Ultrasonic Crosshole Assessment of Fracture Density and Stress Variations in Crystalline Rock

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Summary

The potential for application of seismic methods in the evaluation and monitoring of nuclear waste repositories is immense. Past field studies have established that variations in velocity and attenuation indicate changes in the fracture density of the rock mass surrounding a storage facility. A study was undertaken to determine the effects upon velocity and attenuation of varying stress fields surrounding a crystalline repository. Laboratory experiments performed on fractured core samples found that amplitude and rise time are sensitive to stress applied parallel to travel path and velocity is not. Ultrasonic crosshole measurements were taken within the rock mass surrounding an underground research facility. The crosshole method was able to detect a zone of high fracture density caused by blasting near the surface of the room. The blast damage zone was characterized by relatively low velocities and amplitudes and large rise times. Moving outward into the rock mass, velocity stabilized while amplitude and rise time varied significantly indicating the existence of a stress concentration. This coincides well with the estimated stress distribution based on measured in situ stresses. Other significant variations in acoustic parameters were encountered and attributed to changes in fracture densities.

Introduction

The outlook for the application of acoustic measurements in the evaluation and monitoring of nuclear waste repositories is promising. For crystalline rock, significant variations in velocity and attenuation suggest changes in the fracture density of the rock mass surrounding the storage facility (Blair, 1987; Paulsson *et al.*, 1980; Wong *et al.*, 1983). A proposed theoretical model estimates the number and stiffness of fractures from velocity variations (Pyrak-Nolte *et al.*, 1987). But the interpretation of these variations have not considered changes in the stress fields surrounding a repository. Acoustic measurements taken in coal mines indicate velocity and attenuation are dependent upon stress (Kormendi *et al.*, 1986; Yamshchikov *et al.*, 1974). With this evidence, a study was undertaken to determine the effects of the in situ stress field upon velocity and attenuation in crystalline rock.

Field measurements were taken to examine the ability of the ultrasonic crosshole method to assess fracture density and stress variations in crystalline rock (Fry 1987). In the laboratory, the dependency of velocity and attenuation upon stress applied parallel to the travel path were measured in a fractured core sample.

Fracture Density

Acoustic measurements were taken in the Experimental Room in the Edgar Mine, Idaho Springs, Colorado, USA. The Edgar Mine was originally a silver and gold mine that operated from the 1870's to the turn of the century. The Experimental Room is located on the A-left drift of the mine (Fig. 1a). Blasting techniques developed in the United States and Sweden were used to construct the room. Six different rounds of blasting were used in the beginning construction of the room. Within each of the six rounds, seven radial boreholes were drilled and cored (Fig. 1b). The core samples were logged to catalogue rock types and fracture densities. The principal rock type is a varyingly banded and interlayered biotite gneiss. The gneiss has been heavily injected and extensively recrystallized by granite migmatites and massive granite pegmatites.

The rock mass surrounding the room was assessed by sending acoustic waves between the radial boreholes. A set of acoustic measurements began by locating a source and receiver at the same depth in two boreholes. The source, a piezoelectric crystal, was activated by a voltage pulse with a frequency of 40 kHz. A miniature hydrophone recorded the acoustic wave after it travelled roughly 2.5 m through the rock mass. The recorded wave was averaged 256 times and then displayed on an oscilloscope. Travel time, amplitude and rise time of the first compressional arrival (Fig. 2) were measured. The source and receiver were moved at 0.3 m intervals between each reading.

Acoustic measurements were taken between the horizonal boreholes in rounds one and two (Fig. 3). This combination was chosen because there are insignificant changes in stress parallel to the travel paths. Figure 3 was divided into zones to distinguish between parameter variations. Zone one and four have smaller velocities and amplitudes and larger rise times than zones two, three and five. This indicates that zones one and four have higher fracture densities than the other zones (Blair, 1987). Zone one is referred to as the blast damage zone because the rock contains many microfractures induced by blasting. The blast damage zone normally extends 0.5 to 2.0 m into the rock mass. From the core logging, the fracture density for both horizontal boreholes is the largest between 2.5 and 3.5 m. This interval correlates with the smaller velocities and larger attenuations of zone four. The small variations between the parameters in zones two, three and five are attributed to changes in rock types.

