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A refraction seismic study to determine discontinuity properties in rock-masses

Une étude pour déterminer les variables de discontinuité dans les masses de roches par prélèvements de réfractions sismiques

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ABSTRACT: The possibilities of measuring rock-mass parameters by seismic refraction surveys, particularly those related to discontinuity direction and discontinuity density, have been examined undertaking field work at various sites in the United Kingdom. The results show that seismic wave behaviour in one rock-mass can vary widely as result of mass anisotropy, where the anisotropic character is caused by the orientated discontinuity pattern. Fan-shooting can be a very useful method to determine direction of ground-mass discontinuities.

RESUMÉ: Les possibilitées pour mesurer des variables dans les masses de roches, specialement dans lesquelles qui sont reliées à la direction de discontinuité et la densité de discontinuité par les prelèvements des refractions sismiques, ont été examinés sur le terrain à des locations differentes en Angleterre. Les résultats montrent que le comportement des ôndes sismiques dans les masses de roches peut varier largement à cause de l'anisotropie des masses ou le charactère de l'anisotropie est charactérisé par les systèmes de discontinuité. "Fan-shooting" présente une méthode très utile pour determiner la direction des discontinuitées.

1 INTRODUCTION

The seismic velocity in a rock-mass can vary widely due to anisotropy in the rock-mass, which may result from two main causes. In a layered or bedded material the elasticity modulus perpendicular to the bedding will be different to the elastic modulus parallel to the layers or bedding. The second, and often the most important cause of anisotropy, is due to the pattern of orientated fractures or joints. Most rock-masses possess more than one set of orientated fractures or joints so that because of these, together with the bedding, a 3-fold anisotropy can often be observed in rock-masses.

Bedding, fracture and/or joint directions are of major importance in engineering geology, especially in the design of slopes where directions of discontinuities form design criteria.

For this paper all forms of bedding, fractures or joints are included in the term "discontinuities".

A series of tests have been executed in open-pit mines and quarries in the United Kingdom to investigate the possibilities of measuring discontinuity parameters from seismic velocities in practical engineering geological circumstances.

The objective of the investigation was to develop a method to assess discontinuity geometry and if possible, rock-mass properties using refraction seismic methods. The fieldwork and part of the interpretation was done in co-operation with the Department of Geology of the University of Leeds, United Kingdom.

In the neighbourhood of Leeds a series of quarries with different types of rock-masses were selected. The tectonic and sedimentary structures of the rocks in the quarries chosen were simple and the rocks only slightly weathered, in order to avoid interference with the discontinuity characteristics. At least one side of the measured rock-mass was exposed, thus allowing physical investigation of the generally vertical joints.

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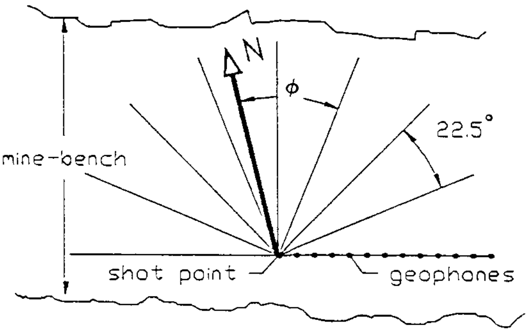

Figure 1: Seismic-fan configuration

2 WORK METHODS IN THE QUARRIES

The seismic measurements were made with a 12-channel Nimbus enhancement seismograph. The geophones were arranged in up to 20 m long straight traverses. A metal tube of about 2 metre high through which a weight could drop was used as a seismic source. The impact point was placed at 1 m or 1.5 m from the first geophone. In most cases two impacts were necessary to record the arrival of the signal. When a good signal was recorded the geophone line was rotated through approximately 22.5 degrees, while the impact point was retained at the same place. This was repeated at least 8 times so that a seismic fan was recorded (fig. 1). Reversed lines were shot to allow correction for dipping refractor planes. In this configuration the impact energy was always broadly the same and initiated a sharp and strong P-wave signal. The traverses were made on flat horizontal benches which made topographical corrections unnecessary. To ensure that measurements were from one layer, the investigations were done on top of a 2-3 m thick layer underlain by a softer layer with lower seismic velocities. In most quarries the softer layer was of shale. Samples of the rocks investigated were taken for laboratory testing.

In the quarries the discontinuities were measured by means of a scan-line technique along the exposed face. The amount of discontinuities per metre scan line were corrected for the angle between discontinuities and exposed face.

