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Open pits, earthquake damage and seismic design: an overview

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Abstract

Despite the limited publicly available detailed reports of earthquake damage, open pits can be vulnerable to the effects of earthquakes. Earthquake-associated damage has been reported in open pit mines in South America, Asia and Oceania. This paper reviews earthquake damage reported in open pits and discusses factors that may impact earthquake performance of open pit slopes. These factors include topography, slope geometry, rock material and mass properties, water management and intrinsic pit design.

This paper highlights that pit slopes that have withstood strong earthquakes in highly active seismic regions are often designed under strict seismic guidelines and provides insights into site-specific seismic hazard assessments and considerations for the seismic design of open pits.

The aim of these assessments is to estimate the likely level of earthquake shaking that the pit may experience during its life and to select the appropriate level of shaking for design by considering not only the site-specific seismic hazard but also the intrinsic pit properties and consequence of failure.

Keywords*:* *seismic design, earthquake performance, seismic hazard assessment*

1 Introduction

Earthquake damage and failure in open pits and mining infrastructure can have serious consequences including:

- Loss of life or injury to personnel.
- Interruption to operations through a loss of road access, potentially impacting transportation of both product and personnel.
- Environmental damage through damage to infrastructure carrying concentrate or mining waste.
- Impact to operations due to loss of power.

Published information regarding earthquake damage in mining infrastructure and associated pit failure is limited. The reported earthquake damage is usually:

- Rockfalls.
- Pit slope failures of limited scale.
- Damage to mining infrastructure (roads, buildings and other equipment) due to the failure of surrounding natural slopes or earthquake shaking.

The limited reporting of earthquake damage is sometimes interpreted as open pits having an intrinsic ability to withstand earthquake loads. In this paper we present examples of reported earthquake damage and provide a discussion on aspects of open pits that influence their performance under earthquake loads. We also propose factors to consider for the seismic design of open pits.

2 Examples of earthquake damage

Some recent examples of reported earthquake damage in mines and associated pit failure are summarised in Table 1.

Table 1 Earthquakes and recorded mining impacts

Year	Country	Earthquake magnitude	Impacts
2008	China	7.9	Multiple failures triggered in the coal mines of China's Sichuan province (anecdotal reports).
2010	Chile	8.8	Mining infrastructure damage and temporary closure of 20% of the mining operations in Chile (El Mundo 2010). No specific or technical information of type of damage or pit failure reported.
2015	Chile	8.3	Mining infrastructure damage and temporary closure of 37% of the mining operations in the region (Nueva Mineria 2016). Information of the type of damage not reported.
2018	Papua New Guinea	7.5	This event caused widespread failure of natural slopes. A total of 160 people were reported to have been killed and many others badly injured by the main event. Impacts of the earthquake to mining operations included: Damage to gas and electricity infrastructure at Porgera gold mine. (https://postcourier.com.pg/quake-rocks-shela-shp/) Large-scale failure of the natural slope, damaging site access road and pipelines connecting Ok Tedi mine to the town of Tabubil (Figure 1). (https://postcourier.com.pg/landslip-blocks-mines-access-road/) ExxonMobil suffered damage to buildings and infrastructure at the Hides gas field, with the facility not operational for eight weeks and numerous slope failures along the pipeline.

Figure 1 Aerial view of the failure of natural slopes associated with the magnitude 7.5 earthquake in Papua New Guinea on 26 February 2018. The failure blocked the access to the Ok Tedi mine

A study of earthquake disruption of copper mines in South America by Schenebele et al (2019) listed the impacts of strong earthquakes on mining operations. The impacts vary from no damage reported, to interruption, closures and mine collapses. In large part mining interruption was associated with road closures, lack of electricity and structural damage. No details regarding the 'mine collapses' were published.

There are also additional anecdotal reports, not officially published, of earthquake damage in other open mines including:

- Chuquicamata Copper Mine in Chile: reports of earthquake-induced slope failure prompting the adoption of advance monitoring and mitigation measures.
- Bingham Canyon Mine in USA: reports of ground movement and slope instabilities triggered by seismic activity.

