UNCERTAINTY IN GEOTECHNICAL SITE CHARACTERIZATION USING SURFACE WAVE TECHNIQUES - A REVIEW

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ABSTRACT

Surface wave methods are most commonly used in seismic microzonation studies for the purpose of in-situ dynamic site characterization. Surface wave methods are based on the dispersive characteristic of Rayleigh wave in vertically layered medium. In surface wave methods experimental dispersion curve constructed from field testing is inverted to get one dimensional shear wave velocity profile. However, the inverse problem solution is not unique and provides many equivalent shear wave velocity profiles for a considered site. This uncertainty associated with surface wave tests is an area of great concern because there can be significant effects on the outcomes of the site specific seismic hazard assessment. Some research has been attempted in the recent past to quantify the uncertainty and its impact on dynamic site characterization. Apart from the uncertainties from the inversion, there is measurement uncertainties in phase angle and phase velocity associated with surface wave measurements. In this article, we examine the measurement of different uncertainties and their impact on geotechnical site characterization given in different studies by various researchers.

Keywords: Dispersion Curve, Coefficient of Variation, Surface Wave Methods, Ground Response.

INTRODUCTION

Surface waves can be used in site characterization on the basis of shear stiffness profiles with depth of geotechnical sites. Surface wave tests utilize the dispersion property which makes the velocity of
Rayleigh wave frequency dependent in layered medium. Rayleigh waves are a combination of P and SV waves. In a homogeneous layered medium, the particle motion of the fundamental mode of Rayleigh waves is retrograde elliptical and propagates along the free surface. Longer wavelengths penetrate up to greater depths and reflect the elastic properties of deeper layers. On the contrary, shorter wave lengths are responsive to the physical properties of near-surface layers (Fig. 1). For a specific mode, surface wave will attain a unique phase velocity for each unique wavelength and it will lead the surface wave dispersion.

![Figure 1: Geometrical dispersion in layered media (after Rix, 1988).](image)

In surface wave testing, experimental dispersion curve is constructed from field data and then by inverse problem solution shear wave velocity profile can be obtained. Surface wave methods which are non-invasive can provide information of large volume of soil deposit in a very short duration of time. Applications of surface waves started in the 1950s with the discovery of Steady State Rayleigh Method (Jones, 1958), but their revolution arrived only in the last two decades with the SASW method (Nazarian et al., 1983), MASW (Park et al., 1999; Xia et al., 1999; Miller et al., 1999). In this paper our main aim is to study the measurement uncertainty of surface wave methods and its consequences on seismic site response analysis for geotechnical site characterization.

**SURFACE WAVE METHODS**

Different types of surface wave methods are used for extracting the dispersion curve from the field measurements. In active-source tests, waves are generated using a seismic source (Stokoe et al., 1994; Park et al., 1999), whereas in passive-source tests, constant vibration of earth’s surface or microtremor is used for the surface wave analysis (Horike, 1985; Louie, 2001; Strobbia and Cassiani, 2011). For active and passive source tests, we get different frequency components which are directly related to the depth of investigation. In active source tests, we usually get high frequency components but in passive-source tests low frequency components are obtained. Sometimes both active and passive-source tests are used together for getting shear wave velocity profile up to larger depths and better resolution at lower depth.

**UNCERTAINTY ASSOCIATED WITH SURFACE WAVE METHODS**

Few research have been attempted to measure the uncertainty associated with the results of surface wave testing. Geophysical techniques, invasive or non-invasive can be used for geotechnical site characterization which is the main basis of other geotechnical studies like – seismic site response,
liquefaction analysis, ground motion attenuation relation etc. So, it is very much important to quantify the uncertainty and treated properly, otherwise it may cause severe consequences on other studies.

