional topographic irregularities such as long ridges and cliffs of height greater than about 30 m, it recommends the following amplification factors ( $S_T$ ) for the seismic action:

- For sites near the top edge of isolated cliffs and slopes,  $S_T \geq 1.2$ . This may be the case most applicable to open pits;
- For ridges with crest width significantly less than the base width,  $S_T \geq 1.4$  near the top of slopes for average slope angles greater than 30 degrees, and  $S_T \geq 1.2$  for smaller slope angles.
- $S_T$  increased by at least 20% in the presence of a loose surface layer.

Eurocode 8 also states that in general, seismic amplification decreases rapidly with depth, and that topographic effects are largest and mostly superficial along ridge crests, and much smaller on deep seated landslides where the failure surface passes to near the base. It allows  $S_T$  to decrease as a linear function of the height above the base of the cliff or ridge, and to be unity at the base (i.e. topographical effects to be neglected for deep seated failure surfaces to the base of a cliff or ridge analysed using limit equilibrium methods). This may also be related to scale/averaging effects, which are discussed later in this paper.

Consequently, it would appear that information in the literature and use of empirical methods can only go so far in assessing the general effect of topography on site response for open pit mines. It is suggested that due to the aforementioned variability and lack of precedent, site specific dynamic analysis should be undertaken to assess the effect of topography for those situations where the effects are potentially significant.

## 2.5 DYNAMIC FINITE ELEMENT ANALYSIS TO ASSESS TOPOGRAPHICAL EFFECTS

Although it is becoming more common, the use of dynamic finite element analysis in geotechnical earthquake engineering practice is often considered to be unnecessary and/or difficult to use effectively. However in situations with no precedent or simpler and well tested methodology, dynamic finite element analysis may provide the only suitable approach. Another major advantage of a dynamic analysis is that results can then be used in stability assessments. This is discussed later.

Dynamic modelling is a large topic and a detailed discussion is outside the scope of this paper. However based on experience, the author would like to make a few brief points on dynamic modelling in relation to open pit mines:

- 1 A relatively simple linear elastic material model will usually suffice for site response assessments, due to the relatively high stiffness of hard rock sites and relatively low strains involved in large-scale site response. The selection of material parameters for a linear elastic model is not onerous. If a linear elastic model is considered to be an over simplification of the situation, the only slightly more complex 'equivalent linear' analysis technique is widely used and well recognised in practice.
- 2 Overall model dimensions and boundary conditions need to be carefully considered, due to the scale of open pit mine features being modelled. It can often be difficult to attain a balance between computationally efficient model dimensions and sufficient distance to model boundaries to avoid boundary influence effects, even with appropriate boundary conditions.
- 3 A key factor in dynamic analysis is the relationship between the frequency characteristics of the earthquake motion and those of the site or slope being considered (i.e. the natural period of resonance of the slope). This is often demonstrated in the literature. For example, Ashford *et al.* (1997) demonstrate that the relationship between slope height and shear wave velocity of the ground behind the slope (an important determinant of the natural period of the site) is very important in quantifying the effect of topography.
- 4 Earthquake records for time history analysis that are selected to match design code or site specific hazard study spectra would normally apply to the surface of a flat site. Such records would not usually be directly suitable for use as base input motion to dynamic analysis. It is often required to back-calculate base input motion to ensure that appropriate surface motion is modelled.
- 5 Selection of a sufficient number of appropriate earthquake records is required. Although not strictly applicable to geotechnical earthquake engineering of slopes, AS1170.4:2007 (Earthquake Actions in Australia) does not specify the minimum number of earthquake records to be used in time history analysis, but requires that the response spectra from the records used, either individually or in combination, shall approximate the design spectrum. In comparison, NZ1170.5:2004 (Earthquake Actions – New Zealand) requires the use of at least three earthquake records for time history analysis, with a process provided for scaling the records to match the design spectrum. Based on experience, the author suggests that a minimum of three appropriate earthquake records are used in any analysis, and ideally more than three if it is computationally practical. This is one means of reducing the uncertainty in the analysis, and provides a range of results that can be interpreted with a higher degree of confidence than results obtained using a single record.

### 3 SLOPE STABILITY

#### 3.1 INTRODUCTION

The slope stability aspects of this paper focus on how the nature of open pit mine features affect seismic stability assessment approaches. The importance of considering the scale and dynamic properties of large rock slopes, as well as topographical effects are demonstrated. This paper does not discuss in detail the methods used to undertake seismic slope stability analysis, which are comprehensively covered elsewhere (for example by Kramer, 1996).

#### 3.2 USE OF CASE HISTORIES TO ASSESS SLOPE STABILITY

The recently published CSIRO book “Guidelines for Open Pit Slope Design” (Read & Stacey, 2009) states that there are no recorded case histories of large scale earthquake-induced mine slope failures having disrupted mining operations, although it notes that there is by no means a wide database that covers all conditions. It goes on to imply that the main reason that seismic stability analysis is undertaken might be because it is required by the mine management or regulatory bodies.

The author tends to agree that earthquakes would not usually pose a significant risk to open pit mines in Australia, but refer to the situations listed in the introduction to this paper, where earthquake performance (not just slope stability) may be important. Unfortunately the lack of case histories for earthquake response of pit slopes means that in such situations, a considerable level of earthquake engineering is usually required. It is noted that for large spoil pile slopes, case histories of rockfill dams and embankments are relevant and readily available. Rockfill dams have typically performed well in earthquakes, and although some deformation, settlement and shallow seated instability can be expected, global instability is not expected (see for example ICOLD, 2001).

#### 3.3 HORIZONTAL ACCELERATION COEFFICIENT IN PSEUDO-STATIC STABILITY ANALYSIS

The limit equilibrium method of slope stability analysis involves many well understood limitations and assumptions, which are not discussed in this paper. Additional assumptions are involved when a horizontal inertial force is incorporated in a limit equilibrium analysis to represent earthquake motion as a pseudo-static horizontal acceleration; these are perhaps not as well understood.

It is common to adopt an acceleration coefficient that corresponds to some fraction of the PGA or maximum acceleration (Kramer, 1996). The reasons for doing this can include the fact that the PGA acts only once and only momentarily during an earthquake, that slopes are not perfectly rigid, and that some minor yielding of the slope is acceptable, so the slope does not need to be designed to completely avoid yielding under the design earthquake. For civil works (mainly soil slopes) the horizontal acceleration coefficient selected is often the PGA, or a proportion of the PGA (Kramer, 1996), with topographical effects rarely accounted for.

