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# A Rock Mass Assessment Experiment in the Artemission Tunnel (Central Greece) Using Seismic Attenuation Measurements

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ABSTRACT

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An attempt is made to assess the quality of a limestone rock mass from seismic attenuation measurements.

Two-component sets of geophones were cemented in the floor and the wall of the Artemission tunnel (Central Greece) and seismic wavelets originating from compressional and shear-wave sources were recorded and analyzed.

By defining the standard deviation of the spectral differences between two adjacent geophones as a measure of the attenuation signature, a very good correlation was established between the variations of the above parameter and of body waves and dynamic elastic moduli at the same sites.

## INTRODUCTION

Knowledge of the mechanical properties of rocks is essential in any rock-mechanics investigation connected either with rock failure applications, such as drilling, blasting, crushing and grinding, or with the prevention of rock failure, to ensure the stability of mining and civil-engineering excavations.

For all of these applications, drilling is an expensive and often damaging alternative. Hence, there is a need for evaluating the quality of large masses of rock using surface geophysical techniques.

Among the different kinds of geophysical measurement techniques, seismic methods, in particular those using a combination of P- and S-wave measurements, have yielded the greatest expectations, because they reflect the engi-

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neering properties of the ground (Knill, 1970; Cratchley et al., 1972; Lama and Vutukuri, 1978; Bamford and Nunn, 1979; Ohya, 1983).

At the effective pressures present in the upper crust, the physical properties of rocks are greatly dependent on crack porosity; in particular, cracks can significantly reduce seismic velocities even in low-porosity igneous rocks (King et al., 1978; Sjögren et al., 1979; Moos and Zoback, 1983). Unfortunately, surface seismic measurements can, in general, give little more than a qualitative indication of in-situ crack porosity because, although velocities are uniquely determined from the crack distribution, the reverse is not true (Nur, 1971).

The in-situ velocities are lower than those measured in the laboratory on small samples taken from the same sites. The difference in velocity correlates with the fracture frequency, although the correlation is different for different areas (Sjögren et al., 1979; Stephansson et al., 1979; Hajnal et al., 1983). This difference is generally attributed to differences in sizes of fracture apertures or porosity.

Despite the diversity of applications of seismic-velocity studies to rock-mass characterisation (Knill, 1970; Knill and Price, 1972), problems do arise when dependence is solely placed on velocity, since unique interpretations cannot usually be made using velocity data alone.

Hence, there is a need to extract as much information as possible from the seismic wave forms encountered. This additional information regarding the rock mass can be obtained when seismic attenuation is taken into consideration (Young and Hill, 1982).

In the present paper, we report the results of a series of in-situ seismic measurements, performed in the Artemission tunnel.

The opening, at the considerable depth of 700 m below ground surface, was excavated by conventional drilling and blasting techniques, and traverses Cretaceous limestones.

The analysis of the data collected included an evaluation of the velocity attenuation of body waves transmitted through the rock.

In addition to the above, the results obtained were correlated with the dynamic elastic moduli derived from seismic velocity measurements.

## EXPERIMENTAL PROCEDURES

Elastic-wave propagation measurements were made in six traverses parallel to the axis of the tunnel. Two of these measurements were made in the wall of the underground opening while the rest were made on the floor (Fig. 1).

The measurements on the floor consisted of a spread of 18 geophone groups with 1.5-m intervals between successive groups (Fig. 2).

Six geophone groups consisted of two geophones attached to small metallic blocks which were cemented in place in the rock mass with chemical cement. These two geophones were mounted one in the vertical direction and one hor-

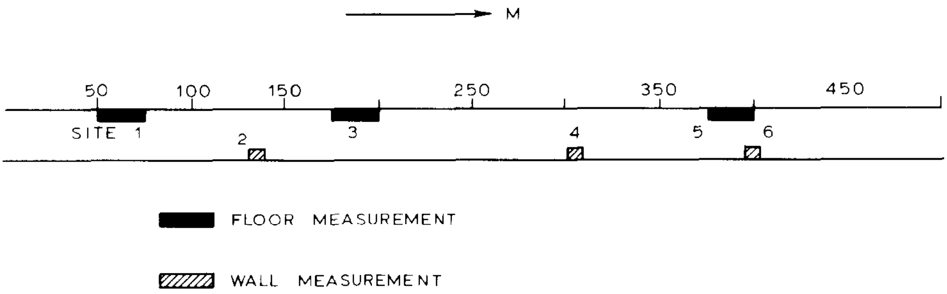



Fig. 1. Sites investigated by seismic measurements.

