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Open source MASW software and results from Icelandic soil sites

Logiciel libre pour mesures MASW et résultats des sites de sol islandais

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ABSTRACT: Multichannel Analysis of Surface Waves (MASW) is a non-invasive, fast and low-cost seismic exploration method for evaluation of near-surface shear wave velocity (V_S) profiles. MASWaves is an open source software for acquiring and analyzing MASW field data that has been under development for the past few years. To date, MASW measurements have been carried out at over twenty different locations in Iceland, ranging from sites characterized by peat and loosely compacted sand to cemented soil materials and soft rock. The methodology used for acquiring and analyzing the surface wave records is described, with emphasis on recent advances in both in-situ procedures and data analysis. A newly developed open database is further introduced where results of MASW measurements carried out at Icelandic sites can be viewed and shear wave velocity/stiffness profiles for different sites compared. The aim is to give engineers and researchers access to the data and allow utilization of the results for, e.g., evaluation of seismic hazard and liquefaction potential, and for defining site-specific earthquake loading according to EC8.

RÉSUMÉ: L'analyse des ondes de surface (MASW) est une méthode d'exploration sismique non invasive, rapide et peu coûteuse qui permet d'évaluer les profils de vitesse d'onde de cisaillement (V_S) proche de la surface. MASWaves est un logiciel libre d'acquisition, de traitement et d'analyse des données de terrain MASW en cours de développement ces dernières années. À ce jour, des mesures MASW ont été effectuées à différents endroits en Islande, allant de sites caractérisés par de la tourbe et du sable faiblement compacté aux sols cimentés et aux roches tendres. La méthodologie utilisée pour acquérir et analyser les enregistrements d'ondes de surface est décrite, en mettant l'accent sur les progrès récents en matière de procédures in situ et d'analyse de données. Une nouvelle base de données ouverte récemment développée est également introduite. Elle permet de visualiser les résultats de toutes les mesures MASW effectuées en Islande et de comparer les profils de vitesse/rigidité des ondes de cisaillement pour différents sites. L'objectif est de donner aux ingénieurs et aux scientifiques l'accès aux données et de permettre l'utilisation des résultats, par exemple. évaluation du risque sismique et du potentiel de liquéfaction, et lors de la définition de la charge sismique spécifique au site conformément à EC8. conformément à EC8.

Keywords: Multichannel Analysis of Surface Waves (MASW); shear wave velocity; stiffness; open source software; open database

1 INTRODUCTION

Surface sediments of different origins are common in Iceland and compacted soils are widely used in civil engineering structures, e.g., as foundation pads, for road construction and in various kinds of dams, dykes and other embankments. Iceland is a seismically active area, characterized by moderate to high seismic hazard, where earthquakes of magnitude up to seven can be expected in inhabited areas. Hence, in addition to obtaining general geotechnical parameters for design, it is important to, e.g., carry out seismic soil classification, map site amplifications and evaluate liquefaction hazard as a part of civil engineering work.

The shear wave velocity (V_S) is an important parameter for design of geotechnical structures subjected to dynamic loads. Various in-situ techniques can be applied to evaluate the V_S-profile of near-surface materials (Kramer 1996). These include borehole measurements, such as cross-hole and down-hole seismic surveys, methods where the resistance of soil to penetration is measured, like the seismic cone penetration test, and surface wave analysis techniques. The two-receiver Spectral Analysis of Surface Waves (SASW) method has been applied at a number of sites in Iceland (Silver et al. 1986; Bessason and Erlingsson 2011). Multichannel Analysis of Surface Waves (MASW) is a newer and more advanced technique, based on simultaneous analysis of surface wave traces acquired by an equally spaced array of receivers, (Gabriels et al. 1987; Park et al. 1999). The technique has gained momentum in recent years for applications within geotechnical and earthquake engineering. MASW can be applied at a wide variety of sites, ranging from clay and silt sites to coarse-grained gravelly sites and soft rock, hence, including locations where, e.g., penetration tests are difficult to carry out.

