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Ultrasonic Characteristics of a Rock Mass

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A programme aimed at the in-situ *assessment of rock properties and rock condition has been undertaken at the Julius Kruttschnitt Mineral Research Centre of the University of Queensland. The project aims to quantify rock mass parameters and to use them in a model of blasting to predict and control fragmentation. A technique for characterization of a rock mass utilizing acoustic data obtained from test or production boreholes was investigated as part of the programme.*

The system is a cross-hole acoustic system which uses wave propagation velocities and the attenuation parameter, Q *(as estimated from a measurement of the change in pulse shape during propagation) to assess the rock mass condition. This system is a modification of the ultrasonic stress monitoring device (USMD) developed by Gladwin [5] in which a magnetostrictive transducer, mechanically clamped in an NX borehole is used to produce ultrasonic pulses of approximately 37.5 kHz. Pulse transmission times to detectors clamped at measured depths are used to produce a velocity profile for distances of up to 15 m from the source hole. The viability of the technique and the required instrument specifications, have been studied in a series of field experiments, which indicate good agreement between structural core log data and pulse rise time.*

Characterization of the state of fracture of a rock mass is being carried out at several sites with markedly different geological environments. These sites include a high grade open cut hematite mine, an open cut coal mine, an underground dolomitic copper ore body, and an underground lead–zinc ore body. The ultrasonic technique is being supplemented by studies in the sonic frequency range using small explosive charges as acoustic sources. A comparison between the two sets of data will be made for both velocity and Q *measurements for the preliminary field experimentation.*

INTRODUCTION

A study aimed at the development of a technique for the *in-situ* determination of a rock mass has been undertaken by the Julius Kruttschnitt Mineral Research Centre of the University of Queensland. The study forms part of a major research programme into the fragmentation of rock by explosives, with the long term aim of optimization of blast design. The investigation uses cross-hole wave propagation techniques to determine the velocity and rate-of-energy attenuation of rock. The structural condition of the rock will be inferred from these parameters, since both velocity and attenuation at low confining pressures are controlled by rock structure.

Analysis in terms of wave velocity and attenuation is being made from a study of both ultrasonic and sonic waves. A magnetostrictive transducer is used for the generation of the ultrasonic signals whilst small explosives are used to produce the higher amplitude, lower frequency signals. The ultrasonic testing equipment is being developed for routine analysis of rock masses and is a modification of that previously reported for *in-situ* velocity and ultrasonic pulse measurements [5–7].

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WAVE VELOCITY AND ATTENUATION AS INDICATORS OF ROCK CONDITION

Wave velocity

Under dry conditions and at low confining pressures, wave velocity is heavily influenced by geological structure [3, 14]. Because of the highly heterogeneous nature of rock masses, a discrete transmitted pulse is received as an extended wave train of multiply reflected compressional arrivals and compressional/shear conversions resulting from interaction with the numerous reflecting interfaces (fractures, fissures, bedding planes, grain boundaries). The first arrival of a mixed wave train can be unambiguously interpreted as a compressional wave along the shortest available acoustic path. Stacey [14] claims that the shear wave is more sensitive to rock structure than the higher velocity compressional wave. Shear wave detection is possible with the ultrasonic source in competent rock and the shear velocities are recorded wherever possible. The ability to detect shear wave arrivals allows the determination of the *in-situ* Poisson's ratio, which is also expected to be structure dependent. Paulsson & King [20] report successful use of compressional and shear wave velocities as indicators of rock properties during thermal stress loading.

The structure dependence of the compressional velocity has been illustrated in studies using both seismic [2,11,14] and ultrasonic [8,10] signals. These studies using compressional velocity data alone have aimed to delineate between competent and heavily fractured rock. The present study aims to define structure more closely and therefore considers an additional study of the shear wave velocity and the compressional wave attenuation parameter, Q.

Wave attenuation

As a spherical acoustic wave radiates from its source, geometric spreading reduces the energy per unit area according to the inverse of the square of the distance from the source. Since the amplitude of the acoustic wave is proportional to the square root of the energy, pulse amplitude decreases with the distance from the source.