An assumption in pseudo-static methods of seismic slope stability that is of specific relevance to this paper is that the applied horizontal force (as a proportion of gravitational force) is assumed to be constant throughout the entire slip mass, both with depth and laterally. This assumption could not usually be considered appropriate for the type of overall slopes involved in open pit mining, and the maximum average acceleration that is experienced by a mine slope will differ from the PGA, but for different reasons than listed above for civil works. Two effects need to be considered:

- 1 TOPOGRAPHICAL EFFECTS, as discussed above. These effects depend on the location of the potential slip surface under consideration in relation to site and mine topography. The effects may either reduce or increase the maximum acceleration experienced by the slope, because topographical effects may increase or decrease ground motion depending on location. Whether the maximum acceleration is increased or decreased depends on factors such as site characteristics (including the slope resonant period compared with the predominant periods of the earthquake motion). Note that in addition to large scale topographical effects, there may be bench scale effects present.
- 2 SCALE EFFECTS. These effects depend on the size of the potential slip surface in relation to the size of the site and mine features. Scale effects typically reduce the maximum average acceleration experienced by the slope. This is discussed below.

### 3.4 SCALE EFFECTS ON AVERAGE ACCELERATION WITHIN SLOPES

The acceleration at any given instant during an earthquake can vary considerably throughout a slope, due to the propagation of oscillatory earthquake motion up through the slope. When the maximum acceleration is experienced in one part of a potential slip mass, another part may experience a far lower acceleration, or even acceleration in the opposite direction, and hence the maximum average acceleration of a slip mass will be lower than the maximum acceleration within the slip mass. The reduction in maximum average acceleration of a slip mass compared with maximum acceleration within a slip mass will be greater for larger slip masses, due to the averaging effect occurring over larger areas. Note that the term 'maximum acceleration within a slip mass' has intentionally been used instead of PGA, because a slip mass may not necessarily extend to the ground surface to which the PGA applies.

These effects have been studied in detail for earth dams and embankments. Part of the well known approach to the seismic response of earth dams by Makdisi & Seed (1978) involves calculating the maximum average acceleration of a slip mass based on a known acceleration at the crest of the dam. In the notation of Makdisi and Seed (Figure 2),  $y/h$  is the ratio of the depth of the slip mass (crest to basal surface) to the overall embankment height, and  $k_{max}/\ddot{u}_{max}$  is the 'maximum acceleration ratio', i.e. the ratio of the maximum average acceleration within the slip mass to the maximum crest acceleration. Figure 2 shows that as the depth of the slip mass increases, there is a reduction in maximum average acceleration as a proportion of the maximum crest acceleration. Note that there is a minimum limit to this reduction, due to the averaging effect.

It is possible to undertake hand calculations to obtain an estimate of the maximum average acceleration of a slip mass as a proportion of the maximum acceleration within a slip mass. These calculations would be based on a comparison of the slope geometry with the seismic wavelength. A dynamic analysis would give more accurate results, and is recommended in preference to hand calculations, since such an analysis would often be required to consider topographical effects anyway.

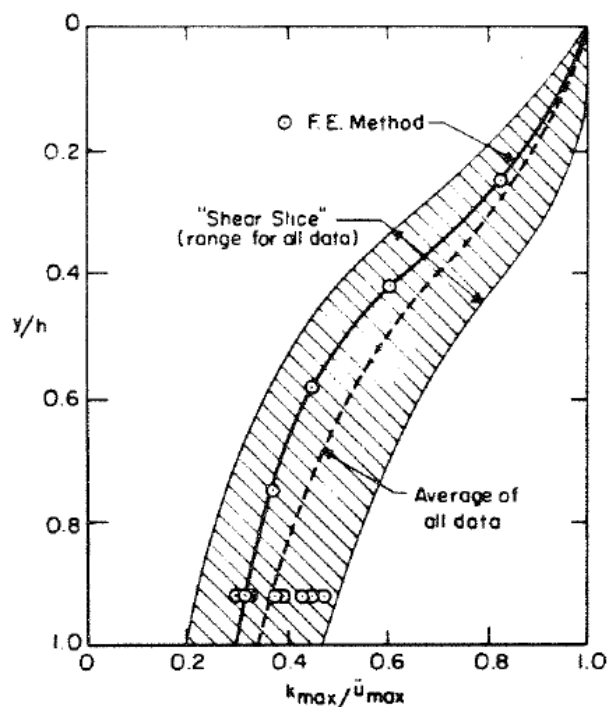


Figure 2: Variation of maximum acceleration ratio with depth of sliding mass (Makdisi & Seed, 1978)

### 3.5 LIMIT EQUILIBRIUM STABILITY ANALYSIS BASED ON DYNAMIC MODELLING

Provided that topographical and scale effects are accounted for, limit equilibrium analysis would often be an appropriate method to assess slope stability. Full dynamic stability modelling is usually too complex to be justifiable; significant input data and very complex material models are required.

When undertaking limit equilibrium analysis based on the results of dynamic analysis, two main options are available:

- 1 A direct link between the dynamic analysis and the limit equilibrium analysis software. This option is preferable because there is an automatic transfer of acceleration data, different levels of acceleration are

used for each slice of the slip mass, and the variation of stability over the duration of an earthquake can be investigated, which also facilitates the use of Newmark methods to estimate displacements if required.

- 2 A manual transfer of results from dynamic analysis into limit equilibrium analysis, by interrogation of the dynamic analysis results. This option is not as accurate or comprehensive as the first, and requires that only a single average value of acceleration is used in the slope stability analysis, rather than allowing the acceleration to vary within the slip mass and over time. However it still allows an informed assessment of stability. This method would also be required if the effects of topography and slip surface size were estimated by empirical methods or hand calculations.

This paper does not cover the interpretation of stability analysis results, although it is noted that the significance of a factor of safety less than one (and any associated deformation) depends on the scale and nature of the slip surface, and the conservatism of input parameters and the analysis method.

## 4 PIT SLOPE CASE STUDY

### 4.1 CASE STUDY DESCRIPTION

The following case study of an open pit mine slope demonstrates how the phenomenon discussed above might be assessed in practice. The pit is located in a seismically active area and features slopes with high consequences of failure in both the temporary and permanent cases. Furthermore, critical infrastructure that is required to be earthquake resistant is located approximately 100 m beyond the slope crest.

The pit is slightly over 300 m deep, with an overall slope angle of approximately 45 degrees. In plan, the pit is approximately 1500 m wide and 2000 m long. Figure 3 presents the two-dimensional model geometry used in the analysis. The issue of whether a two-dimensional analysis is appropriate is not explored here. Overall model dimensions were determined by preliminary analysis to ensure that the boundaries did not affect calculated motion in the vicinity of the pit. Earthquake motion was input as an acceleration at the base of the model.

Dynamic time-domain finite element analysis was undertaken to assess the effects of the pit excavation on site response, and the behaviour of the pit slopes during earthquakes. The analysis was undertaken using Quake/W, part of the Geostudio software package (Geo-Slope, 2008). In this particular example, for the sake of simplicity, the rock was modelled as being linearly elastic with a shear modulus of 10 GPa, which roughly corresponds to a shear wave velocity of approximately 2000 m/s. The pit slope was modelled at a constant 45 degrees with no benches. These assumptions make the analysis suitable for preliminary studies.

