APPENDIX D

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APPENDIX D1

Influence on open pit mining on seismic and aseismic deformation

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Attachment:
ODO2010JUN 15 MASHERS FAULT MODEL RESULTS FOR DPE AND STRESS.ppt

EXTENT OF THE INFLUENCE OF OPEN PIT MINING ON SEISMIC AND ASEISMIC DEFORMATION

Don,

BAE has previously undertaken life-of-mine numerical analysis of deformation, stability and seismicity for the proposed Olympic Dam Open Pit. A useful outcome of the process is the ability to estimate the maximum extent of the zone of influence of the mine in terms of induced movements, stress changes and energy release (correlated with seismic potential).

Background

BAEs 2009 analysis involved the simulation of rock stress and deformation changes induced by the proposed pit and the existing and future underground workings using a strain softening, discontinuum, hydromechanically coupled 3D Finite Element (3D DHMC FE) model. This model included the interpreted geological domains and major structures, including the then current interpretation of the mashers fault.

Models of this kind account for the measured virgin stress condition, the presence of structures included in the model, variations in properties between geological domains, the sequential, iterative extraction process of open pit and underground mining and the effects of water. The modeled rock mass accumulates damage in places of over stressing and the modeled faults can dislocate.

The main variable or assumptions of the 3D DHMC models are the properties of the rock masses, with stresses provided from measurements undertaken by the mine. The rock properties are first estimated using empirical means, then tested and adjusted in small increments until the model is able to replicate measurements and observations at the mine. The model is only considered sufficient when it is able to reproduce the mechanisms of deformation and damage with the required certainty for the current level of study, so this is a robust process and open to limited interpretation; damage is matched to damage, movements to movement and seismic events to energy changes in the models.

For the OD project, the material properties and rock mass response of this model was validated in 2 ways:

- The measured seismic events induced by previous large scale underground stoping were compared to energy dissipated plastically, quarter by quarter in the model. The correlation produced the required result: there is a quantitative probabilistic relation between induced seismicity and modeled rock mass plastic energy release.

  The seismic events used for the calibration were collected by the mine over many years using a sophisticated ISS mine seismic system installed partly for the purpose of model calibration.

- The damage and deformation observed in the mine was compared to the model in key stoping precincts to confirm that the model was able to sufficiently simulate the extent and magnitude of induced damage. BHP Billiton confirmed that the match between modeled and measured damage was sufficient for long term planning purposes.

  The mine staff map damage in work areas, record pillar conditions and stope instability for this purpose.

The model was then used to estimate the extent and nature of mining induced damage and deformation, including seismicity. The focus of the study was on forecasting the levels of induced seismicity in work areas to confirm that the induced seismicity was at acceptable levels (some induced seismicity is unavoidable in any mining operation) and also on stability of the working areas.

The model was able to confirm that going forward, seismicity is similar to the moderate seismicity which has been observed in the past. The full summary is contained in the 2009 BAE report and BAE noted that while all mines must be designed for best practice management OD seismicity is indeed moderate (on a per tonne or event magnitude basis) compared to Western Australian experience.

Discussion of seismicity

The method for seismogenic calibration has been described in detail in Beck et.al. 2002. In summary, Dissipated Plastic Energy (DPE) in the model is compared to seismic event occurrence using the ‘cell evaluation method’ described by Beck and Brady (2002), involving discretising the entire model into regular, volumetric ‘cells’ or ‘test blocks’. The method correlates real event occurrence and the magnitude of modelled DPE, and expresses event probability as the expected number of events within a certain distance of any location in the model within a particular time period. The probability of events of any magnitude can be forecast.

There are a number of conditions that have to be satisfied for the probability to be a true probability and to be a good calibration, as outlined in Beck and Brady 2001:

1. There is near-zero event measured probability at zero modelled DPE release rate. Essentially, this means there are almost no seismic events not accounted for by the DPE relation.

   <u>This is a very useful characteristic for the current consideration: zero DPE in a calibrated model identifies the limit of expected seismicity.</u>

2. There is a peak modelled DPE beyond which the event measured probability decreases. This occurs because beyond this limit, the ground has been conditioned (softened by damage induced by mining) and seismic activity must therefore decrease in that area. In general this accounts for why seismicity occurs where new damage is being induced then subsides as an area becomes de-stressed and damaged by the mining process (remnants left behind during underground mining are a special case but follow the principal).