It is sometimes argued that open pit slopes perform well when exposed to earthquake loading, particularly compared with natural slopes. The relatively limited damage experienced by pits in highly seismic regions is usually used as example of adequate pit performance under seismic loading and suggest open pit slopes may have intrinsic characteristics that contribute to satisfactory performance during earthquakes. The following section discusses the factors that may influence pit performance under seismic loading.

3 Factors impacting pit performance during earthquakes

There are many factors that may affect open pit performance during earthquakes. These factors include topography, slope geometry, pit rock mass, pit water management and pit design.

Some of these factors may be detrimental to pit performance while others may contribute to better withstanding earthquake loads. For example, most studies suggest that topographic amplification may greatly increase the earthquake acceleration at the surface of the slope and most significantly at the crest (Ashford et al. 1997). Toh (2010) and Toh et al. (2013) argue that the effect of man-made alterations to topography (i.e. large open pits) amplifies ground motion at the crest of the pit slopes and ridges. This amplification effect may promote instabilities at the crest or may be detrimental to mine infrastructure located at or close to the pit crest.

Similarly, amplification of seismic waves also occurs where contrasting material stiffness is encountered along the travel path of the seismic wave. Stiffness changes in the pit associated with changes from rock at depth to soil towards the surface, or from rock to highly weathered material, may result in earthquake amplification. Alternatively, this phenomenon is not significant in open pits entirely in hard rock.

Open pit aspects that can contribute to better performance during earthquakes include pit slope geometry, water management and pit shape. The geometry of a slope (convex or concave), for example, has been reported to have a significant impact on amplifying the ground shaking of hills and slope ridges. In relation to open pit mining, Azhari & Ozbay (2017) propose that modifying the natural curvature of the terrain could potentially enhance seismic performance. Similarly, Damjanac et al. (2013) indicate that the circular/elliptical geometry of the pit may contribute to good performance under earthquake loads.

Additionally, water management associated with pit dewatering, or controlling the drainage of surface water into the pit, may prevent or minimise increases in pore pressure during earthquakes. Azhari & Ozbay (2017) argue that pore pressure control, surface water control and/or dewatering in mining likely results in open pits being less prone to failure, as some failure modes such as rock slumps or toppling can be related to increases in pore pressure.

It is also argued that open pit slopes are less prone to earthquake-induced failures as they are typically constructed in more competent material compared with natural slopes. For example, the database of Azhari & Ozbay (2017) showed that 70% of 95 earthquake-induced failures natural slopes were shallow; mostly occurring within top soil or upper weathered/weak highly fractured rock.

Finally, the open pit design itself may also contribute to pit good performance during earthquakes. Typically, open pits are designed to have static factors of safety of around 1.2 or greater. This means the slope may accommodate some degree of earthquake shaking without any substantial detrimental consequence.

Additionally, open pit mines in highly seismically active regions like Chile, Peru and Mexico are subjected to strict seismic guidelines and are designed with the consideration of appropriate earthquake loads specific to their seismic hazard. The design of pit slopes in these countries considers earthquake loads outlined in national building codes or determined through site-specific seismic hazard assessments (Oldecop & Peruca 2012; Chamorro Quezada 2019, Departamento de Seguridad Minera 2010).

The absence of catastrophic failure in open pits in Chile after strong earthquakes is often quoted as example of the good performance of open pits under earthquake load and it has been used, in some cases, to justify the exclusion of seismic design in open pits. What is often overlooked, however, is that these mining operations have been designed to withstand very high earthquake loads and that their seismic design plays a crucial role in their performance under intense earthquake shaking.

A quote from the Chilean mining bulletin Outlet Minero (2017), translated from Spanish, highlights the absence of significant damage in Chilean mines following powerful earthquakes and confirms the role played by their seismic design. The quote states:

> *'The mining infrastructure is governed by stringent seismic regulations. Furthermore, mining companies are reluctant to suffer production losses...In countries unaccustomed to seismic activity and lacking necessary regulations, the consequences could be drastically different.'*

Consequently, the adequate performance of open pit mines in highly seismic regions supports the inclusion of earthquake loads for design instead of justifying the contrary. However, as open pits are developed in different geological and risk settings, these differences should be considered for the selection of appropriate earthquake parameters for design.

4 Considerations for seismic design of open pits

The adequate selection of earthquake parameters for pit design should consider:

- Site-specific seismic hazards of the open pit.
- Pit design life.
- Consequences of the failure of the pit.
- Specific guidelines, if available and applicable.