3 VELOCITY ANISOTROPY

The seismic refraction velocities measured in the quarries and mines are plotted in fig. 2 which also shows the visually observed discontinuity directions in the quarry faces. The seismic velocities clearly show anisotropic behaviour related to the discontinuity directions (fig. 2). The maxima of the measured velocities approximately coincided with the directions of the discontinuities. Even in the Magnesian Limestone quarry, where the seismic refraction curves indicated a three layer system, the maximum velocities of the second and third layers reflected the visually observed discontinuity directions.

4 VELOCITY ANISOTROPY FUNCTIONS

To attempt to quantify the joint densities and probably rock-mass parameters, a velocity variation function developed by Crampin was used. Crampin et.al. (1980, 1984) have developed a method to estimate discontinuity directions, discontinuity densities and the degree of water saturation of the discontinuities from velocity anisotropy measured by 'seismic fan' shooting. The method used by Crampin is based upon theoretical considerations developed by Garbin & Knopoff (1973, 1975a and 1975b) and Hudson (1975, 1981) which were used to explain velocity anisotropy in the upper earth mantle. They assumed that the theoretical rock-mass contains a series of thin, penny-shaped cracks, whose diameter is small compared to the seismic wavelength, and where the overall cracked volume is large in comparison with the wavelength. They developed formulae for both a dry and a saturated series of cracks. For more than one series of cracks the harmonic mean of the anisotropy of each series of cracks was calculated. The resulting formula (Crampin 1980) was:

$$V = \frac{V_0}{\dfrac{1-w}{Rdry_1 * Rdry_2} \quad \dfrac{w}{Rwet_1 * Rwet_2}} \tag{1}$$

$$Rdry_i = \frac{1}{\sqrt{1 + \frac{8}{3} e_i \left[\frac{8}{7}(c_i^2 - c_i^4) + \frac{(1+2c_i^2)}{4}\right]^2}}$$

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$$Rwet_i = \frac{1}{\sqrt{1 + \frac{64}{21} e_i(c_i^2 - c_i^4)}}$$

$c_i = \cos(\phi - \sigma_i)$

V = P-wave velocity
V_0 = P-wave velocity in rock material in-between the discontinuities
w = degree of water saturation of discontinuities
e_i = discontinuity density of set i (in discontinuity volume per rock-mass volume)
ϕ = direction of seismic ray path
σ_i = direction of discontinuity of set i

Formula 1 has been used to estimate discontinuity and rock-mass parameters from the velocities measured at the different sites.

5 VELOCITY OPTIMIZATION

Table 1 lists the parameters obtained by optimizing formula 1 with the velocities measured in the quarries. Fig. 2 shows the velocities measured in the quarries and the velocity variation curves calculated from formula 1 using the parameters in table 1 for each quarry. Table 1 also includes the discontinuity properties measured in the quarries, such as direction and density, and the intact-rock ultra-sonic velocity measured on laboratory samples. It was impossible to measure the degree of saturation of the discontinuities, but it is assumed that the weather during and directly before the survey gave an indication of the degree of water saturation. An account of the weather conditions is included in table 1.

1. Discontinuity direction
A nearly perfect fit between the measured directions in the quarries and the results of the optimization was obtained for the strike directions of the discontinuities.

2. Discontinuity density
The discontinuity frequency measured in the quarries was the number of discontinuity planes per meter scan line. The discontinuity density obtained by formulae 1 is the volume occupied by discontinuities per volume rock mass. It is impossible to measure or estimate this later quantity with any form of accuracy. It, is thus not possible to make a strictly quantitative comparison between the observed and calculated joint "density" parameters.

3. Discontinuity "density" ratios
It was hoped that the ratio between the scan line densities of different discontinuity sets measured in the quarries and the ratio between the density of different discontinuity sets obtained by formula 1 would correlate. The ratios are therefore included in table 1, which clearly shows that there seems to be no correlation.

4. Degree of saturation
The degree of saturation of discontinuities resulting from optimizing formulae 1 is listed in table 1 together with a description of the weather. The optimized percentages seam to correlate reasonably well with what could be expected based on the weather and visual inspection of the sites.

5. Intact rock velocity
The intact rock material velocity was measured with pulse waves on laboratory samples. The frequencies in a pulse wave were higher than the frequencies used in the field seismic survey. While the velocity of a seismic wave is dependent on the frequency, the differences between laboratory and estimated field values for intact rock material velocities should not be as great as shown in table 1. From table 1 it can be seen that only for the Black-Hill quarry an approximate correlation was obtained.

6. Correlation between estimated velocity curves and field velocities.
The overall correlation between the optimized and measured velocities is poor (fig. 2).