In addition to this loss of energy, a signal propagating in an imperfectly elastic medium is attenuated by absorption of energy in the imperfections. The attenuation of a plane sinusoidal wave is represented by the quality factor, Q, defined in terms of the fractional loss of maximum stored energy per cycle (equation 1).

$$Q^{-1} = \frac{1}{2\pi}(\Delta E/E_{\max}). \quad (1)$$

For dry rocks, Q is independent of frequency over a reasonable frequency range [4]. The attenuation coefficient, α, can be defined directly in terms of Q as

$$\alpha = \frac{\pi f}{Qv} \quad \text{where } f \text{ is the frequency and } v \text{ is the wave velocity} \quad (2)$$

Since the fractional loss of energy per cycle is a constant, the higher frequency components of a pulse will spatially attenuate more rapidly than the lower frequency components, leading to a decrease in the sharpness of the pulse with increasing distance of propagation. Thus, pulse broadening can be used as a measure of the Q value of the medium of propagation. The dependence of pulse width on travel time has been experimentally determined by several workers [7,12,13], and it forms the basis of the current study of attenuation of pulses in rock masses. Stacey [14] concluded that both compressional and shear wave broadening was indicative of fracture density. Meister [10] used ultrasonic pulse attenuation to determine the depth of fracturing behind excavation tunnel walls. The present study aims to determine compressional wave attenuation on a routine basis in operating mining environments to aid the assessment of *in-situ* rock condition prior to blasting. The method of determination of pulse broadening is the rise time measure outlined by Gladwin and Stacey (Fig. 1). This method is highly favoured because it is less sensitive to errors arising from multiple arrivals and the effects of signal noise. The experimentally derived rise time relation (equation 3) used by Gladwin & Stacey [7] has also been obtained from theoretical considerations [9,16].

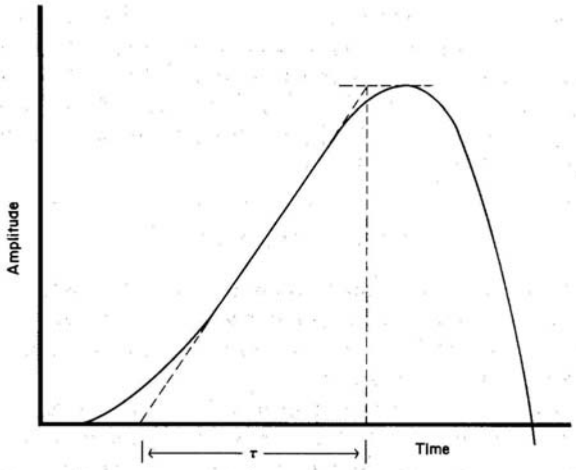

Fig. 1. Pulse rise time definition for determination of pulse broadening.

$$\tau = \tau_0 + c\int_0^T \frac{dt}{Q}. \quad (3)$$

In recent experiments observing stress–strain hysteresis loops [1], anelastic attenuation in rock subjected to strains of seismic magnitude has been shown to be linear, so that attenuation of a complicated waveform can be predicted from the separate attenuations of its Fourier components. The first order approximation however, appears only to be valid for small strain amplitudes (less than 10^{-6}) [15]. The ultrasonic experiments use very low strain amplitudes ($\simeq 10^{-10}$) and are therefore expected to exhibit linear attenuation characteristics. The pulse broadening law observed by Ricker [13] is not supported by any recent experimental or theoretical studies.

For saturated and partly saturated rocks, pulse velocity and Q are dependent on the degree of saturation [16,19]. Spencer [19] also shows a frequency dependence of Q at frequencies in the low kilohertz range. Our object in the present study is to provide a technique for identification and isolation of zones of abnormal rock properties in a region under study. To date a uniform state of saturation has been experienced and no attempt has been made at identification of variations of observed properties caused solely by variations of water content. For reasonably consistent saturation state, the frequency dependence of Q identified by Spencer [19] is negligible even for the small explosive sources which have spectral peaks at about 10–12 kHz in our experience.

EXPERIMENTAL

Cross-hole ultrasonic evaluation of rock masses has been undertaken in two main test sites—a disused granite quarry in Brisbane and in several underground locations in the Mt Isa Mine.