To date, MASW measurements have been conducted at over twenty locations in Iceland. These sites are characterized by a wide variety of soil materials. In this paper, the methodology used for acquiring and analyzing the surface wave records is described, with emphasis on recent advances in both in-situ procedures and data analysis. The first version of an open database is introduced, where results of MASW measurements, carried out at different locations in Iceland, can be viewed and shear wave velocity/stiffness profiles for different sites compared. The main aim is to give engineers and researchers access to the data and allow utilization of the results for, e.g., evaluation of seismic hazard and liquefaction potential, and for defining site-specific earthquake loading according to Eurocode 8 (EC8).

2 MASW

An application of the MASW method is, in general, divided into three steps:

1. *Field measurements:* In-situ measurements to acquire multichannel surface wave records.
2. *Dispersion analysis:* Evaluation of the experimental Rayleigh wave dispersion curve based on the recorded surface waves.
3. *Inversion analysis:* Assessment of the V_S-profile by inversion of the experimental dispersion curve.

The resolution of MASW diminishes with increasing depth (Foti et al. 2015). The prospective investigation depth range is restricted by the observed dispersion curve wavelengths. A simple, widely accepted, rule-of-thumb for interpretation of fundamental mode dispersion curves (e.g., Garofalo et al. 2016) is to limit z_{max} (m), the maximum depth of the V_S-profile, as

$$z_{max} \leq \gamma\lambda_{max} \text{ with } \frac{1}{3} \leq \gamma \leq \frac{1}{2} \quad (1)$$

where λ_{max} (m) is the longest wavelength and, similarly, to limit h_1, the thickness of the top-most layer (m), as

$$h_1 \geq \xi \lambda_{min} \text{ with } \frac{1}{3} \leq \xi \leq \frac{1}{2} \quad (2)$$

where λ_{min} (m) is the shortest retrieved wavelength.

It is commonly recognized that the set-up of the measurement profile, i.e., the length of the receiver spread and the source offset, affects the acquired dispersion data (Dikmen et al. 2010; Ivanov et al. 2008; Ólafsdóttir et al. 2016; Park and Carnevale 2010). The observed effects suggest that a wider range of dispersion curve wavelengths, and, consequently, an increased investigation depth range, can be obtained by combination of data acquired by measurement profiles of different lengths (Ivanov et al. 2008; Ólafsdóttir et al. 2018c). Furthermore, the acquired surface wave records are affected by various, correlated and uncorrelated, noise sources. Hence, when several records are gathered at a single station, some variability among the resulting dispersion curve estimates will be observed. An assessment of the uncertainty associated with the experimental dispersion curve both allows the analyst to more rationally evaluate the overall quality of the data, and to present the V_S-profile with upper and lower boundaries. Alternatively, the inversion results can be presented as a set of V_S-profiles those theoretical dispersion curves lie between the upper and lower boundary experimental curves.

2.1 MASWaves

MASWaves is an open source Matlab-based software for acquiring and processing MASW field data that has been under development at the University of Iceland for the past few years (Ólafsdóttir et al. 2018a; 2018b). The processing part of MASWaves consists of three separate tools. First, a basic dispersion analysis tool (MASWaves Dispersion) to identify an experimental dispersion curve from a single multichannel surface wave record. Second, a tool to add up dispersion curves obtained from multiple surface wave registrations (MASWaves Combination). Third, an inversion analysis tool (MASWaves Inversion) to evaluate the shear wave velocity profile of the test site by backcalculation of the combined dispersion curve. Ólafsdóttir et al. (2018a; 2018c) provide a more detailed description of the computational procedures behind MASWaves Dispersion and MASWaves Inversion, and the method used in MASWaves Combination for evaluation of composite dispersion curves. The software can be downloaded at masw.hi.is, along with a user guide and sample data.

Recently, a specialized data acquisition tool (MASWaves DAQ) was added to the software collection of MASWaves. The new tool provides a direct connection between the data acquisition hardware (for current applications, a pair of NI USB-6218 multifunction I/O devices from National Instruments) and the processing tools. That is, the data acquisition software provides the analyst the opportunity of carrying out preliminary real-time analysis of the recorded data, e.g., for quick assessments of data quality in-situ. Hence, if required, the configuration of the survey profile or values of different measurement control parameters (such as the recording time) can be adapted to better suit the characteristics of the test site, as judged based on the results of the preliminary analysis.