Marosi and Hiltunen (2004a) found out the uncertainty in terms of coefficient of variation (COV) in SASW phase angle and SASW phase velocity from different acquisitions and in the same testing configuration. A large sample of test data was collected from two test sites and uncertainty were determined for each phase of SASW. They found out that there was low measurement uncertainty (COV ~ 2%) in the phase angle and phase velocity data and the data appeared to be normally distributed (fig. 2a). Fig. 2a describes a normal probability plot of phase velocity data collected for the same frequency at different receiver spacings from the PSTT site. Fig 2b shows the variation of the COV of phase velocity with frequency for both the PSTT and TENN site data. A typical value of 2 % (mean=1.93 %) of COV is observed. The uncertainty appears to be maximum at both ends of the frequency range.

Figure 2: (a) Normal probability plot for phase velocity samples at 36 Hz for various receiver spacings, PSTT site, (b) COV of phase velocity data for PSTT and TENN site (Marosi and Hiltunen, 2004a)

Figure 3: (a) Normal probability plot for shear wave velocity, TENN site (b) Mean shear wave velocity profiles with standard deviation at Tenneco Automotive Corporation site (Marosi and Hiltunen, 2004b)
Marosi and Hiltunen (2004b) evaluated the measurement uncertainty of shear wave velocity having a COV of 5–10% and thus inversion is magnifying the uncertainty. Study also reported that shear wave velocity samples are normally distributed at a particular depth and there is an increase in uncertainty with depth. Fig.3 shows the test results of a site at Tenneco Automotive Corporation site.

Lai et al. (2005) presented a study to assess how the uncertainty of the experimental dispersion curves is mapped into shear wave velocity profiles obtained by inversion process. They collected experimental data of multiple shots with same testing configurations at two sites in Italy. They found out two distinct regions in the experimental dispersion curves separated by a threshold frequency. The threshold value of frequency between these two regions is near about 10-12 Hz above which dispersion curve is associated with very low value of uncertainty and below this uncertainty is very high. Uncertainty associated with the obtained shear-wave velocity profiles using Occam’s algorithm is having a low coefficient of variation of 4%. High uncertainty at low frequency of experimental dispersion curves contributes higher uncertainty with depth.

EFFECT OF UNCERTAINTY ON $V_{S30}$ ESTIMATION

In most geotechnical studies, the site is characterized on the basis of the shear-wave velocity of upper 30m ($V_{S30}$) as it mainly responsible for modifying the seismic ground motion. In most of the microzonation studies accurate determination of spatial distribution of $V_{S30}$ plays an important role in seismic hazard analysis. As the surface wave methods are very much convenient than other geotechnical investigations, now a days it is widely used to characterize the near surface geotechnical sites.

Moss (2008) carried out a study with existing available comparative and blind shear-wave velocity tests to find out intra-method and inter-method variability for $V_{S30}$ estimation. The intra-method coefficient of variation of invasive tests is between 1-3%. Slightly higher COV is observed for non-invasive tests with a value of 5-6%. He combined the results from the previous studies and the different intra-method variability in terms of coefficient of variation (Fig. 4) is estimated.

![Figure 4](image_url)
Comina et al. (2011) presented a study on the effect of non-uniqueness of the inverse problem solution in $V_{S30}$ estimation. A Monte Carlo approach was used for the inversion of experimental dispersion curves to get a set of equivalent shear-wave velocity profiles. Even though inversion provides several equivalent velocity profiles but their estimate of $V_{S30}$ is very similar having a COV ~ 2%.

**Figure 5:** Monte Carlo inversion of active surface-wave data at Pontremoli site: (a) experimental and numerical dispersion curves, (b) shear-wave velocity profiles from Monte Carlo analysis compared to down-hole test results (Comina et al., 2011)

Fig. 5 shows a case history in Pontremoli site where active surface-wave test has been carried out. Twenty two sets of equivalent profiles are extracted from Monte Carlo inversion of active surface wave data compared to down-hole test result. The estimated COV of $V_{S30}$ from equivalent velocity profiles is very low (~2%). So, they concluded that inversion non-uniqueness will not significantly affect the accuracy and reliability of $V_{S30}$ estimate.