   This too is important for the current considerations: areas influenced by the mine are not all seismic, and do not remain seismic. Mining induced seismogenic zones are transient associated with damage in areas that have relatively larger amounts of stored elastic energy compared to aseismic areas.

3. There is a linear, log-normal relationship between event probability and DPE. This is discussed in detail in Beck et al 2009 and occurs because of the strain softening characteristics of geological materials.

The final calibration achieved for ODO is shown for a number of OD materials in Figure 1, showing that the result is consistent with these requirements.

Each visible data point represents a calculation involving many hundreds of seismic events within a certain magnitude and DPE range. The data points are the average probability (not single events) for a discrete DPE range that the probability calculation has been undertaken for. In this case the probability equates to the chance of having an event at the indicated magnitude, within a 25m radius of the test location during the time period of the model step. A probability of >100% means that more than one event should be expected.

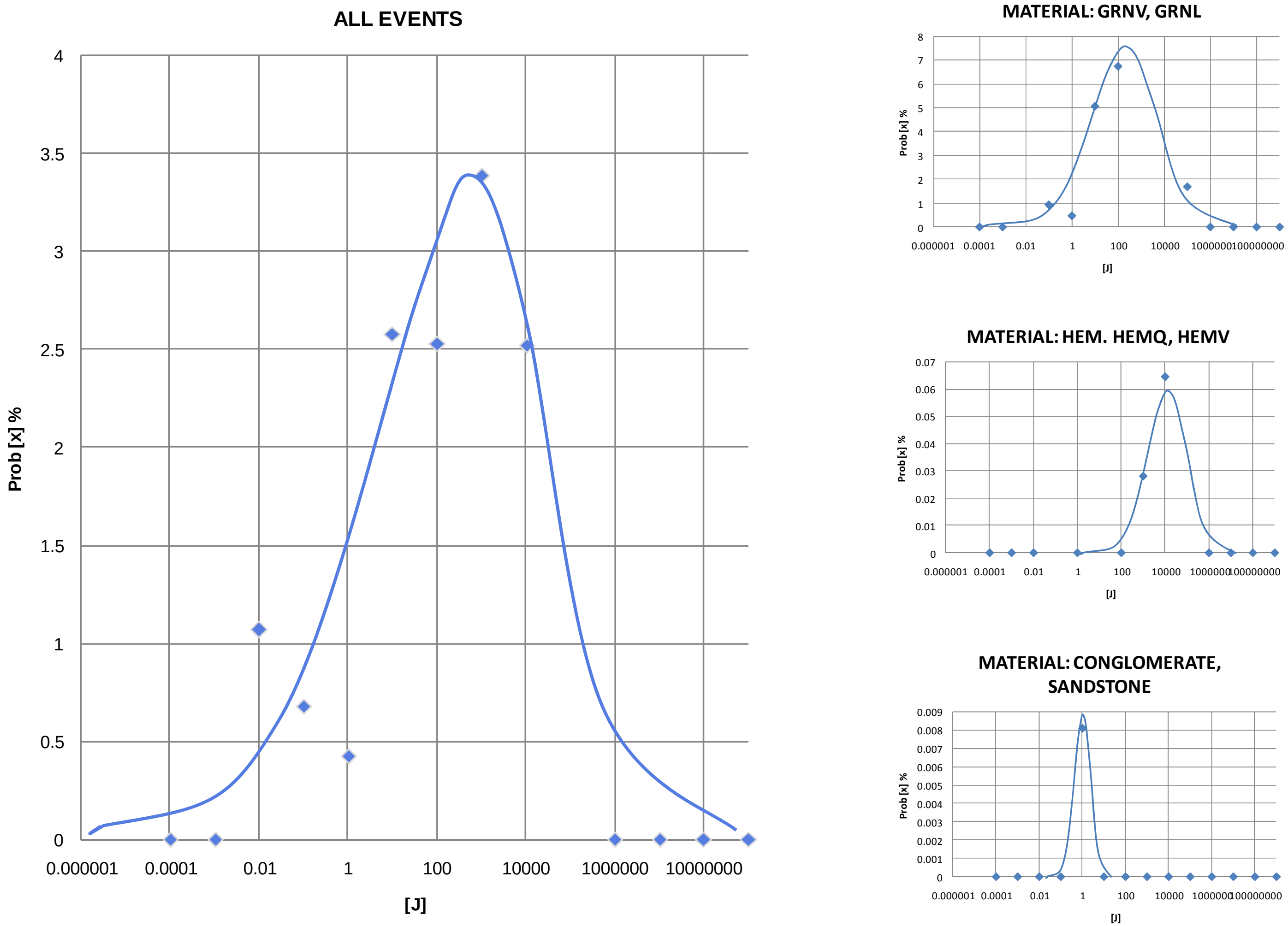
The calibration clearly shows very low event probability at zero DPE, justifying its use as one criteria for identifying the expected limits of induced seismicity around the mine. In effect, modelled DPE can be interpreted as follows:

– At zero DPE, there is a very low probability of seismicity. The actual rate is essentially zero.
– At above-zero DPE, DPE correlates with the probability of having a seismic event.

- The nature of the DPE release – the rate of change and the volume of the damage zone determines the nature of the seismicity for short periods but over longer periods and across the mine volume the Gutenberg Richter relation holds: the population of events, in terms of the expected proportion of events at a given magnitude is relatively constant. In effect, higher (DPE predicted) event probability correlates with a higher probability of larger events.

  Studies at a large number of mines show that the GR relationship is implicit in the DPE probability calculations. See for example Beck et al 2007.

Figure 1 Correlation between DPE and event probability; all rock types for OD

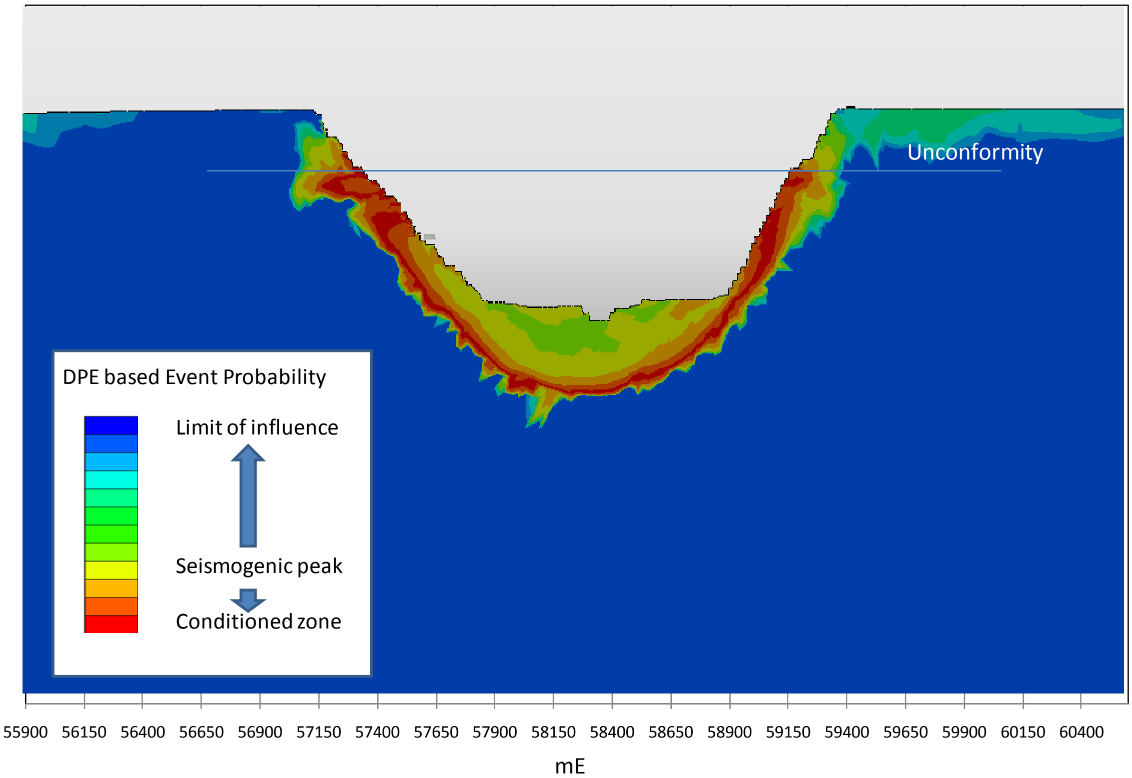


Model Results for the Mashers Fault zone

Model results are shown in the attachment for DPE on sections through t he Mashers fault at selected years. The model results show all the DPE occurring over a particular year, and not the DPE released instantaneously.

