Monitoring of mining-induced seismicity at Grassy Trail Reservoir

Contrôle de la sismicité causée par l'exploitation minière au Réservoir de Grassy Trail

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ABSTRACT
Mining-induced seismicity was monitored at Grassy Trail Reservoir in eastern Utah. Coal mining activity at increasing proximity required evaluation and monitoring of potential impacts to the reservoir and earthfill embankment dam. Attenuation relationships for small-magnitude near-source events were used to predict the ground motions at Grassy Trail. Geotechnical instrumentation was installed and monitored on the dam and reservoir rim to allow assessment of impacts as mining drew near. The number of seismic events detected at the reservoir was related to the distance to the area being actively mined, and the intensity of ground shaking at the reservoir appeared to be a function of both distance and event magnitude. A comparison of predicted and recorded ground motions is presented herein, along with a general discussion of the dam's overall performance.

RÉSUMÉ
La sismicité causée par l'exploitation minière a été surveillée au Réservoir de Grassy Trail situé dans l'est de l'Utah. La proximité de plus en plus rapprochée de l'exploitation houillère a nécessité l'évaluation et le contrôle des impacts sur le réservoir et sur le barrage en terre. Des relations d'atténuation pour des événements sismiques de petite magnitude parvenus près de la source ont été utilisées pour prédire les mouvements du sol sur la piste de Grassy Trail. Une instrumentation géotechnique a été installée sur le barrage ainsi que sur le bord du réservoir et a été contrôlée pour permettre d'évaluer les impacts à mesure que l'exploitation se rapprochait. Le nombre d'événements sismiques détectés sur le réservoir était lié à la distance par rapport à la zone activement exploitée, et l'intensité des tremblements du sol sous le réservoir semble être en fonction de la distance et de l'ampleur de l'événement sismique. Une comparaison entre les prédictions des mouvements du sol et les mouvements tels qu'ils ont été observés est présentée ci-dessous, ainsi qu'une discussion générale de la capacité de performance du barrage.

Keywords : earth dam, geotechnical instrumentation, mining-induced seismicity

1 INTRODUCTION

Grassy Trail Reservoir is located in the Roan Cliffs region in Carbon County, Utah. The reservoir is impounded by an earthfill embankment dam constructed in the early 1950s, having a structural height of 27 m and a crest length of 183 m. The hillsides surrounding the reservoir are historically prone to landslides.

As longwall coal mining operations in the nearby West Ridge Mine progressed toward the reservoir, it became necessary to evaluate potential effects of mining on this water storage facility. In 2004, a monitoring program was implemented to document potential impacts, including ground shaking, deformation and changes in seepage patterns.

2 GEOLOGIC SETTING AND MINING CONDITIONS

The dam and reservoir are located on the Colton Formation, consisting of Tertiary beds of mudstone and shaley siltstone interbedded with thin quartzose sandstone with sparse limestone beds. The formation is primarily of alluvial origin, with some marginal lacustrine and deltaic deposits (Weiss et al. 1990).

The mine extracts coal from the Lower Sunnyside Seam, located within the Upper Cretaceous Blackhawk Formation. The Blackhawk Formation contains predominantly quartzose sandstone interlayered with shaley siltstone, shale, carbonaceous shale and several coal seams, and is bound by the Castlegate Sandstone Formation above and the Blue Gate Member of the Mancos Shale below (Weiss et al. 1990). The coal seam averages 2.4 m thick, and the mine panels are each 244 m wide. The hillsides west of the reservoir provide an average of about 600 m of cover over the nearest mine panels.

Figure 1 shows the basic site layout. This study focused on seismicity associated with mine Panels 6 and 7. Panel 6 mining provided an opportunity to collect data and assess potential impacts prior to mining of Panel 7. Panel 6 was mined through much of 2005, and the shortest distance between the dam and the edge of this panel was about 730 m. Panel 7 mining began in December 2005 and continued through much of 2006. The shortest distance between the dam and the edge of Panel 7 was approximately 583 m (500 m vertical and 300 m horizontal).