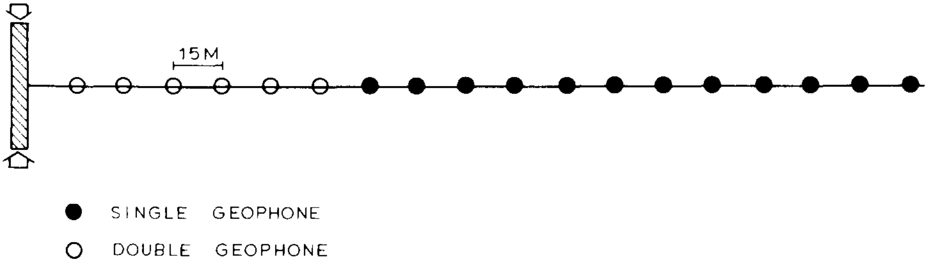
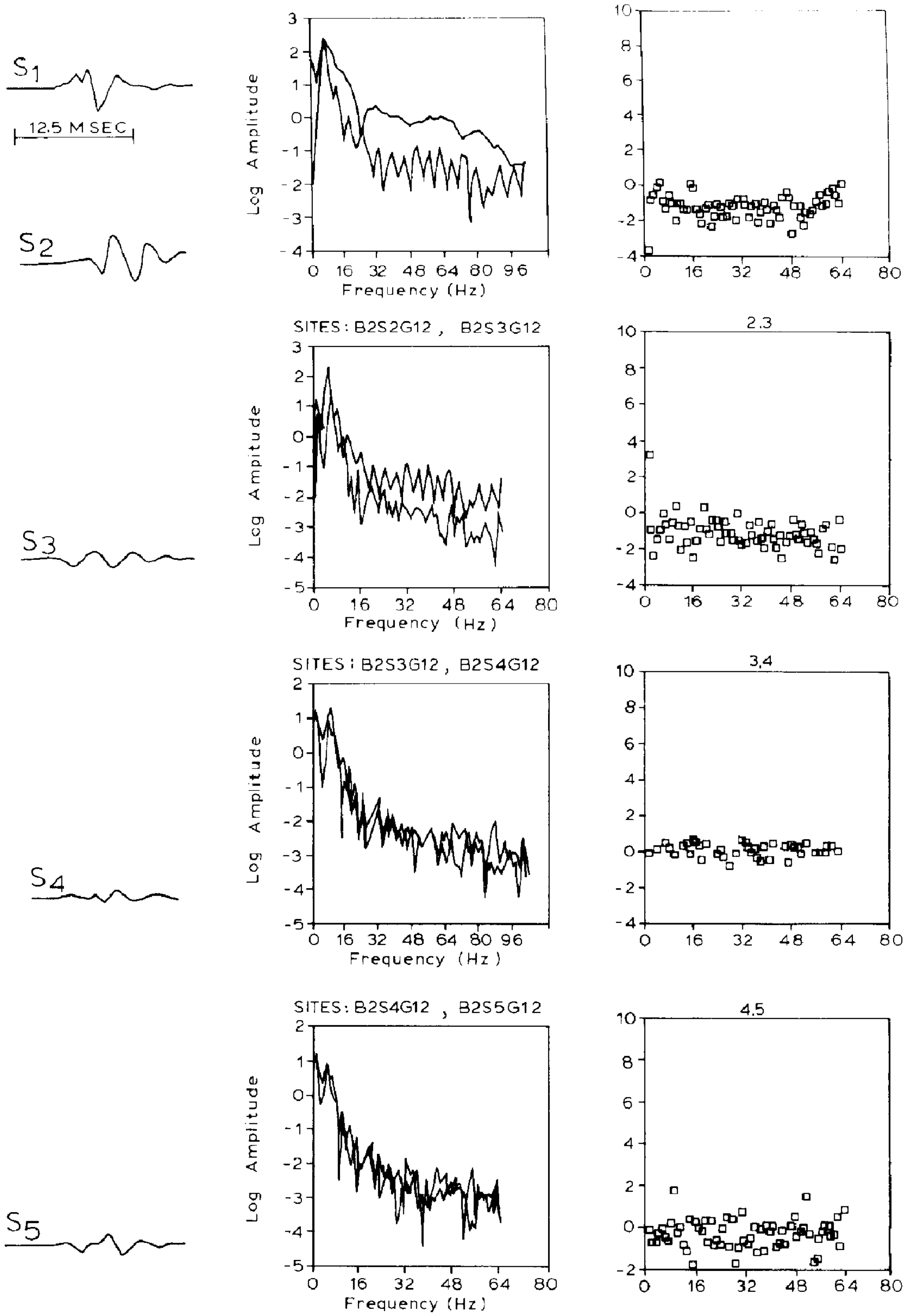



