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Combination of dispersion curves from MASW measurements

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ABSTRACT

Multichannel analysis of surface waves (MASW) is a seismic exploration method for determination of near-surface shear wave velocity profiles based on analysis of horizontally travelling Rayleigh waves. This paper aims to propose a methodology and recommendations for combining dispersion data from several multichannel records. The dispersion curves are added up within logarithmically spaced wavelength intervals and the uncertainty of the mean phase velocity estimates is evaluated by using classical statistics and the bootstrap. The results indicate that combining multiple dispersion curves, which have been gathered by receiver spreads of different lengths (but with the same midpoint), can increase the investigation depth of the survey, improve its resolution at shallow depth and overall improve the reliability of the results as compared to the use of a single record. Moreover, the uncertainty of the combined mean dispersion curve can be determined and further used to present the shear wave velocity profile with upper and lower boundaries.

1. Introduction

The shear wave velocity (V_S) of near-surface materials is an important parameter in various geotechnical and earthquake engineering projects. The small-strain shear modulus of individual soil layers (G_0) is directly proportional to the square of their characteristic shear wave velocity. Furthermore, the shear wave velocity is fundamental in assessing soil amplification and for seismic site classification [1–3].

Several in-situ methods exist for evaluation of near-surface shear wave velocity profiles [1,4]. These include methods that require access to a drilled borehole, such as down-hole and cross-hole seismic surveys, methods where the resistance of soil to penetration is measured like the standard penetration test (SPT) and the cone penetration test (CPT), and surface wave analysis methods, such as the multichannel analysis of surface waves (MASW) method. Surface wave analysis methods utilize the dispersive properties of surface waves, commonly Rayleigh waves, propagating through a heterogeneous medium [5,6]. The shear wave velocity profile is subsequently obtained by backcalculation of the dispersion data by assuming a layered soil model. Compared to other available methods, surface wave analysis methods are low cost, as well as being non-invasive and environmentally friendly since they neither require heavy machinery nor leave lasting marks on the surface of the test site. Moreover, surface wave methods are applicable at a wide variety of sites, ranging from very fine grained silty soil sites to coarse grained gravelly sites, and even soft rock, hence, including locations where for example penetration tests are difficult to apply. MASW is a relatively new surface wave analysis technique [7,8] that has attracted an increased attention in recent years [9]. The main advantages of the MASW method, as compared to a two-receiver analysis [10], include a more efficient data acquisition in the field and improved data processing procedures where data from multiple receivers is analysed simultaneously [8]. Furthermore, the MASW method makes it possible to identify higher mode dispersion curves based on the recorded surface wave data [11].

Determination of experimental Rayleigh wave dispersion curves is a critical stage in the application of MASW. An inaccurate or erroneous experimental dispersion curve can cause severe errors in the backcalculated shear wave velocity profile [8,12,13]. At locations where the fundamental mode of the Rayleigh wave prevails, the retrieved fundamental mode wavelength range constrains the investigation depth range of the survey [14]. In short, the longer the maximum retrieved wavelength, the greater the prospective maximum investigated depth, and the shorter the minimum recorded wavelength, the better the resolution of the survey at shallow depth. The configuration of the measurement profile, including the length of the receiver spread (L) and the distance from the impact load point to the first receiver (x_1), is known to affect the acquired dispersion data [15–23]. The observed effects suggest that a wider range of dispersion curve wavelengths can be obtained by combination of data acquired using measurement profiles with different L and/or x_1 [16,17,24,25]. Furthermore, the acquired surface wave records are affected by correlated and uncorrelated noise sources. The manual aspect of the analysis, particularly the visual identification of dispersion curves based on images of

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processed data, also adds to the uncertainty associated with the dispersion curve estimates. Hence, when repeated measurements are carried out, some variability among the resulting dispersion curve estimates will be observed. Multiple records thus result in multiple curves, which combined may improve the estimation of the actual dispersion curve. As the individual dispersion curves may cover different wavelength ranges, the combined curve can include a wider range of wavelengths than any single experimental curve, and, hence, lead to an increased investigation depth range. Combination of dispersion data from several multichannel records can also be achieved by adding (stacking) multiple dispersion images before extracting a single dispersion curve. Stacking of multiple dispersion images can reduce noise and help identification of the fundamental mode dispersion curve [24,26–28]. By averaging the dispersion data post dispersion curve extraction, the uncertainty of the mean dispersion curve estimate can be evaluated, for instance, in terms of parametric or non-parametric confidence intervals for the mean dispersion curve. The uncertainty analysis can provide the analyst a more rational evaluation of the quality of the dispersion data and the combined dispersion curve. The uncertainty of the combined mean dispersion curve can further be utilized to present the shear wave velocity profile with upper and lower boundaries.

Few authors have obtained composite experimental dispersion curves with phase velocity uncertainties as a part of an active-source MASW survey. The combined curves have been constructed based on dispersion curves obtained by repeated shots [29,30], dispersion data gathered using different shot positions [21,31,32] or measurement profiles of different lengths [25]. Furthermore, in a few studies where the experimental dispersion curve has been identified from a stacked dispersion image, the experimental uncertainty has been assessed using the dispersion curves extracted from the single shot images [27,28]. However, in all above-mentioned studies, the main objective has not been computation of composite experimental dispersion curves, hence, the dispersion curve combination and uncertainty evaluation procedure is not well described and no general recommendations are given.