The initial assessment of seismic design requirements for a pit should consider its regional seismic hazard, as different pits are in different tectonic settings and are exposed to different levels of earthquake activity and earthquake intensities. Regional seismic hazard information is usually readily available and can be rapidly determined from published information and/or national earthquake codes.

Additionally, the selection of appropriate earthquake parameters should also consider the pit design life. The longer the design life, the higher the probability of the pit experiencing significant earthquake shaking because higher earthquake magnitudes occur less commonly; hence they have a lower probability of occurrence in a short design life. However, as the probability of the occurrence of larger earthquakes increases with time, so their probability of occurrence increases with longer design life.

Finally, the consequences of the pit slope failure (i.e. social, economic, and environmental) should also be considered in the assessment of adequate earthquake parameters for design. Different consequence levels include low, significant, high or extreme/catastrophic consequence. For example, those pits with high or catastrophic consequences of failure may adopt design criteria for earthquakes with higher magnitude and hence with a lower probability of occurrence during the design life, as a measure to prevent catastrophic failure.

These initial considerations on the pit regional earthquake hazard, design life and consequences of failure provide context for the adequate selection of the earthquake parameters for design and the required level of assessment.

These initial considerations may indicate that seismic design is not necessarily required. Estrada & Weir (2022) argue, for example, that in regions of low seismic hazard–like Australia, where earthquake recurrence is low–the inclusion of earthquake loads for open pit slope design may not always be required. They recommend specific seismic design and assessment of slope stability with appropriate earthquake loads for open pits in Australia where:

- Slope failure has a high or catastrophic consequence.
- Slopes, excavated or natural, interact with mine infrastructure (including roads), and where failure or damage may result in high financial or social consequences, significant interruption of production and/or injury.
- Slopes have complex or adverse geology or structural features with potential instability issues.

Alternatively, if consideration of the regional seismic hazard, pit design life and consequence of failure supports seismic design, then a site-specific seismic hazard assessment may be required to estimate the specific levels of earthquake shaking that may affect the pit.

4.1 Seismic hazard assessment

Seismic hazard assessments aim to forecast earthquake occurrence and its resultant ground shaking. Probabilistic seismic hazard assessments (PSHA) use a probabilistic framework to quantify the uncertainties associated with the estimation of the hazard and provide estimated ground shaking in terms of probability of exceedance during a period of time (i.e. the design life of the pit).

A PSHA aims to consider all possible earthquake events and resulting ground motions, along with their associated probabilities of occurrence, to find the level of ground motion intensity exceeded with a tolerable low rate. Basic steps to undertake a PSHA include (Baker 2013):

1. Defining a seismic source model which includes –
    a. Identifying all earthquake sources capable of producing damaging ground motions.
    b. Characterising the distribution of earthquake magnitudes (rates at which earthquakes of various magnitudes are expected to occur).
    c. Characterising the distribution of source-to-site distances associated with potential earthquakes.
2. Predicting the resulting ground motion intensity (resultant ground shaking at the site) as a function of earthquake parameters such as magnitude and distance, site conditions, type of fault etc. by using ground motion models.
3. Combining uncertainties in earthquake size, location and ground motion intensity using probabilistic methods.

The outputs of a PSHA that can be used as direct inputs in the seismic design of open pit slopes include:

- Earthquake peak ground accelerations (PGA) at the pit.
- Earthquake response spectrum – a response spectrum describes the maximum response of a single degree of freedom (SDOF) oscillator to a particular input motion as a function of the natural period, T, of the system. The acceleration response spectrum is a plot of the spectral acceleration (SA), the maximum acceleration experienced by the system (i.e. SDOF) at any time during a particular

earthquake, against the period of the system. It indicates how systems (i.e. open pits) with different dynamic properties (expressed as their fundamental periods) would respond to the same earthquake.

- Earthquake acceleration time histories (i.e. accelerograms) representing the earthquake hazard at the site.

The PSHA outputs can be used as inputs for different levels of seismic design, from pseudo-static analysis (which uses PGA as input) to limit equilibrium methods and non-linear dynamic analysis (which use response spectra and earthquake acceleration time histories as inputs). Toh et al. (2013) provide a framework for the application of some of these seismic analyses in open pits.

