Evaluating the effectiveness of the MASW technique in a geologically complex terrain

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Abstract. MASW surveys carried at a number of sites in Pulau Pinang, Malaysia, showed complicated dispersion curves which consequently made the inversion into soil shear velocity model ambiguous. This research work details effort to define the source of these complicated dispersion curves. As a starting point, the complexity of the phase velocity spectrum is assumed to be due to either the surveying parameters or the elastic properties of the soil structures. For the former, the surveying was carried out using different parameters. The complexities were persistent for the different surveying parameters, an indication that the elastic properties of the soil structure could be the reason. In order to exploit this assumption, a synthetic modelling approach was adopted using information from borehole, literature and geologically plausible models. Results suggest that the presence of irregular variation in the stiffness of the soil layers, high stiffness contrast and relatively shallow bedrock, results in a quite complex f-v spectrum, especially at frequencies lower than 20Hz, making it difficult to accurately extract the dispersion curve below this frequency. As such, for MASW technique, especially in complex geological situations as demonstrated, great care should be taken during the data processing and inversion to obtain a model that accurately depicts the subsurface.

1. Introduction

Over the years, the multichannel analysis of surface waves technique has been utilized for various environmental and engineering applications [1,2,3,4,5,6]. However, the success of this technique lies in accurately determining the dispersion curve from the field data [6]. A common approach is to transform the field data from the time–space domain (t-x) into the frequency-velocity domain (f-v) using phase-shift transform [7], as it provides a convenient and effective means by which the dispersion trend can be imaged [8,9]. However, the phenomenon of mode misidentification, modal superposition and influence of higher modes can result in complicated dispersion curve trend on the resulting f-v spectrum, making the inversion into soil shear wave velocity model inaccurate.

In this paper, we evaluate the complexity of the f-v spectrum obtained from MASW measurements conducted at various sites in Pulau, Pinang. As a starting point, the complexity of the phase velocity spectrum is assumed to be due to either the surveying parameters or the elastic properties of the soil structures. To test the effect of the surveying parameters, surveys were carried out using different acquisition parameters. The complexities were persistent for all of the surveying parameters used which indicates that the later assumption (i.e. soil structure complexity) could be the reason. In order to exploit this assumption, a synthetic modelling approach was adopted using information from
borehole data, literature and geologically plausible models. The limitations/challenges posed by the geology is evaluated and the potential pitfall associated with inaccurate estimation is presented.

2. Site Description
The survey sites are located in the south eastern part of the Penang Island (Pulau Pinang) (figure 1a) and are all on the main campus of the Universiti Sains Malaysia (USM). The study area is composed of granite, specifically, the South Pinang Pluton - a classification based on the proportion of the alkali feldspar in granite. A further subdivision of the pluton puts the study area under the Batu Maung Granite (figure 1b). Overlying the rocks are Pleistocene deposits, which consists of sand, gravel, clay, silt and peat [10]. These are the residual soils formed mostly from the weathering of the parent granitic rock. The thickness of the residual soils in Pulau Pinang ranges from about 2.41 to 40 m, with a variation of shear parameters with depth [11]. The digital elevation model for the study area shows that site 6 is at a higher elevation compared to the other sites. A borehole log from USM, main campus gives the lithology as follows: silt, clay, sand, silt and sand, to a depth of about 28 m [12]. This sequence corresponds to that of the Pleistocene deposits for Pulau Pinang [10].

Figure 1. (a) Geological map and Digital elevation model of the study area, showing the MASW sites [10] (b) Map of Penang Island (www.asiaexplorers.com).

3. Methodology
The MASW utilizes the dispersive nature of Rayleigh waves generated by the interaction of P- and S-waves at the surface of the earth. The measured Rayleigh waves motions depend on the properties of the medium, the frequency of the waves, and the distance from source location to the ground motion detector [13]. The measured Rayleigh wave can be from using active sources, such as a sledge hammer, weight or vibroseis; or from the measurement of ambient sources (passive MASW). Recording parameters are set to optimize the signal received and a 24-channel seismograph is usually employed. The obtained seismogram is then transformed to the frequency - phase velocity (f-v) spectra using algorithms such as the phase-shift method [7]. The dispersion curve as observed on the f-v spectrum is extracted and forms the basis for the inversion to estimate the shear wave velocity profile. In most applications, the fundamental mode is utilized for the inversion process, but several authors have reported that the inclusion of higher modes during the inversion process stabilizes the
inversion, improves the accuracy of the determined Vs profile and also the higher modes are more sensitive to Vs variation at greater depths [14,15,3,16,17].

3.1 Data Acquisition and Processing
Data were acquired at six different locations in Penang Island (figure 1). A 24-Channel ABEM terraloc Mark8 Seismograph recorded and vertically stacked impacts of a 12-lb hammer on a 1ft² plate at each shot station. Although it is ideal that a 4.5Hz geophone is used for MASW investigation, previous works have shown that even with the use geophones with higher natural frequency, it is possible to obtain a resolution lower than the natural frequency of the geophones [18]. As such, our measurements were done using both 28Hz and 4.5Hz vertical geophones. Different geometry and acquisition parameters were tested at each location, the resulting f-v spectrum was assessed and that which produced the best - resolved dispersion curve for each site location was selected. The parameters for the data analysed are as presented in Table 1.