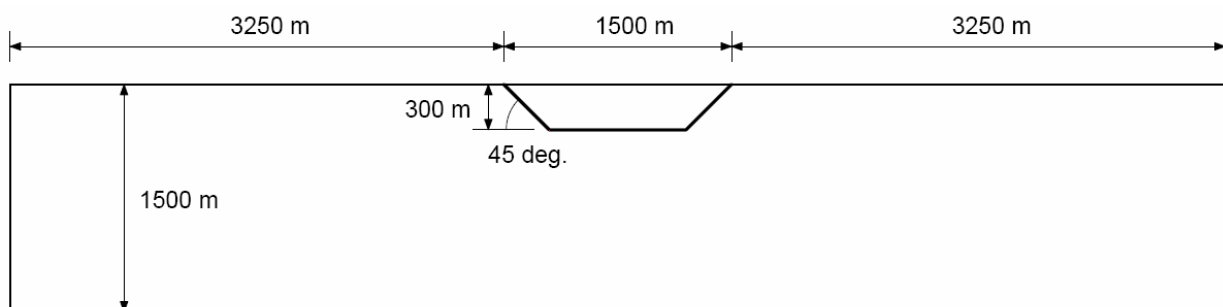


Figure 3: Model geometry for pit slope case study.

Table 2: Ratio of the PGA with pit excavated to the PGA with no pit excavation, at various distances back from crest

<i>Sine wave period (seconds)</i>	<i>Distance back from crest</i>						
	<i>0 m</i>	<i>100 m</i>	<i>200 m</i>	<i>300 m</i>	<i>450 m</i>	<i>600 m</i>	<i>750 m</i>
0.1	0.97	0.92	0.98	1.04	0.95	1.03	0.96
0.3	1.05	1.03	1.04	1.05	1.04	1.02	1.00
0.5	1.07	1.05	1.04	1.05	1.05	1.03	1.02
0.7	1.13	1.12	1.12	1.13	1.15	1.18	1.20
0.9	0.96	0.95	0.92	0.90	0.90	0.91	0.94
1.1	1.01	1.00	0.97	0.93	0.89	0.88	0.87
1.3	1.11	1.09	1.08	1.06	1.04	1.02	1.01
1.5	1.17	1.17	1.15	1.14	1.12	1.10	1.08
1.7	1.17	1.16	1.16	1.15	1.14	1.12	1.11
1.9	1.14	1.14	1.14	1.14	1.13	1.13	1.12
2.1	1.10	1.10	1.10	1.10	1.10	1.10	1.10
2.3	1.04	1.04	1.05	1.05	1.06	1.06	1.07
2.5	1.02	1.02	1.02	1.03	1.04	1.04	1.05
<i>Average</i>	1.07	1.06	1.06	1.06	1.05	1.05	1.04

#### 4.2 TOPOGRAPHICAL EFFECTS OF PIT EXCAVATION ON SITE RESPONSE

The effects of the pit excavation on site response are of interest firstly because of implications for the design criteria of infrastructure beyond the crest, and secondly because of its effects on accelerations within potential slip masses.

An initial set of parametric analysis involved subjecting the model to vertically propagating sinusoidal acceleration of amplitude 0.5 g and of different periods. The purposes of this initial analysis was to assess the dynamic characteristics of the slope in terms of natural (resonant) period, and to act as a first-pass analysis before using more complex and chaotic real earthquake time history records.

Table 2 shows the ratio of the PGA with the pit excavated to the PGA with no pit excavation at various distances back from the crest location. The general trend is that the PGA amplification decreases with distance back from the slope. Although this trend is not always visible for a given sine wave period, it is clear in the average values and it is expected that trend would be visible for real earthquake motion because it is comprised of motion of many different frequencies.

In Table 2, the PGA shows variability and frequency-dependence that is significant with respect to the factors of safety often accepted in mining operations. However PGA is only one parameter in site response. It is often more important and insightful to look at the ground response in terms of spectral acceleration across a range of periods.

Figure 4 (top) shows the spectral amplification ratio at the crest of the pit slope for all of the various periods of sinusoidal motion investigated. The spectral amplification ratio is the ratio of the response spectrum with the pit excavated to the response spectrum with no pit excavation, and shows both the effect of the pit excavation on site response, and the approximate natural period of the slope.

The effect of the pit excavation is to amplify the response spectra compared to those for the flat ground case. The greatest amplification occurs between 1.4 seconds and 1.7 seconds. This indicates that the natural period of the slope lies somewhere within this range (it could be determined more precisely using modal analysis). The sine waves that give the highest spectral amplification are those with periods close to the natural period of the slope. These are not marked in Figure 4 (top), but are shown clearly in Figure 4 (bottom).

Figure 4 (bottom) shows, for each of the sinusoidal motion periods investigated, the maximum spectral amplification at the crest of the slope (at any period of the response spectrum). It is seen that the sine wave periods that give the greatest amplification (1.4, 1.5, and 1.6 seconds, unlabelled in Figure 4) give an indication of, and most closely correspond to, the natural period of the slope. Table 2 also demonstrates this, for the PGA.

