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The attenuation effects of surface-wave propagations on rockmass using SASW method

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Abstract: A considerable amount of research has been devoted to the subject of attenuation of motion resulting from the geometrical and material dampings on soil medium. However, there are very few studies available on the effect of attenuation of rockmass at the moment. In this study, the loss of the amplitude (A) or energy vibration due to the geometrical and material dampings of Rayleigh waves were estimated by SASW method. The results of measurements were analyzed in the frequency domain and the attenuation characteristics of rockmass were studied in term of a *frequency-independent* attenuation coefficient (α_0), by applying Bornitz equation. The experimental curve is fitted to a corresponding theoretical curve, in order to obtain a *frequency-independent* attenuation coefficient (α_0). The aim of this survey is to characterize the attenuation coefficient of surface waves on rockmass, as a result of discontinuity spacing using the SASW method.

INTRODUCTION

Engineers, geophysicists and seismologists often use surface waves for material characterization across broad ranges of scales from the near-surface to the whole of earth's crust. If an impulse of short duration is created at the surface of an elastic half space, the body waves can travel within the interior or along the surface of the ground and may be compression waves (P-waves), travelling with velocity Vp, or distortional, i.e. shear waves (S-waves). The body waves travel into the medium with hemispherical wave fronts as shown in Figure 1.

The propagation velocity of S-waves, Vs, and the ratio Vp/Vs depends on the values of the Poisson ratio, n (Fig. 2). The value of shear wave velocity of geomaterials (Vs) decreases with increasing value of cyclic shear strain. However, for cyclic strain amplitudes less than 10^{-5}, the value of Vs remains practically constant.

Surface waves include both Rayleigh and Love waves, however for near-surface site characterization, the methods utilize only Rayleigh waves. The Rayleigh waves will propagate radially outwards along a cylindrical wave front. The vertical ground displacement due to the Rayleigh wave arrival is much greater than that for P- and S-waves. Since P-waves are the fastest, they will arrive first followed by S-waves and then the Rayleigh waves.

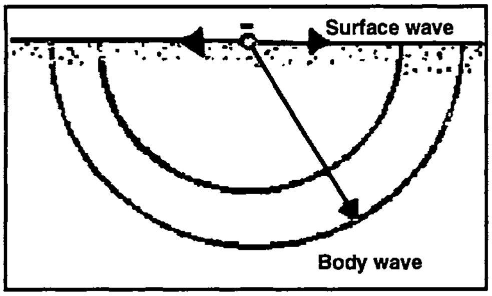

Figure 1. The space of seismic waves propagation (from Das, 1983).

The surface waves can travel only in the vicinity of the ground surface and be either out-of-plane Love waves (L-waves) or in-plane Rayleigh waves (R-waves). The L-waves are horizontally polarized shear wave and they exist only when there is a surface low-velocity layer on top of higher velocity layer. Their velocity of propagation does not differ appreciably from that of S-waves. The propagation velocity of R-waves, V_R, is slightly lower than V_S, according to Figure 2, and their particle motion has both vertical and horizontal components. The diagram of Figure 3, depicts the rapid decay of vibration amplitude of R-waves propagate along a surficial layer having a thickness equal to one wavelength.

Rix *et al.* (2001) and Athanasopoulus *et al.* (2000) used surface wave measurements to determine the material damping ratio profile of a layered soil deposit and effect of soil stiffness in the attenuation, respectively.

The attenuation characteristics of propagating seismic waves (which depend on wave characteristics and medium) have been the subject of extensive theoretical and

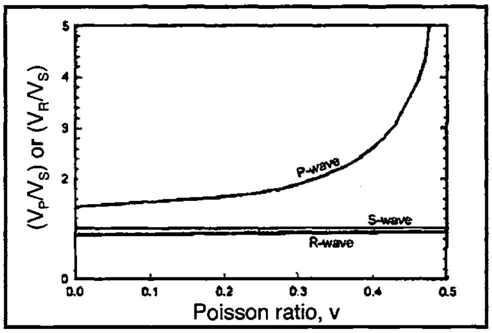

Figure 2. Relationships between propagation velocities of seismic waves (from Athanasopoulus *et al.*, 2000).

Table 1. Attenuation coefficients (α) for 50 Hz seismic waves (from Clark, in Dobrin, 1988).

