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Attenuation from seismic refraction surveying as a ground investigation aid

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Abstract

Ground investigation applications of the seismic refraction technique are briefly reviewed and the rock mass parameters which may be obtained from seismic velocity discussed. The phenomenon of seismic attenuation is explained and techniques for its measurement described. The pulse broadening technique is found to give the best measure of seismic attenuation.

Introduction

Seismic refraction is an engineering geophysical technique which is widely used in ground investigation work, but its full potential has not yet been achieved.

Seismic velocities obtained from seismic refraction surveys are commonly used to determine the depth to bedrock and yield valuable geotechnical information regarding the rock mass. The attenuation of a seismic wave is a phenomenon which is not always widely applied in ground investigation work. The authors believe it shows considerable promise for describing the rock mass.

A selection of the data acquired over a period of two years during the course of routine commercial shallow seismic refraction surveys in Ireland carried out by Geocom Ireland Ltd has been used for measuring the seismic attenuation, and their relation to rock masses has been investigated.

Applications of seismic refraction to ground investigation

For the application of seismic refraction to ground investigation, the seismic wave source should ideally be a broad band source producing a broad range of frequencies. This can best be achieved by using an explosive charge as the source. However, there are many logistical difficulties associated with the use of explosives and consequently a sledgehammer or weight drop is more commonly applied for ground engineering works. Frequency analysis of the spectrum produced by a sledgehammer compares favourably with that of an explosive source (Miller *et al.* 1986). A sledgehammer produces a seismic wave with a dominant range of frequencies between 50 and 100 Hz. It achieves a depth of effective investigation of up to 20 m and resolution of generally between 5 and 10%, both factors depending on the site conditions such as wind, rain, geophone coupling and the nature of the transmitting medium.

Seismic refraction surveys have been used to evaluate the *in situ* rock mass for a number of characteristics, notably deformability, strength, rippability, discontinuity frequency and anisotropy, grout take, and stress field (Sjogren *et al.* 1979; Knill 1969; Onodera 1963; Ginzberg *et al.* 1983; Nunn *et al.* 1983). It has also been used for ground characterization by zoning on the basis of velocity (Worthington 1984).

Measurement of seismic attenuation

As a seismic wave passes through the ground it becomes attenuated i.e. the energy of the wave is absorbed. It has been found through field and laboratory studies (Attewell & Ramana 1966) that the higher-frequency components of the wave are absorbed more quickly than the lower-frequency ones. This results in a change in shape of the waveform. As the higher frequencies are filtered out, the lower frequencies become predominant and the wave becomes flatter and broader, a process known as 'pulse broadening' (Fig. 1).

Attenuation will occur in any medium except a perfect vacuum but different media will attenuate seismic waves at different rates, depending on their properties. It is possible to determine the rate of attentuation of a wave by examining the change in shape of the wave or by analysing the variation in amplitude of the various components of its frequency spectrum as the wave passes through the medium.

Alternatively, by looking at wave attenuation it is possible to deduce the nature of the transmitting medium itself; in particular the quality of the rock mass. Although the phenomenon of seismic attenuation has been recognized for many years (Ricker 1953) and its relationship to rock mass quality has been demonstrated (Gladwin & Stacey 1974), very little work has been done to relate the two factors systematically.

The exact mechanisms of attenuation are still not fully understood but they are believed to involve both

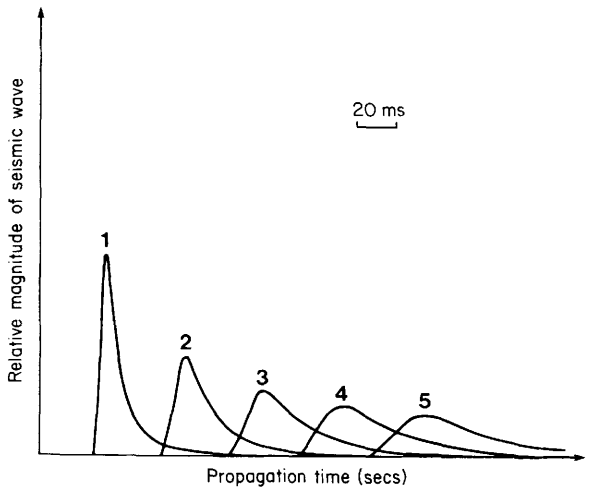

FIG. 1. The progressive change in shape of an original spike input during its propagation through the ground due to attenuation (redrawn from Keary & Brooks (1984)). The numbers above each wave represent the time in seconds that has elapsed for that wave after it had been created.

a fluid flow mechanism, i.e. the effect of the fluid in the pores and cracks of saturated and partially saturated rocks, and a frictional mechanism involving sliding between the cracks and grains in the rock. In saturated rocks the fluid flow mechanisms perform a secondary role to friction (Johnston *et al.* 1979).