An array of five core drilled holes (HQ size) was drilled in the quarry floor for the purposes of verification of equipment and techniques. Core recovery enabled an independent means of structure assessment. The array was almost linear with holes slightly offset to minimize interference of the signal propagating between any pair of holes. The maximum transmission distance was 13 m. All holes were drilled to a depth of 20 m and logged at 1 m intervals for all combinations of hole pairs. The holes were surveyed to enable calculation of interhole spacing to within 2 cm at any depth. Signals were recorded in digital form and analysed using a microprocessor-based signal processor. Two recordings are required at each depth—a high resolution recording of the first arrival to enable accurate rise time determination, and a full waveform recording to enable detection of shear arrivals and other reflected arrivals. Figure 2 shows a sequence of full waveform recordings in which both compressional and shear arrivals can be readily detected.

When analysing the high resolution waveforms (0.5 μsec/point), only first arrivals whose shape was undistorted to the first zero cross were considered reliable. A plot of minimum rise time against travel time is shown in Fig. 3 for the granite quarry data. The

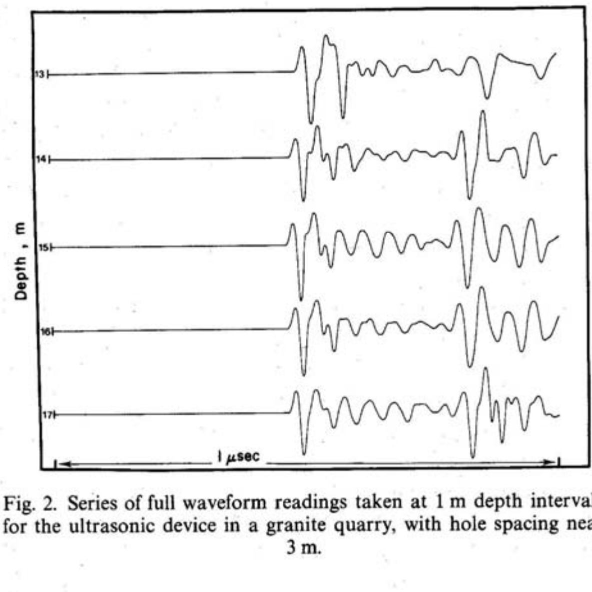

Fig. 2. Series of full waveform readings taken at 1 m depth intervals for the ultrasonic device in a granite quarry, with hole spacing near 3 m.

linearity is in agreement with the simple rise time relation (equation 3) and gives a Q value of 180 ± 6. By plotting all reliable rise time estimates it is hoped to deduce the degree of fracturing from the scatter of data points above the linear plot of Fig. 3. Local variations in rise time have successfully defined areas of greater fracturing in agreement with core log analysis. In general, near-surface rock exhibited a reduced velocity and an increased rate of attenuation, indicating the extent of induced fracturing from previous blasting and the possible effects of weathering [17].

Ultrasonic evaluation has also been undertaken in several underground locations at Mt Isa. Four 100 mm dia holes were drilled into the side of a drive to a depth of 5 m and with a maximum separation of 10 m. The experiment was performed in a dolomite copper ore body.

Operation of the instrument in a mining environment was hampered by a significantly lower signal-to-noise ratio, which reduced the effective transmission distance. The problem has been largely overcome by recording several hundred pulses on magnetic tape and subsequently adding the pulses using computer-based techniques. The summation results in an increase in the signal-to-noise ratio by a factor of $N^{\frac{1}{2}}$ where N is the number of summations. The technique is considered to be more accurate than analysis of a single pulse and will be used for all future studies.

The data obtained from this study are also in agreement with the simple rise time relation (equation 2) as shown in Fig. 4. This plot gives an average Q value of 125 ± 4 from analysis of the enhanced waveforms. A general trend of increasing velocity and Q with increasing depth was noted, indicating the extent of blast induced damage behind the wall.

In an attempt to increase the range of the study beyond the scope of ultrasonics, experiments using small explosives as sonic sources were undertaken. The explosives used were 100 mm long sticks of molanite detonated in 50 mm dia holes at a depth of 5 m. Signals obtained from this were recorded on magnetic tape with strong signals being detected at 63 m from the point of detonation. Preliminary analysis indicates that these detonations produce a dominant frequency of approximately 10 kHz.

A rise time analysis of this data also yielded a linear relationship (Fig. 4) with an estimated Q value of approximately 136 ± 5 providing reasonable agreement with the ultrasonic study. There is no evidence in the data of Fig. 4 of decrease of Q at small distances due to failure of the 'small strain' assumption for the explosive charges used. Significant non-linearities would displace observed rise times from the line shown. The sonic study using small explosives is not expected to be as reliable as the ultrasonic study since estimates of velocity and pulse rise time are obtained from a single pulse rather than a series of repeated, highly reproducible pulses. The sonic study however, is far more suited to a study of heavily fractured rock masses because the initial pulse is of higher amplitude and lower frequency.