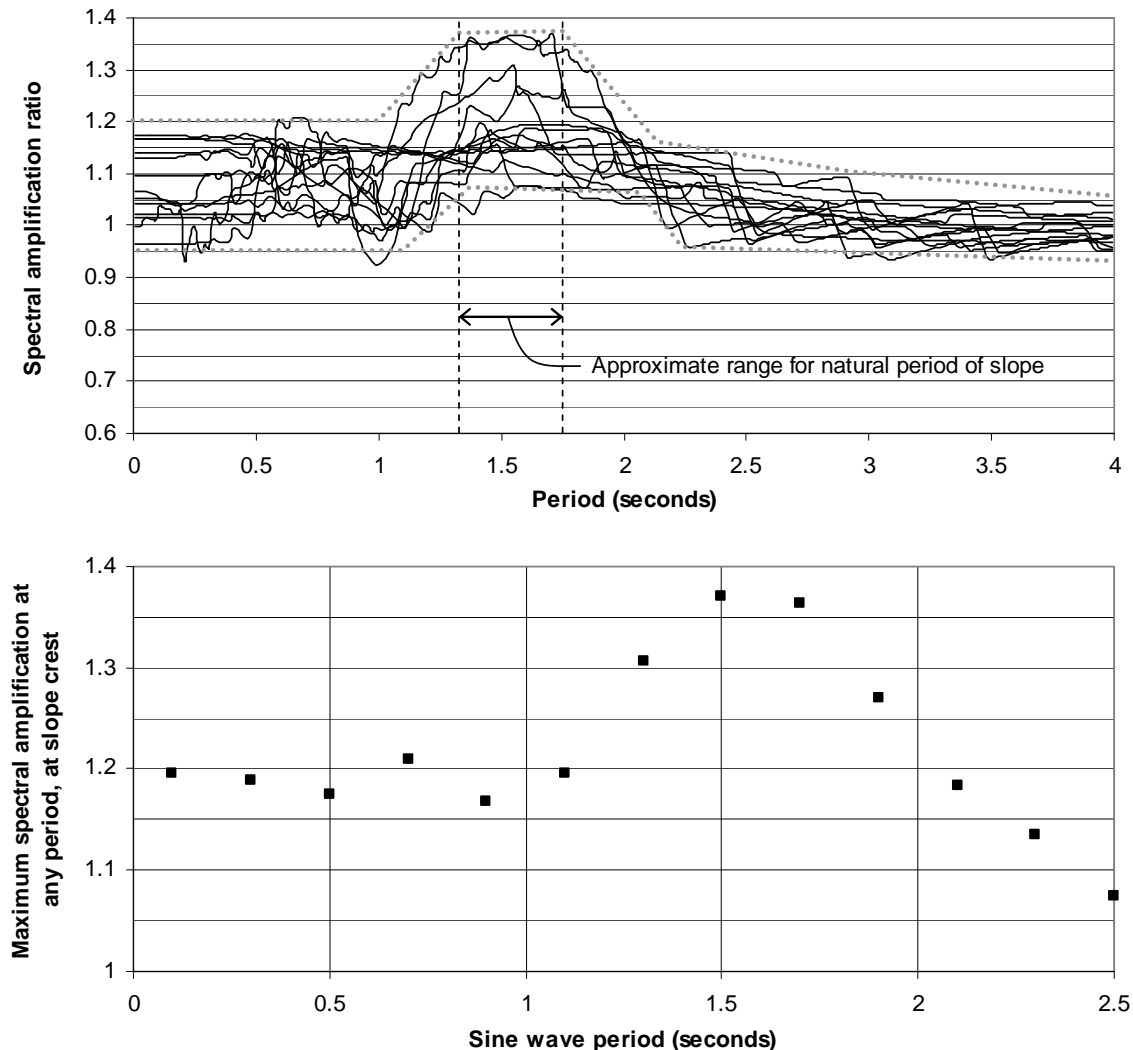


Figure 4: Top – Spectral amplification ratio at crest of pit slope for all periods of sinusoidal motion, Bottom – Maximum spectral amplification at crest of pit slope versus sinusoidal motion period

A second set of analysis involved subjecting the model to real earthquake records. These records were selected such that for a flat site with no pit excavation, the resulting response spectra at the surface were a suitable approximation to the design response spectrum for a flat site. Figure 5 presents the spectral amplification ratios for three earthquake records at a point 100 m back from the crest of the pit slope (where motion is similar to that at the crest). This point was selected because it is the point closest to the crest where critical infrastructure is located. In many cases, it would be unlikely to have infrastructure closer to the crest than this, due to potential static slope stability issues.

Figure 5 shows that the spectral amplification for real earthquake records is within the bounds of the amplifications calculated using simple sinusoidal input motion. This demonstrates the value of the initial simple analysis, and also the importance of assessing the natural period of the slope. With an excavated pit as compared to flat ground, spectral acceleration is higher across virtually the entire range of periods that are applicable to structures such as buildings (say 0.5 seconds to 2.0 seconds), with a maximum increase of over 30% occurring around the natural period of the slope. This is significant in terms of the seismic hazard for structures, and would have implications for their earthquake resistant design.

The increases in PGA (spectral acceleration at a period of 0 seconds) 100 m back from the crest with the pit excavated are 4%, 10%, and 14%, for the three earthquake records used, which fall between the average and maximum PGA amplification values at that location for the sine wave analysis (Table 2). These results, and the previously discussed spectral amplification, are reasonably consistent with the range of results reported by Bouchon (1973) for depressions, and by Ashford *et al.* (1997) for stepped half spaces.

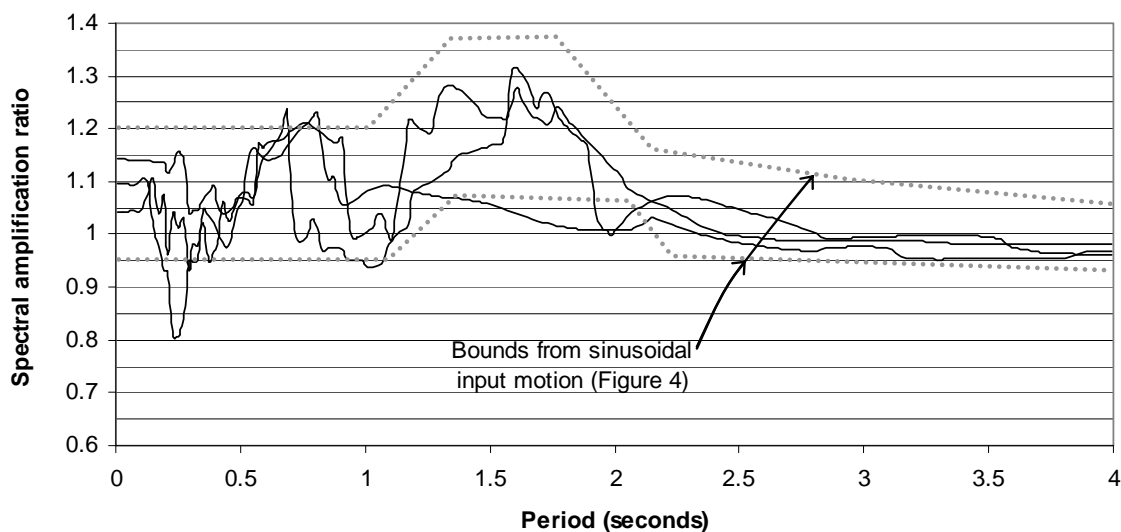


Figure 5: Spectral amplification ratios of response with pit excavation to response with no pit, 100 m back from crest

#### 4.3 PIT SLOPE SEISMIC STABILITY

The implications of the topographical and scale effects investigated in the dynamic analysis on stability of the pit slopes were explored. In this paper, comparisons are made between three potential slip surfaces of differing size and location, to demonstrate the influence of site response on slope stability. These three slip surfaces are shown in Figure 6. Material strength for seismic analysis, interpretation of the factor of safety, and methods to estimate slope displacements in instances of a factor of safety less than unity, are important aspects of seismic slope stability but are not discussed in this case study.

Topographical effects, as discussed previously, can mean that the excavation of a pit causes the maximum acceleration at the slope crest to increase from the flat ground value. However, at any given time, including the instant of maximum crest acceleration, the accelerations throughout the slope will vary and even possibly act in opposite directions at different locations. An example of this is shown in Figure 7, which presents acceleration magnitude vectors at the instant of maximum crest acceleration for one of the earthquake records considered.

The nature of these scale effects was investigated for the three potential slip surfaces in Figure 6, by interrogating the results from the computer software used. In this software, the dynamic finite element analysis can be automatically linked to the slope stability analysis, allowing quick and accurate results to be obtained. The maximum into-slope crest acceleration was obtained from the site response analysis described above (equivalent to the crest PGA, if the PGA acts into the slope). Absolute acceleration of the model in the into-slope direction (e.g. as shown in Figure 7) is unfavourable for slope stability, because it results in a relative out-of-slope inertial force within the slip mass. This inertial force is equivalent to what is modelled as a pseudo-static acceleration in limit equilibrium analysis.