An advantage of a site-specific PSHA is that different levels of earthquake shaking during a period can be estimated. PSHAs express different levels of earthquake shaking in terms their probability of being exceeded in a certain period. As different earthquake levels of shaking can occur during the pit life – for pits with high or extreme/catastrophic consequences of failure, for example – it may be appropriate to include designs for earthquake loads associated with low or very low probability of exceedance during the design life.

The following section presents an example to illustrate these concepts.

4.1.1 An example of the rationale

The following is an example to show the rationale on how the factors listed in Section 4 can be considered to assess appropriate levels of earthquake shaking for design and to provide context for the results from PSHA.

This example considers a mining operation in a region of high seismic hazard. The mining operation includes three open pits with the following design life and consequence level:

- Open pit 1 – 30-year design life, extreme consequence.
- Open pit 2 – 50-year design life, significant consequence.
- Open pit 3 and dump – 100-year design life, high consequence.

Based on the consequence level of the pits and their seismic hazard setting, it is deemed that they should be designed to withstand earthquake loads to minimise the probability of failure. Therefore, seismic design is required.

Furthermore, based on the assessed consequences of failure and design life, different levels of earthquake shaking/intensity (earthquake shaking with different probabilities of exceedance) are considered for each pit design, as shown in Table 2.

Table 2 shows the probability of earthquake exceedance considered for the design of each pit in this example, which is based on the pit's consequence level. Note that the considered probability of exceedance for design is an example. Adequate earthquake probabilities of exceedance are assessed based on the specific characteristics of the open pits and mining operations.

Table 2 also shows the earthquake return period that is associated with the adopted probabilities of exceedance for the specific design life. The earthquake return period is estimated by assuming that the seismicity of the region follows a random Poisson process, as it is normally assumed for PSHA.

Therefore, the probability that a ground motion, such as PGA or SA, exceeds a certain value in a time period is given by:

$$P[X \geq x] = 1 - e^{-\lambda[X \geq x]t} \tag{1}$$

where λ [X ≥ x] is the annual mean number of events in which the ground motion parameter of interest exceeds the value x. Then the 'return period' is defined by:

$$R(x) = \frac{1}{\lambda[X \geq x]} = \frac{-t}{\ln(1 - P[X \geq x])} \tag{2}$$

Table 2 Example of design life, consequence level, probability of exceedance and equivalent return period

Open pit	Design life (years)	Consequence level	Considered probability of earthquake exceedance (%)	Equivalent earthquake return period (approximate years)
1	30	Extreme	2	1,500
2	50	Significant	10	500
3	100	High	4	2,500

Table 2 shows that the lowest considered probability of exceedance does not necessarily result in the highest level of earthquake shaking for design (i.e. earthquake associated with the largest return period) because the design life is considered in the assessment.

In this example, open pit 1 has the highest (extreme) consequence of failing and therefore its seismic design considered an event with a very low probability of being exceeded (2%) within its design life of 30 years. The equivalent return period of this event is 1,500 years. However, this return period is lower than that associated with the design of open pit 3 (i.e. 2,500 years, which is associated with a higher level of shaking) despite the consequence level of open pit 1 being higher than open pit 3. The higher level of earthquake shaking considered for the design of open pit 3 results from consideration of its longer design life.

Following the assessment of the adequate level of earthquake shaking to be included in the design, a PSHA can specifically compute the required ground motions to be used for that design. As such, following this example, the PSHA can estimate the earthquake shaking at the site associated with return periods of 500, 1,500, 2,500 years, etc.

In this example, a PSHA was undertaken following the steps listed in Section 4.1 to estimate the earthquake ground motions associated with earthquake return periods of periods of 500, 1,500, and 2,500 years. The following was provided as part of the assessment:

- PGA associated with earthquake return periods of 500, 1,500 and 2,500 years (Table 3).
- Earthquake response spectra associated with earthquake return periods of 500, 1,500 and 2,500 years (Figure 2).
- Earthquake acceleration time histories (i.e. accelerograms) representing the earthquake motions associated with earthquake return periods of 500, 1,500 and 2,500 years (Figure 3).