Stress distribution

The presence of the room causes the vertical and horizontal stress fields to deviate around the room (Fig. 4). In this case, the vertical stress is in accordance with the gravity stress, and the horizontal stress is slightly larger than the vertical stress (Hustrulid *et al.*, 1981). The effect of the vertical field upon the room is that tangential compressive stresses are concentrated in the walls, and small tangential tensile stresses

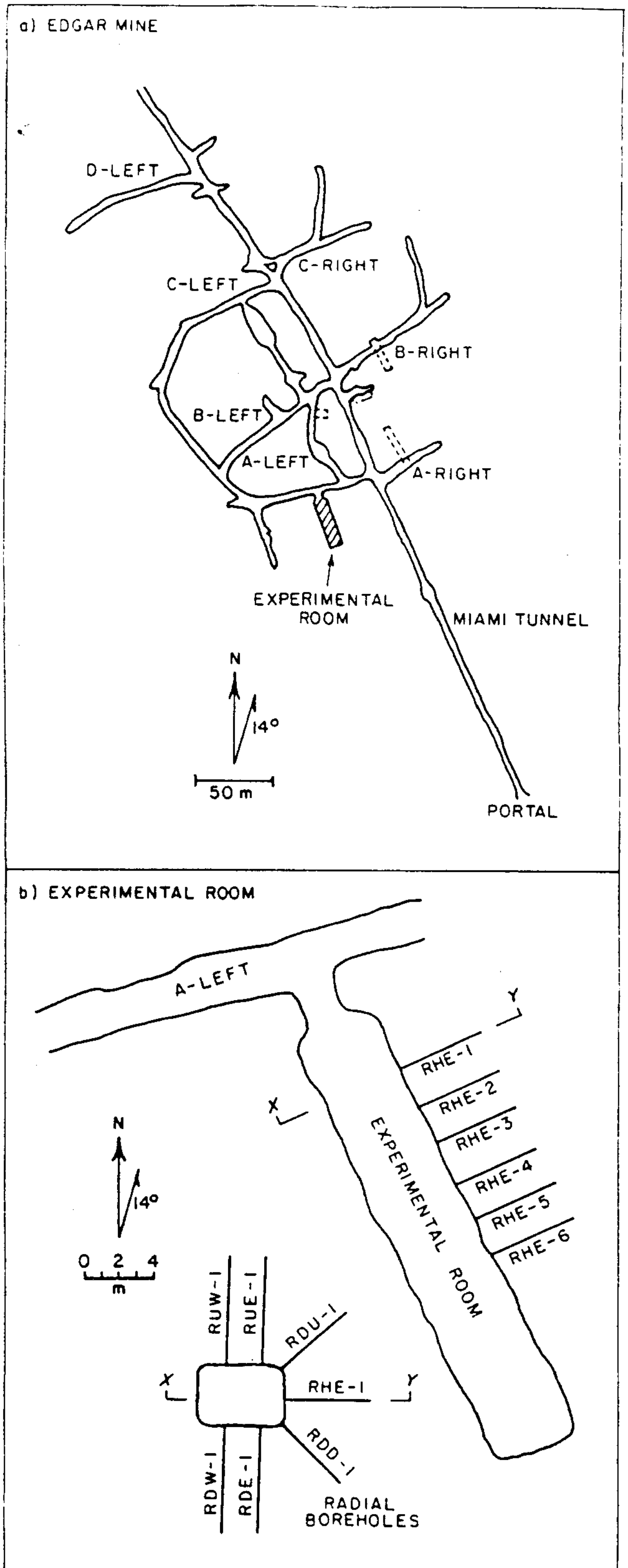

FIGURE 1
A plan section of the (a) Edgar Mine and an enlarged plan and cross section of the (b) Experimental Room.

