Soil Dynamics and Earthquake Engineering 87 (2016) 82–92

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Surface-wave testing of soil sites using multichannel simulation with one-receiver

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
11 April 2016
Accepted 24 April 2016
Available online 10 May 2016

Keywords:
Surface-wave testing
Reciprocity principle
Minimally invasive
Multichannel analysis of surface waves
Higher modes

ABSTRACT

This paper presents a study on the application of the multichannel simulation with one-receiver (MSOR) surface-wave testing method for geophysical profiling of soil sites. The MSOR method reverses the roles of source and receiver in the widely-used multi-channel analysis of surface waves (MASW) method. To examine the feasibility and accuracy of utilizing MSOR for soil sites, finite element simulations of MSOR testing are performed for three types of soil profiles containing horizontal interfaces, a vertical fault, and a dipping interface, respectively. The effects of variations in the moving impact locations on the uncertainty and repeatability of the dispersion trends are analyzed for the different soil profiles. Real-world case studies are carried out to examine the equivalency of the MSOR and MASW methods for quantifying surface-wave dispersion trends of soil profiles, as well as the advantages of MSOR testing with embedded geophones to obtain more extensive multimodal dispersion data. From the computational simulations and field case studies, MSOR is demonstrated to be equivalent to MASW testing for practical purposes. In addition, MSOR has the advantages of reduced instrumentation cost, improved portability, enhanced ability to measure multi-mode dispersion curves by utilizing borehole geophones, and the potential for improving efficiency of 3-D stiffness profiling.

1. Introduction

Geophysical surface wave methods have been widely utilized in research and practice to infer stiffness profiles of layered media by employing dispersion characteristics of surface waves (e.g., [1–9]). Surface wave testing procedures for soil sites typically employ either the two-receiver spectral analysis of surface waves (SASW) method ([1,10]), or a seismograph with an array of receivers in the multichannel analysis of surface waves (MASW) method ([3]). In the past few decades, the MASW method has gained increasing popularity for seismic profiling of soil sites (e.g., [3–5,11–14]).

In this paper, the feasibility and validity of using the multichannel simulation with one-receiver (MSOR) method for soil sites is investigated by computational and experimental studies. Because only one geophone, one triggered hammer, and two channels of data acquisition are needed, the equipment for MSOR testing can be carried in a single backpack and is more economical and portable than that of multichannel methods. Application of MSOR testing for geophysical profiling of soil and rock thus has the potential to expand the usefulness of surface-wave methods for various scenarios, such as testing in developing countries where budgets are limited, at remote test sites that are difficult to access, or in emergency response situations after natural disasters.

The reciprocity principle has been widely used for interchanging source and receiver locations in seismic testing ([15–17]). Arntsen and Carcione [18] numerically demonstrated the feasibility of applying reciprocity with distributed sources instead of point sources. Wapenaar [19] reported that the reciprocity principle is satisfactory with different characteristics of source and receiver, provided that the amplitude of the signal is not critical. Traditional active surface wave methods extract frequency-related dispersion information from multichannel field data by employing an array of point receivers and a distributed active source. For near-surface profiling, the point receivers typically consist of 24 or 48 geophones coupled to soil by ground spikes, with the source consisting of a sledgehammer striking a 15-cm or 20-cm square aluminum plate. If the multiple receivers and single impact location are exchanged for multiple impact locations and a single receiver, the dispersion images of the two testing procedures should theoretically be equivalent based on the reciprocity principle. The single-receiver MSOR method has been applied to nondestructive testing of pavements ([20–25]) and soils ([26–28]), but whether the principle of reciprocity holds in practice for actual soil profiles and testing conditions including the presence of external noise is examined in this paper.

The MSOR method has two primary requirements: (1) repeatable impacts that can generate waves with consistent energy,

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http://dx.doi.org/10.1016/j.soildyn.2016.04.013

timing, and triggering (e.g., [23]) and (2) accurate and consistent impact locations. To exclude negative effects caused by these inconsistencies, an FEM simulation was first employed to study the reciprocity of dispersion images for MASW and MSOR methods for three types of site structures under ideal testing conditions. The cross-correlation function was then used to statistically analyze the distribution of sampling time-lags among stacking signals, which can arise from the impact inconsistencies mentioned above. To understand how such inconsistencies can cause potential errors in the test results, a uniform distribution of sample lags was employed to simulate the effect of variations in impact locations on the accuracy of dispersion data. One real-world case study was performed using both MASW and MSOR at the same soil site to demonstrate their equivalence in terms of the reciprocal dispersion data. A second real-world case study was carried out using MSOR with embedded geophones (referred to as the MMSW method) to systematically measure more extensive multimodal dispersion data.

