The importance of crustal shear wave velocity profile for ground motion modelling

Hing-Ho Tsang, Nelson T. K. Lam, S. H. Lo

***Abstract*—**The potential seismic amplification and attenuation properties of an area are well correlated with the shear wave velocity (*SWV*) profile of crustal rock. When local strong motion records are lacking, the attenuation behaviour of future earthquakes can be inferred from a crustal SWV model that is representative of the area of interest. Details of the SWV profile close to the earth surface (1-2 km depth) are particularly critical. Unfortunately, such details cannot be obtained by conventional seismic reflection/refraction surveys. This study demonstrates the use of information from a combination of sources to produce a set of composite SWV profiles for four principal geological formations that are prevalent in Hong Kong. Their respective local upper crustal modification factors have been computed and the significant differences have been highlighted.

***Keywords*—**attenuation, earthquake, ground motion, microtremor, seismological modelling, shear wave velocity

I. Introduction

THE attenuation behaviour of earthquake ground shaking is highly complex, but can be approximated by a series of "filters", each of which represents a seismic wave generation (or modification) mechanism along its entire transmission path between the source (at depth) and the site of interest (on the surface). The properties of these filters can be generalised at a range of scales depending on the considered mechanism and the method of modelling. Attenuation factors can be classified into (i) regional factors, (ii) local factors, and (iii) site factors.

Regional factors characterise the seismic wave generation and transmission mechanisms that can be generalised to a whole region (in the order of 100 km), and comprise the following: (i) source factor; (ii) geometric attenuation factor; and (iii) whole path attenuation factor. Local factors, which are the focus of this paper, characterise the extent of amplification and attenuation mechanisms in the upper crust, which operate on distance scales of several kilometres. Site factors characterise the filtering mechanisms within the soil sedimentary layers overlying bedrock, which operate on much smaller distance scales of tens of metres.

This paper, which describes a methodology for seismic attenuation modelling in the vicinity of the southeast Asian city of Hong Kong, demonstrates the use of information from a combination of sources to constrain the model SWV profiles (in the format conforming to Chandler *et al.* [1]) for four principal geological formations that are prevalent in Hong Kong: (i) granitic rock; (ii) volcanic rock; (iii) heavily-jointed volcanic rock; and (iv) meta-sedimentary rock. The meta-sedimentary rock in Hong Kong consists of deep deposits (~ 900 m) of meta-siltstone (schist), underlain by marble.

II. *SWV* Profiling from Engineering Boreholes Data (Bedrock Depth up to 30m)

Four principal types of measured *SWV* data are available for Hong Kong. The first comprises very extensive engineering borehole data for soil and reclamation sites throughout the territory, for which *SWV* data for the upper 10-15 m of the underlying bedrock is frequently obtained. This data has been categorised according to the main geological formations prevalent in Hong Kong, which comprise granitic, volcanic, heavily-jointed volcanic and meta-sedimentary rocks, and have been plotted in Figs. 1(a)-(d), respectively. This ground investigation database covers all principal built-up areas in Hong Kong, and is considered representative of the entire Hong Kong region.

Regression analyses were used on each set of boreholes data to determine representative values of *SWV* at 30m depth, denoted as $V_{s,30}$ (at 6m depth, denoted as $V_{s,6}$, in the case of meta-sedimentary rock), for various geological formations that are prevalent in Hong Kong. Results are summarised below, in (1)-(4):

Granitic formation:

$$V_s(Z) = 1350\left(\frac{Z}{30}\right)^{\frac{1}{4}} \quad Z < 120\text{m} \tag{1}$$

Volcanic formation:

$$V_s(Z) = 2200\left(\frac{Z}{30}\right)^{\frac{1}{4}} \quad Z < 32\text{m} \tag{2}$$

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Heavily-Jointed Volcanic formation:

$$V_s(Z) = 1600\left(\frac{Z}{30}\right)^{\frac{1}{4}} \quad Z < 48\text{m} \tag{3}$$

Meta-Sedimentary formation:

$$V_s(Z) = 1150\left(\frac{Z}{6}\right)^{\frac{1}{4}} \quad Z < 6\text{m} \tag{4}$$

As the thickness of weathered rock in Hong Kong is highly variable (hence site-dependent), the depth ranges proposed in (1)-(4) have been guided by the measured *SWV* of the deeper unweathered rock layers (refer Sections III and IV).