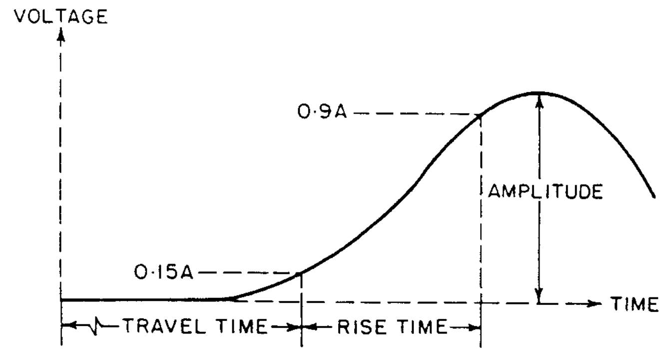

FIGURE 2
Acoustic parameters: amplitude, maximum voltage; travel time, time difference between the 15% of amplitude and time zero; and rise time, time difference between the 90% and 15% of amplitude.

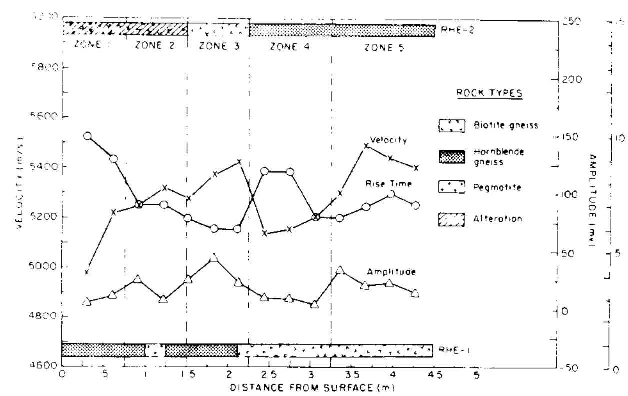

FIGURE 3
Acoustic parameters as a function of distance from the surface for boreholes RHE-1 and RHE-2.

are created within the floor and roof (Obert *et al.*, 1967). The opposite effect occurs for the horizontal field. Adding the vertical and horizontal effects gives tangential compressive stresses, about two times the original stresses, around the periphery. The theoretical distribution of stress is a maximum at the surface and decreases as the distance increases from the surface until approximately one diameter, where it returns to the original stress. But in practice the maximum stress occurs at some depth because of the blast damage zone.

Laboratory experiments

Acoustic measurements were taken in a fractured core sample while under an applied stress. The core sample is from a vertical roof borehole in round two at a depth of 2.5 m. It has four equal-spaced fractures with varying dip angles and a length of 90.8 cm. The sample with piezoelectric transducers on each end was placed between the platens of a compressive testing machine. A load was applied parallel to the axis of the sample and an acoustic measurement was taken. Acoustic waves were transmitted through the sample by exciting the source with a 30 kHz voltage pulse. The transmitted wave was averaged 16 times and then displayed on an oscilloscope. Acoustic measurements were taken between 0.0 and 6.0 MPa at roughly 0.6 MPa intervals.

The dependency of velocity, amplitude and rise time upon applied stress were measured (Fig. 5). Increasing the stress parallel to the travel path increased the velocity and amplitude and decreased the rise time. Amplitude and rise time were more sensitive to stress variations than velocity. For example, a relative change in stress of 5.0 (500% increase) resulted in a 3% increase in velocity, a 130% increase in amplitude and a 25% decrease in rise time.

Interpretation

Acoustic parameters were measured between the vertical floor boreholes in round one to determine if a stress concentration could be detected (Fig. 6). From the laboratory results, stress variations were indicated by changes in amplitude and rise time and not velocity. Therefore, variations in velocity must reflect changes in the fracture density. Two zones of fracture density were determined from the variations in velocity. Zone one is the blast damage zone because it has a lower velocity than zone two. There are no significant changes in velocity and borehole geology for zone two. But there are significant variations in amplitude and rise time which indicates there is a stress concentration in zone two. The shape of the amplitude and rise time variations is very similar to the shape of the practical stress distribution of Fig. 4. The extent of the blast damage zone was influenced by the stress concentration. The blast damage extended 0.8 m into the rock mass without the concentration of stress (Fig. 3) and 0.5 m with stress concentration (Fig. 6).