Table 3 Peak ground acceleration estimated to be associated with the different return periods considered for design

Return period (years)	Peak ground acceleration (g)
500	0.21
1,500	0.3
2,500	0.49

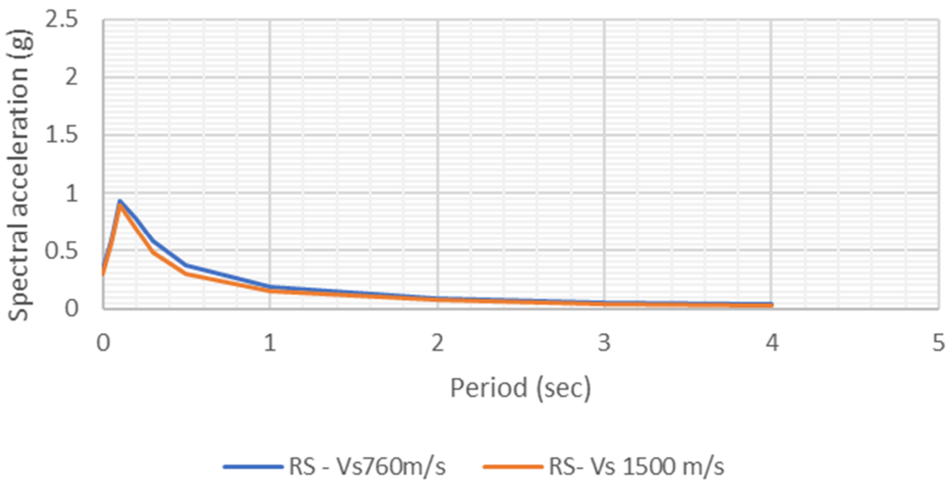

Figure 2 Example of site-specific PSHA response spectra developed specifically for the site and associated with an earthquake with a 1,500-year return period

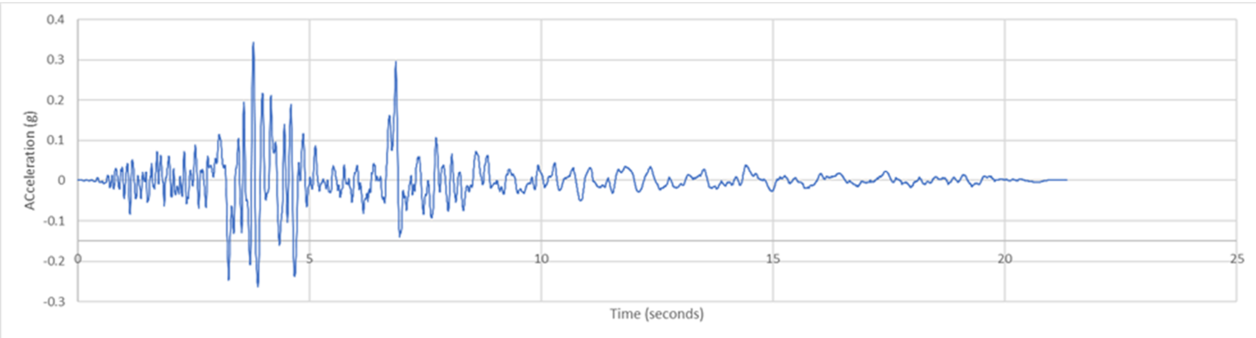

Figure 3 Example of site-specific earthquake time history (accelerogram) representing the ground motion at the site associated with an earthquake with a 1,500-year return period

These PSHA outputs can then be used as inputs for different levels of seismic design.

5 Conclusion

Limited damage has been reported in open pit operations following strong earthquakes. There are different factors that may contribute to pit performance under earthquake loading, including pit geometry, rock mass, water management and pit design.

The absence of catastrophic failure in open pits in highly seismic areas is sometimes used to justify the exclusion of seismic design in open pits. However, what is often overlooked is that mining operations in highly seismic active regions are often designed to withstand very high earthquake loads.

The adequate selection of earthquake loads and parameters for pit design should consider the specific characteristic of the pit, including its regional seismic hazard, design life and consequence of failure. These considerations inform the selection of appropriate levels of earthquake shaking to be included in the design.

A site-specific PSHA can provide the pit specific earthquake level of shaking required for design.

An example is provided to show the rationale on how the different pit factors can be considered to assess appropriate levels of earthquake shaking for design and to provide context on the results from the PSHA.

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