Australian Earthquake Engineering Society 2011 Conference, Nov 18-20,
Barossa Valley, South Australia

Evaluation of earthquake-induced displacement of aggregate mine slopes

James N. Dismuke
Senior Geotechnical Engineer
Arup
Sydney, New South Wales
Email: james.dismuke@arup.com

ABSTRACT

Site-specific seismic hazard and ground response analyses were used to determine seismic slope displacements to justify side slope inclinations of 1.25 to 1 (horizontal to vertical) and mining depths of 135 meters for an open-pit aggregate mine in Irwindale, California.

City of Irwindale guidelines for stability of open aggregate mine slopes include criteria for evaluating slope stability under static and earthquake loading conditions. The guidelines recommend shear strength parameters for sand, gravel, and cobble deposits and stipulate a maximum seismic slope displacement. Typical practice in the City of Irwindale is to determine potential seismic slope displacement using the simplified procedure of Makdisi and Seed (1978).

In addition to simplified procedures, seismic slope displacement was evaluated using Newmark-type sliding block analyses. Site-specific probabilistic seismic hazard analyses were undertaken to develop design acceleration response spectra. Recorded acceleration-time histories were spectrally matched to design acceleration response spectra. Surface ground motions were deconvolved using one-dimensional equivalent linear seismic site response analyses. Newmark-type displacement was determined using results of two-dimensional dynamic finite element model.

Keywords: seismic slope displacement, aggregate mine, sand gravel cobble, Newmark

1 INTRODUCTION

Irwindale, California, located in the eastern foothills of Los Angeles County, is home to several open-pit aggregate mines. The City of Irwindale has imposed guidelines for evaluation of pit slopes that stipulate strength parameters, factors of safety for slope stability, and seismic deformation criteria. This paper describes analyses of proposed deeper mining slope configurations that were carried out between 2005 and 2007, which progressed from simplified analysis methods to two-dimensional (2D) site response analyses with estimation of Newmark-type seismic deformation.

2 THE SITE

The site is located within a large alluvial fan to the south of the San Gabriel Mountains, about 30 km east of Los Angeles, as shown on Figure 1. Sand and gravel deposited by the San

Gabriel River at the Site are several hundred metres deep and are described, for purpose of mine slope stability, in terms of upper and lower formations. Both upper and lower formations contain sand, gravel, and cobbles, the primary difference being age. At the site, the upper formation is about 6m thick and is underlain by the lower formation to the depth of interest (135m).

