CHARACTERIZING THE STIFFNESS OF A SHALLOW BEDROCK SITE USING THE MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW) METHOD WITH RAYLEIGH AND LOVE WAVES

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Abstract

The Multichannel Analysis of Surface Waves (MASW) method continues to increase in popularity as a tool to characterize subsurface stiffness for geotechnical engineering purposes, particularly in cases where seismic site characterization is important. MASW is commonly performed using vertical impacts on the ground surface to generate Rayleigh waves (i.e., MAS_RW). The dispersive behavior of the Rayleigh wave is then imaged by transforming the raw waveforms from the time-space domain into the frequency-phase velocity domain. A characteristic dispersion curve for the site is selected based on examining the pattern of energy accumulation in the dispersion image. An inversion algorithm is then implemented to locate the most probable subsurface stiffness profile that caused the measured dispersion curve. While much research has been devoted to MAS_RW, horizontally-polarized Love waves have seen limited use in MASW investigations (MAS_LW), despite evidence to support some advantages in their implementation. In this study, MASW was performed using both Rayleigh and Love waves to characterize conditions at the same shallow bedrock site. To allow for a direct comparison between the results of Rayleigh waves and Love waves, the survey lines for both MASW tests were located in exactly the same position. Generally, the subsurface stiffness profiles resulting from inversion of the MAS_RW and MAS_LW dispersion curves agreed reasonably well. However, there were some subtle differences in interpretation of the dispersion images. This paper summarizes field conditions and testing configuration, followed by a discussion of data analysis and interpretation.

Introduction

The Multichannel Analysis of Surface Waves (MASW) method has been receiving growing attention in geotechnical engineering as a non-destructive testing method since its inception in the late 1990s (Park et al., 1999; Xia et al., 1999). The primary outcome of MASW is a shear wave velocity profile (V_s) which represents the stiffness of subsurface layers. MASW accomplishes this by measuring the dispersion of surface waves (i.e., Rayleigh or Love waves), whereby different frequency components travel at different velocities through the domain. Then, in an inversion process, an initial subsurface V_s profile is iteratively modified until the corresponding dispersion curve from forward modeling matches the measured dispersion curve from the field data.

Currently, acquisition and processing of Rayleigh waves (MAS_RW) is the most commonly used approach in MASW. Rayleigh waves result from constructive interference of primary wave (P-wave) and vertically polarized shear wave (SV-wave) energy generated by vertical impacts on the ground surface. However, Love waves can serve as an alternative energy source for performing MASW (MAS_LW). Love waves, introduced mathematically by A.E. Love (1911), are formed by total internal reflections of horizontally polarized shear wave (SH-wave) energy. Performing MAS_LW can potentially offer a number of advantages. For example, the inversion of dispersion curves generated using Love wave is proven to be more stable and simpler comparing to Rayleigh wave inversion (Safani et al., 2005;

Xia, 2014). Therefore, Love waves tend to reduce the non-uniqueness of the inversion and improve the reliability of the final inversion results (Xia et al., 2012). Love wave dispersion images are also less prone to mode misidentification (Xia et al., 2012). This can prove highly important in cases with shallow bedrock where higher modes may dominate the dispersion record (e.g., Yong et al., 2013).