At the exact time that this maximum into-slope crest acceleration acts, the average acceleration within the slip mass was assessed. Table 3 presents these two results for each of the three potential slip masses considered, as well as the ratio of the two results. The following observations are made:

- The ratio of average acceleration within a slip mass to crest acceleration decreases with increasing slip mass size.
- For the largest slip that extends from toe to crest, this ratio ranges between 41% and 46%.
- There is little difference in the ratio between the 150 m and 75 m deep slips, which is between 49% and 63%.
- The exact ratios in any particular case would depend on slip mass geometry related to slope geometry (depth and lateral extent of the slip mass) and how the earthquake motion travels through the slope (including wavelength and speed of travel), which is affected by the dynamic properties of rock.

The importance of considering all time steps when assessing maximum average acceleration within a slip mass is emphasised. Initially, the instant of maximum average acceleration will be unknown, and will not usually correspond exactly to the instant of peak input motion.

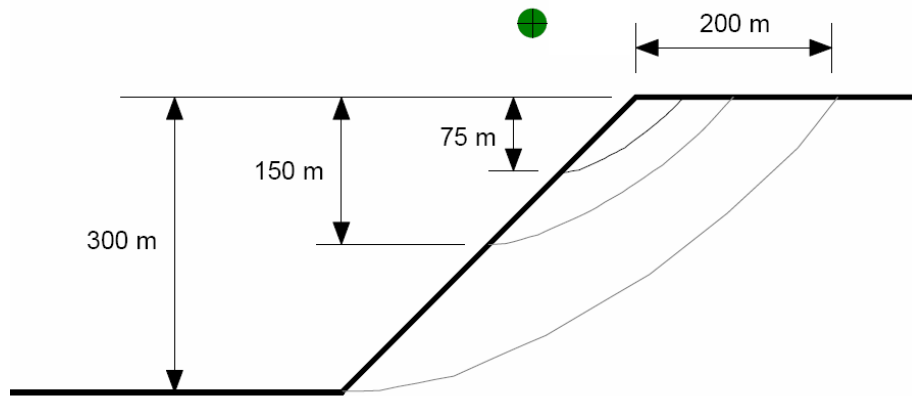


Figure 6: Potential slip surfaces for which topographical and scale effects were investigated

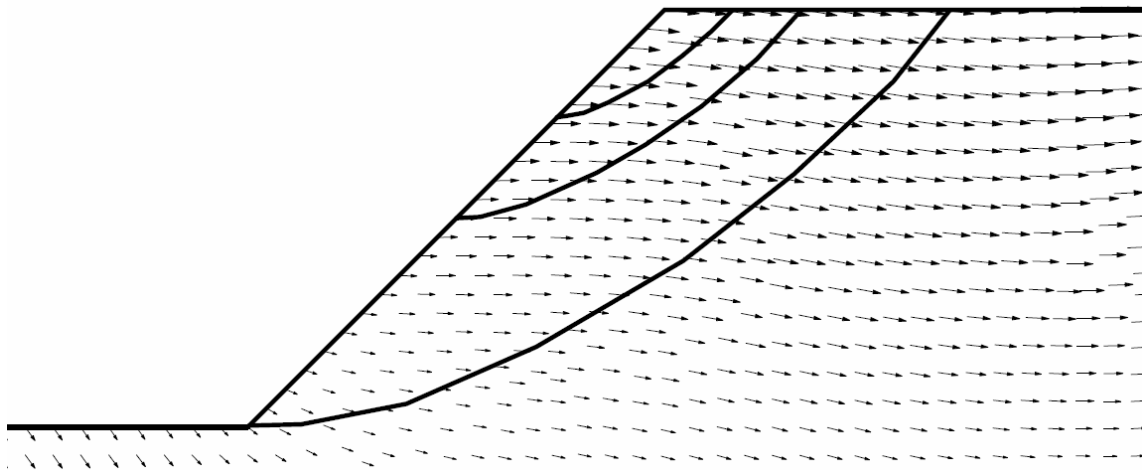


Figure 7: Acceleration magnitude vectors at the instant of maximum crest acceleration

Table 3: Comparison of maximum crest acceleration and average acceleration within slip mass, for three different sizes and locations of slip masses

Size of slip mass (Figure 6)	Maximum into-slope crest acceleration (g)			Average into-slope acceleration within slip mass at time of maximum into-slope crest acceleration (g) (proportion of max. crest acceleration in brackets)		
	EQ #1	EQ #2	EQ #3	EQ #1	EQ #2	EQ #3
300 m deep slip mass extending from toe to crest of slope	0.24	0.59	0.39	0.11 (46%)	0.26 (44%)	0.16 (41%)
150 m deep slip mass extending over top half of slope				0.14 (58%)	0.37 (63%)	0.19 (49%)
75 m deep slip mass extending over top quarter of slope				0.12 (50%)	0.37 (63%)	0.19 (49%)

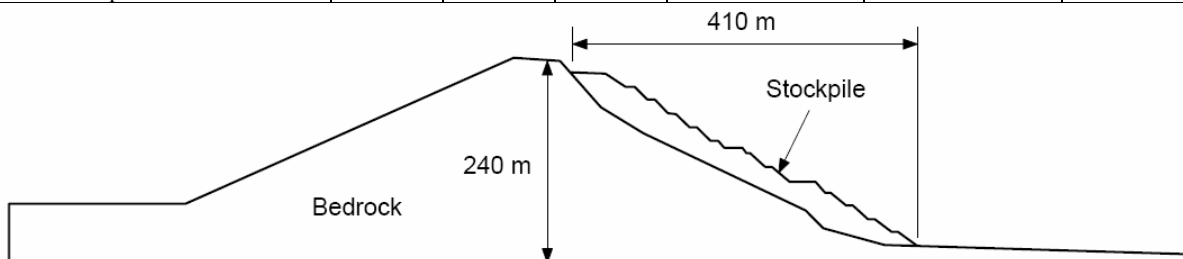


Figure 8: Model geometry for spoil pile case study

## 5 SPOIL PILE CASE STUDY

### 5.1 CASE STUDY DESCRIPTION

Spoil piles are a common feature of open pit mines. The following case study of a mine ore spoil pile further demonstrates aspects of seismic behaviour discussed earlier in this paper. The spoil pile is in a seismically active area. There are relatively high consequences of failure, because there is an acid rock drainage system within the spoil pile, and the ore will also need to be accessed to be processed in the future. Furthermore, critical infrastructure is located a short distance beyond the toe of the spoil pile.

The spoil pile is located on the side of a ridge that increases in steepness from being 20-25 degrees near its toe, to close to 40 degrees at its crest. The spoil pile is approximately 230 m high (toe to crest), with an average slope angle of 25 degrees that is formed by a series of benches and 35 degree inter-bench slopes. In places, the spoil pile has greater than 40 m depth of ore.