**EFFECT OF UNCERTAINTY ON GROUND RESPONSE ANALYSIS**

From above study, it is very clear that the inversion is the most critical step of surface wave tests. The solution of the inverse problem is non-unique and results provide several equivalent velocity profiles which are having good fit with the experimental dispersion curve. Non-uniqueness of the solution of dispersion curves provide only one of the possible solutions and the final model strongly depends on the initial one. Few studies have been carried out to find out the consequences of this non-uniqueness on ground response analysis.

Foti et al. (2008) studied the consequences of surface wave inversion on seismic site response analysis. Synthetically they generated a set of equivalent profiles (Fig. 6a) which are having good fit with the experimental dispersion curve. These equivalent profiles are then subjected to conventional 1D ground response analysis. The result shows that equivalent profiles with respect to surface wave testing are also equivalent with respect to site amplification (Fig. 6b). The amplification spectra are very similar for the frequency band below 10 Hz and value of the coefficient of variation of peak amplitude is in the order of 3-5%.
Later, the above study was extended by Boaga et al. (2011) for different impedance contrast and found out that the equivalent profiles (Fig. 7a) as a result of surface wave inversion are not equivalent in terms of seismic ground response analysis. It shows a sample synthetic study of case-A in which there is a very smooth increase of velocities with depth. The amplification spectra (Fig. 7b) show significant differences in terms of peak frequency varies from 0.5 to 3.3 Hz and exhibit similar peaks in terms of amplitude. For low impedance contrast, the effect is very much pronounced and for high impedance contrast, the equivalent solutions have a very little influence.

Figure 7: (a) 1D equivalent shear-wave velocity profiles. (b) Amplification spectra from the equivalent shear-wave profiles (Boaga et al., 2011).

Generally 1D model is used for the dispersion curve interpretation of surface wave data. When a soil deposit is laterally heterogeneous, 1D velocity distribution model errors can lead to significant consequences on the consistency of the resulting shear-wave velocity distribution. This may differ from actual velocity distribution and can result into erroneous site response analysis. Boaga et al. (2012) described the possibility of analyzing the seismograms using a multi-offset phase analysis (MOPA) for
the detection and location of the lateral discontinuities, and a better model parameterization. They used two synthetic laterally heterogeneous models and carried out ground response analysis by considering it as a standard 1D without using MOPA and 2D profile using MOPA.

![Image](image_url)

**Figure 8:** (a) Synthetic model A, (b) Amplification function for Model A inverted without MOPA with a standard 1D approach, (c) Amplification function for Model A using MOPA (Boaga et al., 2012).

Fig. 8a shows one of the considered synthetic model and Fig. 8b,c are the amplification spectrums by considering standard 1D model and 2D model, respectively. It is very much evident from the figure that 1D analysis provides significantly different results in comparison with 2D velocity distribution, particularly in terms of site response prediction.

**SUMMARY AND CONCLUSIONS**

From the studies of previous researchers on surface wave uncertainty on geotechnical site characterization and their consequences on ground response analysis, following conclusions are drawn:

- Measurement uncertainty in phase angle and phase velocity is very low in comparison with shear-wave velocity uncertainty. Surface-wave inversion magnifies the uncertainty and it increases with depth. As the inverse problem solution is non-unique, several equivalent profiles which are having good fit with the experimental dispersion curves are obtained.

- The estimated uncertainty of $V_{S30}$ from equivalent velocity profiles is very low (~2%). So, it can be said that inversion non-uniqueness will not significantly affect the accuracy and reliability of $V_{S30}$ estimate.
Equivalent profiles as results of surface wave inversion are not equivalent in terms of seismic ground response analysis. Subsurface profile where there is a very smooth increase of velocity with depth, i.e., for low impedance contrast, the amplification spectra shows significant differences in terms of peak frequency and exhibit similar peaks in terms of amplitude.

The consequences of lateral heterogeneities on seismic site response analysis are very much significant. The use of MOPA as pre-processing of standard MASW data can provide more realistic estimation of subsoil scenario and accurate assessment of design ground motion.

REFERENCES