Fig. 2. Geophone layout.

Fig. 3. Geophone layout for seismic measurements at site 2.


S1
12.5 M SEC
S2
S3
S4
S5
Log Amplitude
Frequency (Hz)
SITES: B2S2G12 , B2S3G12
SITES: B2S3G12 , B2S4G12
SITES: B2S4G12 , B2S5G12
2,3
3,4
4,5

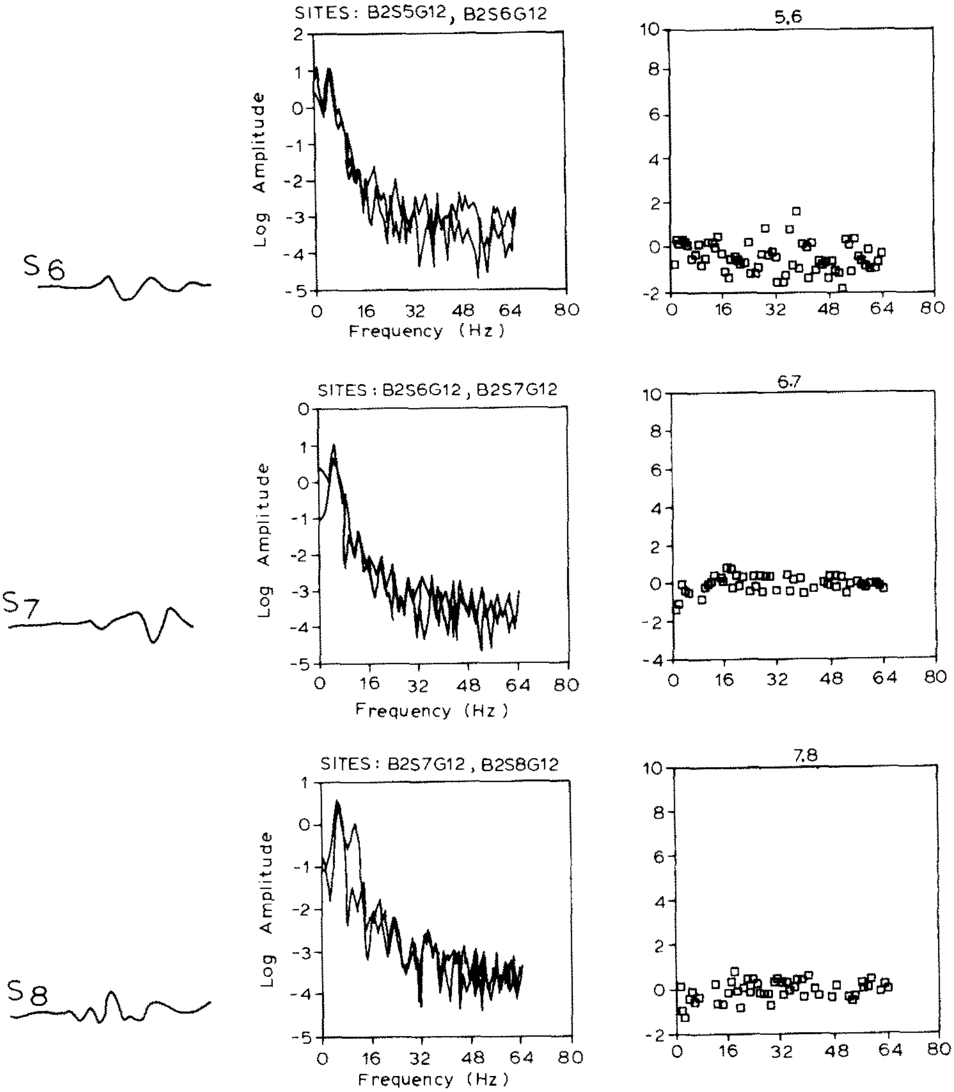



Fig. 4. Wavelets with amplitude spectra and corresponding scatter graphs.

izontally oriented at 90° to the profile line (Fig. 3). The next 12 places in the spread were covered by single geophones, cemented into the rock.

In order to install the geophone blocks directly into the rock, a trench was excavated on the tunnel floor that exposed the rock surface. Since this soon became filled with water, a pump was operated continuously, being stopped just prior to each measurement.

The basic equipment used for recording the arrivals was a 24-channel GEOMETRICS ES2413 seismograph. To generate SH waves on the tunnel floor, a shear-wave source consisting of a length of hardwood timber pinioned firmly to the ground by the weight of a truck was used. The timber was positioned at right angles to the direction of the spread and was struck on its end with a sledgehammer to yield a seismic impulse which consisted predominantly of horizontally polarized shear waves. For the measurements carried out on the wall, we used a metallic pole placed in the rock mass. Reversed polarization was obtained by striking the timber or the pole on the opposite ends, so that we observed a 180° polarity reversal in the seismograms (Tselentis et al., 1987). This helped in picking the correct arrival times for the shear waves.

The waveforms obtained were analyzed to determine the arrival times of the seismic waves, so that the velocities could be determined using the distances between the pairs of geophones.

## ATTENUATION ANALYSIS

Attenuation decreases the amplitude and frequency contents of all seismic waves propagating within a rock mass.