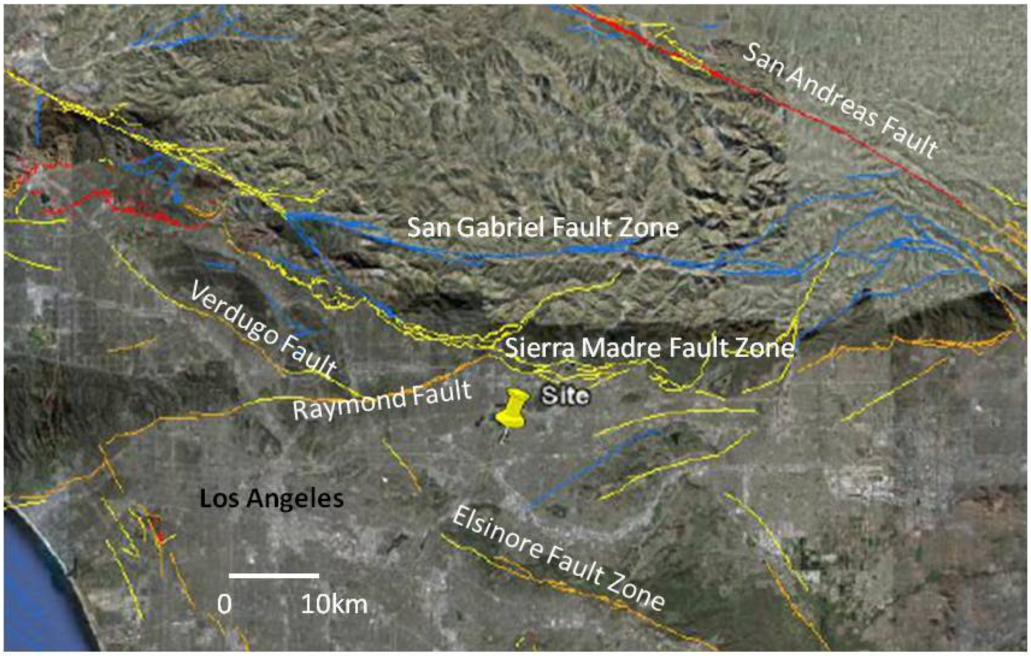

Figure 1: Site Location Map (Source: Google Earth v6.0.3.2197 and U.S. Geological Survey, 2006)

Proposed Deeper Mining Slopes

The proposed mining configuration comprises 2:1 (horizontal to vertical) slopes with an approximately 40m wide bench near mid-slope. The proposed final depth of mining is on the order of 135m. Figure 2 depicts a typical mining configuration.

Shear Strength

Conventional field investigation methods are not capable of penetrating the coarse deposits, so strength parameters were determined from the results of full scale load tests and back analysis of shear strength from tall slopes with near vertical faces. The load tests were performed in dry and saturated conditions by loading a 3m by 4m concrete slab adjacent to an approximately 10m vertical cut. Pre-weighed concrete loading blocks were placed successively, block-by-block, until failure of the vertical cut occurred. Saturated tests were facilitated by inundation of infiltration trenches located near the test locations.

Test results were evaluated by a panel of experts and shear strengths based on the test results are recommended in The Irwindale Slope Stability Committee (ISSC) “Guidelines for Stability Analyses of Open-Pit Mine Slopes,” (the Guidelines), as shown on Figure 3. For slope stability analyses using this shear strength model, the transition between Upper Geologic Formation and Lower Geologic Formation is specified to occur over at least 5 layers of increasing strength.