This paper aims to propose a methodology for combining dispersion curves from several multichannel records for the purpose of producing a reliable combined mean dispersion curve over a wide range of wavelengths. In this work, only the fundamental mode of Rayleigh wave propagation is considered. However, the methodology can be extended to higher modes as well. A number of records acquired by different measurement profile configurations at a silty sand test site are used to demonstrate the methodology. Recommendations for optimal measurement profile parameter/dispersion curve combinations in the context of ranges of wavelengths and phase velocities are presented. The uncertainty of the combined mean dispersion curve estimates was quantified, using both classical statistics and bootstrapping. The inverted shear wave velocity profiles are presented to further assess the effects of the different dispersion curve combinations. Similar results have been observed at other sandy test sites where the proposed methodology has been applied.

2. Multichannel analysis of surface waves

An application of MASW includes three steps; field measurements, dispersion analysis and inversion analysis [8]. An overview of the MASW method, as it is applied in this paper, is provided in Fig. 1. Surface waves are generated by an active seismic source and the wave propagation is recorded by multiple geophones that are evenly spaced along the survey line (Fig. 1a–c). Each multichannel surface wave record is transformed into a dispersion image and the corresponding (elementary) fundamental mode dispersion curve is identified (Fig. 1d–f). The elementary dispersion curves are subsequently combined into a single experimental curve and the uncertainty associated with the combined mean curve evaluated (Fig. 1g). Finally, the shear wave velocity profile is obtained by inversion of the combined mean dispersion curve by assuming a plane-layered elastic earth model (Fig. 1h–k). Under a mild lateral shear wave velocity variation, the backcalculated shear wave velocity profile can reasonably be assigned to the centre of the receiver spread [33].

In general, the resolution of surface wave analysis techniques, such as MASW, diminishes with increasing depth [34]. That is, while the analysis can resolve relatively thin layers and modest shear wave velocity variations close to the surface, only major variations in shear wave velocity/layering can be detected at greater depths. Furthermore, the fundamental mode Rayleigh wave dispersion curve is poorly sensitive to variations in material properties at depths greater than one third to half the maximum resolved wavelength (λ_{max}) [14,34,35]. Hence, a commonly used rule of thumb for interpretation of fundamental mode dispersion curves is to limit the maximum depth of the shear wave velocity profile (z_{max}) by the longest retrieved wavelength (e.g. [8,14,34,36]) as

$$z_{max} \leq \gamma\lambda_{max}, \quad \frac{1}{3} \leq \gamma \leq \frac{1}{2} \tag{1}$$

where γ is the ratio of the maximum depth of the shear wave velocity profile to the longest wavelength. Similarly, limiting the thickness of the top-most layer (h_1) by the shortest retrieved Rayleigh wave wavelength (λ_{min}) has been recommended (e.g. [8,14,36]), i.e.

$$h_1 \geq \zeta\lambda_{min}, \quad \frac{1}{3} \leq \zeta \leq \frac{1}{2} \tag{2}$$

where ζ is the ratio of the minimum thickness of the top-most layer to the shortest wavelength, as the fundamental mode dispersion data does not provide sufficient information to constrain the solution at shallower depths. When MASW surveys are carried out, the focus is commonly on achieving a particular investigation depth, and, therefore, on obtaining a certain maximum Rayleigh wave wavelength. However, as the shallowest soil layers have an influence on the entire experimental dispersion curve, information about the short wavelength wave components is also of importance [34]. Thus, even in cases where a detailed analysis of the shallowest soil layers is not a main objective, an experimental dispersion curve covering a wide range of wavelengths can be of value in order to constrain the inversion and increase the accuracy of the inverted shear wave velocity profile.

Ideally, the dispersion analysis should provide identification and extraction of the (elementary) dispersion curve for each mode. However, in-situ surface wave registrations are incomplete to some extent, imposing various challenges when dispersion curves are identified based on a dispersion image. Uncertainty associated with the experimental dispersion data can arise from an improper application of the middle-of-receiver spread assumption, measurement and sampling errors (e.g. due to limitations of the measurement equipment or an imprecise measurement profile set-up), and coherent or uncorrelated noise in the recorded signal [30,34,37]. Quantification of how the error associated with the recorded surface waves is propagated through the different data processing steps has however been reported as problematic [30]. Direct estimates of the statistical distributions of the extracted phase velocity values (i.e. at each wavelength/frequency) can nevertheless provide a measure of the error associated with the Rayleigh wave dispersion data. The processing of the recorded data and the dispersion curve identification/extraction can further introduce uncertainty in the experimental dispersion curves [30,34,37]. The fundamental mode of Rayleigh wave propagation typically prevails at sites where the shear wave velocity increases gradually with increasing depth [12,34,38,39]. At sites characterized by a more irregularly varying stiffness profile, higher modes can play a significant role in certain frequency ranges, thus making the identification of the fundamental mode dispersion curve difficult. In such cases, misidentification of mode numbers or superposition of dispersion data from two (or more) modes can occur, resulting in an apparent dispersion curve that does not correspond to any of the real modes [12,13,34]. A further source of uncertainty is potential inter-analyst variability associated