If $A_1(f)$ and $A_2(f)$ are the amplitude spectra of the wavelets at two geophones located at different distances from the signal source, with respective propagation path lengths $x_1$ and $x_2$, then:

$$\log[A_1(f)/A_2(f)] = k(x_2 - x_1)f + c \tag{1}$$

where $k$ is the attenuation and $c$ is a constant accounting for spreading losses and calibration errors.

Estimates of $A_1(f)$ and $A_2(f)$ were obtained by taking discrete Fourier transforms of the recorded waveforms.

When subject to an input of energy, a rock acts as a filter, with fractures acting as filter networks absorbing frequency components within the input energy spectrum in a complex way (Young and Hill, 1982). Hence, the attenuation, obtained as a ratio of the amplitude spectra between two consecutive geophones describes the properties of the filter itself or, in other words, of the rock mass.

Fig. 4 shows the amplitude spectra obtained for the first eight geophones of spread 2, while the corresponding scatter graphs represent the differences in spectra obtained between adjacent geophones. An increase of the scatter around the mean value in the above graphs reflects a higher degree of inhomogeneity of the rock mass that can be attributed to fracturing.

Sites between geophones 3–4, 6–7 and 7–8 show less scatter, indicating a better quality of the rock mass. As a quantitative measure of the above scattering effect, we take the corresponding standard deviations.

In order to test the validity of the above, we attempted to correlate these results with the dynamic elastic moduli of the rock mass at the same sites.

From the arrival times of P- and S-waveforms and the corresponding distances between pairs of geophones, the P- and S-wave velocities were determined.

Fig. 5 depicts the measured in-situ P- and S-wave velocities together with the standard deviations of the scatter graphs obtained. Judging from this figure, a significant decrease in both P- and S-wave velocities is observed between geophones 5 and 6, while in the same area an increasing degree of scatter is obtained.