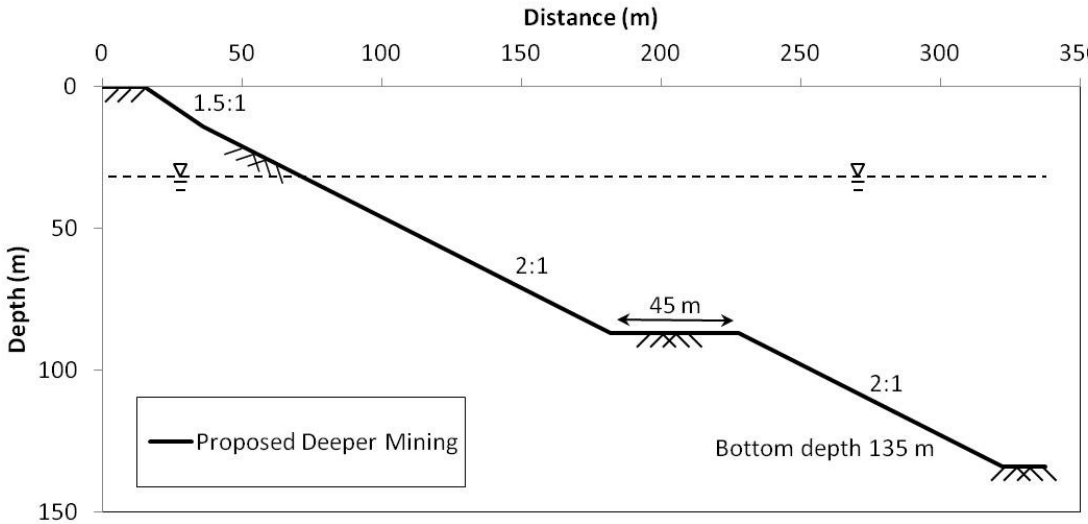

Figure 2: Typical Mining Slope Configuration

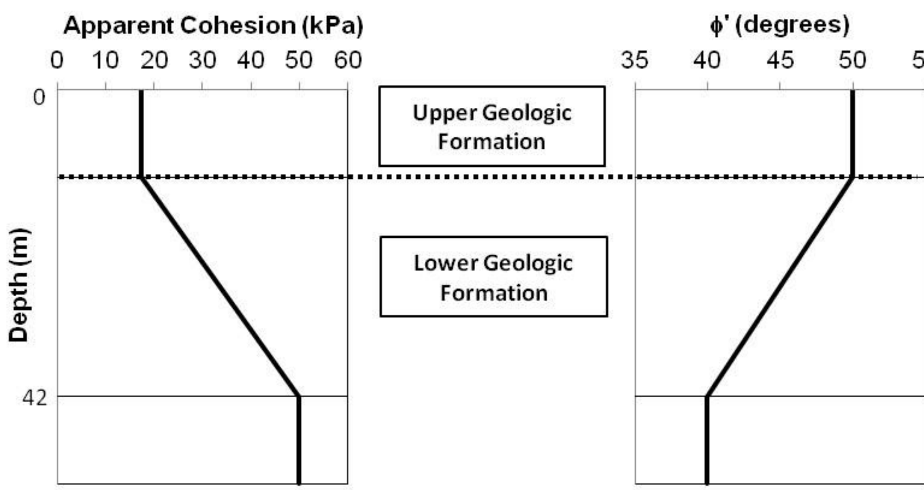

Figure 3: Shear Strength Parameters for Upper and Lower Geologic Formations

3 EVALUATION OF PROPOSED DEEPER MINING SLOPE

The Guidelines stipulate a minimum static factor of safety for slope stability (FS) of 1.5 and maximum permanent seismic slope deformation of 2cm. Slope stability analyses were performed using Spencer's method for limit-equilibrium, and demonstrated that the proposed mining slope configuration has the minimum FS.

Permanent seismic slope deformation was estimated using the simplified procedure of Makdisi and Seed (1978) with modification of k_{max} according to Ashford and Sitar (2002). The estimated seismic slope deformation was also determined to meet the criteria set forth in the Guidelines (less than 2cm). In fact, the results of the stability analyses and seismic deformation estimates far exceeded expectations, prompting a closer look at the conservatism of using the simplified Makdisi and Seed (1978) method, which was developed for embankments, as opposed to a tall sand, gravel, and cobble mine slope.

4 EVALUATION OF MAXIMUM SAFE YIELD SLOPES

A second set of proposed mining slopes was developed with the intention of pushing the slope inclinations and depth to the limit of the design criteria. This was accomplished by directly calculating the Newmark slope displacement, instead of relying upon the displacements computed using the Makdisi and Seed (1978) procedure. Slope configurations comprising steeper slopes without a mid-slope bench were denoted "maximum safe yield" slopes, as shown on Figure 4. The presence of free water necessitated that slopes were set at an inclination of 2:1 for prevention of wave-lap erosion.

