Source Properties of Mining-Induced Seismicity

Or

Control of Strong Ground Motion of Mining-Induced Earthquakes by the Strength of the Seismogenic Rock Mass

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Summary of presentation at workshop on Extreme Ground Motions at Yucca Mountain on Tuesday, August 24, 2004

The seismogenic setting of the deep gold mines in South Africa is similar in some ways to that at Yucca Mountain and different in others. The similarities include (1) an extensional state of stress for which the maximum principal stress is vertical and the minimum horizontal principal stress is approximately half the vertical, or overburden, stress and (2) a depressed water table. In the case of the deep mines, the water table is depressed from its natural level near the surface due to pumping operations necessary to prevent flooding of the underground workings. The main difference between the two settings is the contrast in geologic age or tectonic activity. Within the Witwatersrand basin where the gold mining takes place, the rocks are of Archean age and there is no tectonic activity in contrast to Yucca Mountain within which the tuffs at the repository horizons are approximately 12 million years old.

The geologic age difference notwithstanding, the well-studied mining-induced seismicity in South Africa can provide insights regarding the nature of the ground motion that might affect Yucca Mountain and, in particular, factors that might limit this ground motion. On Monday, I argued that the highest likely PGV that might affect the repository at Yucca Mountain would be associated with the ground motion adjacent to the Solitario Canyon fault, assuming that it ruptures to the surface. This raises the questions of what factors might limit the near-fault PGV. Here I propose that the strength of the seismogenic rock mass limits the near-fault PGV and review observations that support this assertion.

Figure 1 shows shear strength as a function of depth of the Witwatersrand quartzites estimated using four independent techniques. The circles are estimates based on Byerlee's law of friction with zero pore pressure. The agreement between these and the other three types of estimates (McGarr, 2001) suggests that to a good approximation, the bulk strength of this seismogenic region is that of a pervasively-faulted rock mass and falls somewhere in the range of 30 to 60 MPa.

McGarr (2001) showed that based on laboratory evidence and a well-accepted dynamic rupture model (Madariaga, 1976) that near-fault PGV is limited according to

$$PGV \leq 0.25 \beta \tau / G \qquad (1)$$

where β is the shear wave speed of about 3.7 km/s, τ is the shear strength, and G the modulus of rigidity is about 3.76×10^4 MPa. If the shear strength is 60 MPa, near the top of the range in Figure 1, then using (1) the near-fault PGV is limited to 1.5 m/s. This result is consistent with the general observation that the support used in the production stopes can accommodate a rate of stope closure of approximately 3 m/s without failing.

The example described in my report presented on Monday is also consistent with the bound on near-fault PGV of 1.5 m/s. Briefly, the far-field ground velocity indicated a source rise time of 0.16 s, which when divided into the maximum slip of 0.2 m observed on the extensive fault zone several km below the recording site yielded a near-fault PGV of 1.25 m/s or greater.

Stope support occasionally fails, however, over fairly localized production areas suggesting that PGV may sometimes exceed 3 m/s, or so. These high inferred PGV's may be the result of rupture through previously-intact quartzite. If so, then, as explained by McGarr (2001), the relevant shear strength is at least 164 MPa, which, if used in (1) yields a near-fault PGV of 4 m/s.

There may be seismic evidence for near-fault PGV's that are about this high. Figure 2 shows one component of ground acceleration and velocity recorded at a hypocentral distance of 152 m from a mining-induced earthquake at a depth of 3 km (McGarr et al., 1981; McGarr, 1991). The seismic moment of this event, 1.7×10^{12} N-m, indicates that within the fault zone there was a high-slip patch with about 0.018 m of offset (McGarr and Fletcher, 2003). Assuming that slip on this patch was responsible for the peak acceleration and peak velocity pulses (Figure 2) each of which have durations of 0.005 s, one can divide the inferred rise time of 0.005 s into the maximum slip of 0.018 m/s to infer an average slip rate of 3.6 m/s or a peak slip rate of 7.2 m/s, which yields a near-fault PGV of 3.6 m/s. If these inferences are correct and can be generalized, then in a given seismogenic setting, the highest near-fault PGV's are likely to be due to seismic rupture through asperities composed of intact rock within much broader fault zones.

Conclusions:

1) Rock strength seems to control near-fault PGV according to

$$PGV \leq 0.25 \frac{\beta}{G} \tau$$

2) Exceptionally high near-fault PGV's may be due to the failure of asperities composed of intact rock.
3) Mining-induced ground motion results could be applied to the Yucca Mountain PSHA problem if rock strength differences are taken into account.

Recommendations:

1) Laboratory experiments involving both frictional sliding and fresh rock fracture could be run to investigate the factors that influence PGV and to assess the validity of the inferences presented here.

2) There are many ground motion data sets for mining-induced earthquakes that can be analyzed to infer near-fault PGV in reasonably well-understood seismogenic circumstances.

Figures

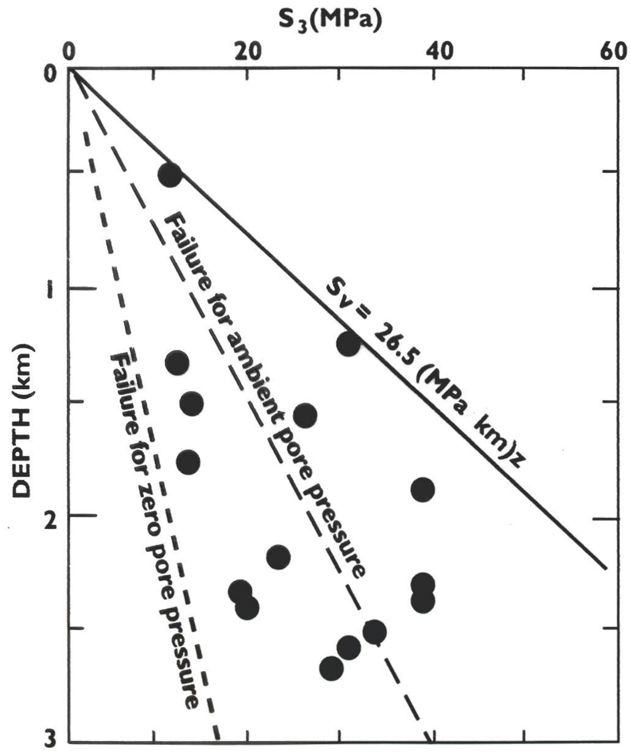

Fig. 1 In situ stresses as function of depth in the Witwatersrand gold fields.

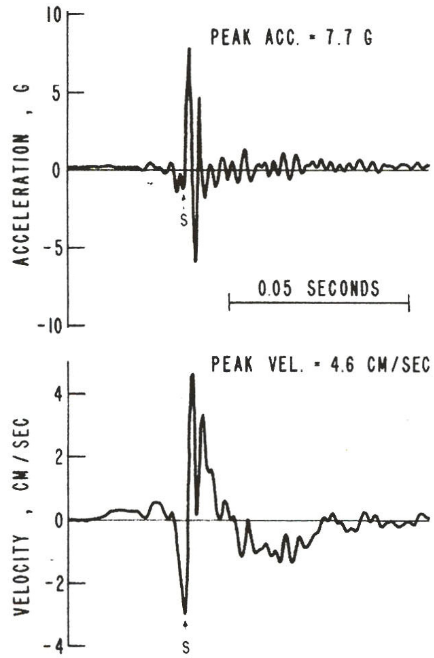

Fig. 2 One component of ground acceleration and velocity measured in a borehole at a hypocentral distance of 152 m from a mining-induced earthquake at about 3 km depth.

References

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