Material and Source	Velocity (km/s)	α km^{-1}
Granite		
- Quincy, Mass	5.0	0.2-0.3
- Rockport, Maine	5.1	0.237
- Westerly, RI	5.0	0.384
Basalt		
- Painesdale, Mich	5.5	0.414
Diorit	5.78	0.21

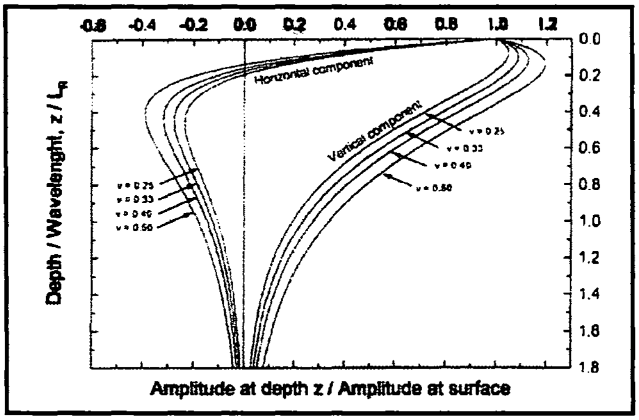

Figure 3. Decay of amplitude of Rayleigh waves with depth from the ground surface (from Athanasopoulos *et al.*, 2000).

experimental study. Attenuation coefficient have been measured for a variety of earth material, especially in seismic reflection exploration (Table 1), but the mechanism for attenuation in many types of rocks is not very well understood (Dobrin, 1988).

A considerable amount of research has been devoted to the subject of the attenuation of motion resulting from radiation and material dampings on soil medium. However, very few studies are available on the effect of attenuation of rockmass. The aim of this survey is to characterize the attenuation coefficient of surface waves on rockmass as a preliminary study on rock discontinuity using SASW method.

THEORETICAL BACKGROUND

In a homogeneous halfspace the R-waves are non dispersive, i.e. the value of propagation velocity, V_R, is independent of the frequency of vibration, f (or the corresponding wavelength, L_R). The R-wave wavelength is related to the propagation velocity (also termed phase velocity) through the frequency of vibration following equation:

$$V_R = f \cdot L_R \qquad (1)$$

When body waves spread out along hemispherical wave front, the energy is distributed over an area that increases with square of radius, $\varepsilon \propto \frac{1}{r^2}$, where e is the energy per unit area and r is the radius. However, the amplitude is proportional to the square root of the energy per unit area, $A \propto \sqrt{\varepsilon}$ or $A \propto \frac{1}{r}$. Along the surface of the halfspace only, the amplitude of body waves are proportional to $\frac{1}{r^2}$ or $A \propto \frac{1}{r^2}$ (Das, 1983).

Similarly, the amplitude of the Rayleigh waves, which spread out in a cylindrical wave front, is proportional to $\frac{1}{\sqrt{r}}$. Thus the attenuation of the amplitude of the Rayleigh waves is slower than that for the body waves. The loss of the amplitude of waves due to spreading out is called geometrical damping or radiation damping. Mathematically, this is usually described by:

$$A_2 = A_1 \left[\frac{r_1}{r_2}\right]^n \qquad (2)$$

where A_1 is the amplitude of vibration at distance r_1 from the source, A_2 the amplitude of vibration at distance r_2 from the source and n the attenuation coefficient due to geometrical damping.

The value of the attenuation coefficient, n, depends on the type of seismic wave, the location and type of the source. Table 2 gives the values of n for various combinations of source location and type (Kim and Lee, 1998).

Table 2. Values of attenuation coefficient (n) due to radiation damping for various combinations of source location and type (from Kim and Lee, 1998).

Source location	Source type	Induced Wave	n
Surface	Point	Body wave	2.0
		Surface wave	0.5
	Infinite line	Body wave	1.0
		Surface wave	0
In-depth	Point	Body wave	1.0
	Infinite line	Body wave	0.5

The amplitude or energy of vibration of seismic waves is also loss as dissipated energy during their propagation by the material damping capacity of geomaterials (D).

Accounting for both geometrical and material dampings, the vertical amplitude of Rayleigh waves can be given by equation:

$$A_2 = A_1 \sqrt{\frac{r_1}{r_2}}\, e^{-\alpha(r_2 - r_1)} \qquad (3)$$

where a is the attenuation coefficient due to material damping (m^{-1}). For the case of surface wave where the source is located on the surface, it gives the value of n = 0.5, which will be used in this study. The general form of the equation (3) is known as the Bornitz equation (Das, 1983).