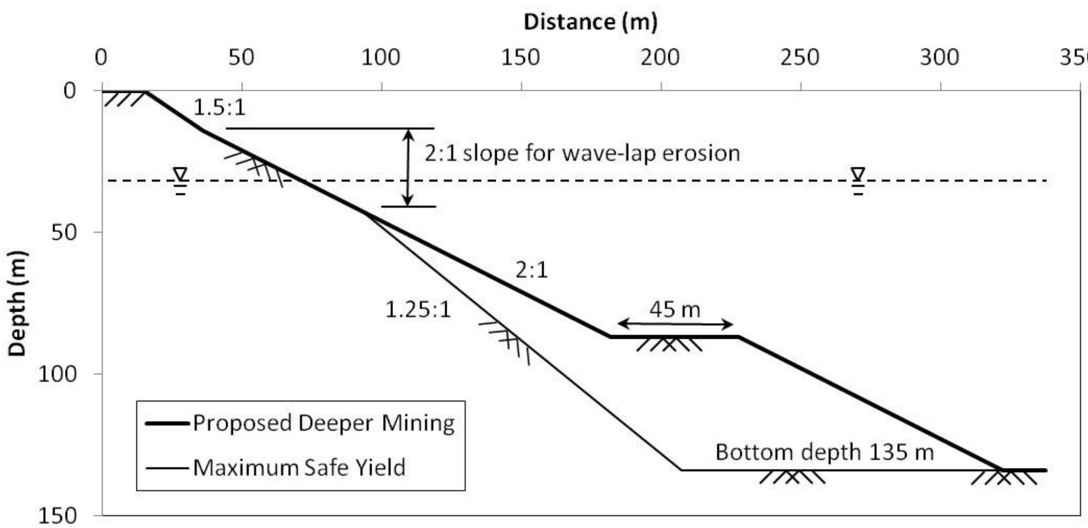

Figure 4: Typical Maximum Safe Yield Slope Configuration

In order to calculate Newmark slope displacement, a probabilistic seismic hazard analysis was conducted, a 2D seismic site response analysis was performed, and the resulting response of the slope was double-integrated to obtain the estimated permanent deformation. This approach represented the first time an analysis procedure other than simplified procedures were used for open-pit aggregate mine slope design in Irwindale, since inception of the Guidelines.

Probabilistic Seismic Hazard Analysis

The site is located in seismically active Southern California near many active faults, as indicated on Figure 1. Previous ground motion estimates used for analyses of the site relied upon a probabilistic seismic hazard analysis (PSHA) performed for a nearby mine pit. Comparison of the previous hazard with the 2006 (current at that time) national seismic hazard model on the CGS and USGS websites indicated that the previous ground motions were larger than current estimates, 475-year return period PGA of 0.55g versus 0.5g, respectively. Thus, it was advantageous to perform a site-specific PSHA to provide a current estimate of ground motion hazard.

The results of the site-specific PSHA indicated, for reference, PGA of 0.49g for a 475-year return period. The equal hazard spectra determined through the site-specific PSHA is shown on Figure 5. A key feature of a PSHA is the ability to deaggregate the results to determine which earthquake scenarios contributed the greatest amount to the hazard, thus guiding selection of acceleration-time histories. The deaggregation of the hazard indicated that majority of the hazard is due to M6.5 to 7 earthquake at distance of about 5 to 15 km.

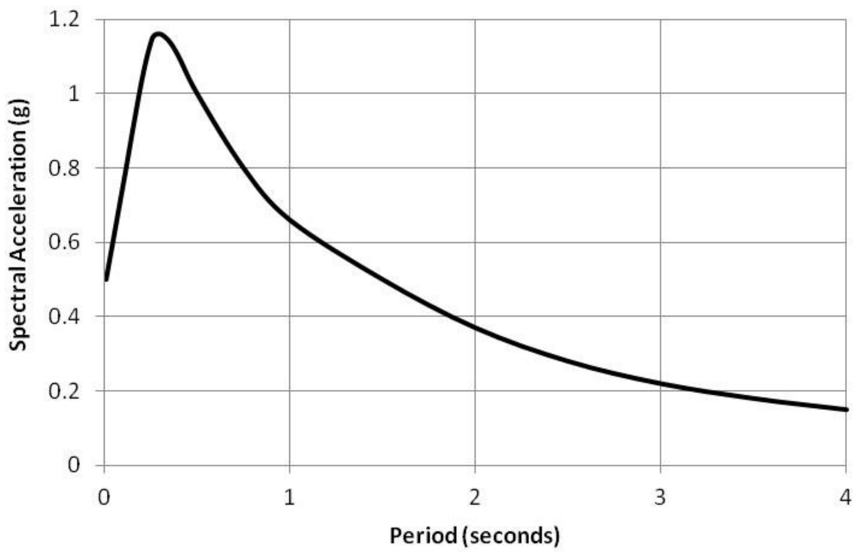

Figure 5: Horizontal Equal Hazard Spectra for 475-year Return Period (5% Damped)

