Higher Modes and Superposed Mode Behavior for Flexible Pavement Layer System

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Abstract. This paper presents the study of modes behavior in pavement layer system using Common Array Profiling Spectral Analysis of Surface Waves (CAP-SASW) testing method. Method for evaluation and testing the materials at pavement sites are traditionally destructive. The utilization of non-destructive method such as CAP-SASW is a very useful advantage, however deeper study on its mode behavior for pavement layer is not proven. Comparing both theoretical and experimental generated modes, this paper aims to provide precise configuration measurement in sampling pavement materials besides understanding its modes behavior.

1. Introduction
Roads and highways are crucial part of today’s infrastructure and economy. Flexible pavement is widely used in all hierarchy of roads and streets. Therefore, maintenance of the road network is a significant consideration in highway and transportation engineering researches [1]. Due to the budget constraint and with the purpose of minimizing the effects on traffic, a complete renovation or major restoration of the roads would not be practical [2]. Pavement assessment conventionally uses destructive methods such as coring and CBR. But a good non-destructive method would be such a useful advantage, as it is proved that suitable pavement rehabilitation design is feasible to be developed to provide a practical solution to overhaul and maintain a nation’s road network [2].

In surface wave propagation, general mode and higher modes are the unique characteristics in multilayered system. When the surface waves travelled through this multilayered system, the stiffness of each layer will affect the surface wave propagation [3, 4]. The difference in layer stiffness could refrain the stress waves in some layers, or causes some refractions and reflections, which leads to different ray paths, and finally producing different propagation velocities even at the same frequency point. To identify the velocities of these general mode and higher modes, transfer matrix method [5, 6] and dynamic stiffness matrix method [7] could be used.

The superposed mode in surface wave propagation is also an essential characteristic, because this mode is the actual mode that is generated during the measurement. The superposed mode is suitable for 3-dimensional wave propagation, which is in cylindrical pattern. This propagation is always observed
when the location of the impact source is near to the receiver location, and when the wave still possesses the cylindrical shape. Superposed mode does not fall into any modes in specific, but is superposed in between normal modes. Normal modes consisted of general mode and higher modes. The superposed mode is also called apparent velocity or effective velocity. The apparent phase velocities that are calculated or measured will be depending on the actual location of impact source and the receivers [8, 9]. In the measurement of surface wave, there are two approaches to the usage of these surface waves modes. This paper (CAPSASW method) uses the superposed mode, due to the fact that for impact source which is located near to the receivers’ location, the modes separation for the waves measured are not practical. The other approach used by other techniques such as MASW and f-k method is utilizing the general mode and higher modes, because in that approach, the location of impact source is far from the receivers, and this allows better modes separation for the waves measured. However, the later approach also needs larger number of receivers to help with the mode separation [8, 9].

2. Methodology
Spectral Analysis of Surface Waves (SASW) utilizes mechanical surface wave, called Rayleigh wave to evaluate subsurface material of a medium. The surface wave penetrates the media from the surface until the depth of at least one wavelength. This means, we are able to evaluate media with different depth by utilizing different wavelength. One blow from the impact source could produce combination of Rayleigh surface waves which represented a large range of frequency. With the aid of recording device i.e dynamic signal analyzer and high-powered computer, all information in that frequency range could be recorded for particular time.

Typical configuration of Common Array Profiling- Spectral Analysis of Surface Waves (CAP-SASW) at site is to use two number of receivers in an array and an impact source (seismic source) is acted at the end of the array, as shown in figure 1. The same receiver distance is used throughout the measurement. Adequate wavelength range is needed to sample materials in a pavement layered system.

![Figure 1](image)

Figure 1. (a) Hardware configuration for field measurement of CAP-SASW test and (b) CAP-SASW measurement configuration.

3. Result and Discussion
The objective of this paper is to study the wave propagation behavior for pavement layer system. The pavement layer system has irregular dispersive profile, in which the top layer is stiffer-has higher shear wave velocity- compared to the underlying layer. This shows that the velocity of each layer is decreasing with the depth. This feature is opposed to the dispersion profiles of other geological site such as the normally dispersive site or the shallow bedrock site. A site with sandwiched layered system has the nearest uniqueness to pavement layered system. However, for this research of modes behavior in the pavement layered system, one specific profile as shown in table 1, which is similar to the actual pavement layered system as used by Malaysia’s Public Work Department Guideline 2013 [10] on local road has been used. The material characteristics for pavement layered systems allows the presence of inverse velocity.

This research is divided into two studies, which are 1) using receiver distance, \( D = 0.15 \) m, and 2) using receiver distance, \( D = 0.30 \) m. Other than that variable, the frequency range for pavement layer system is found to be relatively higher than the geological sites, thus for both receiver distance, this
research kept the frequency range at 10 kHz. The sample interval taken is 0.0001 s, which gave Nyquist frequency of 5000 Hz, adequately used for profiling the subsurface material as studied in this paper. To get reasonably good resolution, record length of 2048 samples is chosen, with time history record of 0.2047 s. The time signal record is shown in figure 2(a) and figure 2(b).

