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Numerical analysis of the stability of abandoned cavities in bench blasting

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ABSTRACT

When open-pit bench blasting approaches a site with underground cavities, concerns arise regarding the safe blasting distance to prevent collapse of the cavities because such collapses may induce other secondary problems related to the safety and workability of the site. It is therefore necessary to estimate the stability of underground cavities in the proximity of bench blasting. In this paper, blasting tests of small scale were carried out in a site with cavities and field blasting test data were measured to obtain the site-specific attenuation relations of PPV and principal frequency of stress waves. A numerical model is then developed based on these relations to calculate bench blasting induced stress wave propagation. The accuracy of the numerical prediction is verified by the field measured data. The verified numerical model is used to perform a series of simulations. The results are then used to assess the roof stability of cavities adjacent to upper bench blasting. Based on the numerical results, the response characteristics of cavity roof with respect to different explosive charge mass are also studied.

1. Introduction

The existence of abandoned cavities created by previous underground mining activities constitutes a potential hazard to current active aboveground mining operations. In open-pit bench blasting operations the roof of cavity is highly susceptible to collapse due to dynamic failure which endangers the safety of workers and heavy equipment and retards the open-pit mining progress. In response to this situation, prediction of the peak vibration level of cavity roof induced by bench blasting is essential for estimating the stability of underground cavities in the vicinity of the bench blasting.

In practice, some empirical criteria mainly based on Peak Particle Velocity (PPV) of stress wave are used to assess the potential damage and stability of underground cavity in rock mass. For example, based on field tests and observations, Li and Huang[1] proposed some critical PPV values corresponding to four damage levels of cavity wall in rock mass. They are: no damage, slight damage, intermediate damage and severe damage. The intermediate damage level that corresponds to the threshold of falling rocks from the cavity wall, which is the threshold damage level for an underground cavity to collapse, occurs when the PPV reaches 0.82–1.11 m/s for hard rock or 0.9–1.07 m/s for soft rock. In the PPV damage criterion for Swedish hard rock suggested by Persson,[2] the damage is classified into five levels, i.e., incipient swelling, incipient damage, fragmentation, good fragmentation and crushing. The threshold damage of the cavity wall that corresponds to the incipient damage level occurs if PPV exceeds 1 m/s. Some large scaled explosion tests were carried out by the U.S. Army Corps of Engineers between 1948 and 1952 near unlined tunnels in sandstone site.[3] The study classified tunnel damage into four damage zones: intermittent failure, local failure, general failure and tight closure. It was reported that on average the rock in tunnels did not fail until the PPV exceeded 0.9 m/s, and when the PPV was 0.46 m/s or larger an intermittent failure would occur in the tunnels. Similarly, based on a series of roof and floor vibration monitoring and physical observations at Jenny underground coal mine near Inez, Kentucky, Jensen et al. [4] reported that no apparent damage occurred at the peak measured particle velocity of 0.445 m/s and only a few loose stones at 0.127 m/s. Tunstall[5] suggested that peak particle velocity of 0.175 m/s did not cause any damage to underground coal mine opening in very good quality rocks (RMR=85). On the other hand, poor quality rock (RMR=49), which had been loosened by previous open-pit blast vibration, sustained minor visible damage at a peak particle velocity of 0.046 m/s and major damage at a peak particle velocity of 0.379 m/s. Langefors and Kihlstrom[6] concentrated on blasting issues in Sweden, which involve mostly granite. It is reasonable to assume that their defined damage criteria are also suitable for granite. They proposed the following criteria for tunnels: a PPV of 0.305 m/s results in fall of rock in unlined tunnels; a PPV of 0.61 m/s results in formation of new cracks in the rock. Calder and Bauer[7] noted the following relationships: for a PPV of 0.254 m/s, no fracturing of intact rock would occur; for a

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PPV of 0.254–0.635 m/s, minor tensile slabbing would occur; for a PPV of 0.635–2.54 m/s, strong tensile and some radical cracking would occur; for a PPV of 2.54 m/s, complete break-up of rock mass would occur. Oriard[8] found that for particle velocities of 0.125–0.38 m/s in underground coal workings, the falling of partly loosened sections of rock might be expected. Sakurai and Kitamura[9] measured tensile strains and vibrations on the tunnel roofs and sides. They concluded that damage would occur at a particle velocity of 0.35 m/s and they also noted actual reported crack initiation in the concrete lining at 0.338 m/s. Dowding [10] classified unlined tunnel damage into four damage levels as joint movement and fall of loose stones, intermittent failure, local failure and complete closure, and when the PPV was 2 m/s an intermittent failure would occur in the tunnels. The significant variations of the above reviewed criteria obtained by different researchers imply the stability of underground cavity depends on specific site conditions, and indicate it is not possible to derive a universal criterion.