It is known that the attenuation coefficient due to material damping, a, depends on the type of near-surface material and the frequency of vibration.

A simplified analysis of the mechanics of seismic wave propagation in the grounds leads to the following equation for estimating the values of coefficient a:

$$\alpha = \frac{2\pi f D}{V_R} \qquad (4)$$

where V_R is the propagation velocity of R-waves which can be measured by conducting field tests (crosshole, downhole or SASW), D is the damping ratio of the geomaterials and f the frequency of vibration, is readily available.

It should be mentioned that, in addition to the attenuation coefficient (α) which depends on frequency of vibration, a *'frequency-independent'* coefficient of attenuation (α_0) can be defined by writing equation (4) in the form of:

$$\alpha_0 = \frac{\alpha}{f} = \frac{2\pi.D}{V_R} \qquad (5)$$

where a_0 the *frequency-independent* attenuation coefficient having units (s/m). Although the attenuation coefficient (α_0) is much less dependent on frequency compared to the frequency dependant attenuation coefficient (α), it still retains some degree of frequency dependency.

FIELD MEASUREMENTS

The surface waves are detected using sensors planted on the ground surface at known distances along a line which is collinear with the wave source. The generation of surface waves was achieved by using impact surface technique i.e. hammer for distance (r_1) less than 4 meters and dropped weight (weighting around 50 kg's) for distance (r_1) greater than 8 m.

Two geophones have been used to measure ground vibration in the survey. The geophones sensors with a natural frequency of 1 Hz (model L-4 Seismometer) were arranged as shown in Figure 4. This arrangement of geophone spacing is often called the common receivers midpoint geometry and usually used in the SASW survey.

Due to limitations of the recording equipment and the attenuation properties of the near-surface materials, the distance of source to receiver 1 or distance from receiver 1 to receiver 2 (d), should follow the following condition:

$$\frac{\lambda}{3} < d < 2\lambda \qquad (6)$$

where λ is the wavelength of the surface wave under consideration (Heisey *et al.*, 1982 in Matthews, 1996).

The recording system used for this survey is the OROS25 spectrum analyzer that captures signals from the ground motion sensors in the time domain. The time domain data are transformed into the frequency domain. From these spectral data, the ratio (A_2/A_1) of spectrum received by geophone 2(A_2) and that of geophone 1(A_1), is plotted vs frequency range. This plot will acts as a finger print of the near-surface material.

RESULTS OF MEASUREMENT AND DISCUSSION

The analysis started by estimating the Fourier spectra of the vibration time histories. The frequency range in which the results of measurements have the best quality was established by estimating the coherence function of the two time histories. The value of the coherence function

Table 3. Summary of the results of SASW analysis.

No.	r_1(m)	r_2(m)	Freq(Hz)	α_0(s/m)
1.	0.5	1.0	450-500	3.09×10^{-3}
2.	1.0	2.0	350-400	1.98×10^{-3}
3.	2.0	4.0	300-350	1.20×10^{-3}
4.	4.0	8.0	250-300	9.10×10^{-4}
5.	8.0	16.0	200-250	9.08×10^{-4}

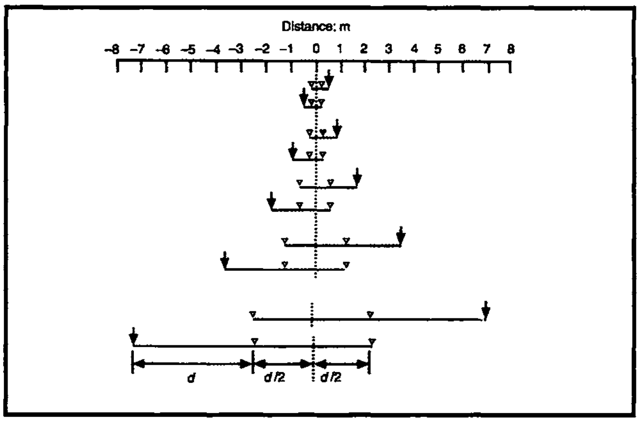

Figure 4. The common receivers midpoint geometry (from Matthews, 1996).

which actually measures the amount of association between two signals for a particular frequency band, may range from 0.0 to 1.0 (Matthews, 1996). When the coherence is equal to 1.0 the two signals are perfectly correlated whereas when the coherence is equal to zero, the two time histories are completely uncorrelated. In this survey, if the coherence drops below 0.98 the two signals should be considered unreliable.