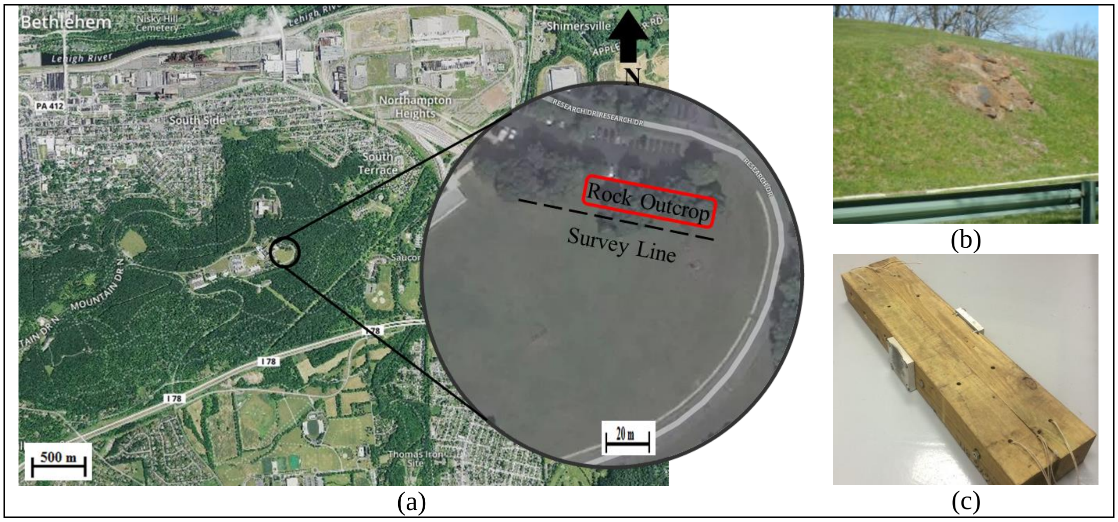
Given that most MASW studies have typically relied solely on Rayleigh waves, the current paper summarizes results from a survey aimed at estimating the stiffness of a shallow bedrock site using both MAS$_R$W and MAS$_L$W. The goal is to augment the existing literature with a case history that provides an additional example comparing Rayleigh and Love waves in the case of shallow bedrock.

Field Testing

The testing site is located at the Mountaintop Campus of Lehigh University, Bethlehem, PA. Rock outcrops (Figure 1-b) were observed at several locations across this site. Three locations at the site were manually investigated using a hand auger. At one location adjacent to the survey line, a stiff layer was encountered at approximately 0.25 m, and at the other two locations farther away from the survey line, the depth of the same stiff layer was approximately 0.4 m. Given the proximity of the survey line to the rock outcrop, it was inferred with confidence that the stiff layer observed during hand augering was the site bedrock layer. A total of six MASW surveys with a common center point were performed using both Rayleigh and Love waves. Details of data acquisition parameters are presented in Table 1.

Table 1: Rayleigh and Love wave data acquisition parameters

Data Acquisition Parameter	MAS$_R$W	MAS$_L$W
Number of channels	24	24
Geophones	4.5 Hz vertical component	10 Hz horizontal component
Receiver spacing (m)	0.5, 1.0, 1.5	0.5, 1.0, 1.5
Source offset locations	±3dx, ±6dx, -12dx	±3dx, ±6dx, -12dx
Impact hammer (lb)	4, 8, 20	20
Impact base plate	30 cm aluminum plate	Wooden source (Fig. 2-c)
Number of averaged stacks	4	4
Sampling interval (ms)	0.125	0.125
Recording duration (s)	2.048	2.048



(a)

(b)