2. Advantages of MSOR for surface-wave testing of soil sites

The single-receiver MSOR method (Fig. 1(a)) has several advantages compared to multi-receiver methods such as MASW, including: (1) greatly reduced instrumentation costs, since only one sensor and a two-channel data acquisition system are required; (2) increased portability, as a multichannel seismograph with external battery source and string of geophones are not required; (3) more extensive measurement of higher modes if using a single borehole for downhole receiver measurements with moving impacts at the soil surface in the Minimally-invasive Multimodal Surface Wave (MMSW) method detailed in [26,28]; (4) the potential to be faster than MASW if a movable powered impact source is used, as the set-up time for a string of geophones and cables is eliminated; and (5) ease in obtaining 3-D stiffness profiles as the source can readily be moved along different horizontal lines, compared to reinstalling an entire string of geophones multiple times to cover the entire testing area for MASW.

As mentioned above, a modified form of MSOR testing was one important component in the recently developed Minimally-invasive Multimodal Surface Wave (MMSW) method ([26,28]). The principle behind MMSW is that individual modes of surface waves exhibit different dominant depths at which their motion is most significant. MMSW is a hybrid surface-and-borehole method (Fig. 1(b)), as it employs geophones installed at various depths within the soil to measure Rayleigh-wave motion due to an array of impacts on the ground surface. By superimposing the dispersion curves obtained at each sensor depth, more extensive higher modes can be reliably measured compared to surface-only MASW or MSOR tests. The MMSW method is minimally invasive in that the maximum sensor depth needed is typically only about 15–20% of the maximum profiled depth, whereas cross-hole or down-hole tests require the sensor to be installed up to the maximum profiled depth. Preliminary MMSW tests conducted using a hand-augured borehole up to a maximum geophone depth of 3.35 m at the East River Valley site are detailed in [28].

3. FEM simulations of MASW and MSOR at soil sites

To assess the feasibility of applying the MSOR testing procedure to various soil profile types, the finite element method was utilized to simulate moving impact locations and a fixed geophone at the ground surface. The soil models defined in Tables 1–3 were analyzed in Abaqus 6.10-1, using infinite elements on the two lateral boundaries and a fixed bottom boundary. A transient rectangular pulse force, having a duration of 0.04 ms and a very nearly uniform spectral density in the frequency range of interest (5–100 Hz), was applied to simulate the dynamic loading of a sledge hammer on the free surface over an array of source locations, and the time history of vertical velocity was calculated at the geophone locations. The velocity records were assembled to form simulated multichannel records, from which the dispersion images were calculated using the Phase-velocity and Intercept-time Scanning (PIS) procedure detailed in [29]. The PIS procedure is a modification of the phase-scanning wavefield transformation method of [30] by scanning of the phase-velocities and intercept-times of a series of harmonic signals obtained by Fourier transformation of raw multichannel data in the space-time ($x-t$) domain. The stacked amplitudes of the harmonic signals are calculated and normalized for a range of scanning phase velocities at each frequency of interest, and a 2D dispersion image is then constructed in the form of a contour plot of the normalized stacked amplitude versus phase velocity and frequency.

The MASW test procedure was also simulated for the same models, by reversing the geophone and source locations from the MSOR simulation. Finally, dispersion images of MASW velocity data for each soil model were calculated and compared against their counterparts from MSOR data. The results are detailed in the following sections.

3.1. Case 1: Site with three horizontal layers

Case 1 consists of a site with uniform horizontal layers, as assumed in the theoretical matrix method formulations presented in [29]. The MSOR moving impacts were applied successively to the 24 source locations shown in Fig. 2, which have a spacing of 1 m and a first offset of 2 m from the single geophone. Fig. 3 shows that the dispersion trends of the MSOR and MASW simulations, as well as their theoretical counterpart obtained via the transfer matrix method, are all in good agreement. Thus the equivalency of the MASW and MSOR testing approaches is demonstrated for this case of uniform horizontal layers and idealized testing conditions without impact inconsistencies or external noise. Slight variations in the FEM dispersion curves are apparent in the figure. It can be shown that simulations using the stiffness matrix method will

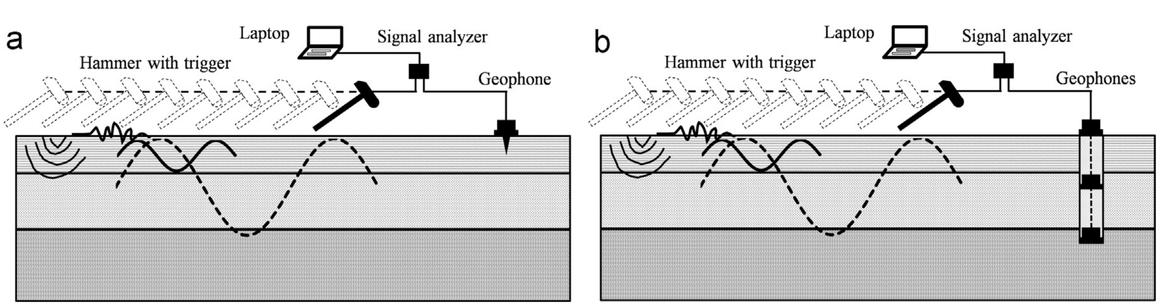

Fig. 1. Schematics of a) MSOR and b) MMSW testing methods.