The performance of the dispersion and inversion analysis tools of MASWaves has previously been validated by comparison with results obtained by other software packages and theoretical results presented in the literature (Ólafsdóttir et al. 2018a; 2018b). Furthermore, for verification of results obtained by a combined use of the data acquisition, dispersion and inversion analysis tools, MASW measurements were carried out at four well-characterized geotechnical research sites in Norway (Ólafsdóttir et al. 2019a). The results indicate that the V_S-profiles obtained by using MASWaves match those measured by invasive techniques (seismic cone penetration tests and seismic dilatometer tests), thus verifying the performance of the data acquisition, dispersion and inversion analysis tools. The MASWaves V_S-profiles further compare well with results of MASW measurements conducted in independent field testing campaigns, as well as results of laboratory tests carried out on samples collected at the Norwegian research sites.

A graphical overview of the data acquisition process and the subsequent data processing and inversion, as it is conducted in this work, is provided in Figure 1. A brief description of each step is provided in the following subsections.

2.1.1 Field measurements

For data acquisition, twenty-four low-frequency geophones are lined up on the surface of the test site with equal spacing *dx* (Figure 1a). The geophones used in this work are of type GS-11D from Geospace Technologies and have a natural frequency of 4.5 Hz and a critical damping ratio of 0.5. A wave is generated by an impact load (in most cases a sledgehammer blow) that is applied at a distance x_1 from one end of the receiver spread and the wave propagation is recorded (Figure 1b). A preliminary analysis of the recorded data can be carried out within the environment of MASWaves DAQ. The data acquisition process is repeated a few times by using different measurement profile configurations, i.e. profiles with different values of x_1 and/or *dx*, while keeping the midpoint of the receiver spread fixed (Figure 1c). For the majority of the Icelandic test sites, survey profiles with a receiver spacing of 0.5 m, 1.0 m and/or 2.0 m and a source offset in the range of 3-30 m were used. On average, four to six multichannel records were acquired with each survey profile configuration.