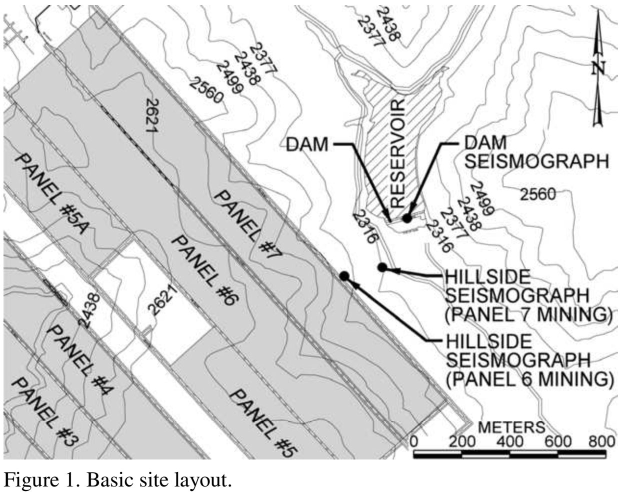

Figure 1. Basic site layout.

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3 REGIONAL MINING-INDUCED SEISMICITY

Research by the University of Utah Seismograph Stations (UUSS) and others was reviewed to develop estimates of event magnitudes and associated ground shaking for the region. These records included 100 events located in the near vicinity of Grassy Trail Reservoir, ranging from 1.2 to 3.2 in magnitude and dating back to 1962 (Arabasz & Burlacu 2004). Also considered were events attributed to Willow Creek and Trail Mountain Mines, located at distances of about 40 km and 80 km, respectively, from Grassy Trail. This data set included 49 events originating in Trail Mountain Mine with magnitudes ranging from 1.0 to 2.2, and a single magnitude 4.2 event recorded near Willow Creek Mine (Arabasz et al. 2002, 2005; McGarr and Fletcher 2005).

Noting that existing seismic attenuation relationships were generally unsuitable for assessing the low-magnitude near-source events of most interest in mining, McGarr and Fletcher (2005) revised the general ground motion equation of Joyner and Boore (1988) to fit data from Trail Mountain and Willow Creek Mines. Their purpose was to assist in attempts to predict mining-induced ground motions at an earthfill dam near Trail Mountain Mine. The form of the revised equations is:

$$\text{Log}(y) = a + bM + d\log(R) + kR + s \quad (1)$$

In Equation (1), y is the ground motion parameter of interest, such as acceleration or velocity, M is the event magnitude, and R is the site-to-source distance. The constants a and b specify the magnitude dependence, d and k describe the distance dependence, and s is the site factor. Along with revised constants, McGarr and Fletcher's (2005) approach varied from that of Joyner and Boore (1988) in assuming linear magnitude dependence and use of hypocentral distance for the R variable.

4 MONITORING PROGRAM

The monitoring program at Grassy Trail Reservoir included survey points, piezometers, observation wells, seepage collection points, vertical inclinometers and portable seismographs. Reports from the University of Utah Regional Seismograph network were monitored to track the number and magnitudes of seismic events occurring in the mine and vicinity. The accuracy and completeness of seismic reports for the region benefited from the August 2003 installation of a new UUSS station above West Ridge Mine.

Frequent site inspections and instrumentation readings were performed during mining of Panels 6 and 7. Reports were distributed to interested parties, including representatives of regulatory agencies and local governments. An action plan was established prior to mining Panel 7, requiring immediate dam inspection and instrumentation readings if a reported event exceeded a predetermined threshold magnitude.

5 RECORDS OF MINING-INDUCED EVENTS

Two portable seismographs were used to monitor mining-induced vibrations at the reservoir. The "hillside" device was located on the hillside above the dam, between the mine and the dam's west abutment. During Panel 6 mining, this instrument was located such that the shortest direct distance to the edge of the panel was about 600 m, which approximated the distance between the dam's west abutment and the nearest point on Panel 7. After Panel 6 was complete, this device was moved down the hillside closer to the dam (see Figure 1). The "dam" seismograph was located on the crest of the dam near its maximum section during mining of both panels.

The vibration detection instruments provided a record of the peak longitudinal, vertical and transverse velocities and accelerations for each event detected. The distance between each instrument and the center of the active longwall at a given time was assumed to be the approximate hypocentral distance for events occurring at that time.

Records for each event were visually reviewed, and those having waveforms inconsistent with seismicity were assumed to be caused by people, animals or other non-seismic factors. Between January 2005 and September 2006, over 1500 apparent mining-induced events were recorded by the hillside device, as well as about 1000 events on the dam. Approximately 330 of the events recorded were reported and assigned magnitudes by UUSS based on data from permanent seismic stations in the region. Reported magnitudes ranged from 1.1 to 2.6.