The processing of the data was done using the SurfSeis 4.0 software developed at the Kansas Geological Survey. The processing steps employed for our data set are as outlined in figure 2. The SurfSeis 4.0 software generates an overtone image (frequency-phase velocity spectrum) using the phase-shift method [7]. The steps involved in the phase-shift method includes: Fourier transformation and amplitude normalization, dispersion imaging and extraction of dispersion curve [19]. The frequency - phase velocity spectrum (f-v spectrum) was obtained for each shot, from the different locations, using the normal/accurate algorithm.

| Site | Type of Receiver | Receiver Spacing (m) | Source Offset (m) | Sampling Interval (µs) |
|------|------------------|----------------------|------------------|------------------------|
| 1    | 4.5Hz            | 1                    | 1                | 2000                   |
| 2    | 4.5Hz            | 2                    | 2                | 1000                   |
| 3    | 4.5Hz            | 1                    | 5                | 1000                   |
| 4    | 28Hz             | 1                    | 5                | 1000                   |
| 5    | 28Hz             | 2                    | 5                | 1000                   |
| 6    | 28Hz             | 2                    | 5                | 1000                   |

3.2 Synthetic Modelling
Synthetic seismograms can be used to analyse the effects of survey parameters as well as earth models on seismic wave propagation. Different techniques are available for the generation of synthetic seismograms ranging from reflectivity method, full wave theory, finite difference etc. [20]. To generate the synthetics for this study, the Computer Programs in Seismology developed by R. B.
Hermann was utilized [21]. The modal summation method was used to generate the synthetics for each earth model, after which the data was then transformed to the f-v spectrum for using the SurfSeis software.

The generation of the synthetic seismograms was carried out to ascertain possible cause(s) of the complicated dispersion curve pattern on the f-v spectrum. Since the f-v spectrum forms the basis for the extraction of the dispersion curve, it is expected that similar earth models should result in a similar spectrum, from which the dispersion curve can be extracted. As such, we generated synthetic seismograms using earth model from borehole data for USM main campus [12], relatively thick unconsolidated sediments overlying the bedrock and a shallow bedrock, giving rise to model 1, 2 and 3 respectively (Table 2). The Vp, Vs and density values were estimated based on literature [22, 23]. A vertical point source was simulated, which was convolved with a Ricker wavelet -25Hz, with attenuation introduced to take into consideration real earth scenario. Uniform quality factors (Qp = 200 and Qs = 100) were used for all layers and a source at zero depth for all models. Subsequently, the generated synthetics were processed using the Surfseis software.

As part of the synthetic data analysis, theoretical dispersion curves were also calculated using the gpdc program of the open source software Geopsy. The computed curves were then compared with the dispersion curve trend as obtained from the synthetic seismograms.

| Table 2. Earth model parameters used for synthetic modelling. |
|---------------------------------------------------------------|
| Layer | Vp(m/s) | Vs(m/s) | ρ(g/m³) | h(m) | Lithology         |
|-------|---------|---------|---------|------|-------------------|
| Model 1 |         |         |         |      |                   |
| 1     | 560     | 220     | 1.60    | 7    | Stiff Silt        |
| 2     | 600     | 280     | 1.75    | 10   | Hard Silt         |
| 3     | 500     | 200     | 1.90    | 13   | Stiff Clay        |
| 4     | 1000    | 350     | 1.95    | 19   | Medium Dense Sand |
| 5     | 914     | 320     | 2.0     | 28   | Hard Silt         |
| 6     | 1200    | 370     | 2.07    | ∞    | Dense Sand        |
| Model 2 |         |         |         |      |                   |
| 1     | 600     | 290     | 1.75    | 10   | Residual Soil     |
| 2     | 4700    | 3210    | 2.6     | ∞    | Granite           |
| Model 3 |         |         |         |      |                   |
| 1     | 600     | 290     | 1.75    | 2    | Residual Soil     |
| 2     | 4700    | 3210    | 2.6     | ∞    | Granite           |

4. Results
Figure 3 shows the f-v spectrum for sites 1, 2 and 3. It can be observed that the dispersion curve trend is not continuous for all three sites, and the general trend of the curve indicates a complex interplay of modal curves. Modal jumps are also observed in all of the spectra at different frequencies (the circles). For all three sites, the modal jumps occur at frequencies between 18 Hz to 30 Hz. Any extraction of either the fundamental curve or higher modes can lead to erroneous results as the modal curves observed seems to be a superposition of dispersion curves.
The resulting spectrum for the other locations (sites 4, 5 and 6) is presented in figure 4. The resolvable frequency is about 12Hz for sites 4 and 5, although the spectrum has been computed to 4Hz. Site 4 shows complex modal characteristics at frequencies less than the resolvable frequency (12Hz), with a relatively uniform dispersion curve above 12 Hz, an indication of a relatively uniform lithology. For site 5, the modal jump is observed at above 30Hz, unlike that for the spectra shown in figure 3. The resulting f-v spectrum for site 6 shows quite complicated spectrum with no possibly identifiable dispersion curve. Field observation indicates that the bedrock appears shallower at this location, with the presence of a granitic outcrop nearby. This is corroborated by the Digital elevation model (figure 2), which indicates a higher elevation.