III. *SWV* Profiling from SPAC Surveys (Bedrock Depth 30-200m)

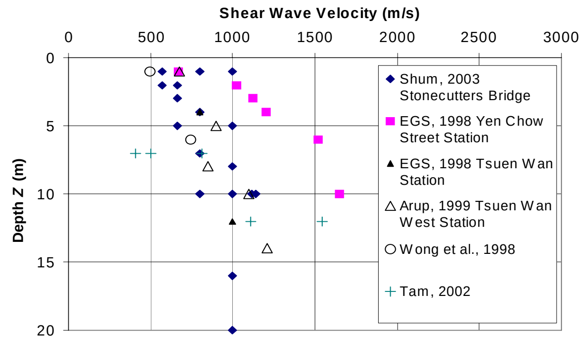
The second type of *SWV* data has been obtained from microtremor surveys using the SPAC technique [2]. The SPAC technique appears to be extremely well suited to the measurement of *SWV* profiles in urban areas [3]. Its advantages include its non-invasiveness (no drilling required), speed of data acquisition, low cost and the ability to be able to provide *SWV* information over a wide range of depths. A series of SPAC surveys were undertaken at five sites in Hong Kong, comprising two on granitic bedrock, two on volcanic bedrock and one on meta-sedimentary bedrock, to develop an average *SWV* profile from the surface to an approximate depth of 200m.

The SPAC technique measures the propagation of microtremors – very low amplitude ground motions – that occur as the result of both natural (wind, wave action, atmospheric variations) and man-made (road traffic, trains, industrial noise) phenomena. Microtremors form a background ‘field’ of (low-amplitude) seismic waves that varies slowly in space and time, with most of the energy transported as surface waves. Surface waves are dispersive (i.e. velocity of propagation is dependant upon frequency), with the velocity of any given phase (frequency) being governed (predominately) by the *SWV* structure of the earth.

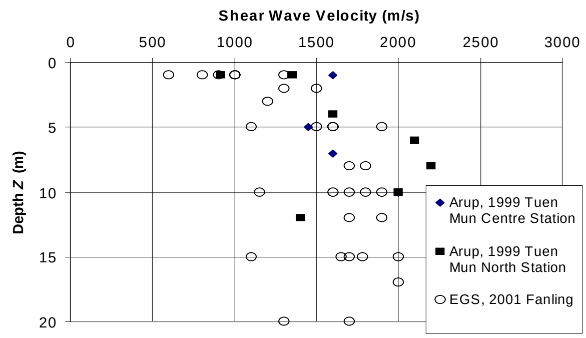
Microtremor surveys require a relatively flat area, clear of obstructions and dominant sources of microtremor waves. Geophone arrays were deployed so as to achieve the maximum possible array size in the available space. Hexagonal arrays (Fig. 2) provide best results when microtremors originate from a limited range of directions. The interpreted *SWV* profiles for the five sites are shown in Fig. 3.

IV. SWV Profiling from Monitoring of Quarry Blasts (Bedrock Depth 200-1500m)

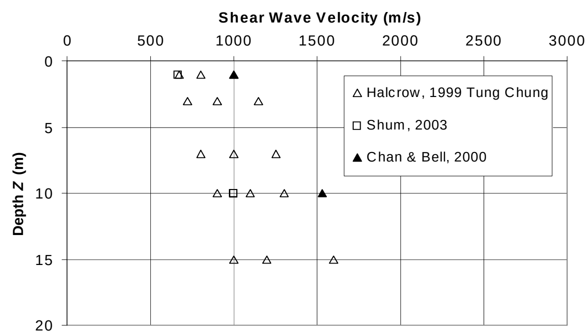
The third type of measured *SWV* data has been obtained from a recent study on the upper crustal structure of Hong Kong [4]. This study used short-period group velocity (T = 0.4 – 1.3 s) dispersion of R_g waves generated by quarry blasts within the city, and has yielded reliable *SWV* data for the depth range of approximately 200 m to 1500 m (1.5 km), as shown in Figs. 4(a) and (b). In this depth range, rock units are primarily igneous and