The maximum horizontal velocity component for each of the reported events is plotted versus the estimated distance to the center of the active longwall on Figure 2, and the maximum horizontal acceleration component is plotted versus distance on Figure 3. The majority of the records (about 90 percent) indicated peak velocities of less than 0.5 cm/s and peak accelerations less than about 0.03g. Intensity of ground shaking was evidently a function of distance to the active mining operation. Velocities exceeding 1 cm/s and accelerations greater than 0.1g were only detected when the center of the active longwall was within 1 km of a given instrument.

The distribution of event records across the range of reported magnitudes is shown on Figure 4. Each event reported and assigned a magnitude by UUSS was typically recorded by both

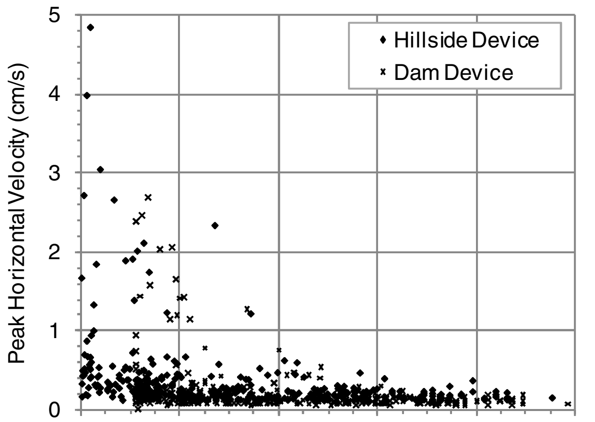

Figure 2. Peak velocity versus estimated distance to mining.

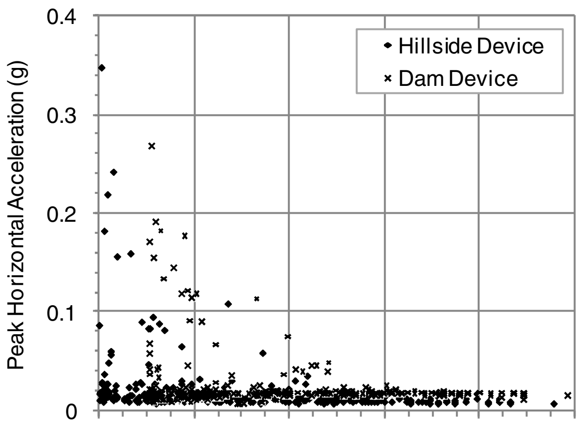

Figure 3. Peak acceleration versus estimated distance to mining.

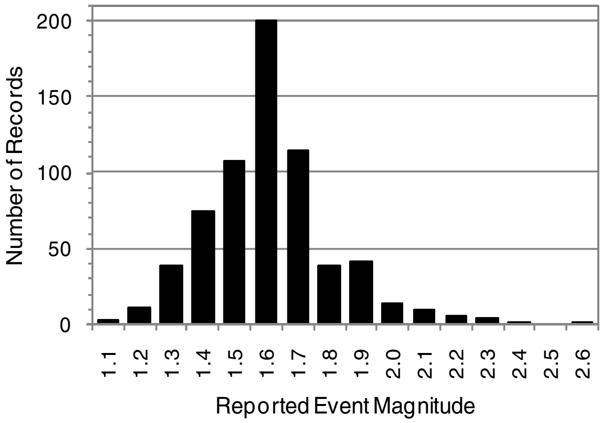

Figure 4. Distribution of reported event magnitudes

the hillside and the dam seismographs, resulting in two records for each event. Therefore, the 200 records obtained for events of magnitude 1.6 represent two records for each of 100 events.

The largest accelerations and velocities were typically the result of larger-magnitude events, and were recorded when mining occurred relatively close to the dam. The seven events of magnitude 2.2 or greater were recorded while the center of the active longwall was within 1 km of the instruments.

