1. 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) area factors (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 factors (representing properties of seismic waves generated at the source of the earthquake); (ii) geometric attenuation factors (representing the spatial spread of the radiated seismic energy); and (iii) whole path attenuation factors (representing the dissipation of energy along the wave transmission path before the seismic waves reach the “upper crust”, comprising approximately the upper 4 km of the earth’s crust). Local factors 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.

Determination of source and geometric attenuation factors follows relatively well defined procedures, however modelling upper crustal effects requires information on the crustal shear velocity profile (SWV) to depths of several kilometres (where seismic waves are generated). SWV profiles are not readily obtainable at these depths. A modelled SWV profile for the generic "Rock" conditions of California was developed by Boore and Joyner (1997) and has been used in the determination of crustal factors forming part of the seismological model for Californian conditions (Atkinson and Silva, 1997; Atkinson and Boore, 1998). The seismological model so obtained was incorporated into ground motion simulations and response spectrum modelling.

This paper, which describes a comparable 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 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. This study has the unique feature of focusing on the modelling of the intra-regional variations in the SWV profile in bedrock (which affects the attenuation behaviour of seismic waves). An important element in the SWV profiling is the use of passive seismic microtremor measurements using an array of seven geophones in conjunction with the innovative SPatial Auto-Correlation (SPAC) processing technique, which is an inexpensive, and non-intrusive, way of obtaining rock SWV information to rock depths of up to 100-200 m or more.

2. 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 catagorised 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 by inference the resulting SWV profile 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 Eqs. (1a)-(1e):

Granitic formation: $$V_s(Z) = 1350\left(\frac{Z}{30}\right)^{\frac{1}{4}} \qquad Z < 120m \qquad (1a)$$

Volcanic formation: $$V_s(Z) = 2200\left(\frac{Z}{30}\right)^{\frac{1}{4}} \qquad Z < 32m \qquad (1b)$$

Heavily-Jointed Volcanic formation: $$V_s(Z) = 1600\left(\frac{Z}{30}\right)^{\frac{1}{4}} \qquad Z < 48m \qquad (1c)$$

Meta-Sedimentary formation: $$V_s(Z) = 1150\left(\frac{Z}{6}\right)^{\frac{1}{4}} \qquad Z < 6m \qquad (1d)$$

As the thickness of weathered rock in Hong Kong is highly variable (hence site-dependent), the depth ranges proposed in Eqs. (1a)-(1e) have been guided by the measured SWV's of the deeper unweathered rock layers (refer Sections 3 and 4). In other words, the assumed depth value (for a given geological formation) is measured from the intersection between the weathered layer and the underlying unweathered layer (the top of the 'fresh' bedrock).

3. 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. The SPAC technique (Aki, 1957; Okada, 2003; Asten *et al.*, 2002) appears to be extremely well suited to the measurement of SWV profiles in urban areas (Asten, et. al. 2003; Roberts and Asten, 2004; Roberts and Asten 2005; Apostolidis et al. 2004). Its advantages include its non-invasiveness (no drilling required), speed of data acquisition, low cost and the ability to be able to provide shear wave velocity information over a wide range of depths. In October 2004, a series of SPAC surveys were undertaken at five sites (refer Table 1 and Fig.2) in Hong Kong, comprising two over granitic bedrock, two on volcanic bedrock and one on meta-sedimentary bedrock, to develop an average shear wave velocity 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 shear-wave velocity structure of the earth.

The SPAC technique has as its basis, a mathematical formulation first put forward by Aki (1957) which shows that the azimuthally averaged signal coherency measured using an array of geophones is related to the velocity-frequency characteristics of the ground beneath the array. By measuring microtremor signal coherency in the field, it is therefore possible to estimate the shear-wave velocity structure in the subsurface over a wide range of depths.