Dynamic time-domain finite element analysis was undertaken using Quake/W (Geo-Slope, 2008) to assess topographic effects of the ridge and spoil pile on site response, and the implications for slope stability. In this particular example, for the sake of simplicity, the rock was modelled as being linearly elastic with a shear modulus of 2.5 GPa, roughly corresponding to a shear wave velocity of approximately 1000 m/s. The spoil pile material was modelled as a non-linear elastic material, with maximum shear modulus (at zero strain) increasing with depth, and a modulus reduction curve used to describe the way that shear modulus decreases with increasing dynamic shear strain. These and other properties of the spoil ore were based on testing data and published information for rockfill and gravels. The more complex material model for the spoil pile was justified because strains within the spoil pile are much higher compared with the bedrock, and the behaviour of the spoil pile was of greater interest in terms of slope stability.

Figure 8 presents the model geometry used in the analysis. In this case study, the model was not required to extend deeper than the base of the ridge. This was because the flat ground seismic hazard had already been assessed, and it was only required to assess the effects of the ridgeline on spoil pile site response. However, both sides of the ridgeline were required to be modelled to properly capture these effects. Three earthquake records appropriately representing the flat ground hazard were used, and motion was input as an acceleration at the base of the model.

### 5.2 TOPOGRAPHICAL EFFECTS OF RIDGELINE ON SITE RESPONSE

For this site, two topographical effects are present; the amplification of the flat ground motion up towards the crest of the ridge, and the amplification of the motion from along the natural ground surface (incorporating ridge effects) up through the spoil pile. An initial dynamic analysis investigated the first of these effects, without the spoil pile present.

Figure 9 presents some results from the initial analysis. It shows the spectral amplification ratio from motion at the base of the model to the crest of the ridge for the three earthquake records used. The natural period of the ridge is estimated at 0.35 seconds, which is the period where the greatest amplification of spectral acceleration occurs. This maximum amplification is over 12 times, and importantly is relatively insensitive to the specifics of the input motion (i.e. the spectral amplification curves are roughly the same, even though the input motion spectra are not). It is noted (but not shown) that as well as the amplification of spectral acceleration, the ridge also tends to lengthen the period of the motion, because its natural period is longer than the predominant period of the base input motion.

Table 4: Amplification of flat ground surface PGA at various locations up ridge (no spoil pile)

Location	Earthquake record					
	EQ #1		EQ #2		EQ #3	
	PGA (g)	Amplification	PGA (g)	Amplification	PGA (g)	Amplification
Model base	0.63	-	0.86	-	0.73	-
Flat ground at spoil pile toe	0.65	1.03	0.90	1.05	1.18	1.62
10% of the distance up the slope	0.76	1.21	1.02	1.19	1.27	1.74
60% of the distance up the slope	1.90	3.02	1.56	1.81	1.46	2.00
Ridge crest (near side)	3.39	5.38	2.80	3.26	2.51	3.44
Ridge crest (far side)	3.35	5.32	2.79	3.24	2.64	3.62

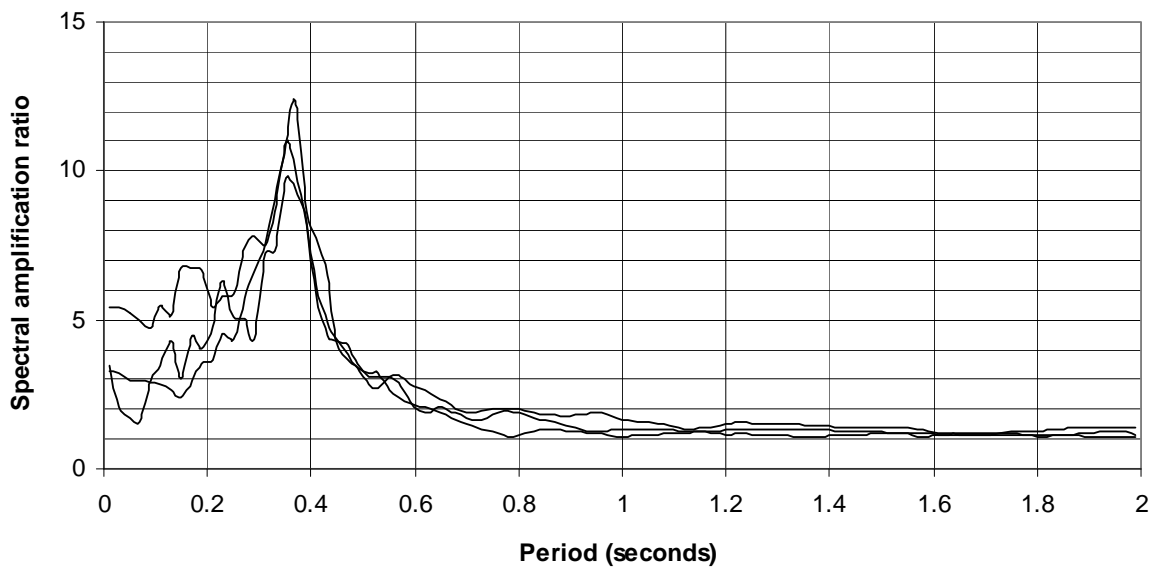


Figure 9: Spectral amplification ratios from motion at base of model (input motion) to motion at crest of ridge

Table 4 presents the amplification of the flat ground surface PGA at various locations up the ridge. There is a roughly linear increase in PGA amplification with distance upslope from the toe towards the crest. The amplification of flat ground surface PGA at the ridge crest is between 3.24 and 5.38 times (also see Figure 9 at a period of zero seconds). This is significantly higher than the minimum value suggested by Eurocode 8 for such slopes (refer Table 1), possibly because the ridgeline is much larger in size than the minimum sizes considered in Eurocode 8. The amplification is within the bounds of amplification values reported in other studies of ridges and mountains (refer Table 1).

### 5.3 DYNAMIC RESPONSE OF SPOIL PILE INCORPORATING RIDGELINE EFFECTS

A second dynamic analysis investigated the second topographical effect, that of amplification of motion from the natural ground surface up through the spoil pile. This analysis incorporated the topographical effect of the ridge discussed above.

Table 5 presents the amplification of the flat ground surface PGA at various points along the (buried) natural ridge surface, and the corresponding points directly above on the spoil pile surface. Comparing Table 4 with Table 5 for the points on the natural ground surface 60% of the distance up the slope and at the ridge crest, it can be seen that the presence of the spoil pile slightly reduces the amplification at the natural ground surface. This effect is likely due a combination of widening of the ridge crest, flattening and smoothing-out of the overall slope, and surcharging.

It is also seen that PGA is amplified from the natural ridge surface to the spoil pile surface directly above. This amplification through the spoil pile material itself (i.e. the numbers noted in brackets in Table 5) ranges from 1.43 to 2.46 times, and is larger than the reduction of PGA at the natural ground surface caused by the presence of the spoil pile. The overall effect of the spoil pile is therefore to further amplify the PGA.

Because there is no infrastructure located on the spoil pile, the change in response spectra due to the presence of the spoil pile is not as important as in the previous case study. Rather, the main implications of topographical effects are for slope stability, for which PGA is an important parameter. Consequently, response spectra are not presented in this section. The spoil pile only slightly modified the shape of the spectra from those summarised in Figure 9, but caused greater amplification.