Seismic Site Response Analyses

The input acceleration-time history for the Newmark deformation analysis was determined by extracting the computed response along the potential slip surface from the results of a 2D seismic site response analysis. The steps involved with the seismic site response analysis performed for the project were:

1. Develop input acceleration-time histories from actual recorded records;
2. Deconvolve the acceleration-time histories from ground surface motions to ground motions within the soil; and
3. Perform 2D site response analysis using the deconvolved acceleration-time histories.

Acceleration-time histories

Recorded acceleration-time histories were selected from the strong motion databases available on CGS and Pacific Earthquake Engineering Research Center (PEER) websites (CGS, 2011 and PEER, 2011, respectively). Ground motion records were selected based on the magnitude and distance deaggregation discussed above, as well as style of faulting and subsurface conditions. A total of 6 acceleration-time histories were selected and spectrally matched to the equal hazard spectra determined by the PSHA shown in Figure 5. Table 1 summarizes the time histories used for the analyses.

Table 1: Summary of acceleration-time histories

Station	Earthquake	M_W	Faulting Mechanism	Site Geology	Closest Distance to Fault (km)	Component	*Original Records* Peak Ground Acceleration (g)	*Original Records* Peak Ground Velocity (m/s)	*Original Records* Duration[1] (s)	*Spectrally Matched Records* Peak Ground Acceleration (g)	*Spectrally Matched Records* Peak Ground Velocity (m/s)	*Spectrally Matched Records* Duration[1] (s)
Rinaldi Receiving Station	1994 Northridge	6.7	Thrust	Alluvium	8.6	S49W	0.84	1.7	7.05	0.53	0.71	8.51
Sylmar Converter Station	1994 Northridge	6.7	Thrust	Alluvium	8.7	S38E	0.75	1.09	7.28	0.53	0.63	7.77
Fremont School	1987 Whittier Narrows	6.1	Reverse-Oblique	Alluvium	13.9	180	0.29	0.22	5.25	0.45	0.83	6.38
						270	0.38	0.17	5.71	0.47	0.64	5.08
Eaton Canyon Park	1991 Sierra Madre	5.6	Thrust	Alluvium	12.5	0	0.45	0.27	1.22	0.53	0.72	2.76
						90	0.18	0.08	5.27	0.47	0.61	4.74

[1] Duration based on Rathje et al. (1998)

Deconvolve ground motions
Ground motions within the subsurface were deconvolved from spectrally matched acceleration-time histories at the ground surface using equivalent linear 1D site response analysis. Subsurface conditions for the 1D site response analysis were determined from the results of shear wave velocity measurements at the site and the modulus and damping relationships for gravel of Rollins et al (1998), as shown on Figure 6.