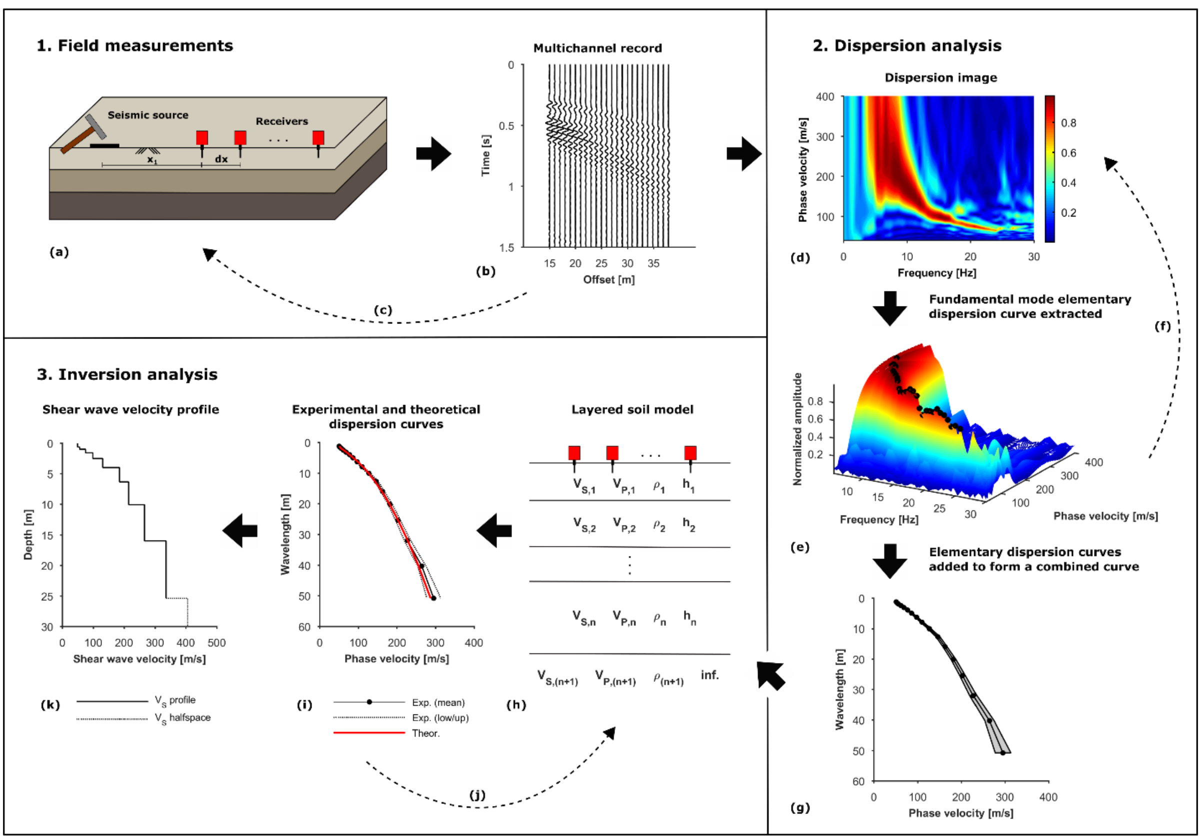

Figure 1. Application of the MASW method.

2.1.2 Dispersion analysis

The processing of the multichannel time series is carried out by using MASWaves Dispersion. A dispersion image (phase velocity spectrum) is obtained for each acquired record (Figure 1d) by the phase shift method (Park et al. 1998). The spectral high-amplitude bands display the dispersion characteristics of all types of waves contained in the recorded data and are used to identify the fundamental mode of the Rayleigh wave propagation (Figure 1e). In cases where the data quality is insufficient, stacking of several velocity spectra, prior to identification of experimental dispersion curves, can be of value.

A dispersion curve identified based on a single (stacked or unstacked) velocity spectrum is here referred to as an elementary dispersion curve. Each spectrum is processed separately (Figure 1f) and the resulting elementary curves combined within logarithmically spaced wavelength intervals (Figure 1g) using MASWaves Combination. Within each interval, the identified dispersion curve phase velocity values are added up and their arithmetic mean used as a point estimate of the phase velocity of the Rayleigh wave components belonging to the given wavelength range. The spread of the dispersion curve data points is represented by the standard deviation of the phase velocity values within each interval.

2.1.3 Inversion analysis

The inversion of the composite dispersion curve is conducted with MASWaves Inversion. The inversion is carried out based on the assumption that the underlying structure of the test site can be adequately described by a semi-infinite stratified soil model, where each layer is assumed to be flat and have homogeneous and isotropic properties. The thickness of the top-most soil layer and the depth to the top of the half-space are recommended to coincide with the approximate investigation depth range described by Eqs. (1) and (2), as well as any previous knowledge of the characteristics of the test site. The parameters used to describe the properties of each layer are shear wave velocity, compressional wave velocity (V_P) (or Poisson's ratio (ν)), mass density (ρ), and layer thickness (h) (see Figure 1h). A theoretical dispersion curve is computed with the stiffness matrix method (Kausel and Roësset 1981), based on a preliminary estimate of the soil model parameters, and compared to the experimental curve (Figure 1i). Subsequently, a Monte Carlo-based process is used to search for the V_S-profile (i.e. V_S and h for each layer) that provides 'the best fit' to the experimental data (Figure 1j). The profile that results in an acceptable fit, and is believed to realistically represent the characteristics of the test site, is taken as the result of the survey (Figure 1k). Upper and lower boundary V_S-profiles can be obtained by inverting the upper and lower boundary (mean ± standard deviation) experimental dispersion curves in a similar way. Alternatively, the inversion results can be presented as a set of V_S-profiles, those theoretical dispersion curves lie between the upper and lower boundary experimental curves.

3 MASW MEASUREMENTS IN ICELAND

Application of the MASW method in Iceland began in 2013. During the autumn of 2013, the first MASW surveys were carried out close to Arnarbæli on the bank of the river Ölfusá in South Iceland. Between 2014 and 2018 the MASW method was further applied at sixteen natural soil sites in South and North Iceland (Figure 2). The survey locations range from soft soil sites to sites characterized by cemented soil materials and soft rock. In addition, repeated field measurements have been conducted at the Arnarbæli site in order to confirm the repeatability of the analysis and the consistency of the results obtained by using the data acquisition, dispersion and inversion analysis tools of MASWaves.