An example is shown in Figure 2 below.

Figure 2 Example of DPE release in a particular year around the pit on a section through Mashers Fault



There are several important characteristics:

– DPE must be interpreted differently in different geological domains:

- Above the unconformity no seismicity is currently measured as the material is too soft to generate detectable events. There is plastic deformation and energy changes but the seismic efficiency must be near zero – almost none of the plastic energy released as degradation manifests as seismicity.

  This means that DPE above the unconformity can be ignored.

- Below the unconformity the GR relation for the Masher fault zone will hold over time.

  The zone is soft and weak so not expected to be particularly seismically active, but generally some events are to be expected, much as some are observed in the quieter, soft sandstones and conglomerates.

As a conservative estimate, the DPE/probability relation for 'all rock types' can be used though this represents a scenario with much upside for the mine (compare the probabilities vs DPE for sandstone with the 'all events' relation in Figure 1 for example).

This conservative assumption will overestimate seismicity in Masher fault zone as the rock there is much softer and weaker than the average for the whole rock mass but is sufficient for a first pass assessment.

– On this basis, the seismogenic zone (limits of induced seismicity) can be interpreted to grow proportionally in increments matched to the changes in the shape and size of the pit. This encourages release of energy in smaller, more frequent increments and is a fundamental principal of management of mining induced seismicity.

  This is very important: for a very large event to occur, much larger than expected based on the current seismic population, the mine would need to isolate a very large area of the fault with very high confinement, generate large amounts of elastic strain and then cause instantaneous release of that stored energy by inducing an increment of damage that allowed that energy to release.

  If this scenario were occurring it would be clearly visible and it is not. There is no indication of significant releases of energy and the continuous release of DPE in regular increments as shown disconfirms the possibility of regional scale events by this mechanism.

– It is entirely clear that the damage to masher fault does not occur in a small number of very large steps as would be needed for a regional scale seismic event (>4.0 ML for example) to occur. Rather, the energy is released incrementally in approximately similar amounts in each step. Based on experience, this is considered best case or practice for managing mining induced interaction with fault zones for seismic outcomes.

– In addition to DPE, stress change can be used to interpret the zone of influence of mining:

  - The extent of mining induced stress changes is naturally a good indicator of the zone of influence of the mining – seismic events which occur outside the zone of influence can be considered natural and un-influenced by the mine. Images showing stress contours across the masher fault are included as attachments.

  - The results show that the areas of high DPE discussed above are largely de-stressed, not highly stressed. This means that the mechanism of damage is largely de-stressing (loss of confinement) rather than over-stressing and this is favourable.

  - Stress changes occur in regular increments proportional to the amount of extraction in the year. Like DPE, regular frequent smaller changes in stress confirm good management of seismic potential.

Effects of seismicity on workings

The possible effects of seismicity on the underground workings are discussed in detail in BAE 2009 so will not be discussed here except to say that future occurrences are expected to be somewhat similar to previous occurrences. The changes between past and previous experience are summarised in the earlier report.

The effects of induced or natural seismicity on the stability of the pit slopes was not discussed in the previous BAE report. Generally, large pit slopes are historically resilient to seismic events - induced or natural. OD is not in a high seismic prone area (for natural events) and simple application of design factors to account for dynamic loading should be sufficient to account for the expected range of natural events and is unlikely to result in changes to global pit design as the dynamic load scenarios that need to be considered are very likely to be benign.

The existing numerical models are also already explicit FE models, so can be used to simulate the effects of large seismic events, blasting or induced events on stability of the pit including the effects of repeated cyclic loading. Where these effects are expected to be minor, such analysis is usually only undertaken where a specific vulnerability is identified, for example if there is a particular sector of the pit with a geometry that suggest it may be susceptible to dynamic loading. Such scenarios are dealt with in final design stages as a very detailed design is needed for the analysis.

Enquiries and Confirmation

If you have any enquiries regarding this report, please contact BAE

Kindest Regards,

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