Table 5: Amplification of flat ground surface PGA at various locations along natural ridge surface and spoil pile surface

Location	Earthquake record					
	EQ #1		EQ #2		EQ #3	
	PGA (g)	Amplification	PGA (g)	Amplification	PGA (g)	Amplification
Model base (input motion)	0.63	-	0.86	-	0.73	-
Natural ridge surface, 10% of the distance up the slope	0.76	1.21	0.98	1.14	1.44	1.97
Spoil pile surface, directly above the above location	3.23	5.13 (1.59 from natural surface)	2.41	2.80 (2.46 from natural surface)	2.06	2.82 (1.43 from natural surface)
Natural ridge surface, 30% of the distance up the slope	1.06	1.68	1.40	1.63	1.29	1.77
Spoil pile surface, directly above the above location	3.68	5.84 (1.59 from natural surface)	3.35	3.90 (2.39 from natural surface)	2.53	3.47 (1.96 from natural surface)
Natural ridge surface, 60% of the distance up the slope	1.78	2.83	1.46	1.70	1.52	2.08
Spoil pile surface, directly above the above location	3.31	5.25 (1.50 from natural surface)	2.81	3.27 (1.92 from natural surface)	3.00	4.10 (1.97 from natural surface)
Crest of spoil pile	2.47	3.92	2.75	3.20	1.89	2.59
Ridge crest (far side)	3.24	5.14	2.60	3.02	2.26	3.09

#### 5.4 SPOIL PILE SEISMIC STABILITY

The dynamic analysis discussed above demonstrated that in this case, the use of seismic hazard information relating to flat ground is inappropriate as a direct input to stability assessments. Of interest is the net effect of topographical amplification on spoil pile stability. In particular, differences in behaviour of small and large potential slip masses, and of slip masses in different locations, are important in terms of assessing the effects of an earthquake on the drainage system and infrastructure.

Figure 10 shows representative slip masses that were considered in the stability analysis. The slip masses cover a range of sizes and locations. Note that for stability analysis, appropriate material strengths must be assigned. In this case study, a weaker layer over the top of the surface of the bedrock was included.

For the stability analysis in this particular case study, the results of the dynamic finite element analysis were directly incorporated in the limit equilibrium stability analysis that was undertaken using Slope/W, part of the same software package (Geostudio) as Quake/W (Geo-Slope, 2008). The effects of horizontal acceleration on slice inertial force and slice base normal stress are incorporated in the calculated finite element stresses. These stresses were directly used to calculate parameters for the method of slices. This allowed the factor of safety for the slip surface to be calculated at each time step of the earthquake record.

Furthermore, the software was also able to automatically undertake a Newmark sliding block type of calculation. This calculation estimates the displacement of a rigid block (i.e. the slip mass) which is assumed to move during instances when the average acceleration on the block exceeds the yield acceleration (i.e. when the factor of safety of the slip mass drops below unity). Details of this method are not discussed further, but the comparison of displacements between different potential slip masses provides more insight than comparing factors of safety alone. It is noted that the assumption of a rigid slip mass probably underestimates displacements.

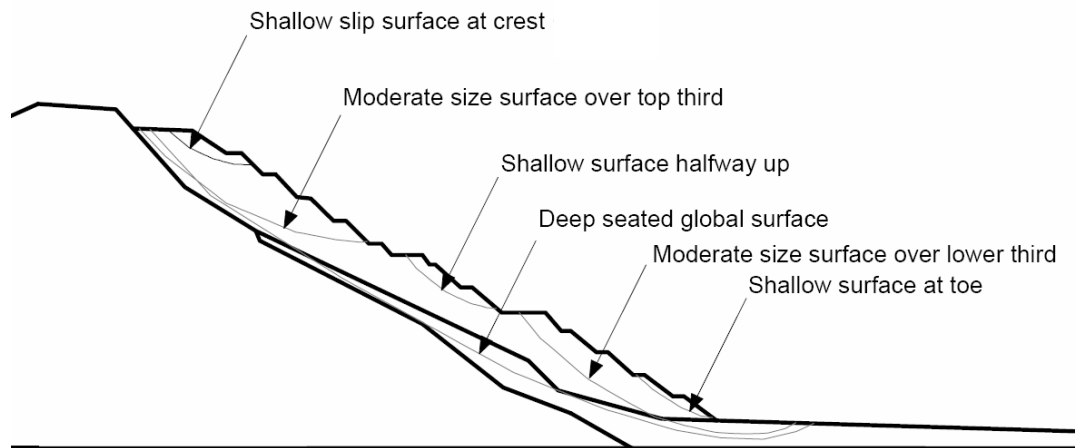


Figure 10: Representative slip masses considered in spoil pile stability assessment

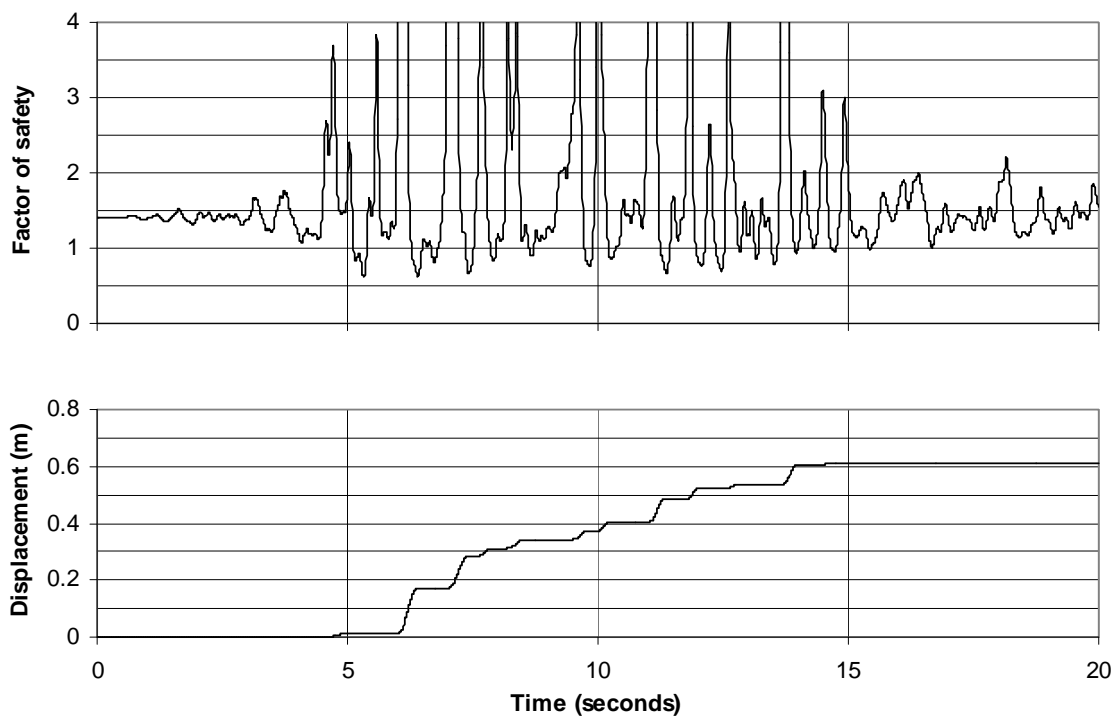


Figure 11: Example of variation in factor of safety and accumulation of movement along slip surface versus time

Figure 11 shows an example of how the calculated factor of safety of a potential slip mass varies with time during an earthquake record, and how the Newmark sliding block approach can be used to estimate the movement that occurs along the slip surface each time the factor of safety drops below unity. Note how displacement accumulates during instances where the factor of safety is lower than unity; during these periods the slope is assumed to be yielding in a perfectly plastic manner. The particular example in Figure 11 relates to the deep seated slip surface for earthquake record #2 in Table 6, which has a total calculated displacement of 0.61 m. Note that these types of calculations can also be undertaken manually if required.