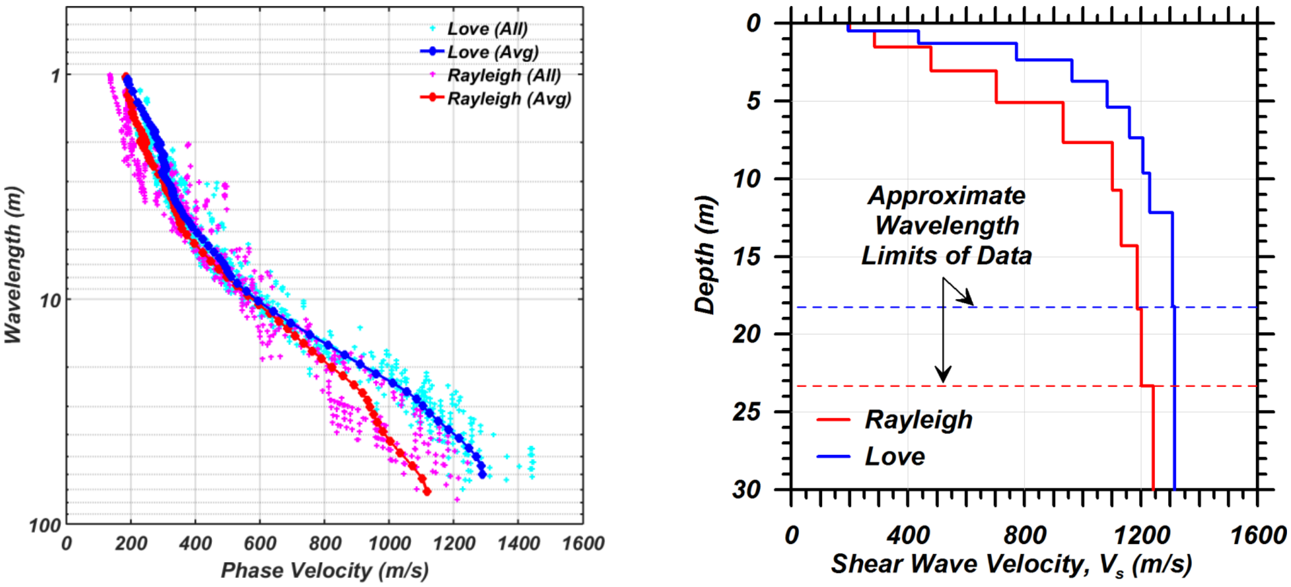
(c)

Figure 1: (a) Lehigh Mountaintop Campus and survey line (USGS 2016) (b) rock outcrop at the site, and (c) wooden source.

Results and Discussion

Post-processing of the collected waveforms was carried out using the Geometrics SeisImager/SW software which generates dispersion images using the phase-shift method (Park et al., 1998). Then, for each record, a dispersion curve was selected by extracting the peak values of accumulated energy at different wavelengths in the resulting overtone image. This was repeated for each shot record, resulting in multiple dispersion curves for each array. An averaging function was then applied to these curves, which yielded a representative dispersion curve for each survey line. An initial subsurface V_s profile was assumed, and forward modeling was used to compute its theoretical dispersion curve. This theoretical dispersion curve was then compared to the measured field dispersion curve and the subsurface V_s profile was iteratively modified until the difference between these two curves was less than a root-mean-square error (RMSE) of 5%.

The Rayleigh and Love wave dispersion curves extracted from the overtone images for all records are plotted in Figure 2-a. Included in this figure are the representative composite curves obtained from the average of all associated dispersion curves for Rayleigh and Love waves. A smoothing algorithm was also applied that computed the average of three adjacent data points in the direction of wavelength.



(a) (b)

Figure 2: Comparison of MAS$_R$W and MAS$_L$W (a) dispersion curves (b) inverted V_s profiles.

It is apparent from Figure 2-a that Love waves generally traveled faster at a given wavelength when compared to Rayleigh waves. Safani et al. (2005) noted this trend in a previous study and attributed it to transverse isotropy of the underlying subsurface. However, Safani et al. (2005) also noted that the pattern reverses at longer wavelengths, where Rayleigh waves travel at phase velocities at least 10% higher than Love waves. That was not the case at this site. In fact, Love waves traveled as much as 15% - 20% faster than Rayleigh waves at longer wavelengths that penetrate deeper into the underlying subsurface. This implies that the bedrock at this site may exhibit appreciable transverse isotropy in the direction of SH-wave polarization, particularly at larger depths. This pattern was less significant at shorter wavelengths indicative of the near surface.