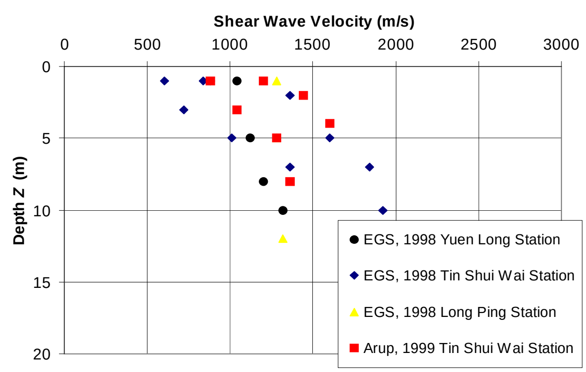
(a) Granitic formations



(b) Volcanic formations



(c) Heavily-jointed volcanic formations



(d) Meta-sedimentary formations (schist)

Fig. 1 Shear wave velocity (*SWV*) measurements obtained from instrumented boreholes for weathered rock materials in Hong Kong

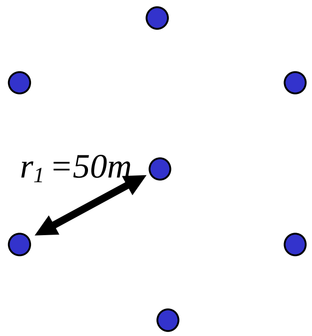


Fig. 2 Example of hexagonal geophone array configurations employed in the microtremor surveys

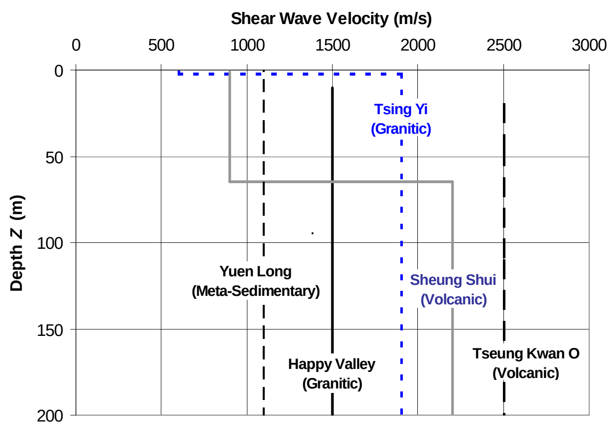
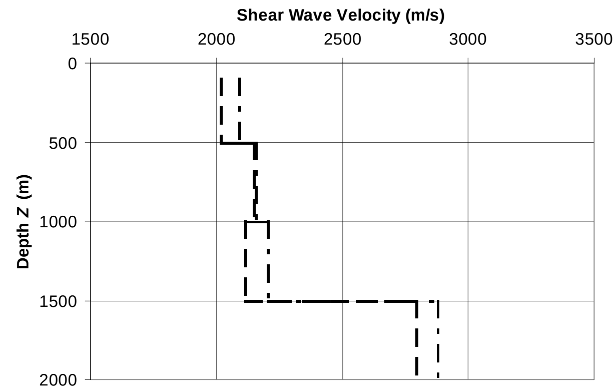


Fig. 3 Crustal shear wave velocity (*SWV*) obtained from SPAC measurements (zero depth represents top of bedrock)

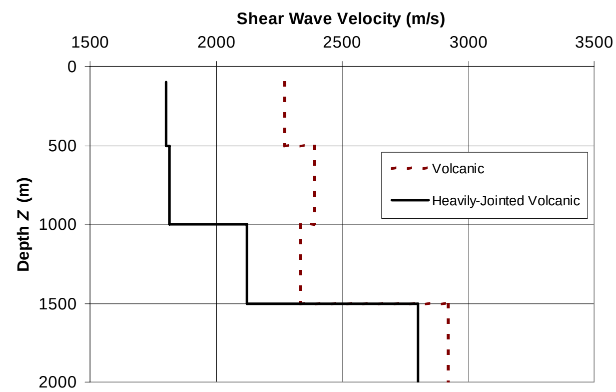
are free from weathering. There is a widespread presence (throughout Hong Kong) of a layer with near-constant *SWV* in the order of 2 km/s. This rock layer is underlain by a much harder basement rock with significantly higher *SWV*, as indicated by the velocity discontinuity at depth of around 1.5 km.