Figure 2. Sites in Iceland where MASW field data have been acquired. Natural soil sites are shown by red dots whereas man-made fillings (i.e., earth dam sites) are shown by black dots.

MASW surveys have also been conducted on the crests of three dams in Iceland's south central highlands; Sultartangi dam, Sporðalda dam and Sigalda dam. The Sultartangi and Sporðalda dams have a central core of moraine and/or loess, whereas the Sigalda dam is without a central core and has a frontal cladding of asphalt. The use of MASW for evaluation of the stiffness properties of the three dams is discussed by Ólafsdóttir et al. (2019b).

The V_S-profiles obtained for four of the natural soil sites and one of the earth dam sites are compared in Figure 3. The half-space V_S in each case is indicated by a dashed line. A brief description of the characteristic soil type at each site, along with its USCS (Unified Soil Classification System) classification, is provided in Table 1. The V_S-profiles shown in Figure 3 were selected such that they represented sites characterized by different soil types. That is, silty sand at the Akureyri airport site, well graded sand at Bakkafjara harbour, poorly graded sand at Miðalda few kilometers east of Þorlákshöfn, and cemented silty sand at the site located in the vicinity of the town Hella. The compacted rock-fill material used in the Sigalda dam is classified as well graded gravel. The investigation depth of the MASW surveys was in most cases in the range of 20-25 m, as estimated with Eq. (1). For further comparison of the estimated V_S-profiles, the average shear wave velocity ($\bar{V}_{S,d}$) of the upper-most d = [5,10,20,30] m at each site is provided in Table 1. The $\bar{V}_{S,d}$ velocity (m/s) was obtained as (CEN 2004)

$$\bar{V}_{S,d} = \frac{d}{\sum_{j=1}^{N}\left(\frac{h_j}{V_{S,j}}\right)} \tag{3}$$

where $V_{S,j}$ (m/s) and h_j (m) denote the shear wave velocity and thickness of the j-th layer, respectively, for a total of N layers down to depth d (m). In cases where the estimated V_S-profile goes down to a depth less than d, the profile is extrapolated using the half-space velocity down to d meters.

As shown in Figure 3, the well-compacted earth dam site has much more stiffness than the three natural sandy sites at Akureyri, Bakkafjara and Þorlákshöfn. Furthermore, the site close to Hella, which is characterized by cemented soil materials, shows even higher velocities, reaching values above 760 m/s (i.e., engineering bedrock) at a depth of around 10 m.

In Eurocode 8, the European standard for design of structures in seismic zones (CEN 2004), construction sites are classified into five categories (ground types) based on the average V_S of the upper-most 30 m at the sites (Eq. (3) with d = 30 m). The ground type is further used to account for the effects of the local ground conditions on the seismic action and, hence, fundamental for determination of site-specific design spectra. The soil classification group of the natural test sites at Akureyri, Bakkafjara, Þorlákshöfn and Hella is provided in Table 1.

Table 1. Overview of site characteristics of four natural soil sites and one earth dam site where MASW measurements have been carried out. The soil classification is based on the Unified Soil Classification System (USCS). The values of the average shear wave velocity of the upper-most 5 m, 10 m, 20 m and 30 m at the sites are estimated by use of MASW. The Eurocode 8 ground type for the natural soil sites is further provided.