6 VELOCITY RATIOS

Many authors (among others Deere et.al. 1967, Lykoshin et.al. 1970) have proposed that the ratio between the field seismic velocity and the laboratory velocity could be used as a means of quantifying the quality of a rock-mass. Other authors have tried to establish relations between minimum and maximum measured seismic velocities and quality of a rock-mass (among others Merkler et.al. 1970, Knill 1970). The relationships by the different authors are defined in different forms but none takes into account the direction dependency of the seismic velocity.

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Table 1. Measured and optimized discontinuity and rock-mass parameters.

			[unit]	NCB-mine	Black Hill quarry	Greehow Hill quarry	Magnesian Limestone quarry	
rock type				siltstone with shale/coal layers	sandstone with shale layers	limestone	magnesian limestone	
							2(1)	3(1)
discontinuity direction		measured	[degrees]	112	000	015	153	
		estimated	[degrees]	090	347	014	180	-
discontinuity direction		measured	[degrees]	205	075	292	063	
		estimated	[degrees]	202	088	320	071	084
discon-tinuity	frequency	measured	[joints/m]	1.8	2.1	2.1	2.7	
	density	estimated	(2)	0.04	1.00	1.00	0.03	0.00
discon-tinuity	frequency	measured	[joints/m]	1.6	1.5	5.9	2.2	
	density	estimated	(2)	0.66	0.35	0.44	0.76	1.00
discontinuity ratio		measured		1.13	1.40	0.36	1.23	
		estimated		0.06	2.86	2.28	0.04	-
weather				dry (4)	drizzle, standing water (5)	dry, standing water (6)	dry (4)	
discontinuity water saturation		estimated	[%]	65	67	94	41	49
intact rock velocity		measured	[km/s]	(3)	3.06	6.04	(3)	2.44
		estimated	[km/s]	1.88	3.96	3.76	0.85	1.55

notes:

(1) two different refractors have been investigated.
(2) unit is discontinuity volume per rock-mass volume.
(3) no ultrasonic velocity measured.
(4) although it was dry during testing, it had been raining during the days before the testing.
(5) draining of discontinuities at bench-face was seen.
(6) the rock-mass was covered by clay overburden on which water stood; discontinuities expected to be filled with water saturated clay.

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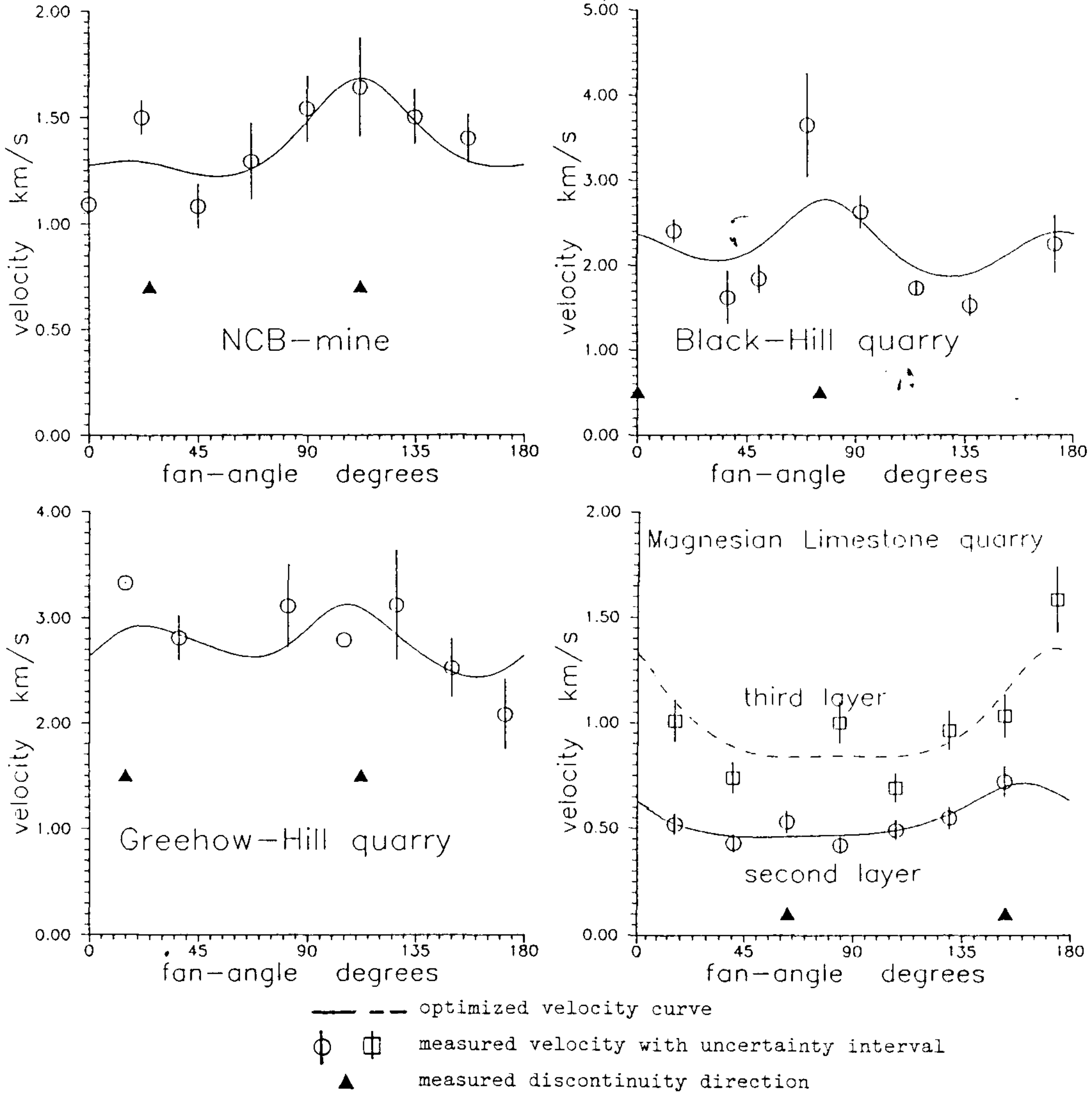