The velocity of each layer has been determined by incorporating information obtained from seismological surveys employing different techniques. In combining results obtained from the two surveying techniques, a weighing factor of 0.2 was assigned to results derived from each of the two array (SPAC) surveys and 0.3 for each of the two blast monitoring surveys.

The modelled *SWV* profiles representing the granitic, volcanic, heavily-jointed volcanic and meta-sedimentary rocks, in the unweathered zone are defined by (5)-(8), respectively.



(a) Granitic formations



(b) Volcanic formations

Fig. 4 Crustal shear wave velocity (*SWV*) obtained from monitoring of quarry blasts [4]

Granitic formation:

$$\begin{aligned} V_s(Z) &= 1900 \text{ m/s} && 120 < Z < 500 \text{ m} \\ V_s(Z) &= 2150 \text{ m/s} && 500 < Z < 1000 \text{ m} \\ V_s(Z) &= 2160 \text{ m/s} && 1000 < Z < 1500 \text{ m} \end{aligned} \quad (5)$$

Volcanic formation:

$$\begin{aligned} V_s(Z) &= 2240 \text{ m/s} && 32 < Z < 500 \text{ m} \\ V_s(Z) &= 2390 \text{ m/s} && 500 < Z < 1000 \text{ m} \\ V_s(Z) &= 2330 \text{ m/s} && 1000 < Z < 1500 \text{ m} \end{aligned} \quad (6)$$

Heavily-jointed volcanic formation:

$$\begin{aligned} V_s(Z) &= 1800 \text{ m/s} && 48 < Z < 500 \text{ m} \\ V_s(Z) &= 1820 \text{ m/s} && 500 < Z < 1000 \text{ m} \\ V_s(Z) &= 2120 \text{ m/s} && 1000 < Z < 1500 \text{ m} \end{aligned} \quad (7)$$

Meta-sedimentary formation:

$$\begin{aligned} V_s(Z) &= 1150 \text{ m/s} && 6 < Z < 30 \text{ m} \\ V_s(Z) &= 1250 \text{ m/s} && 30 < Z < 100 \text{ m} \\ V_s(Z) &= 1350 \text{ m/s} && 100 < Z < 500 \text{ m} \\ V_s(Z) &= 2100 \text{ m/s} && 500 < Z < 1500 \text{ m} \end{aligned} \quad (8)$$

V. *SWV* PROFILING FROM SEISMIC REFRACTION DATA (BEDROCK DEPTH 1500 TO 8000M)

Finally, the regional seismic refraction data, available from CRUST2.0 [5], has been employed to provide estimates for the *SWV* profile at depths exceeding 1 km. The sixteen 2×2 degree (latitude and longitude) tiles surrounding Hong Kong in CRUST2.0 indicate a SWV discontinuity at 1.5 km depth, where the hard crystalline (basement) rock crust interfaces with the overlying granitic/volcanic rock crust, and this is consistent with observations from the monitoring of quarry blasts (Section IV). The CRUST2.0 database also indicates *SWV* of 3.5 km/s at 8 km depth (refer Fig. 5). This *SWV* information can be extrapolated upward through the earth's crust according to a suitable power law, with $n = 1/12$. The n value is changed to 1/6 at 4 km depth to account for the non-linear correlation between *SWV* and *PWV* at shallower depths [1], refer Fig. 5. The model profile representing these basement crystalline rock layers is shown in Fig. 5, and is defined by (9) and (10), respectively.