Seismic attenuation data are usually presented in terms of either the dimensionless seismic attenuation parameter, Q, or of the attenuation coefficient, α. Two formulae relate these parameters to the seismic velocity, V, and the dominant frequency, f:

$$Q = \pi f / \alpha V \tag{1}$$

when α is in units of inverse length, or

$$Q = 8.868\pi / \alpha \tag{2}$$

where α is in units of decibels per wavelength (dB/λ).

To a first approximation, the dominant frequency can be measured by the time between successive phases of a pulse. Table 1 shows typical values relating these attenuation parameters to rock mass type. In the case of weathered and broken rock the various attenuation mechanisms show a greater influence on the seismic pulse. This results in increased attenuation of each wave as it passes through the rock mass.

TABLE 1. *Relation between Q and α values and rock mass type (after Hatherly* 1983)

Q	α (db/λ)	Rock mass description
20–100	1.36–0.27	Clastic sedimentary rocks e.g. sandstones and shales
150–600	0.18–0.05	Metamorphic rocks e.g. slates and phyllites
200–600	0.14–0.05	Igneous rocks e.g. granites and basalts

From equation (1) it can be seen that for constant values of Q and V the higher-frequency components of the wave will be attenuated more quickly than the lower-frequency components. The ground is acting as a high-frequency filter which reduces the amplitude of the higher-frequency components of the wave and thus broadens the pulse.

There are three approaches to the actual measurement of seismic wave attenuation:

(1) Spectral analysis: the measurement of the change in amplitudes of the various frequency components of the seismic pulse as the wave passes through the ground.
(2) Amplitude decay: the analysis of the decay in amplitude with distance of the first arrival of the seismic wave.
(3) Pulse broadening: the measurement of the change in width of the first seismic pulse with distance from the source.

Spectral analysis

Spectral analysis, involving the analysis of changes in the seismic frequency spectrum due to attenuation, has been used by Newman & Worthington (1982) and Young & Hill (1986) as an indicator of rock mass quality.

A rock mass will behave as a low-pass filter which allows the low-frequency components of the wave to pass whilst filtering out the high-frequency components. The precise frequencies which are attenuated will depend on the individual nature of the rock mass i.e. each rock mass will have its own attenuation spectrum.

The spectral analysis technique measures the attenuation spectrum of a rock mass by comparing the frequency spectrum or Fourier transform of an input signal with the frequency spectrum of an output signal. The ratio of input to output spectra provides the attenuation spectrum which is characteristic of a particular rock mass (Young & Hill 1986).

Amplitude decay

The second approach involves the analysis of the decay of the amplitude of the first seismic wave event with distance. The loss of amplitude of a seismic wave is due to two major effects: one is the geometrical spreading of the wave and the other is the attenuation of the wave. Therefore, before the decay due to attenuation can be analysed, it is necessary to quantify and remove the effect of geometrical spreading.

Newman & Worthington (1982) also used this technique to study attenuation. They measured the peak-to-peak amplitudes of the first cycles of each wavelet. These amplitudes were then normalized by dividing by the relevant amplitude of the reference wave, these ratios being corrected for geometrical decay on the assumption of a perfectly spherical spreading pattern. The residual attenuation, β, obtained after this correction had been made, was related to Q by the following formula:

$$\beta = \pi F_{av}/QV \tag{3}$$

where F_{av} is the dominant frequency of the signal and V is the appropriate velocity.

Pulse broadening

The third approach for the measurement of attenuation is based on pulse broadening. Ricker (1953) first investigated this and considered the pulse width to be proportional to the square root of the travel time. This relationship has been shown to be incorrect and it is now accepted that the two are directly proportional (Gladwin & Stacey 1974). The following equation is used to relate the pulse width τ to the travel time T:

$$\tau = \tau_0 + CT/Q \tag{4}$$

where τ_0 is the initial pulse width and C is a constant as defined by Hatherly (1983).

This method is preferred by the authors because it is independent of the geometrical decay of the wave and much of the interference which is associated with shallow seismic refraction data may be avoided, provided that measurements are made on the first quarter cycle of the first event (Hatherly 1986).