The synthetic shot gather and the resulting f-v spectrum for model 1 is shown in Figure 5. The fundamental mode is seen to be dominant over the entire frequency range of the spectrum. The spectrum resembles that obtained for the sites 4 and 5 (figure 4a and 4b) respectively. Distortion is observed on the dispersion curve trend at frequencies less than about 12 Hz is (Figure 4a), where the trend of the curve as seen on the f-v spectrum does not follow the theoretical fundamental dispersion curve (black line). We can thus infer a possible similar lithology between this model and that for sites
4 and 5. For model 2 (figure 6), the f-v spectrum predicts dominance of the first higher mode between 10 Hz and 15Hz, after which the fundamental mode becomes dominant. The dominance of the higher mode at these frequencies, with a total disappearance of the fundamental model can be likened to the spectra of sites location 1, 2 and 3, which might be as a result of a layer with high stiffness contrast. For the shallow bedrock model, the f-v spectrum (figure 7), shows similarity with that obtained for site 6, with no easily identifiable dispersion curve on the spectrum at frequency lower that 45Hz. The calculated dispersion curve for this model does not follow the observable trend on the f-v spectrum, as the maximum frequency calculated by the gpdc program is 20Hz.

Figure 5. (a) Synthetic Seismogram of the earth model 1 in Table 1. (b) f-v spectrum for the synthetics, with the black representing the fundamental mode, yellow the first higher mode and the grey the third higher mode.

Figure 6. (a) Synthetic Seismogram of the earth model 1 in Table 1. (b) f-v spectrum for the synthetics, with the black representing the fundamental mode and the yellow line the first higher mode.

From our results, we can infer that the dispersion curves as observed on the f-v spectra for our study area, show similar patterns with the assumed models for the synthetics. And as such, the complexities observed might be as a result of the characteristics of the assumed model. For sites 4 and 5, in which the f-v spectra show complex interplay of the different modal curves at the low frequency end of the spectrum the cause is probably due to the irregular variation in stiffness at depths. While for sites 1, 2 and 3, which exhibited a disappearance of the modal curves at between 18 Hz to 30 Hz, with the higher modes having more energy at those frequencies (figure 3), a possible cause might be as a result of the presence of a stiff bottom layer or great stiffness contrast, as observed in model 2. Although, further investigation of this phenomenon needs to be done. For site 6, the inability to identify any possible dispersion curve trend might be as a result of the presence of a shallow bedrock. Also, from
the synthetics, we can observe that below about 15Hz, there seems to be a deviation between the theoretical dispersion curve calculated and the dispersion trend as observed on the f-v spectra of the synthetics (figures 5 and 6).

Figure 7. (a) Synthetic Seismogram of the earth model 1 in Table 1. (b) f-v spectrum for the synthetics, with the black representing the fundamental mode.

But at frequencies greater than about 15Hz, the observed dispersion curve seems quite continuous and the fundamental mode seems to be dominant. As such, assuming an average velocity of 250 m/s at 15Hz, the wavelength of propagation would be approximately 16.7 m. Using the depth to wavelength approximation \( (\lambda/2) \) [24], the resolvable depth of penetration will thus be about 8 m. As a further test, an inversion of the dispersion curve as extracted from f-v spectrum for model 1 was carried out, using the Surfseis 4.0 software. The parameters used to compute the synthetic seismogram was also used as the initial model parameters for inversion. The Vs model obtained from the extracted dispersion curve shows a good fit to a depth of about 10 m, after which there is a marked deviation between the obtained Vs model from the inversion and that of the model, for each of the layers, especially for the low velocity layers (figure 8).

Figure 8. Vs model with depth for model 1.
5. Conclusion
Complexities in the f-v spectrum observed from the processing of the active MASW data resulted in difficulty in accurately extracting the dispersion curve, consequently making the inversion into soil shear wave velocity model ambiguous. In order to determine the possible source of these complexities, synthetic seismograms were generated based on models from borehole data from the study area and possible geological scenarios. Results suggest that the presence of irregular variation in the stiffness of the soil layers, high stiffness contrast and relatively shallow bedrock, results in a complex f-v spectrum, especially at frequencies lower than 15Hz, making it difficult to accurately extract the dispersion curve. The implication of which is that it might be difficult to accurately define the lithology at depths lower than about 10 m. Hence, for MASW interpretation, especially in complex geological situations such as irregular variation in stiffness, high stiffness contrast between the unconsolidated sediments and the bedrock, as well as for shallow basement great care should be taken during the data processing and inversion. As much as possible higher modes dispersion curves, if properly identified, can be included in the inversion process to improve the resolution and stabilize the model [17, 25]. In addition, an integration of other geophysical techniques can be employed to constrain the obtained model [26]. This is to forestall misinterpretation of the result, which might lead to an inaccurate characterization of the subsurface under investigation.

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