SPAC microtremor surveys require a relatively flat area, clear of obstructions and dominant sources of microtremor waves. At the five sites identified in Fig. 2, geophone arrays were deployed so as to achieve the maximum possible array size in the available space (in most cases a sporting field of some kind was used). Table 1 lists the location and relevant array sizes for each site. Although hexagonal arrays (refer to Fig. 3) provide best results when microtremors originate from a limited range of directions, a nested triangular array (refer to Fig 3.) was used on one site for logistical reasons in order to maximise the use of the available space. Using these arrays, a series of recordings of vertical ground motion was made at each site for approximately 300 seconds. Processing methodology similar to that outlined by Roberts and Asten (2004) was used to produce a series of SPAC spectra for each site. Forward modelling then allowed a best-fit shear velocity profile to be obtained for each site. The interpreted shear velocity profiles for each of the five sites are shown in Fig. 4.

Larger arrays allow better resolution of shear velocity at depth, however logistical limitations (primarily the open space available for most sites) limited the array radius to 50 m or less. Since bedrock was overlain by tens of metres of soil, the resolution of the bedrock shear velocity was limited to a single representative value for most of the sites. The precision of this estimate is variable, but is typically on the order of 10%. At the Sheung Shui site, where space permitted deployment of a larger array, the resulting spectra allowed better resolution of the bedrock velocities.

4. 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 (Mak, 2005). This study used short-period group velocity (T = 0.4 – 1.3 sec) 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. 5(a) and (b). In this depth range, rock units are primarily igneous and 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 modelled SWV profiles representing the granitic, volcanic, heavily-jointed volcanic and meta-sedimentary rocks, and the representative profile for Hong Kong, in the unweathered zone are defined by Eqs. (2a)-(2d), respectively.

Granitic formation:

$$\begin{aligned} V_s(Z) &= 1900\text{ m/s} && 120 < Z < 500\text{ m} \\ V_s(Z) &= 2150\text{ m/s} && 500 < Z < 1000\text{ m} \\ V_s(Z) &= 2160\text{ m/s} && 1000 < Z < 1500\text{ m} \end{aligned} \tag{2a}$$

Volcanic formation:

$$\begin{aligned} V_s(Z) &= 2240\text{ m/s} && 32 < Z < 500\text{ m} \\ V_s(Z) &= 2390\text{ m/s} && 500 < Z < 1000\text{ m} \\ V_s(Z) &= 2330\text{ m/s} && 1000 < Z < 1500\text{ m} \end{aligned} \tag{2b}$$

Heavily-Jointed Volcanic formation:

$$\begin{aligned} V_s(Z) &= 1800\text{ m/s} && 48 < Z < 500\text{ m} \\ V_s(Z) &= 1820\text{ m/s} && 500 < Z < 1000\text{ m} \\ V_s(Z) &= 2120\text{ m/s} && 1000 < Z < 1500\text{ m} \end{aligned} \tag{2c}$$

Meta-Sedimentary formation:

$$\begin{aligned} V_s(Z) &= 1150\text{ m/s} && 6 < Z < 30\text{ m} \\ V_s(Z) &= 1250\text{ m/s} && 30 < Z < 100\text{ m} \\ V_s(Z) &= 1350\text{ m/s} && 100 < Z < 500\text{ m} \\ V_s(Z) &= 2100\text{ m/s} && 500 < Z < 1500\text{ m} \end{aligned} \tag{2d}$$

The velocity of each layer has been determined by incorporating information obtained from seismological surveys employing different techniques. For example, the SWV profile in the uppermost unweathered zone for granitic rock was estimated in accordance with measurements obtained from both the geophone array surveys (with data subject to SPAC analyses) and the blast monitoring survey (with data subject to dispersion analyses). 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 blast monitoring surveys were assigned heavier weighing factors in view of the more consistent measurements obtained from the individual surveys.

5. SWV PROFILING FROM SEISMIC REFRACTION DATA (BEDROCK DEPTH 1000 to 8000m)

Finally, the regional seismic refraction data available from the internet-based Global Crustal Model (2001), also known as CRUST2.0, 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 4). The CRUST2.0 database also indicates SWV of 3.5 km/sec at 8 km depth (refer Fig. 6). 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, according to recommendations by Chandler *et al.* (2005), refer Fig. 6. The model profile representing these basement crystalline rock layers is shown in Fig. 6, and is defined by Eqs. (3a) and (3b), respectively.