Table 6: Displacements of slip masses assessed using Newmark sliding block approach

Location of slip mass	Displacement (m)				Average strain along slip surface
	Earthquake record			Average	
	EQ #1	EQ #2	EQ #3		
Shallow slip surface at crest of spoil pile	1.35 m	1.87 m	0.70 m	1.3 m	2%
Shallow slip surface halfway up spoil pile	2.16 m	3.03 m	0.99 m	2.1 m	3%
Shallow slip surface at toe of spoil pile	2.06 m	3.01 m	1.64 m	2.2 m	3%
Moderate size slip surface over top third of spoil pile	0.38 m	0.95 m	0.25 m	0.5 m	0.2%
Moderate size slip surface over lower third of spoil pile	0.11 m	0.15 m	0.01 m	0.1 m	0.04%
Deep seated global slip surface beneath entire spoil pile	0.29 m	0.61 m	0.19 m	0.4 m	0.07%

Table 6 presents calculated displacements of the representative slip masses for the three earthquake records used in the dynamic analysis. There is a clear difference in displacements for different slip mass size and location. The difference in strain along the slip surface is much greater still, and emphasises the difference between displacements of smaller and larger slip surfaces. Average accelerations within slip masses are not presented here, and were discussed in the previous case study. The following points are noted:

- The displacements and strains along shallow slip surfaces are all relatively high and all similar. This is mainly due to the amplification of motion up through the spoil pile itself (Table 5), and also the fact that the surfaces are not deep so are more subject to the full effects of maximum surface acceleration. The assumption of a rigid sliding mass in Newmark calculations may not be valid at such high strains and hence collapse may occur.
- Moderate size slip surfaces have smaller calculated displacements and strains than shallow surfaces, because the average acceleration within a slip mass as a proportion of the surface acceleration decreases as slip surface depth increases.
- The moderate size slip surface over the lower third of the spoil pile has lower calculated displacement and strain than the one over the upper third. This is due to topographical amplification of ground motion being higher for locations further towards the ridge crest.
- The deep seated global slip surface has a low average displacement, and in this particular case the movement is not of great concern. The high surface accelerations experienced by the global slip mass are somewhat negated by the simultaneous lower accelerations experienced deeper down and the fact that maximum accelerations do not act concurrently over the entire height of the spoil pile.

## 6 CONCLUSIONS

This paper has emphasised some aspects of earthquake engineering for open pit mines. The effects of earthquakes on open pit mines will not often be significant compared with other aspects of design, especially in Australia. However, there are situations where the seismic behaviour of mine works is critical, and in such situations there is a lack of precedent, applicable methodologies and case histories.

This paper has demonstrated two important features of the seismic behaviour of open pit mines; the effect of natural and man-made topography on site response, and the implications of site response and the nature of potential slip masses on slope stability. It is suggested that dynamic analysis is required to obtain meaningful insights into these features of response. Case studies presented in this paper show that meaningful insights based on sound engineering principles can be obtained with the use of appropriate seismic analysis techniques.

Studies reported in the literature and the case studies described in this paper indicate that, amongst other things:

- The effect of man-made and natural topography is generally to amplify ground motion at the crests of pit slopes and ridges, and up through spoil piles. The natural period of such features is an important factor in assessing topographical effects.
- Topographical effects alter the response spectra that are used in design of mine infrastructure.
- Topographical effects also modify the value of the maximum ground acceleration coefficient (used in pseudo-static limit equilibrium slope stability analysis) from the value applicable for a flat ground case.
- Slip mass scale effects mean that the maximum average acceleration within a slip mass during an earthquake is less than the maximum acceleration experienced at any one point within the mass

(including at the surface). These scale effects are more pronounced for larger and deeper potential slip masses.

- The combination of topographical and scale effects means that the appropriate or equivalent value of the pseudo-static acceleration coefficient in slope stability calculations is highly dependent on both the size and location of the potential slip mass under consideration.

The author does not hope nor suggest that high-level seismic analysis is undertaken for all open pit mines. Rather, he is of the opinion that when there is an engineering reason to assess the effects of earthquakes on an open pit mine, such an assessment should be thorough and not attempt to treat the problems in an overly simplistic manner. At a minimum, the aspects of seismic behaviour discussed in this paper should be accounted for.

## 7 ACKNOWLEDGEMENTS

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## 8 REFERENCES

- Ashford, S.A., Sitar, N., Lysmer, J., & Deng, N. (1997). "Topographic effects on the seismic response of steep slopes". *Bulletin of the Seismological Society of America*, 87(3):701-709.
- Bouchon, M. (1973). "Effects of topography on surface motion". *Bulletin of the Seismological Society of America*, 63(2):615-632.
- Celebi, M. (1987). "Topographical and geological amplifications determined from strong-motion and aftershock records of the 3 March 1985 Chile earthquake". *Bulletin of the Seismological Society of America*, 77(4):1147-1167.
- Comité Européen de Normalisation (2003). "Eurocode 8: Design of structures for earthquake resistance. Part 5: Foundations, retaining structures and geotechnical aspects". Final draft.
- Davis, L.L. & West, L.R. (1973). "Observed effects of topography on ground motion". *Bulletin of the Seismological Society of America*, 63(1):283-298.
- Geli, L., Bard, P., & Jullien, B. (1988). "The effect of topography on earthquake ground motion: a review and new results". *Bulletin of the Seismological Society of America*, 78(1):42-63.
- Geo-Slope International Ltd (2008). Geostudio software package.
- International Committee on Large Dams (2001). Bulletin 120, "Design features of dams to resist seismic ground motion".
- Kramer, S.L. (1996). "Geotechnical earthquake engineering". Prentice-Hall Inc., NJ.
- Makdisi, F.I. & Seed, H.B. (1978). "Simplified procedure for estimating dam and embankment earthquake-induced deformations". *ASCE Journal of the Geotechnical Engineering Division*, 104(GT7): 849-867.
- Read, J. & Stacey, P., editors (2009). "Guidelines for open pit slope design". CSIRO Publishing, Victoria, Australia.
- Standards Australia (2007). AS1170.4, "Structural design actions. Part 4: Earthquake actions in Australia".
- Standards New Zealand (2004). NZS1170.5, "Structural design actions. Part 5: Earthquake actions – New Zealand".