Figure 2: Velocity anisotropy

To illustrate the value of the use of velocity ratio without taking into account the direction, the authors have calculated the ratios of the field seismic velocities measured on the testing sites to the laboratory velocities (fig. 3).

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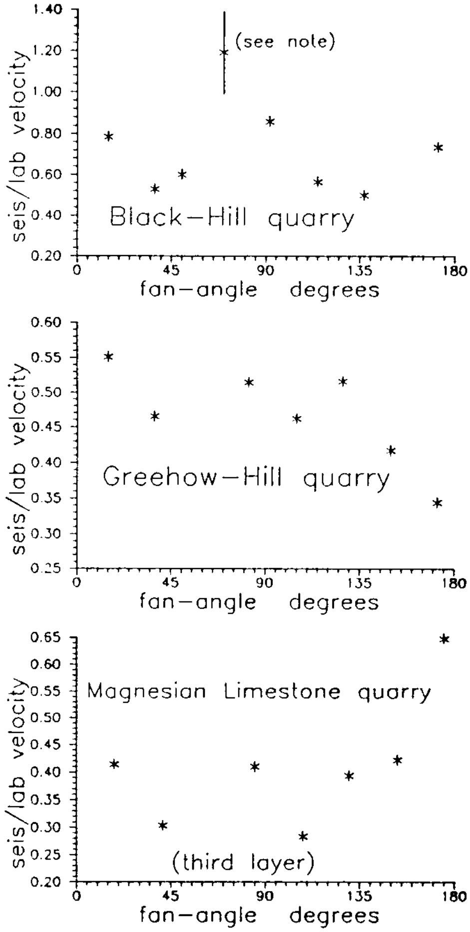

Figure 3: Velocity ratios

note: uncertainties in the interpretation of the seismic field data give a seismic velocity larger than the laboratory velocity.

7 CONCLUSIONS

The field work has demonstrated the influence of mass anisotropy on seismic velocity. This clearly argues for care in using velocity measurements as a guide to rippability. Using the Caterpillar rippability chart for a 41-B ripper, in the Greehow-Hill limestone quarry the fan velocities indicate un-rippability in one direction (3.3 km/s) and rippability (2.3 km/s) in another direction. In the Black-Hill sandstone quarry velocities indicated rippable (vel. 1.5 km/s) in one direction and un-rippable in another (3.7 km/s).

Refraction fan profiling allows rough determinations of the directions of discontinuities to be made. However, identifying discontinuity "densities" in the rock-mass from refraction seismic profiling appears to be of limited use and may lead to erroneous conclusions if the geometry of the rock-mass discontinuities is not known beforehand.

The seismic fan tests clearly show that the fit of formula 1 on the measured velocities is poor. A condition for formula 1 to be valid is that the radius of the cracks should be small compared to the wavelength of the seismic waves and this condition has most probably not been fulfilled. It would appear that the application of the Crampin/Knopoff formula is of limited value for practical engineering geological purposes.

The rock-mass "quality" determined by means of the ratio field seismic velocity/laboratory velocity clearly only pertains to the direction of the particular seismic profile. However, differences in peak velocities from fan shooting may be taken as a rough indication of rock-mass anisotropy. Further investigation by whatever methods would be required to determine the cause of the anisotropy.

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