Upper Crystalline Layer:
$$V_s(Z) = 3300\left(\frac{Z}{4000}\right)^{\frac{1}{6}} \qquad 1500m < Z < 4000m \qquad (3a)$$

Lower Crystalline Layer:
$$V_s(Z) = 3500\left(\frac{Z}{8000}\right)^{\frac{1}{12}} \qquad 4000m < Z \qquad (3b)$$

6. CLOSING REMARKS

This paper presents a case study in which the SWV profile of the upper crust was modelled based on information obtained from borehole data, array-based microtremor measurements, monitoring of quarry blasts and crustal-scale seismic refraction measurements. The surveys, each of which provided shear velocity over differing depth ranges, enabled a seismological model for Hong Kong to be developed for stochastic simulations and seismic hazard analysis. Details of the stochastic simulations and the seismological modelling are discussed elsewhere (e.g. Lam *et al.*, 2005).

7. ACKNOWLEDGEMENTS

This paper forms part of the outcome of major strategic research programmes undertaken by the Centre for Earthquake Engineering Research (CEER) at the University of Hong Kong in collaboration with the Centre for Environmental and Geotechnical Applications of Surface waves (CEGAS) at the Monash University and the Earthquake Engineering Research Group at the University of Melbourne. The work described in this paper was substantially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKU 7004/02E). The sensors used in the microtremor observations discussed in this paper were provided by the Australian National Seismic Imaging Resource (ANSIR). Invaluable contributions and support over the years by Professor John Wilson, Professor T Balendra and Gary Gibson in related research are gratefully acknowledged. The authors are also very grateful to invaluable advice provided by Euan Smith, David Dowrick and Peter Davenport from New Zealand over the years.

8. REFERENCES

Aki, K., (1957). Space and time spectra of stationary stochastic waves, with special reference to microtremors. Bulletin of the Earthquake Research Institute 35, 415-456.

Apostolidis, P., Raptakis, D., Roumelioti, Z., and Pitilakis, K., (2004) Determination of S-wave velocity structure using microtremors and SPAC method applied in Thessaloniki (Greece), Soil dynamics and earthquake engineering. Vol. 24: 49-67.

Asten, M., Lam, N.T.K., Gibson, G., Wilson, J.L., (2002) Microtremor survey design optimized for application to site amplification and resonance modelling. Proceedings of Australia Earthquake Engineering Society Conference, Adelaide.

Asten, M.W., Dhu, T., Jones, A., and Jones, T., (2003) Comparison of shear-velocities measured from microtremor array studies and SCPT data acquired for earthquake site hazard classification in the northern suburbs of Perth W.A. Proceedings of a Conference of the Australian Earthquake Engineering Soc., Melbourne, Paper 12.

Atkinson, G.M., Silva, W., (1997) An empirical study of earthquake source spectra for Californian earthquakes. Bulletin of the Seismological Society of America 87, 97-113.

Atkinson, G.M., Boore, D.M., (1998) Evaluation of models for earthquake source spectra in Eastern North America. Bulletin of the Seismological Society of America 88(4), 917-937.

Boore, D.M., Joyner, W.B., (1997) Site amplifications for generic rock sites. Bulletin of the Seismological Society of America 87(2), 327-341.

Chandler, A.M., Lam N.T.K., Tsang H.H., (2005) Shear wave velocity modelling in crustal rock for seismic hazard analysis. Soil Dynamics and Earthquake Engineering 25, 167 – 185.

Global Crustal Model CRUST2.0., (2001) Institute of Geophysics and Planetary Physics, Univ. of California, San Diego. http://mahi.ucsd.edu/Gabi/rem.dir/crust/crust2.html

Lam, N.T.K., Venkatesan, S., Wilson, J.L., Asten, M.W., Roberts, J., Chandler, A.M. Tsang, H.H., (2005) Generic approach for modelling seismic hazard. Invited paper by International Journal for Advances in Structural Engineering (accepted and in-press).

Mak, S., (2005) Seismic analysis for the South China region. MPhil Thesis, Department of Earth Sciences, The University of Hong Kong.