Also evident in Figure 2-a is the relative level of variability in the dispersion curves acquired from the different offset locations and receiver spacings. This provides a general sense of the level of uncertainty in the predicted subsurface velocities. Generally, for both Rayleigh and Love waves, the variability increased at longer wavelengths. This is not surprising given that surface wave methods can struggle to accurately characterize the V_s of relatively high velocity rock because wavelengths much longer than typically recorded are required to constrain the estimates (Yong et al., 2013). Nevertheless, at this site the Love wave dispersion curves exhibited less overall variability. Rayleigh wave dispersion curves suffered from nearly the same level of scatter at shorter wavelengths (e.g., < 5 m) as they did at longer wavelengths, which indicates less confidence in velocity predictions. Dispersion curves generated using Love waves also were more likely to demonstrate fundamental mode behavior. This meant less sections of the Love wave dispersion curve were removed for the interpolation involved to develop the representative fundamental mode dispersion curve. This made them easier to process and reduced the overall scatter in the results. Such observations have been highlighted in previous studies (e.g., Xia et al., 2012).

Figure 2-b presents the inverted V_s profiles using both the Rayleigh and Love wave composite dispersion curves, respectively. Based on the dispersion trends in Figure 2-a, predictably MAS_LW estimates an overall stiffer V_s profile when compared to the results using MAS_RW. The predicted V_s for bedrock using Love waves is approximately 5 – 10% higher when compared to the results from the Rayleigh wave inversion. Additional information would be necessary at this site to serve as ground truth and allow definitive comments to be made regarding the accuracy of the two V_s profiles, particularly for the predicted bedrock velocity. However, a few additional comments can be made based on the level of effort involved for inversion as well as the limitations on the data. First of all, Rayleigh wave inversion converged to an RMSE of 5% using fewer iterations. However, despite requiring additional iterations, Love wave inversion was noticeably faster in terms of computation time. Such behavior can be attributed to the increase in stability and decrease in complexity of Love wave inversion in relationship to Rayleigh wave inversion (Safani et al., 2005; Xia, 2014). Figure 2-b also presents the limitations of the acquired data based on the one-third wavelength approximation for depth of penetration. Rayleigh waves were able to penetrate as much as 20% deeper than Love waves at this site despite the lower overall predicted V_s using Rayleigh waves. This discrepancy in depth of penetration agrees reasonably well with previous observations (e.g., Yin et al., 2014). If the goal is to acquire as much velocity information with depth at a site, surface wave testing using Love waves may not be the most well-suited approach. However, as noted previously, one would generally expect increased confidence in the resulting Love wave V_s predictions due to the smaller overall scatter in the dispersion data.

Conclusions

In this study, one shallow bedrock site was investigated using surface wave testing with both Rayleigh and Love waves. Multiple surveys were performed for each method using different receiver spacing so that dispersion curves could be extracted over a broad range of wavelengths. Each survey was collocated so that there was a common midpoint for all testing performed at the site. This allowed comparisons to be made in the dispersive behavior of Rayleigh and Love waves at this site as well as the corresponding V_s profiles after inversion.

From an examination of the dispersion curves, it was noted that the Rayleigh wave data exhibited significant scatter throughout the range of wavelengths acquired during testing. The Love wave dispersion curves generally revealed less variability, were more likely to exhibit fundamental mode behavior throughout the range of measured wavelengths, and predicted an overall increase in phase velocity relative to the Rayleigh wave dispersion curves. This resulted in predictions of bedrock V_s on the order of up to 10% higher using Love waves, which may point to the presence of appreciable transverse isotropy within the bedrock at this site. However, the depth of penetration for the Love waves were as much as 20% shallower when compared to Rayleigh waves, despite the larger V_s values predicted using Love waves. Finally, Love wave inversion required more iterations than Rayleigh wave inversion to reach the same convergence criteria of 5% RMSE. However, the additional iterations did not result in any additional computation time. In fact, computation time for Love wave inversions were on average much faster than Rayleigh wave inversions due to the inherent stability and decrease in complexity resulting from V_p independence. Given these advantages, future MASW studies should continue to consider the use of Love waves, particularly in cases where shallow bedrock is present at the site. In these circumstances, Love waves perform favorably as demonstrated in this study and many of its limitations are less critical than at sites where shallow bedrock is not present.

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