Site	**Year of MASW**	**Type**	**Soil**	**USCS group**	$\bar{V}_{S,5}$	$\bar{V}_{S,10}$	$\bar{V}_{S,20}$	$\bar{V}_{S,30}$	**EC8 ground type**
Akureyri airport	2015	Natural site	Holocene fluvial sand	SM	91	123	167	196	C
Bakkafjara harbour	2014	Natural site	Modern littoral sand	SW	142	174	224	258	C
Sand mine close to *Hella*	2015	Natural site	Late-glacial cemented Aeolian silty sand	-	284	339	478	588	B
Sigalda dam (*Sigöldustífla*)	2018	Earth dam	Well graded gravel	GW	224	278	346	387	-
Miðalda east of *Þorlákshöfn*	2015	Natural site	Alluvial sand	SP	166	174	197	221	C

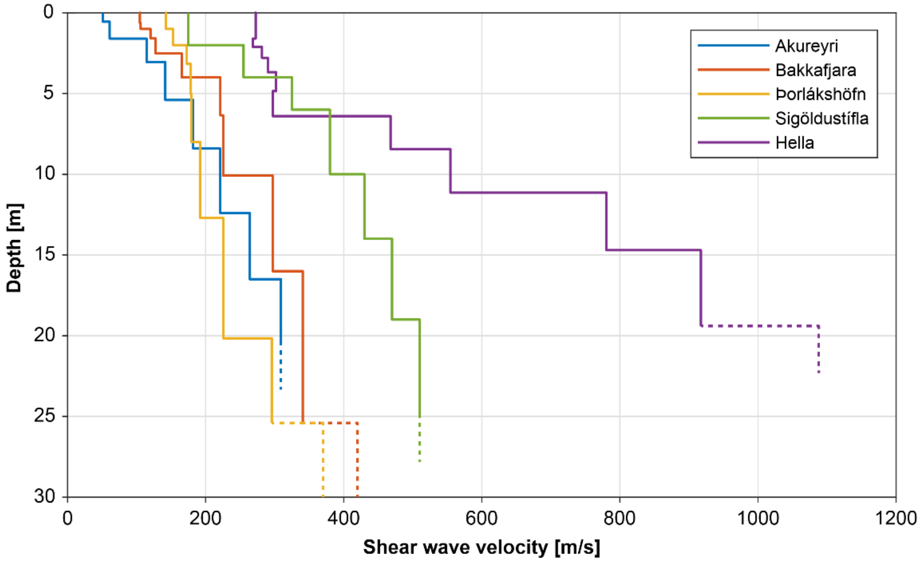

Figure 3. Comparison of shear wave velocity profiles obtained for four natural soil sites (Akureyri, Bakkafjara, Þorlákshöfn and Hella) and one earth dam site (Sigöldustífla).

3.1 Open database for MASW measurement results

The first version of an open database for storing processed MASW data has been made available on the project's webpage (masw.hi.is). As the database is under development, adjustments of the data structure and modifications of the user interface will be carried out as needed. Currently, the information stored for each test site consists of the following:

- *Site location*, including maps and GPS coordinates of MASW profile midpoints.
- *Brief site description*, including USCS classification (where available), estimated location of the groundwater table, estimated material mass density and other appropriate soil material parameters.
- *MASW profile configuration*, such as number and type of geophones and geophone layout.
- *Test results*, including experimental dispersion curves, estimated shear wave velocity profiles (as figures and tabulated values) and estimated values of the average shear wave velocity as a function of depth (as figures and tabulated values for selected depths).

4 SUMMARY

The shear wave velocity profile is a fundamental parameter in soil dynamics and geotechnical earthquake engineering. MASW is a non-invasive, fast, and low-cost seismic exploration method for evaluation of near-surface V_S-profiles. The use of MASW for characterization of Icelandic soil sites began in 2013 and MASWaves, an open source software for acquiring and analyzing MASW field data, has been under development for the past few years.

In this paper, the methodology used for acquiring and analyzing the multichannel surface wave records is reviewed, with emphasis on recent advances in both in-situ procedures and data analysis, and results of MASW measurements conducted at five natural and man-made sites are presented. The first version of an open database is further presented, where results of MASW measurements carried out at Icelandic sites can be viewed and shear wave velocity/stiffness profiles for different sites compared. The aim is to give engineers and researchers access to the data and allow utilization of the results for, e.g., evaluation of seismic hazard and liquefaction potential, and for defining site-specific earthquake loading according to EC8.

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6 REFERENCES

Bessason, B., Erlingsson, S. 2011. Shear wave velocity in surface sediments. *Jökull* **61**, 51-64.

CEN. 2004. *EN1998-1:2004. Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings*, European Committee for Standardization, Brussels, Belgium.