OAP/BD (2005) Buildings Department, Government of the HKSAR, The Seismic Effects on Buildings in Hong Kong, Consultancy Agreement No. CAO K49, conducted by Ove Arup and Partners (HK) Ltd. [Confidential].

Okada, H., (2003) The Microseismic Survey Method: Society of Exploration Geophysicists of Japan. Translated by Koya Suto, Geophysical Monograph Series No. 12, Society of Exploration Geophysicists, Tulsa.

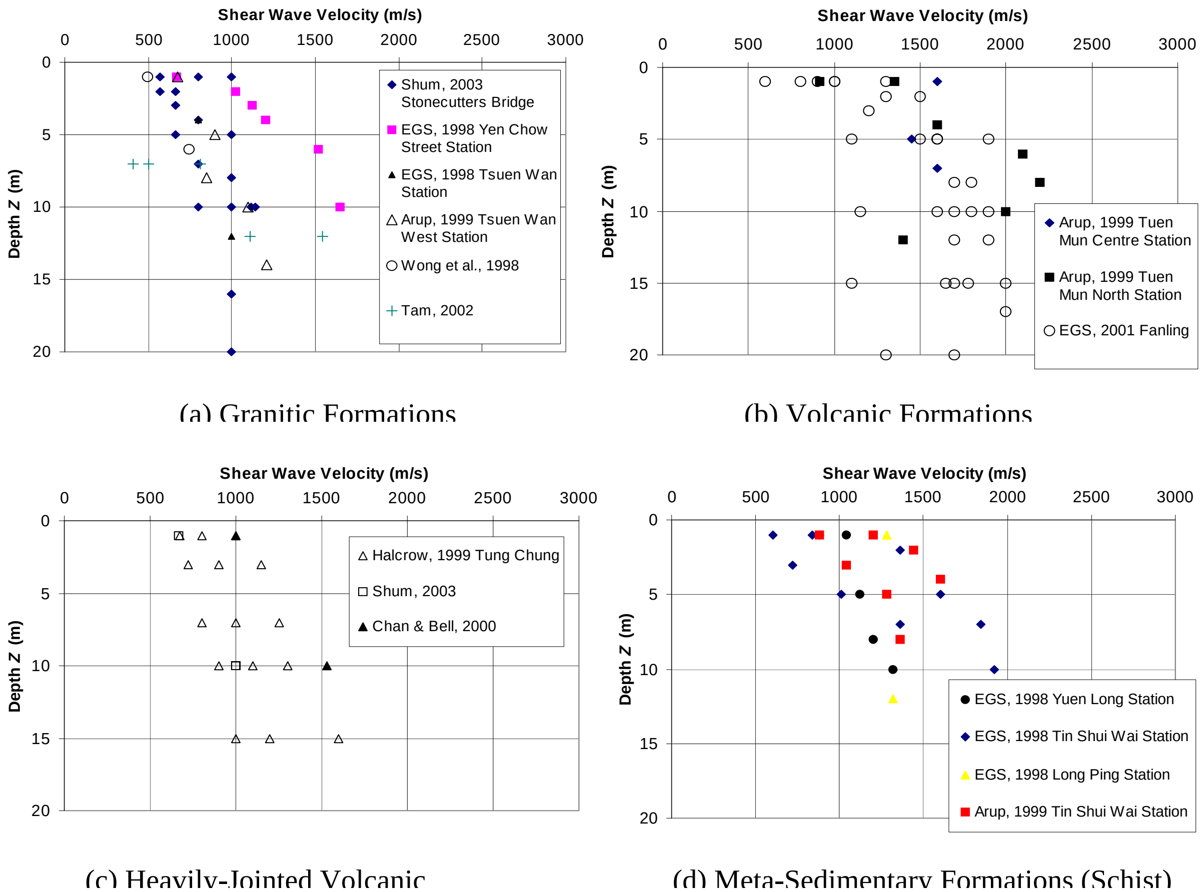
Roberts, J. and Asten, M., (2004) Resolving a velocity inversion at the geotechnical scale using the microtremor (passive seismic) survey method. Exploration Geophysics 35 (1), 14-18.