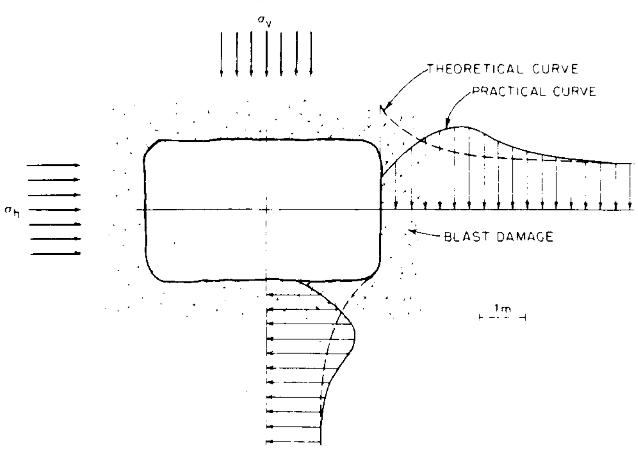

FIGURE 4

The theoretical and practical stress distribution along vertical and horizontal reference lines.

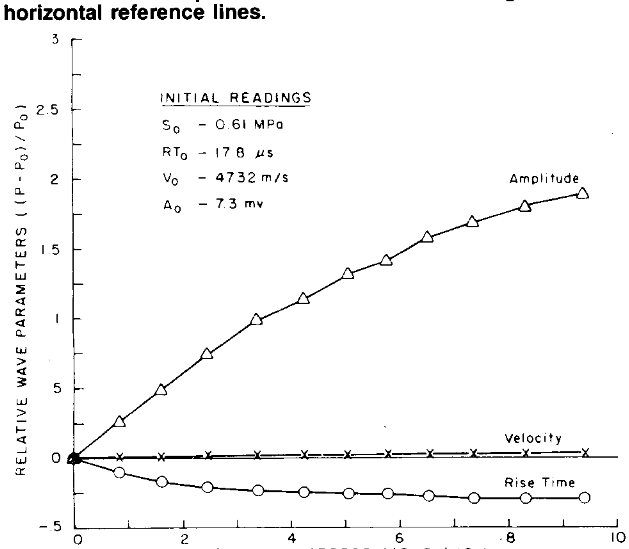

FIGURE 5

Relative change in acoustic parameters plotted against relative change in stress.

Conclusion

The ultrasonic crosshole method can assess fracture density and stress variations in crystalline rock. In the absence of stress variations, crosshole measurements described zones of low and high fracture densities. But the method had difficulty in distinguishing between small changes in rock type and fracture density. The results from laboratory experiment aided in the interpretation of crosshole measurements taken in the region of stress variations. Increasing the applied stress parallel to the travel path in fractured core sample increased the amplitude and decreased the rise time. Crosshole measurements detected a stress concentration by variations in amplitude and rise time, while the velocity remained unchanged.

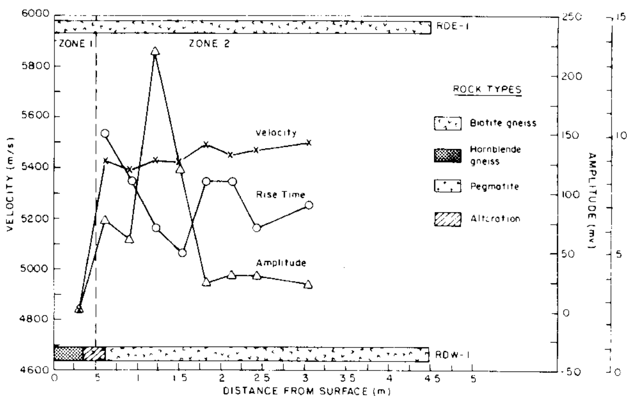

FIGURE 6

Acoustic parameters as a function of distance from the surface for boreholes RDW-1 and RDE-1.

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