Analysis of results

There are various ways of determining the pulse width (Kjartansson 1979). The most suitable are: (i) measurement of the pulse rise time, i.e. the maximum amplitude divided by the maximum slope (giving a value of $C = 0.5$); and (ii) the measurement of the separation between the first point of inflection and the first peak (giving a value of $C = 0.3$ according to Hatherly (1983)); see Fig. 2 for illustrations of these measurements. Hatherly (1986) considers the second method of determination to be preferable because it is more accurate since it does not involve the measurement of amplitude and requires less calculation, therefore reducing potential errors.

The traces used for this analysis should all be from a single shallow bedrock refractor and should be free from significant background noise. Since only the traces from the bedrock refractor are selected for measurement, the maximum number of geophones per spread should be used. For this analysis the data from each spread was analysed separately as the authors believe this achieves better resolution. In the case of the Glanmire site, an average of 22 traces was analysed per spread. There should not be significant variation in the thickness of the surface layer over the distance of the spread.

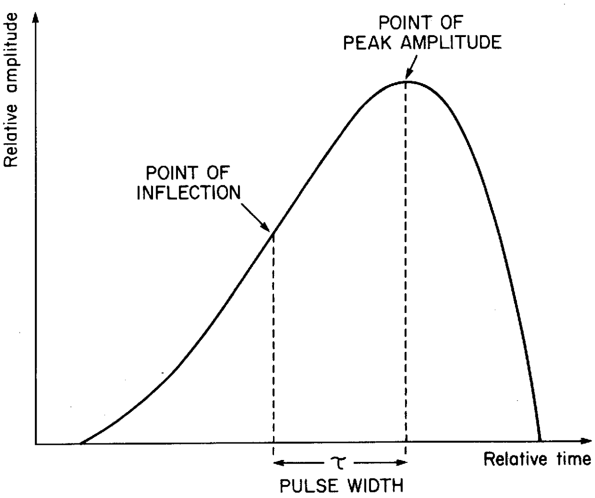

FIG. 2. Seismic trace showing the first event with points of inflection and peak amplitude indicated together with the pulse width, τ.

It is possible to analyse the sensitivity of the parameter Q to small variations in the measurement of the parameters used to determine the seismic attenuation by varying the values of first the travel time and then the pulse width for a particular geophone spread. It was found that a 10% reduction in a single travel time value for a spread produced a 3% increase in the Q value together with a 6% increase in the standard error of Q. A 10% reduction in a single pulse width caused a 5% reduction in the Q value together with a 12% reduction in the standard error of Q. The Q values and their standard errors have in general been found to be most sensitive to variations in the pulse width values. This highlights the need for careful and accurate measurements of the attenuation parameters and these can be aided by:

1. removing the effects of variations in the gain settings,
2. avoiding selective filtering,
3. using a broad band source and broad spectrum, high resolution geophones,
4. digitally recording data to facilitate automatic data handling,
5. using multi-channel seismograph equipment,
6. good geophone coupling.

Attenuation related to rock mass assessment

The seismic attenuation parameter, Q, obtained by the analysis of seismic refraction results has been

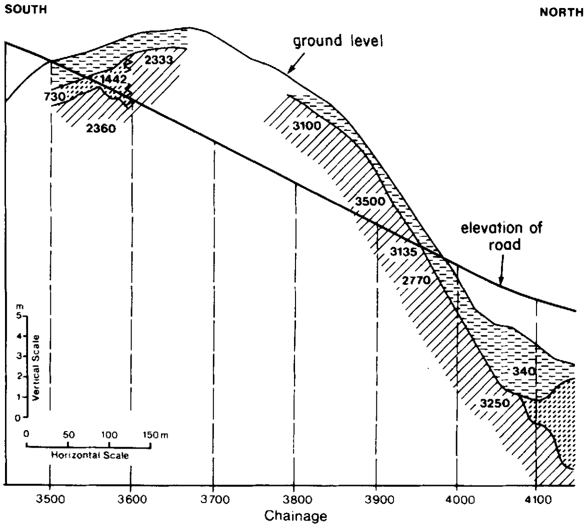

FIG. 3. A north–south orientated section of the road cut under investigation at Glanmire. The numbers refer to the average local P-wave velocities in m sec^{-1}. There is a vertical exaggeration of 25 on this section.

compared to the standard seismic velocities (V_p and V_s) and to related parameters such as velocity index, modulus of elasticity, and other rock mass descriptors such as Bieniawski's R.M.R. and Barton's q values (summarized in Hoek & Brown (1980)).

The correlation of seismic attenuation with the rock mass rating schemes of Barton and Bieniawski can be illustrated by reference to a case history concerning part of the investigation for a large road cut at Glanmire which is located near Cork in southern Ireland (see Fig. 3). This site has a variety of lithologies and the available seismic data exhibited little background noise. A near-surface main refractor was found to be present and, subsequent to the seismic work, boreholes and trial pits permitted the study and description of the rock mass.