Dikmen, Ü., Arısoy, M.Ö., Akkaya, İ. 2010. Offset and linear spread geometry in the MASW method. *Journal of Geophysics and Engineering* **7**(2), 211-222.

Foti, S., Lai, C.G., Rix, G.J., Strobbia, C. 2015. *Surface wave methods for near-surface site characterization*, CRC Press, Taylor & Francis Group, Boca Raton, FL.

Gabriels, P., Snieder, R., Nolet, G. 1987. In situ measurements of shear-wave velocity in sediments with higher-mode Rayleigh waves. *Geophysical Prospecting* **35**(2), 187-196.

Garofalo, F., Foti, S., Hollender, F., Bard, P.-Y., Cornou, C., Cox, B.R., et al. 2016.

InterPACIFIC project: Comparison of invasive and non-invasive methods for seismic site characterization. Part I: Intra-comparison of surface wave methods. *Soil Dynamics and Earthquake Engineering* **82**, 222-240.

Ivanov, J., Miller, R.D., Tsoflias, G. 2008. Some practical aspects of MASW analysis and processing. *Proceedings of the 21st Symposium on the Application of Geophysics to Engineering and Environmental Problems* (Ed. Kaufmann, R.), 1186-1198. Environmental and Engineering Geophysical Society, Philadelphia, PA.

Kausel, E., Roësset, J.M. 1981. Stiffness matrices for layered soils. *Bulletin of the Seismological Society of America* **71**(6), 1743-1761.

Kramer, S.L. 1996. *Geotechnical earthquake engineering*, Prentice-Hall, Inc., Upper Saddle River, NJ.

Ólafsdóttir, E.Á., Erlingsson, S., Bessason, B. 2016. Effects of measurement profile configuration on estimation of stiffness profiles of loose post glacial sites using MASW. *Proceedings of the 17th Nordic Geotechnical Meeting*, 327-336. Icelandic Geotechnical Society, Reykjavík, Iceland.

Ólafsdóttir, E.Á., Erlingsson, S., Bessason, B. 2018a. Tool for analysis of multichannel analysis of surface waves (MASW) field data and evaluation of shear wave velocity profiles of soils. *Canadian Geotechnical Journal* **55**(2), 217-233.

Ólafsdóttir, E.Á., Erlingsson, S., Bessason, B. 2018b. Open software for analysis of MASW data. *Proceedings of the 16th European Conference on Earthquake Engineering*.

Ólafsdóttir, E.Á., Bessason, B., Erlingsson, S. 2018c. Combination of dispersion curves from MASW measurements. *Soil Dynamics and Earthquake Engineering* **113**, 473-487.

Ólafsdóttir, E.Á., Erlingsson, S. Bessason, B. 2019a. Benchmarking of an open source MASW software using data from four GeoTest sites in Norway. *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering*.

Ólafsdóttir, E.Á., Bessason, B., Erlingsson, S. 2019b. Stiffness profiles of earth dams based on the MASW technique. *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering*.

Park, C.B., Carnevale, M. 2010. Optimum MASW survey–revisit after a decade of use. *Proceedings of GeoFlorida 2010: Advances in Analysis, Modeling & Design* (Eds. Fratta, D.O., Puppala, A.J., Muhunthan, B.), 1303-1312. American Society of Civil Engineers, Reston, VA.

Park, C.B., Miller, R.D., Xia, J. 1998. Imaging dispersion curves of surface waves on multi-channel record. *SEG Technical Program. Expanded Abstracts of the Society of Exploration Geophysicists International Exposition and 68th Annual Meeting*, 1377-1380. Society of Exploration Geophysicists, Tulsa, OK.

Park, C.B., Miller, R.D., Xia, J. 1999. Multichannel analysis of surface waves. *Geophysics* **64**(3), 800-808.

Silver, M.L., Björnsson, B.J., Kiefer, T., Sharma, M., Kotsopoulou, E., Thomas, P. 1986. *Evaluation of the seismic safety of embankment structures of the Thjorsa river basin development in Iceland, final report, Vol. 1-3*. Marshall Silver and Associates Ltd., Chicago, IL.