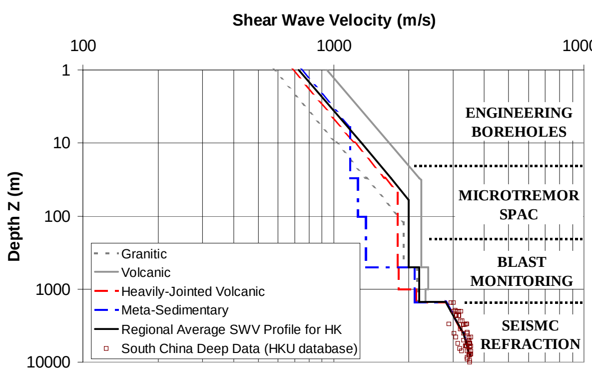


Fig. 5 Crustal shear wave velocity (*SWV*) profile models for Hong Kong

Upper Crystalline Layer:

$$V_s(Z) = 3300\left(\frac{Z}{4000}\right)^{\frac{1}{6}} \qquad 1500\text{m} < Z < 4000\text{m} \tag{9}$$

Lower Crystalline Layer:

$$V_s(Z) = 3500\left(\frac{Z}{8000}\right)^{\frac{1}{12}} \qquad 4000\text{m} < Z \tag{10}$$

VI. LOCAL UPPER CRUSTAL AMPLIFICATION FACTOR $V(f)$

Given the *SWV* models developed in previous sections, the extent of upper-crust amplification may be predicted from (11), using ρ_B and V_B to represent the rock density and *SWV* at the source depth, and ρ_A and V_A for the depth range corresponding to the period of interest.

$$V(V_s, \rho) = \sqrt{\frac{\rho_B V_B}{\rho_A V_A}} \tag{11}$$

To relate the period of interest to the rock depth, the quarter-wavelength approximation method [6] is required. This method allows the values of ρ_A and V_A to be averaged to a depth equivalent to the quarter-wavelength of the upwardly propagating shear wave, for applying (11).

The significant variation of upper-crust amplification factor, $V(f)$, with frequency has been shown in Fig. 6 for the four geological formations commonly found in Hong Kong, and the regional average *SWV* profile (refer Fig. 5). An increase in the value of V with increasing wave frequency is noted in each case. The slope discontinuity occurring at frequency in the order of 0.3-0.4 Hz (except meta-sedimentary) arises due to the velocity discontinuity at the bottom of the constant-velocity layer (depth of 1.5 km) in the rock profiles for Hong Kong (Fig. 5).

VII. LOCAL UPPER CRUSTAL ATTENUATION FACTOR $P(f)$

The upper-crust attenuation factor, $P(f)$, is a local

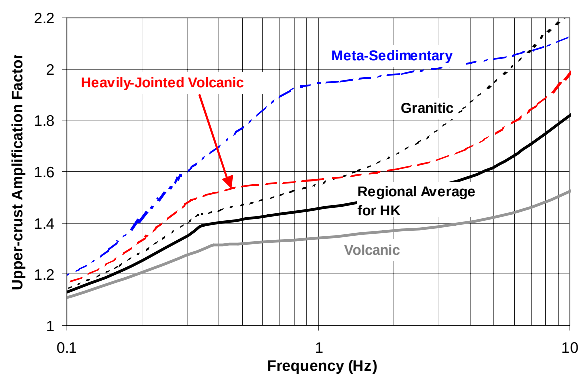


Fig. 6 Variation of the upper-crust amplification factors with frequency for the four geological formations and the regional average for Hong Kong

phenomenon and is represented by a local factor and the mechanism occurs over a short transmission distance. It has been defined in the seismological model by:

$$P(f) = e^{-\pi f \kappa} \tag{12}$$

where the parameter κ (in units of seconds and pronounced "*Kappa*") can be measured from analysis of the Fourier spectrum of seismic waves recorded from the very near-field [7]. An empirical correlation of κ with the average *SWV* of the upper crust V_{uc} (taken as the upper 4 km depth), has been developed by Chandler *et al.* [8] using global information obtained from limited independent studies.

The average *SWV* of the upper-crust V_{uc} was chosen for the purpose of identifying κ (for the respective geological formations prevalent in Hong Kong), in view of the fact that the attenuation mechanism represented by this parameter occurs in the upper 4 km of the earth's crust and hence the inferred κ values account explicitly for local variations in the upper-crust parameters. The values of κ [8] for the granitic, volcanic, heavily-jointed volcanic, meta-sedimentary formations and the regional average are, respectively, 0.032, 0.024, 0.036, 0.040 and 0.030.