Sites between geophones 3–4, 6–7 and 7–8 are characterized by relatively high seismic-wave velocities, indicating a better quality of the rock mass. This observation is in agreement with the fact that at these same sites a smaller amount of scatter is obtained.

One of the most common methods of characterizing a rock mass and estimating fracture intensity assumes that a discrepancy between measured velocity and solid-material velocity may be attributed to fracturing (Gardener, 1984).

In order to measure the solid-material velocity, a number of rock specimens, 7 cm in diameter and 10–12 cm long, with their end faces ground flat and smooth, were used. Compressional and shear wave velocity measurements were

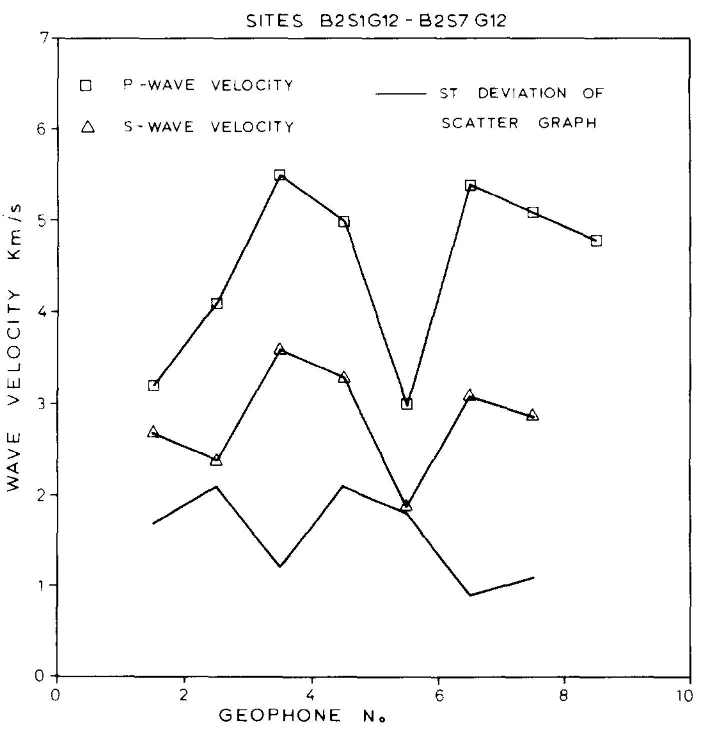



Fig. 5. Variation of P-wave velocity, S-wave velocity and standard deviation of the scatter graphs along site 2.

made using an OYO sonicviewer, giving average values of P- and S-wave velocities of 6.4 km/s and 3.8 km/s, respectively.

Fig. 6 shows the corresponding velocity ratio for the various sites covered in the spread examined and the corresponding standard deviation values of the scatter graphs. It is obvious that at sites where the velocity ratio becomes close to one, indicating an intact rock mass, the degree of scatter attains a minimum.

Next, the P- and S-wave velocities were used to compute the variation of the dynamic elastic moduli of the rock mass, employing the following equations (Lama and Vutukuri, 1978):

$$\upsilon=0.5(V_p/V_s)-1/[(V_p/V_s)^2-1] \quad (2)$$

$$G=\rho V_s \quad (3)$$

$$E=[\rho V_s^{\,2}(3V_p^{\,2}-4V_s^{\,2})]/(V_p^{\,2}-V_s^{\,2}) \quad (4)$$

where $\upsilon$, $G$, and $E$ denote Poisson's ratio, the modulus of rigidity and the modulus of elasticity, respectively, and $\rho$ is the density.