### Table 1. Pavement Layer System.

| Layer | Depth (m) | Shear Wave Velocity, Vs (m/s) | Poisson’s Ratio, $\nu$ | Damping Ratio, D (%) | Density, $\rho$ (kg/m$^3$) |
|-------|-----------|------------------------------|-----------------------|---------------------|---------------------------|
| 1     | 0.10      | 1200                         | 0.350                 | 0.02                | 2300                      |
| 2     | 0.50      | 300                          | 0.400                 | 0.02                | 2100                      |
| 3     | 0.25      | 180                          | 0.400                 | 0.02                | 2100                      |
| Half-space | $\infty$ | 160                          | 0.333                 | 0.02                | 1900                      |

Figure 2. Synthetic seismograms of pavement layer system in time domain, generated theoretically with source distance, $S_1 = 0.30$ m, $S_2 = 0.60$ m, $S_4 = 1.2$ m and $S_8 = 2.4$ m: 
(a) full signal and (b) expanded signal.

Figure 3 shows phase spectrum plot for theoretical simulation of CAP-SASW, for pavement layer system, for receiver distance, $D = 0.15$ m while figure 4 shows the same plot when receiver distance, $D$ is set to 0.30 m. Early evaluation shows that there is a discrepancy in number of jump at frequency range of 9 kHz – 11 kHz for phase spectrum with $D = 0.15$ m. In this case, it is assumed that the real phase cycle is only up until 9000 Hz. Furthermore, if compared with figure 4, figure 3 is found to be incomplete as one full cycle. One complete cycle starts with value 0° at the phase angle and ended when the cycle goes back to 0°. The initial description for this figure is the measurement configuration for receiver distance, $D = 0.15$ m might not be adequate to sample the whole layered system as needed. This initial description, however, does not always represent the final outcome, which is the dispersion curve. Therefore, to prove the initial observation, further study is continued to get dispersion curve as needed.

Utilizing CAP-SASW method, apparent phase velocity dispersion curve has been obtained. The phase velocity dispersion curve is essential because it is used in the inversion process to obtain stiffness profile of the subsurface material. The theoretical phase velocities use forward modelling process [7]. Therefore, it is significant for each profile model studied to give correct information of material for each layer in the system. In the calculation of the theoretical dispersion curve, the array inversion process uses all information regarding the actual location of impact source and receivers during CAP-SASW measurement. On the other hand, the global inversion process does not take into account the actual location of impact source and receivers.

Figure 5 shows the behavior of modes obtained from the CAP-SASW calculation, and normal modes for the same profile, for two receiver distances; i.e 0.15 m and 0.30 m. For theoretical superposed mode, it is calculated using global inversion process. Hence, if the superposed modes are plotted together for all source distance $S_1$ until $S_8$, it can be seen that the dispersion for each source distance is similar. The experimental superposed modes obtained in this figure though, are not the ones obtained from field
measurement, but rather theoretical superposed modes, which takes into account the actual location of impact source and receivers, hence represents the actual location on the field. In other words, experimental superposed modes in this context are the theoretical superposed modes calculated using array inversion process.

**Figure 3.** Phase spectrum for theoretical simulation CAP-SASW for pavement layer system, for receiver distance, $D = 0.15$ m for frequency range of: (a) 15 kHz and (b) focused to the first 5 kHz.

**Figure 4.** Phase spectrum for theoretical simulation CAP-SASW for pavement layer system, for receiver distance, $D = 0.30$ m for frequency range of: (a) 15 kHz and (b) focused to the first 5 kHz.

**Figure 5.** Normal modes of Rayleigh wave and superposed modes from CAP-SASW calculation for pavement layer system with receiver distance of 0.15 m and 0.30 m.

Based on both plots of shear wave velocity, some observations could be made. Firstly, the media profile of pavement layered system has inverse velocity (velocity is decreasing with depth) and totally opposite to the normally dispersive media. Seismic measurement testing on irregular dispersive...
materials needs scrutinized attention so that the final outcome obtained later won’t be misleading and contradictory.

Secondly, the apparent velocity for pavement layer system profile does not follow the governing (general) mode. As similar as the sandwiched case, the apparent velocity involved superposition of general mode and higher modes. At frequency range lower than 200 Hz (or wavelength longer than 2m), the apparent velocities obtained from superposed mode follows the trend of the general mode. However, from the frequency of 200 Hz, the velocity steadily increases until frequency of 2000 Hz (wavelength around 0.35m). For all of the plots, the apparent velocity in theoretical superposed mode has steeper graph gradient as compared to the experimental superposed mode. Again, this happened due to the inversion process which is done to obtain the theoretical superposed mode is not taking into account the actual location of impact source and receivers into its calculations.

Thirdly, as the array inversion process is used to obtained the experimental superposed mode, therefore information regarding the location of impact source and receivers are crucial during the measurement. In both of the graphs, it is observed that for the smaller receiver distance, D = 0.15 m, the experimental superposed modes obtained from all source distance (S1-S8) are more scattered as compare to the receiver distance, D = 0.30 m. This shows that for smaller receiver distance, the modes obtained are less precise, although they are all accurate. The outcomes also conclude that the smaller receiver distance is not suitable or adequate enough to be used to sample or characterized subsurface material of pavement layer system with the required depth and thickness.

4. Conclusion
The usage of superposed modes is significant for CAP-SASW measurement of flexible pavement layered system as it alleviates the chances of misleading result of normal and higher modes on complex site such as pavement site. Receiver distance of 0.30 m is proven useful for better characterizations of subsurface materials on pavement layered system.

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