Roberts, J. and Asten, M., (2005) Estimating the shear velocity of profile of Quaternary silts using microtremor array (SPAC) measurements. Exploration Geophysics 36 (1), 34-40.

Table 1 Details of SPAC surveys conducted in Hong Kong

Site No. (refer Fig. A1)	Site Location	Site Name	Array Configuration * (Radius, m)	Rock Description
1	Hong Kong Island	Happy Valley Sports Ground	50m / 22m hexagonal	Granitic
2	New Territories	Tsing Yi Sports Ground	41m / 18m hexagonal	Granitic
3	New Territories	Fung Kai No.1 Secondary School	50m / 20m hexagonal 95m / 30m triangular	Volcanic
4	New Territories	Tseung Kwan O	48m / 25m hexagonal	Volcanic
5	New Territories	Yuen Long Stadium	40m / 18m hexagonal	Meta-Sedimentary

* Examples of array configurations are shown in Fig. 3.



(a) Granitic Formations

(b) Volcanic Formations

(c) Heavily-Jointed Volcanic

(d) Meta-Sedimentary Formations (Schist)

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

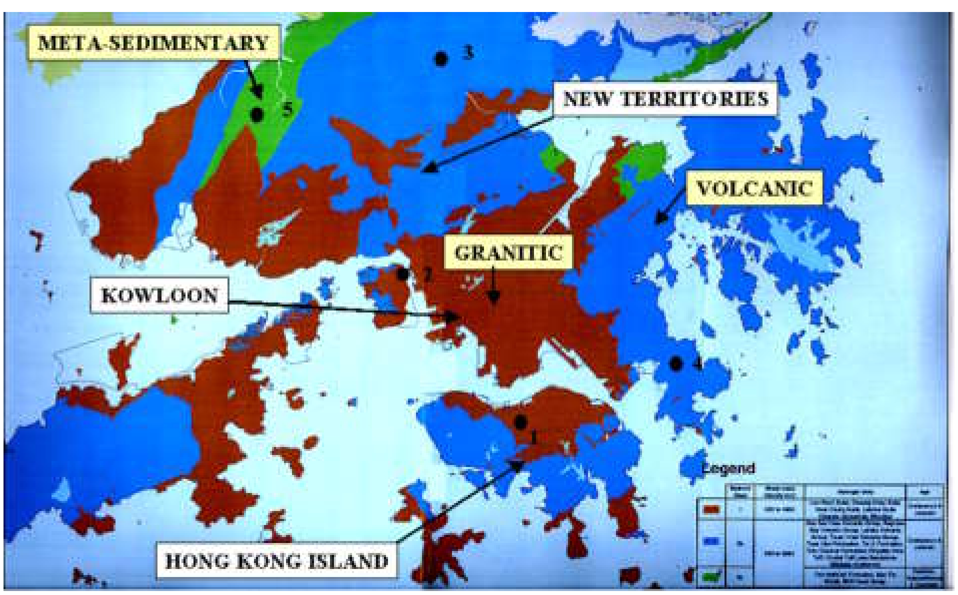
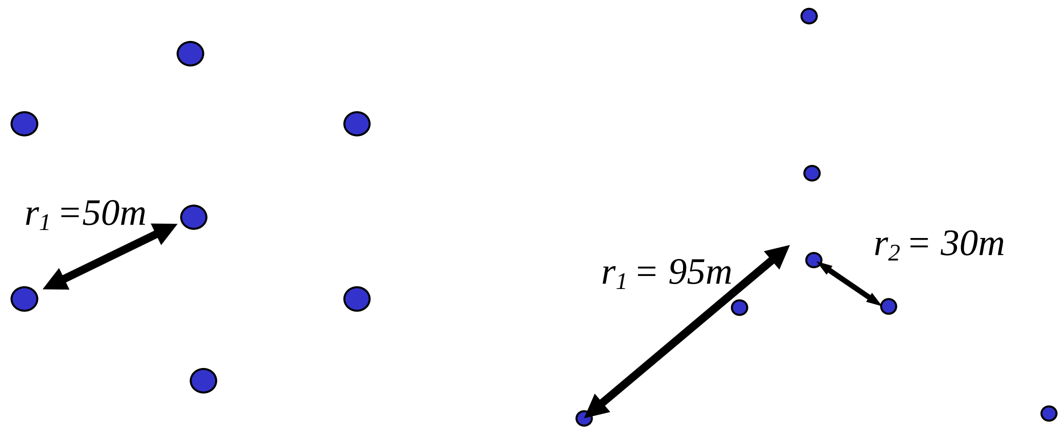