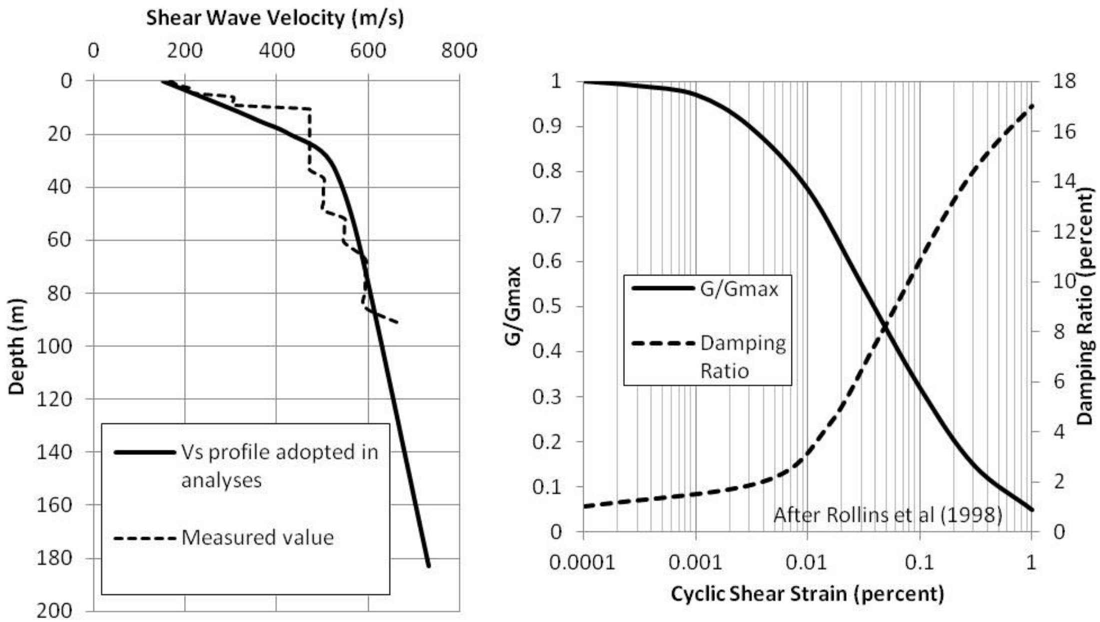

Figure 6: Dynamic Soil Properties Used for 1D and 2D Site Response Analyses

Perform 2D site response analysis
The response of the proposed maximum safe yield slope was computed using a 2D dynamic finite element model with the deconvolved ground motions as input at the base of the model. The subsurface conditions used in the 1D model were also adopted in the 2D model (Figure 6). The average acceleration-time history along the potential failure surface shown on Figure 7 was computed.

Newmark Deformation Analyses
The final step in the maximum safe yield slope evaluation was to determine the seismic deformation by double integrating the acceleration-time history of the slope stability failure surface where the acceleration exceeded k_y. The Newmark-double integration was performed for a suite of k_y to generate the curves shown in Figure 8. The k_y determined for the slope through pseudostatic stability analysis was 0.17; thus, the computed slope deformation is less than 2 cm, which meets the criteria of the Guidelines. In comparison, deformation computed using the simplified Makdisi and Seed (1978) procedure, also shown on Figure 8, is greater than 2 cm and does not meet the criteria of the Guidelines.