6 COMPARSION WITH PREDICTION EQUATIONS

The ground motion prediction equations developed by McGarr and Fletcher (2005) were based on mining-induced events ranging from about 1.0 to 2.2 in magnitude, plus one event of magnitude 4.2. Hypocentral distances for the events varied from about 500 m to almost 10 km. The stations from which data were collected were on solid rock, and it was emphasized that the equations were developed for rock motions and did not consider the site response of the dam. Table 1 lists the constants proposed to predict peak acceleration and velocity for mining-induced events within the range of data considered.

Table 1. Ground motion prediction coefficients for peak acceleration and peak velocity developed by McGarr and Fletcher (2005).

y	*a*	*b*	*d*	*k*	*s*
acceleration	-0.9892	0.8824	-1.355	-0.1363	0.337
velocity	-3.214	0.961	-1.46	-0.0403	0.337

Motions recorded at Grassy Trail Reservoir were compared to those predicted by the equations of McGarr and Fletcher (2005). In these comparisons it was assumed that the source of each recorded event was located at the center of the active longwall. It should be recognized that the data set collected at Grassy Trail was limited to hypocentral distances of about 600 m to 1.6 km, and covers only the low end of the distance ranges used to develop the equations. Both the hillside and dam instruments at Grassy Trail were mounted on soil rather than rock, and some variation in at least the site factor was expected.

Because records of very minor ground shaking associated with small magnitude events greatly outnumbered those of more significant and potentially-damaging ground shaking, the records were sorted into sets covering 0.1-km increments of hypocentral distance. These sets were further sorted into subsets covering magnitude increments of 0.1. The mean peak velocity, mean peak acceleration, and mean estimated distance were then taken from each data subset for comparison with the equation.

Upon comparison, it was observed that the McGarr and Fletcher (2005) relationships under-predicted the upper range of peak accelerations (greater than about 0.05g) by a factor in the order of four to five. A similar trend was observed in the prediction of velocities greater than about 0.5 cm/s.

While no rigorous statistical and seismological fitting analysis was performed, the equation constants were systematically adjusted in attempts to improve the agreement between the computed and recorded values. Substantial improvements were obtained by varying all constants within the constraints identified by McGarr and Fletcher (2005); however, these modifications resulted in only marginally better fits than those obtained by simply increasing the site factor *s* to a value of 1.0, which was the maximum value considered by the developers of the equations.

The velocity and acceleration values initially predicted by the equations are plotted versus the recorded values on Figures 5 and 6, respectively, along with the values predicted after changing the site factor to 1.0. The modified site factor provided a much-improved prediction of the larger velocity and acceleration values, although the tendency remained to under-predict velocities greater than 1 cm/s by about 20 to 60 percent.

7 DEFORMATION, SETTLEMENT AND SEEPAGE

Lateral and vertical displacements of the dam, abutments, and the hillside west of the reservoir were monitored using inclinometers, survey points, and settlement monuments.

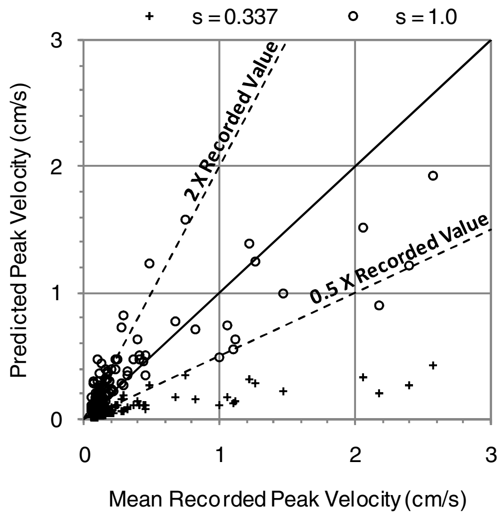

Figure 5. Predicted versus recorded peak velocity.

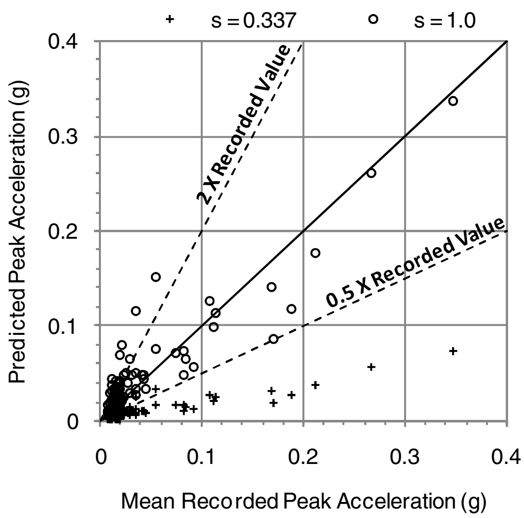

Figure 6. Predicted versus recorded peak acceleration.