The spectral ratio (A_2/A_1) curve when plotted in the form of (A_2/A_1) vs frequency is also termed as a *decay factor* curve. It shows a general trend of frequency dependency, i.e. the value A_2/A_1 decreases with the frequency of vibration. The observed oscillation of (A_2/A_1) vs frequency values can be explained as being the result of the participation of higher modes of vibration in the observed surface motion of elastic, damped, in homogeneous halfspace.

The Spectral ratio (A_2/A_1) vs frequency experimental curve data in Figure 5 has been best fitted to a theoretical curve described by the following equation:

$$\frac{A_2}{A_1} = \sqrt{\frac{r_1}{r_2}}\, e^{-\alpha_0 f (r_2 - r_1)} \qquad (7)$$

where f is the variable frequency of vibration and α_0 the attenuation coefficient due to material damping.

The measurement site is located at an abandoned quarry in Lanchang area, Pahang. It is underlain by igneous rock of rhyolithic composition. The rock is covered with thin soil mixed with gravel. The parameters and results of measurement are listed in Table 3.

For geophone spacing of r_1 = 4 m and r_2 = 8 m, the theoretical curve described by equation (7) will be simplified as:

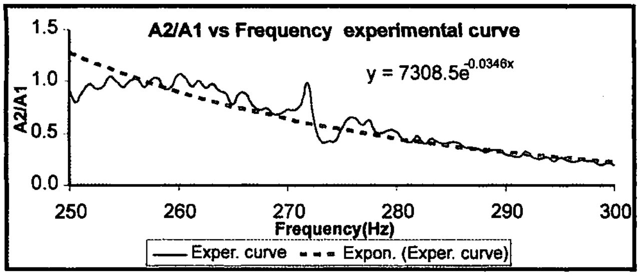

Figure 5. Spectral ratio (A2/A1) versus Frequency experimental curve.

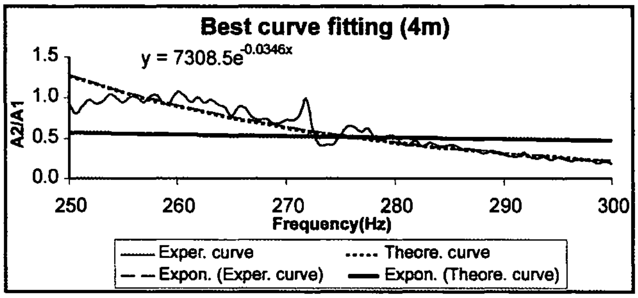

Figure 6. The best curve fitting of experimental and theretical curve.

$$\frac{A_2}{A_1} = \sqrt{\frac{1}{2}}\, e^{-4a_o r} \qquad (8)$$

The value of the *frequency-independent* attenuation coefficient could then be estimated by establishing an exponential equation, that best fits the experimental curve. For this geophone spacing, the value of a_o is calculated to be equal to 9.10 x 10^{-4} (Fig. 6).

The results show that for short geophone spacings which ranges from 0.5 m to 2 m, the value of attenuation coefficients are relatively high compared to that of greater geophone spacing. The high attenuation coefficients appears to be associated with the near-surface soil materials and the presence of fracture (discontinuity) in the upper layer of the rock mass.

CONCLUSIONS

The SASW method has been successfully used to measure the effect of the attenuation coefficient of Rayleigh waves on rock mass. The results of the study reveals that:

the used of common receivers midpoint geometry as geophone spacing in the study of attenuation coefficient effect on rockmass gives an excellent results in the sense that it can determine the shear modulus of the rock mass simultaneously,

a high coherence value of between 0.90 and 1.0, should be used as criteria to determine the range of the frequency to be processed. In addition the *decay factor* curve i.e. the value of the spectral ratio (A2/A1) decreases with frequency of vibration, can also be used in assessing the frequency range,

the value of attenuation coefficient for each geophone spacing appears to correspond to the different depth of measurement and

the attenuation coefficient of the amplitude of Rayleigh wave on the rockmass is much lower than that of the soil material.

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