Fig.2. Simplified geological map of Hong Kong and locations of SPAC surveys. (OAP/BD, 2005)



(a) Hexagonal array with radius = 50 m (b) Triangular array with outer radius = 95 m

Fig. 3. Examples of geophone array configurations employed in Hong Kong microtremor surveys.

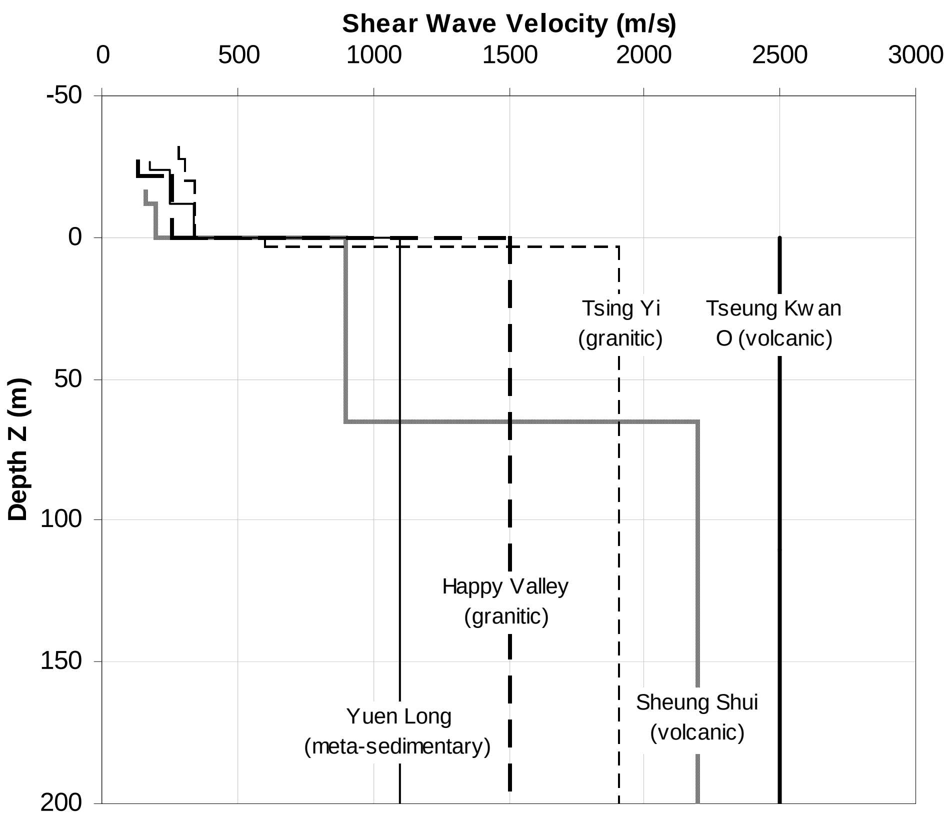
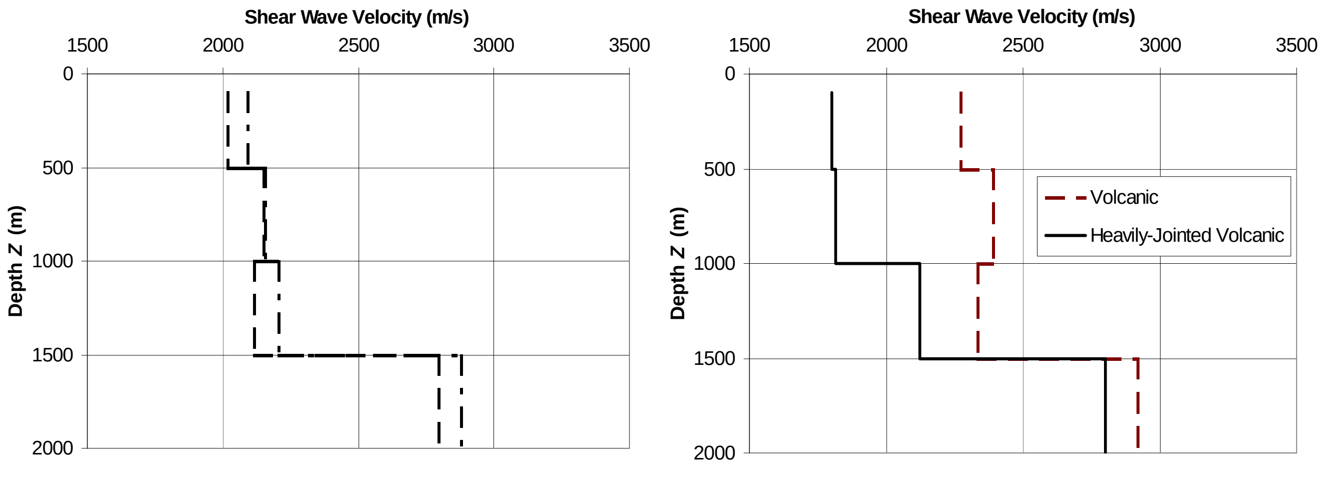