Monitoring of an inclinometer casing extending through the dam into the west abutment indicated that 10 mm of lateral movement occurred during Panel 6 mining, beginning in early 2005 as mining approached the dam, and temporarily ceasing after the longwall had moved away toward the end of the panel. An additional 75 mm of deflection occurred between December 2005 and August 2006 as Panel 7 was mined near the dam. The recorded deflection was primarily into the dam along its longitudinal axis, trending about 15 degrees upstream.

During mining of both panels, deflection of the west abutment inclinometer casing began when the estimated distances between the casing and the center of the active longwall decreased to about 900 m, and progressed until the distance had increased to 1.2 km or greater. A similar trend was observed in an inclinometer penetrating the suspected failure plane of a landslide on the west reservoir rim. These deflections trended eastward into the reservoir basin, but only measured 3 mm during Panel 6 mining and 15 mm during work in Panel 7.

Survey points on the hillside west of the reservoir were monitored at six to eight-month intervals. These surveys indicated that some points moved downward to the east beginning during the mining of Panel 6. The rate of movement increased after mining began in Panel 7. Changes in survey point coordinates were generally less than 300 mm; however, a few points experienced easterly movement of up to 350 mm and downward movement approaching 550 mm. All points appeared to stabilize after mining in Panel 7 was complete.

Seven settlement monuments located along the crest of the dam were surveyed four times between March and May 2006 when mining was occurring nearest the dam in Panel 7. These monuments were also surveyed twice in the fall of 2006, and again a year later. Settlement of the easterly half of the dam appears to have been negligible. The elevations of points on the westerly half of the dam changed less than about 15 mm, with the exception of one monument located near the west abutment. The survey data indicate that this monument rose approximately 60 mm during nearby mining of Panels 6 and 7. Combined with the lateral deflection of the inclinometer in this area, this localized increase in crest elevation suggested that the west end of the dam was pushed slightly upward and eastward during mining. As was the case with the survey points on the hillside, the elevations of monuments on the dam appeared to stabilize after mining near the dam was complete.

Five piezometers and two observation wells were installed in the dam and abutments in 1998 and monitored since that time, providing almost seven years of baseline seepage data prior to this study. Seven additional piezometers were installed at the beginning of 2005. Water levels in the piezometers and wells remained relatively stable during mining of Panels 6 and 7. Seasonal changes related to fluctuations in reservoir elevation were observed to be consistent with those of previous years. Two supplemental piezometers were installed near the west abutment in late 2006 to allow additional monitoring of the phreatic surface in the area of measured deformations. Water levels in these new piezometers have remained relatively stable since the time of installation.

Seepage through the dam, foundation and abutments was monitored at the dam toe drain and at collection systems on each abutment. Seepage rates appeared to correlate with the reservoir water level during and since the mining of Panels 6 and 7. Water collected at the seepage points was consistently clear when observed on a weekly basis, with no reports of cloudy water indicative of internal erosion.

8 CONCLUSIONS

The data collected at Grassy Trail Reservoir provide a valuable case history in ground motions associated with mining-induced seismicity, and potential impacts on a dam and reservoir located very close to the mine. Complexities associated with geology, topography, mining procedures, overburden soils, and the dam itself dictate that these data and findings be treated as site specific. However, insight and experience gained from this project may be carefully projected to similar projects in assessing potential hazards.

Ground motion prediction equations are necessary tools in developing seismic parameters for engineering analysis. An understanding of the equations and the use of sound judgment is essential to their appropriate use. Any application of such equations must consider site-specific effects of soil and topography. After a simple modification of the site factor, the equations developed by McGarr and Fletcher (2005) provide relatively good agreement with peak velocities and accelerations recorded at Grassy Trail Reservoir.

While some deformation appears to have occurred during mining, noticeable impacts ceased after mining near the dam was complete. Observed seepage behavior remains consistent, and no unusual cracking or other evidence of embankment instability has been reported. In light of the apparent mining-induced deformations near the west abutment, continued monitoring is considered critical to verify the long-term performance of the dam.

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