The calculated values of the dynamic elastic moduli are shown in Fig. 7,

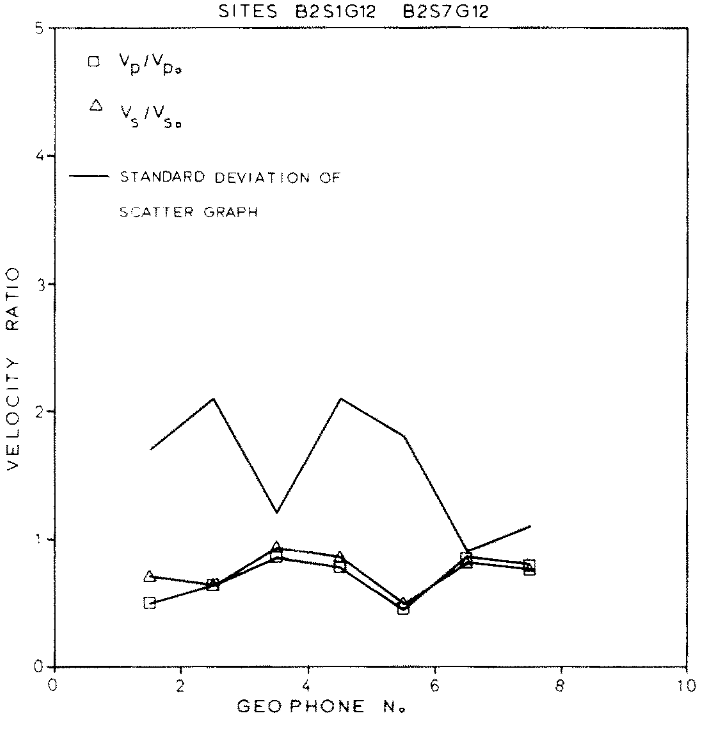



Fig. 6. Variation of $V_p/V_{po}$ and $V_s/V_{so}$ and standard deviation of scatter graphs along site 2, where $V_{po}$ and $V_{so}$ are the solid matrix P-wave and S-wave velocities, respectively.

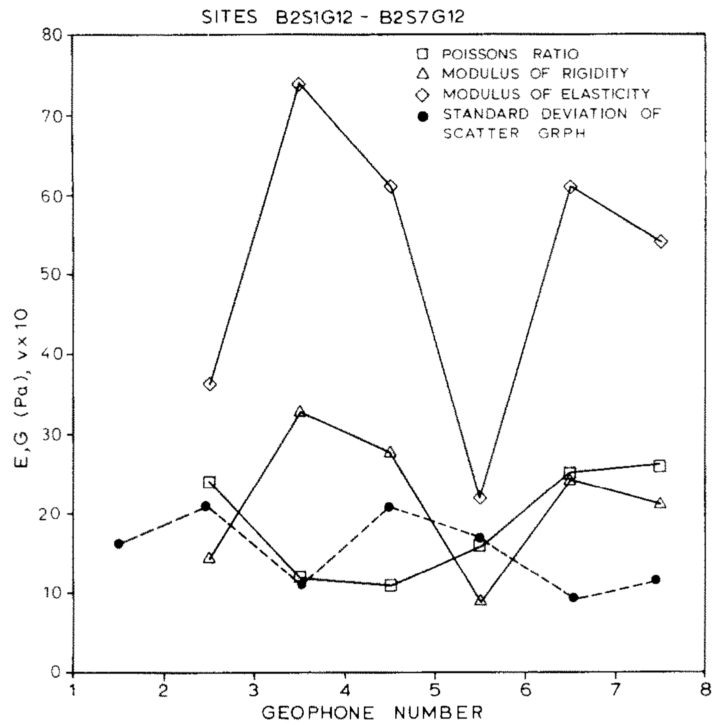



Fig. 7. Comparison of the variation of the dynamic elastic moduli and the standard deviation of the scatter graphs.

together with the corresponding amplitude scatter. The high degree of correlation is obvious.

## CONCLUSIONS

There is ample evidence to show that the velocity and frequency parameters of seismic waves are influenced by the degree of fracturing of a given rock mass.

Although velocity measurements are extensively employed as a quantitative indication of rock mass quality (e.g., rippability tests), a significant increase of the resolution of the single velocity surveys can be achieved by further analyzing the recorded wavelets and incorporating seismic attenuation measurements as well.

Recent developments in microelectric technology have provided very powerful microcomputers, either as separate units or incorporated within the seismic instruments which, when combined with the existing spectral analysis algorithms, provide the geophysicist with a valuable tool to extract more information concerning the rock mass quality from the recorded waveforms.

Our method of analysis involves using the spectral ratio method to construct the corresponding scatter graphs, the standard deviation of which has proved to be a useful indicator of rock mass quality.

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