Fig. 4. Crustal shear wave velocity (SWV) obtained from SPAC measurements (zero depth represents top of bedrock).



(a) Granitic Formations

(b) Volcanic Formations

Fig. 5. Crustal shear wave velocity (SWV) obtained from monitoring of quarry blasts (Mak, 2005).

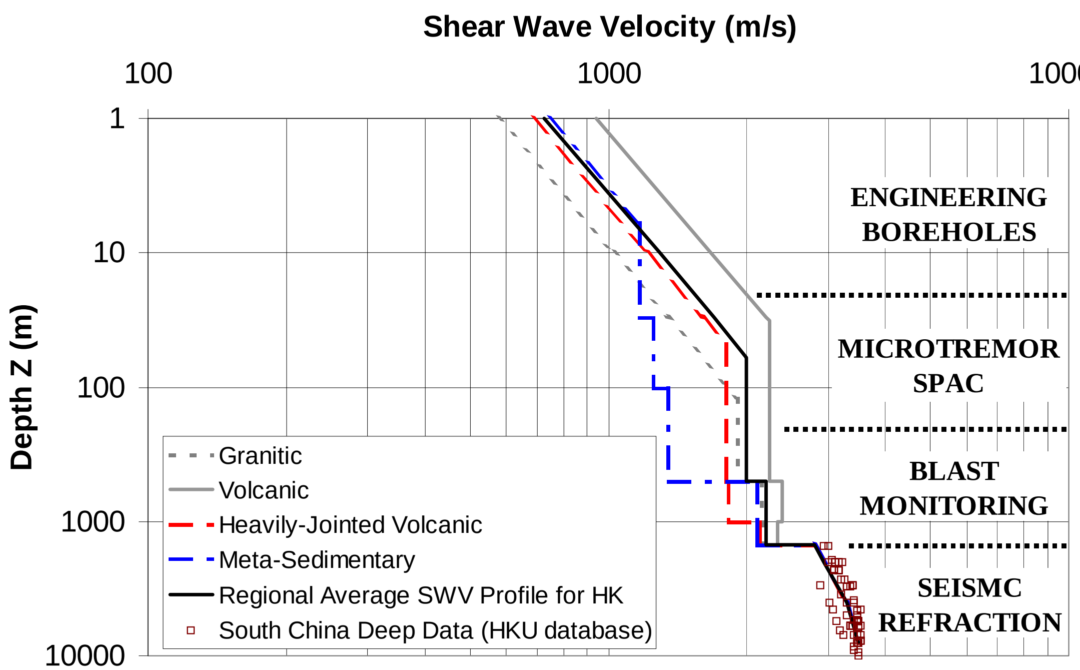


Fig. 6. Crustal shear wave velocity (SWV) profile models for Hong Kong.