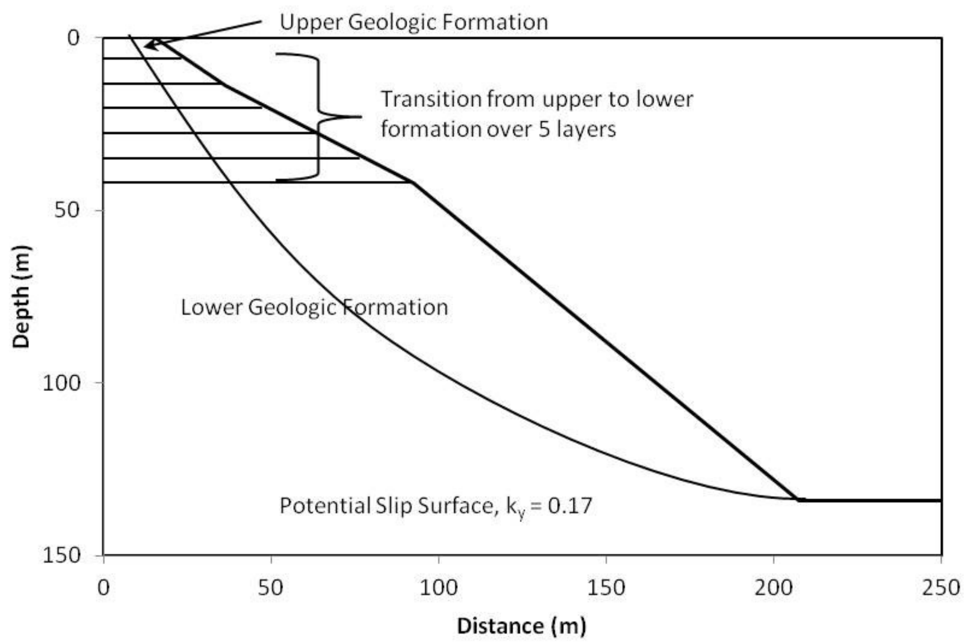

Figure 7: Potential Slip Surface for Maximum Safe Yield Slope

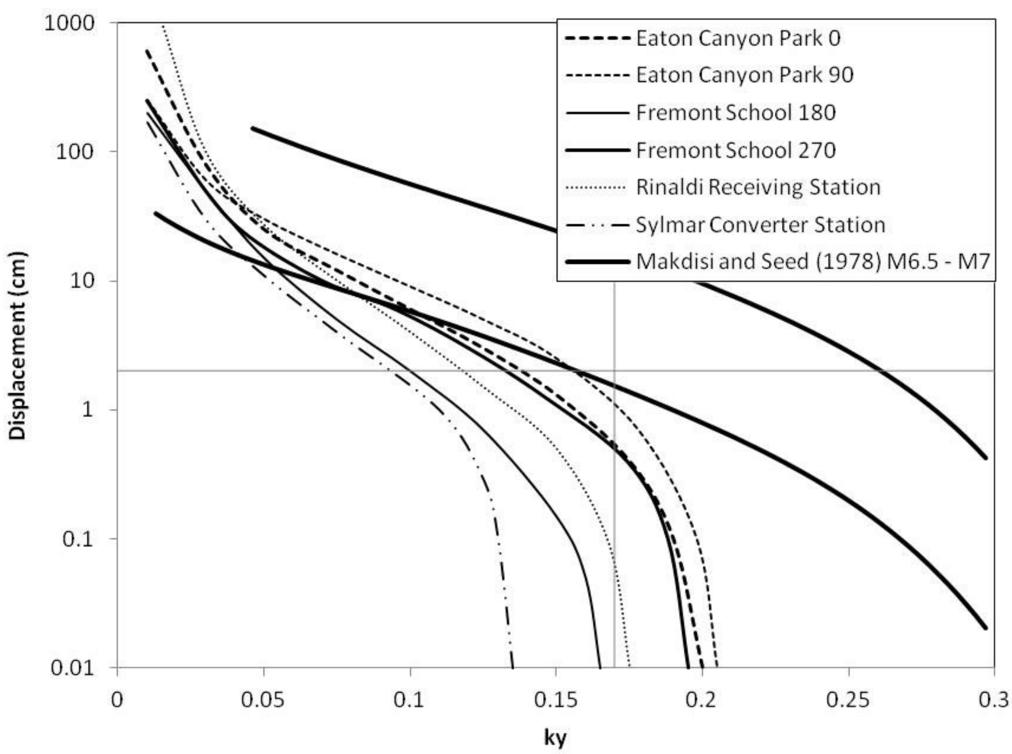

Figure 8: Deformation Chart for Maximum Safe Yield Slope

5 CONCLUSION

The calculation of earthquake-induced slope deformation using Newmark deformation analysis was the first of its kind for mine slopes in Irwindale. Despite the aggressive slope configuration, the seismic deformation was determined to be less than 2 cm when seismic deformation was calculated directly, instead of relying on the simplified procedure of Makdisi and Seed (1978).

Conservatism of Makdisi and Seed (1978)

The Makdisi and Seed (1978) approach for estimating permanent seismic slope displacement is based on the Newmark method, but enhanced for application to earth embankments. By directly computing the seismic response of the mine slope, which is notably different in shape to an embankment, a site specific evaluation of mine slope deformation, that was also acceptable to the City of Irwindale, was possible. Although the analysis presented in this paper for a tall gravel slope is an improvement over a simplified estimate using Makdisi and Seed (1978), the seismic response is decoupled from the deformation analysis. A decoupled analysis may be conservative or unconservative to more accurate, coupled analysis procedures, such as those discussed by Rathje and Bray (2000).