On the other hand, in practice, many empirical PPV attenuation relations are available and can be adopted to estimate the PPV of blast-induced stress waves for safety assessment of underground cavities. Most of these empirical formulae predict PPV of stress waves as a function of geotechnical conditions and scaled distance $R/Q^{1/2}$ or $R/Q^{1/3}$, where R is the distance from the charge centre to the point of interest and Q is the equivalent TNT charge weight. $R/Q^{1/2}$ is used for surface blasting and $R/Q^{1/3}$ is used for free field explosion. By using a proper attenuation relation, the stress wave PPV corresponding to a charge weight and at a given distance can be easily predicted. However, since wave propagation in geological media is highly site dependent and the available empirical formulae were obtained by different researchers based on measured data at different sites, they may give very different predictions of PPV. Therefore, to obtain reliable predictions of PPV at a given site, the ideal approach is to develop a site-specific attenuation relation. Moreover, most empirical formulae were obtained at sites without noticeable cavities. The existence of underground cavities makes the geological media discontinuous, which significantly affects the characteristics of wave propagation, and therefore makes most existing empirical PPV attenuation formulae not applicable to predict PPVs on walls of underground cavities. If stress wave PPV induced from blasting cannot be accurately predicted, a reliable safety assessment of underground cavity is not likely to be achieved.

Besides amplitude of the blast wave and geotechnical conditions, structure responses are also dependent upon ground motion frequency contents. Some criteria and specifications[11–13] used in mining, construction and defence engineering give the allowable vibration limits of structures as a function of ground vibration principal frequency (PF). Therefore, it is also important to determine the frequencies of ground vibrations induced by blasting in order to use those criteria. Not many empirical relations of PF attenuation are available in the literature. Wu and Hao[14] performed numerical simulations and derived empirical PF attenuation of stress waves propagating in granite mass. Hao, et al.[15] proposed some empirical PF attenuation relations based on measured data in field blasting tests in a jointed granite mass. However, like PPV, it is known that PF also attenuates with wave travelling distance and is site conditions dependent. Therefore using PF attenuation relations derived from data in other sites might not give reliable predictions of PF of stress wave in a site under consideration.

This paper presents results of a case study to investigate the stability of an underground cavity near the bench blasting in an open-pit mining site. Some blasting tests of small scale were carried out in the site and field blasting test data were measured to obtain the site-specific attenuation relations of PPV and principal frequency of stress waves. A numerical model is then developed to calculate blasting induced stress wave propagation at the site under consideration. The shape and dimension of the cavity near the lower bench at the site is obtained by laser scans. A detailed 3D finite element model of the site with the cavity is constructed in ANASYS, and LS-DYNA is employed to calculate the stress wave propagation and cavity roof responses. Since the measured data at the site are available, the developed numerical model is used to simulate these blasting cases. The measured data are used to verify the accuracy of the numerical simulations. Very good agreement between the measured and numerically simulated data is obtained. The verified numerical model is then used to simulate stress wave propagation in the site due to bench blasting of different scales. These numerical results can be used together with the allowable vibration limits for cavities and structures to design the blasting and to assess the safety of the cavity and nearby structures.

2. Site description

The site under consideration, Sandaozhuang molybdenum mine, is situated near the town of Lengshui, approximately 257 km southwest of Luoyang city in central China. The Sandaozhuang molybdenum mine has been in continuous operation for more than forty years. From 1970s to early 1980s, state-sponsored enterprise commenced underground mining on a small scale. During the middle and late 1980s, owing to the lack of planning and authorization associated with the rapid economic development, uncoordinated private underground mining started and flourished. The situation became worse in the 1990s with central government, local town council, collective and private enterprises coexisted in this mining district conducting their own mining activities. As a result the situation of mineral resources spoliation inevitably happened. In 2002, the Chinese government issued guidance on mining activities and prevented uncoordinated mining operations in the area. However, by then there were about 200 underground openings left by those uncoordinated mining operations, and over 100 underground cavities were sealed and abandoned. The total volume of underground cavities was estimated at around 1 017.2×10^4 m^3 and the cavities mainly located at an elevation of 1293–1469 m. In 2003, in responding to the market demand, the Sandaozhuang Mining Company ended its underground mining and converted to a large scale open-pit mining and constructed a mill with 5000 t per day capacity to treat its ores. The mill has been enlarged since then. Now it can handle 30,000 t of ore per day to treat ores from a greatly expanded open-pit mining operation.

During the process of peeling off of overlying strata, the thickness between pit bottom and roofs of the cavities is becoming thinner and thinner. Additional loading is also imposed by engineering works directly over the cavities. Moreover, ground vibrations arising from excavation with bench blasting could loosen the support of the walls and roofs of the cavities. The stress by bench blasting may exceed the strength of rock material, thus results in cover collapse. Collapse of these cavities imposes a potential hazard to workers and heavy equipment in the open-pit and is a formidable problem for the Sandaozhuang Mining Company.

3. Experimental design and set up

During the mining activities in Sandaozhuang open-pit, a cavity at level 1426 m was located. In order to study the influence of the cavity on stress wave propagation, measurements of stress waves on rock surface during the blasting in the neighbouring bench were taken. A series of small-scale bench blast tests were conducted at this site. Fig. 1a shows the plan view of the site. Fig. 1b shows a sketch of the blasting design. The bench is 12 m in height and the slope angle is approximately 70°. The charge hole drilled on Level 1438 m has a total depth of 13.5 m with a diameter 'D' equal to either 140 or 250 mm. The upper 'a' m of the stemming depends on the depth of explosive 'b' m and the sub-drilling, which is 1.5 m. Fig. 1c shows the profile of the site. The average rock cover over the cavity area is about 3 m. The cavity is 111.75 m away from the bench blasting hole and has a width of 24.5 m, a length of 34 m and a height of 8 m. In each test, two