The geology of this section was also interpreted from the borehole and trial pit data and this was made available by Cork County Council. Broadly speaking, the geology at the site of this cut consists of folded and fractured Devonian sediments comprising green to brown sandstones and dark grey shales. These rocks have only been affected by very low grade metamorphism (Sevastopulo 1981). The sandstone units are dominant from chainage 3700 to 3850 and the shale is predominant from chainage 3850 to 4000, where the chainages are measured along the centre line of the road in metres (see Fig. 3).

The sandstone rock mass is thickly bedded with moderately to widely spaced joints. The RQD values lie between 0 and 10% in the stress relieved upper sections (<3 m) and between 20% and 60% in the lower, more competent, zones.

The shale rock mass can be described as thinly laminated with moderately to widely spaced joints. The RQD values of the less weathered, deeper shales are similar to the sandstone between 20% and 60%.

The total range of seismic P-wave velocities in this section of the cut varies between 2300 and 3500 m/s^{-1} and have been correlated with the lithologies using the borehole information. This showed that the shales in this section of the cut have velocities of between 2300 and 2770 m s^{-1} and the sandstones of between 3100 and 3500 m s^{-1}. The results of the comparisons of the seismic attenuation with the other rock mass parameters are summarized in Table 2.

The Q values obtained for the rock masses at this site lie within the expected range for near-surface, clastic sedimentary rocks, based on the guide of Table 1. There is some correlation between the Q values and the seismic velocities for each spread at this site. However, a stronger correlation exists between the Q values and the lithologies reported for each spread and also to a lesser degree between the Q values and the RMR and q values. These results suggest that attenuation measurements are sensitive indicators of lithology and, to a lesser extent (given the available levels of data), of discontinuity frequency.

The correlation between Q values and lithology is borne out by looking at data from another site which has been analysed. This site is similarly located in the south of Ireland, near Dungarvan in Co. Waterford. The geology here consists of a Devonian sequence of sandstones and shales. The correlation can be seen from Table 3.

The comparisons of attenuation with lithology confirm the findings of Newman & Worthington (1982) which were concerned with seismic attenuation in chalk and sandstone. Their analysis gave a Q value

TABLE 2. *Results of seismic data analysis for the site at Glanmire together with rock mass ratings for three typical geophone spreads*

Spread No	Dominant lithology	Q value	Standard error of Q	V_p (m s^{-1})	RMR	q
14	Shale	8.69	2.70	2300	45	0.9
15	Shale and fractured, weathered sandstone	6.20	1.41	2330	47	1.0
16	Sandstone	17.42	5.84	3100	59	1.8

TABLE 3. *Results of seismic data analysis for the site at Dungarvan for four typical geophone spreads*

Spread No	Dominant lithology	Q value	Standard error of Q	V_p(m s^{-1})
1	Sandstone	14.38	7.40	3640
3	Shale/Slate	6.56	1.38	2220
4	Shale/Slate	7.57	2.10	3330
6	Sandstone	31.67	2.61	4000

for sandstone of 26 and 9 (mean and standard error) and for fissured chalk of 4 and 3.5. These results led them to conclude that attenuation is a very sensitive indicator of lithology in near-surface strata. This finding is supported by the Irish case histories.

Conclusion

The results from the case history at Glanmire, together with the other sites such as Dungarvan studied over the past two years, have shown that the values of the seismic attenuation parameter, Q, obtained from seismic attenuation studies provide information which can be correlated with certain rock mass properties, in particular lithology and discontinuity frequency.

The Q values were found to broadly indicate the intensity of discontinuities within a rock mass and this has been well demonstrated by comparing the Q values with the rock mass ratings using both the Barton and the Bieniawski methods summarized in Hoek & Brown (1980).

The data used for the attenuation analysis can be readily obtained from any standard refraction survey provided some simple procedures are followed during data collection, in particular with the control of the gain and avoiding selective filtering together with the use of a broad band source and broad spectrum geophones.

A variety of techniques exist for measuring seismic attenuation. One of these, the measurement of the change in width of a seismic pulse with increasing travel time, has been found to be the most easily applied in practice.

The advent of digital data recording and processing means that the extra data processing required to obtain seismic attenuation values may easily be achieved, even on the smallest scale. The attenuation values may then be used, in conjunction with values of seismic velocity and other rock mass quality indices, to provide a greater understanding of the ground being investigated.

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