Scatter of Computed Deformations

The slope deformations shown in Figure 8 demonstrate similar trends in the shape of the deformation versus k_y curves; however, the relative magnitude of the deformation computed for each acceleration-time history may not be as expected. That is, the two time histories with largest magnitude and duration, Rinaldi Receiving Station and Sylmar Converter Station, did not produce the largest deformation for the maximum safe yield slope.

Each time history was spectrally matched to the target uniform hazard spectra; however, only peak response is matched in this procedure. Since k_y, which is the trigger value for the double integration, is less than the spectral accelerations for the periods of interest, the computed deformation is not wholly dependent on peak response. Therefore, it is reasonable to expect scatter in the computed deformation.

Applicability to Australian Practice

The analysis presented in this paper may be implemented in Australia, but several aspects should be updated and improved:

- The target uniform hazard spectra may be developed using PSHA as described. The PSHA should include attenuation equations appropriate for Australia.

- The selection of seed acceleration-time histories presented above attempted to match several aspects of the ground motion. Al Atik and Abrahamson (2010) indicate that magnitude and distance are the most important aspects of the seed time history when spectral matching is to be performed. Future analysis should value magnitude and distance over style of faulting and site conditions.

- The Makdisi and Seed (1978) procedure is simple and easy to use; thus it is a valuable tool to provide a quick first estimate. If slope deformation computed using Makdisi and Seed (1978) is within acceptable limits, there is no need for further analysis, such as with the original deeper mining slopes described in this paper (i.e. it was not necessary to perform the Newmark deformation analysis without consideration of maximum safe yield slopes).

- Consideration should be made regarding the importance of the slope. A coupled deformation analysis may be required if the risk associated with seismic slope deformations is great.

6 REFERENCES

Al Atik, L. and Abrahamson, N., 2010. An Improved Method for Nonstationary Spectral Matching, *Earthquake Spectra,* Volume 26, No. 3, pages 601–617, August.

Ashford, S.A. and Sitar, N., 2002. Simplified Method for Evaluating Seismic Stability of Earth Slopes, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 128, No. 2., February.

California Geological Survey, 2011. Strong Motion Instrumentation Program, current website: http://www.conservation.ca.gov/cgs/smip/Pages/Index.aspx

ISSC, 2003. “Guidelines for Stability Analysis of Open-Pit Mine Slopes,” Irwindale Slope Stability Committee.

Google Inc., 2011. Computer Program for Satellite Imagery, Maps, Terrain, and 3D Buildings, Mountain View, California.

Makdisi, F.I. and Seed, H.B., 1978. Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformation, *Journal of Geotechnical Engineering*, ASCE, v. 104, no. GT7, July.

Newmark, N.M., 1965. Effects of Earthquakes on Dams and Embankments, *Geotechnique* 15, No. 2, pp. 138-160.

Pacific Earthquake Engineering Research Center, 2011. PEER Strong Motion Database, current website: http://peer.berkeley.edu/smcat/

Rathje, E. M., Abrahamson, N. A., and Bray, J. D., 1998. Simplified frequency content estimates of earthquake ground motions, *Journal of the Geotechnical and Geoenvironmental Engineering,* ASCE, Vol. 124, No. 2, February.

Rathje, E. M. and Bray, J. D., 2000. Nonlinear Coupled Seismic Sliding Analysis of Earth Structures, *Journal of the Geotechnical Engineering Division,* ASCE, Vol. 126, No. 11, November.

Rollins, K.M., Evans, M.D., Diehl, N.B., Daily III, W.D., 1998. Shea Modulus and Damping Relationships for Gravels, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 124, No. 5, May.

U.S. Geological Survey and California Geological Survey, 2006. Quaternary fault and fold database for the United States, accessed 7 August, 2011 from USGS website: http//earthquakes.usgs.gov/regional/qfaults/