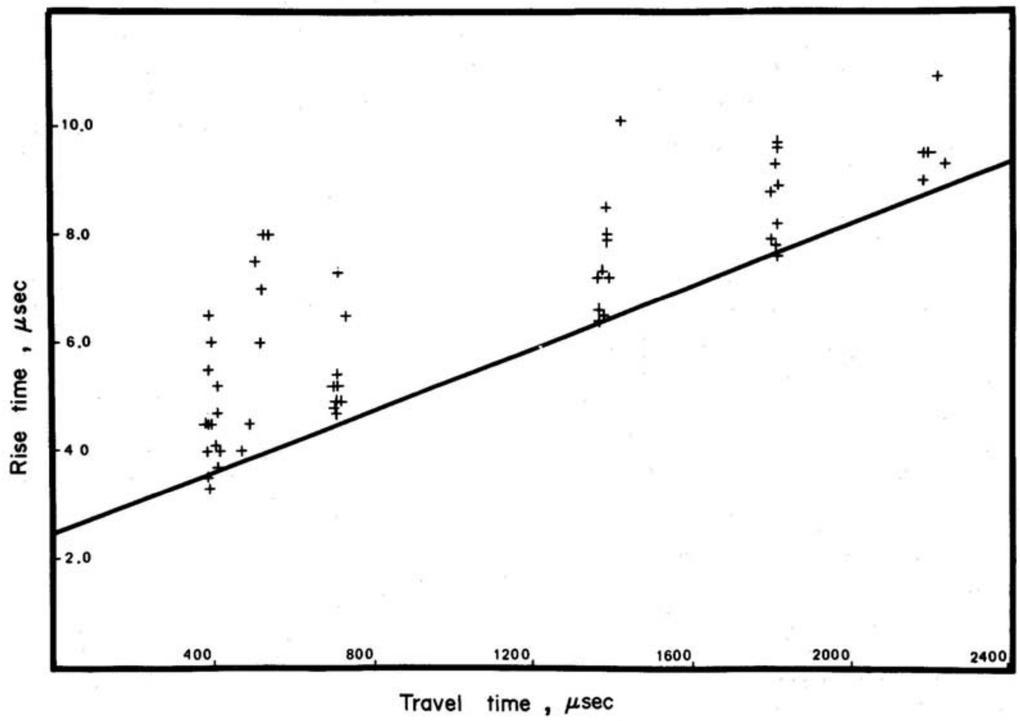

Fig. 3. Minimum rise time relation for ultrasonic device in granite. The wide range of rise times which occur at fixed distance is evident. The lower bound shown represents the highest Q path available and follows the linear rise time relation.

Both sonic and ultrasonic studies yielded average velocities of 6.4 km/sec.

The system is also being tested in production blast holes of 200 mm dia to assess the rock prior to charging. It is hoped that the study will yield reliable information concerning localized areas of anomalous structure or composition.

Many direct comparisons of the pulse rise time method with conventional hole logging techniques have been made. An example in re-crystallized breccia is