The frequency dependent upper-crust attenuation factor $P(f)$ as defined by (12) has been multiplied by the upper-crust amplification factor $V(f)$ derived in Section VI, giving the combined factor as shown in Fig. 7, for the four geological formations commonly found in Hong Kong as well as the regional average.

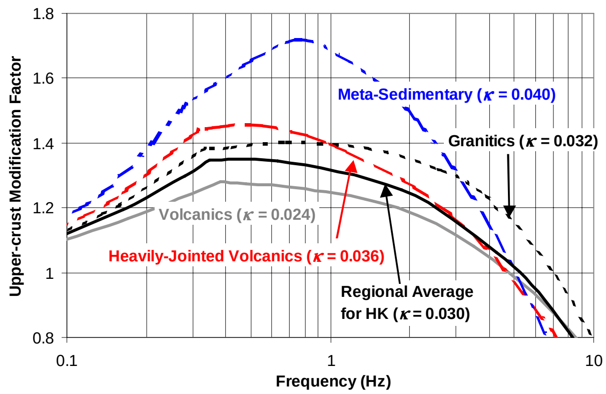


Fig. 7 Variation of the upper-crust modification factors with frequency for the four geological formations and the regional average for Hong Kong

As shown in Fig. 7, some 30 % differences can be resulted in the overall upper-crust modification factors, in particular for the frequency range of engineering interest (0.3 – 2 Hz). It is noteworthy that this significant variation can even be observed in such a small city likes Hong Kong.

Fig. 8 compares the upper-crust modification factor representing conditions in the Hong Kong region with that determined for *Generic Rock* (*GR*) and *Generic Hard Rock* (*GHR*) conditions of California and Central and Eastern North America, respectively [6]. It is shown that seismic waves reaching the rock surface in Hong Kong are characterised by significantly larger lower-frequency components (0.2 – 2.0 Hz) compared with the higher-frequency components (f > 2.0 Hz). Seismic waves with frequency in the order of 0.3 – 1.0 Hz (1 – 3 s period) are subject to the highest net amplification of seismic waves (in the order of 1.35), following emission from the earthquake source. The latter finding, which contrasts with the situation for *GR* (highest net amplification around 1.65, at frequency in the order of 2 Hz or 0.5 s period) is a finding of engineering importance, especially given the prevalence of tall buildings in Hong Kong with natural periods in the order of 2 s or higher. It is further noted that the upper-crust modification factor of Hong Kong for frequency below 0.5 Hz (above 2 s period) is comparable to that of *GR*.

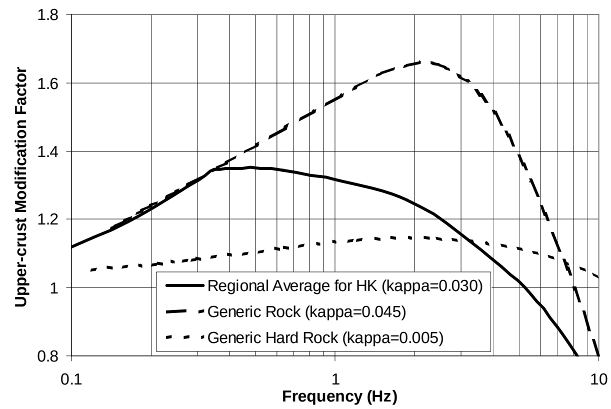


Fig. 8 Comparison of upper-crust modification factor for Hong Kong with those of the *generic rock* (*GR*) and the *generic hard rock* (*GHR*) models of Boore and Joyner (1997) [BJ97]

VIII. Conclusion

1) This paper has demonstrated the use of shear wave velocity (*SWV*) information from a combination of sources to constrain the model *SWV* profiles for four principal geological formations in Hong Kong.
2) The upper crust amplification factor was derived from quarter-wavelength theory based on the developed *SWV* models.
3) The value of κ for the upper crust of the four geological formations and the regional average *SWV* profile for Hong Kong have been determined from an empirical expression obtained in a previous study based on global information. The upper crust attenuation factor has been modelled in accordance with these values of κ.
4) The significant differences in the upper crust modification factor have been highlighted.

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