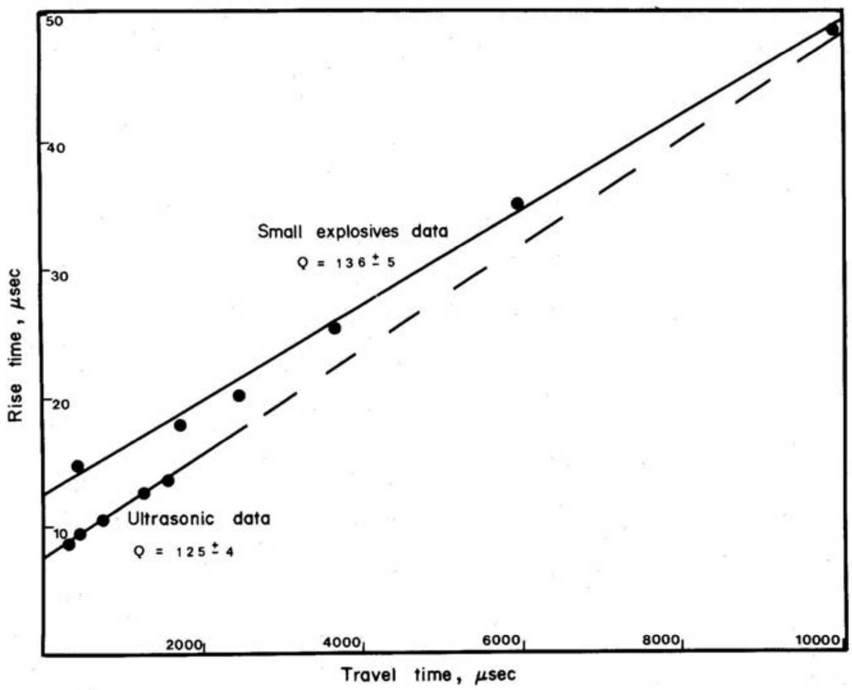

Fig. 4. Rise time relation for ultrasonic device in recrystallized 'dry' shale using signal enhancement, compared with rise time data for small explosives study at the same site. Agreement between the two techniques is good, though the range of the small explosive study in much greater. There is no obvious non-linear behaviour on the small explosive data.

illustrated in section in Fig. 5, in which structure determined in the diamond drill hole XA is extrapolated to the line OB. Rise times from an ultrasonic profile taken parallel to OC are shown. Numbers on the bedding planes at XA represent the thickness and dip angles of low-Q material. The shaded regions on OB are infered from the larger rise times measured and agree well with extrapolated structure from XA.

LABORATORY TESTWORK

All field test work is accompanied by laboratory testing of intact diamond cored samples. Those conducted include ultrasonic velocity determination and measurement of various mechanical and physical properties (density, porosity, unconfined compressive strength, Young's modulus). Attempts are also being made to enable the laboratory determination of the rock quality factor, Q using the logarithmic decrement and resonant frequency techniques [15].

The laboratory velocity and Q determinations are felt to be particularly important as they provide a comparison between intact rock specimens and *in situ* rock masses. Anomalous zones encountered in field tests can be interpreted as either zones of different rock condition or zones of different rock composition by comparison with the laboratory tests conducted on core samples from the test area. In the case of the data from Fig. 3, a zone of thermally-altered granite was well located [17].

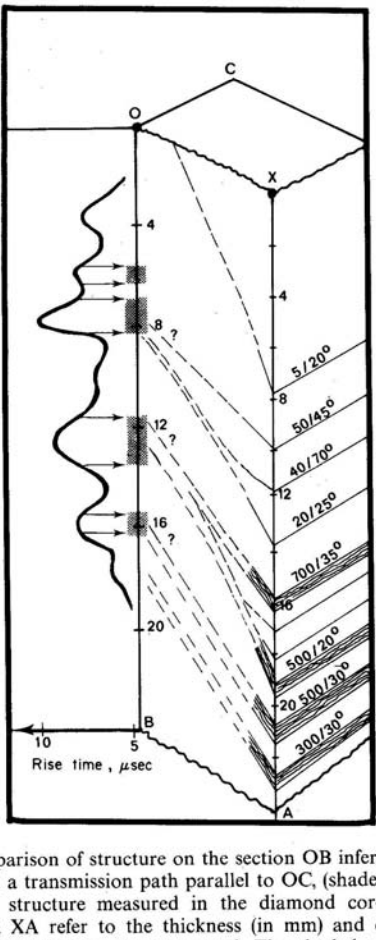

Fig. 5. Comparison of structure on the section OB inferred from rise time data on a transmission path parallel to OC, (shaded areas) with extrapolated structure measured in the diamond cored hole XA. Numbers on XA refer to the thickness (in mm) and dip angle (in degrees) of the bedding planes crossed. The shaded areas indicate zones of high attenuation.

CONCLUSIONS

A routine, diagnostic system for simultaneous measurement of compressional wave velocity and attenuation constant has been developed. For the ultrasonic frequencies, complete hole logs are available. Range limitations for ultrasonic frequencies can be eliminated without loss of information using small explosive charges or other mechanical sources. The attenuation data show high sensitivity to inhomogenieties which correlate well with core log data. Study of any possible systematic differences between sonic and ultrasonic characterization is proceeding. Field studies are continuing in a wide variety of mining environments, including a high grade open cut hematite mine, an open cut coal mine, an underground dolomite copper ore body and an underground lead–zinc ore body.

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