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Benchmarking of an open-source MASW software using data from three Norwegian GeoTest Sites

Validation d'un logiciel libre pour mesures MASW sur trois sites de référence norvégiens

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ABSTRACT: Multichannel analysis of surface waves (MASW) is a seismic exploration method for evaluation of near-surface shear wave velocity (V_S) profiles. Research on the MASW method in Iceland began in 2013 and an open-source tool for acquiring, processing and analyzing MASW field data, MASWaves, has been under development at the University of Iceland in recent years. In order to verify results obtained by the new software, field measurements were carried out at three geotechnical research sites in Norway (NGTS). The test sites are characterized by soft clay, quick clay and silt, respectively, and have all been thoroughly studied in recent years. In this particular study, the results obtained by using MASWaves were compared with results of existing seismic cone penetration tests (SCPT), seismic dilatometer tests (SDMT) and laboratory measurements, as well as results of MASW measurements carried out in independent field testing campaigns. The results show that the V_S-profiles obtained with MASWaves are very comparable to those obtained with the other measurement techniques, thus verifying the performance of the data acquisition, dispersion and inversion analysis tools of MASWaves.

RÉSUMÉ: L'analyse des ondes de surface (MASW) est une méthode d'exploration sismique permettant d'évaluer les profiles de vitesse des ondes de cisaillement (V_S) proche de la surface. La mise en œuvre de cette méthode MASW a commencé en 2013 en Islande et un logiciel libre, MASWaves, permettant d'acquérir, de traiter et d'analyser d'enregistrements des ondes de surface est en cours de développement à l'Université d'Islande. Afin de vérifier les résultats obtenus par le logiciel MASWaves, des mesures ont été effectuées sur trois sites de référence en géotechnique en Norvège (NGTS). Les trois sites sont respectivement composés d'argile molle, d'argile rapide, et de limon, et ont tous été caractérisés de manière approfondie au cours des dernières années. Dans cette étude particulière, les résultats obtenus avec MASWaves sont comparés aux résultats antérieurs obtenus par l'essai de pénétration au cône sismique (SCPT), l'essai de dilatomètre plat sismique (SDMT) et la méthode MASW. Les résultats montrent que les profils V_S obtenus en utilisant MASWaves sont très comparables à ceux obtenus avec les autres techniques de mesure, validant ainsi les performances du logiciel MASWaves.

Keywords: Multichannel analysis of surface waves (MASW); shear wave velocity; open-source software; benchmarking; Norwegian GeoTest Sites (NGTS)

1 INTRODUCTION

Multichannel analysis of surface waves (MASW) is a surface wave analysis method for evaluation of near-surface shear wave velocity (V_S) profiles. The method has a wide range of possible applications within geotechnical and earthquake engineering and can be applied at sites characterized by both fine and coarse materials.

Research on the MASW method in Iceland began in 2013. An open-source tool for acquiring and processing MASW data, MASWaves, is under development (Ólafsdóttir et al. 2018a; 2018b, masw.hi.is) and methods for data analysis and uncertainty assessments have been proposed (Ólafsdóttir et al. 2018c). Validation of evaluated V_S-profiles is an essential part of the software development. In order to confirm results obtained by MASWaves, MASW surveys were conducted at three Norwegian GeoTest Sites (NGTS) (L'Heureux et al. 2017, www.geotestsite.no). Available V_S-profiles from the sites, obtained by different invasive and non-invasive methods such as seismic cone penetration tests (SCPT), seismic dilatometer tests (SDMT), laboratory measurements and MASW, all carried out in independent testing campaigns, were used for verification purposes in the study.

2 MASW

An application of MASW is divided into three steps; data acquisition, dispersion analysis and inversion analysis (Park et al. 1999). Surface waves are generated by an impact load on the soil surface and recorded using an array of low-frequency receivers. A dispersion image that visualizes the dispersion properties of all types of waves contained in the acquired data is obtained. The identified Rayleigh wave dispersion curve is inverted to obtain an estimate of the V_S-profile for the site. The inversion is conducted by iteratively comparing theoretical dispersion curves, obtained from 'trial' layered semi-infinite elastic soil models, to the experimental data, in search of models that fit the observed dispersion curve. By combining data from repeated shots, the experimental dispersion curve can be presented with upper and lower boundary curves (Ólafsdóttir et al. 2018c). An assessment of the uncertainty associated with the experimental curve allows the analyst to more rationally evaluate the data quality and to present the V_S-profile with upper and lower boundaries. The inversion results can also be provided as a set of V_S-profiles whose theoretical dispersion curves lie between the upper and lower boundary experimental curves.

The resolution of MASW decreases with depth (Foti et al. 2015). The investigation depth further depends on the range of retrieved Rayleigh wave wavelengths. A widely accepted rule-of-thumb for interpretation of fundamental mode dispersion curves (Garofalo et al. 2016) is that z_{max}, the maximum depth of the V_S-profile, is

$$z_{max} \leq \gamma\lambda_{max} \text{ with } \frac{1}{3} \leq \gamma \leq \frac{1}{2} \tag{1}$$

where λ_{max} is the longest retrieved wavelength. λ_{max} is further related to the receiver spread length; an increased length of the receiver spread tends to provide a greater investigation depth.

2.1 MASWaves

The data processing part of MASWaves consists of three separate tools. First, a dispersion analysis tool (MASWaves Dispersion) to identify an experimental dispersion curve from a single multichannel record. Second, a tool to add up dispersion curves obtained from multiple surface wave registrations and assess the uncertainty of the composite curve (MASWaves Combination). Third, an inversion analysis tool (MASWaves Inversion) used to evaluate the V_S-profile by inverting the combined dispersion curve. The inversion scheme is initiated by a preliminary estimate of the soil model parameters and a Monte Carlo-based process is used to search for the V_S-profile that provides 'the best fit' to the experimental data. That is, a profile that both realistically represents the features of the test site and whose theoretical dispersion curve fits the experimental data. Ólafsdóttir et al. (2018a; 2018b; 2018c) provide a description of the computational procedures of MASWaves Dispersion and MASWaves Inversion, and the methods used for evaluation of composite dispersion curves and uncertainty assessments. Recent developments are shortly described by Ólafsdóttir et al. (2019).

3 FIELD MEASUREMENTS

For verification of the data acquisition and analysis tools of MASWaves, MASW surveys were carried out at three geotechnical research sites in Norway in June 2018 (Figure 1). The sites are characterized by silt, soft clay and quick clay, respectively (L'Heureux et al. 2017). At each of the three sites, the data acquisition was conducted using an array of 24 vertical geophones with a natural frequency of 4.5 Hz. Table 1 summarizes the main parameters related to the measurements.

3.1 Halden

The research site is located within a recreational park in the town of Halden. The soil profile at the site consists of around 4.5 m thick layer of loose- to medium-dense silty, clayey sand above a layer of normally consolidated, low plasticity clayey silt with a thickness in the order of 10 m. The upper and lower parts of the silt differ slightly. The water content in the upper 6 m of the silt unit ranges from 28-30% while the unit weight is fairly constant at 18.9-19.2 kN/m^3. The lower silt unit, between depths of 10 m and 15 m, shows a gradual decrease in water content down to 20% and an increase in unit weight up to 20.5 kN/m^3. A clay unit is found at the bottom of the silt deposit (Blaker et al. 2016; 2019). The depth to bedrock within the area varies (NGI 2018). However, in the southern part of the site, bedrock is typically identified at a depth of around 21 m (Blaker et al. 2019). The groundwater level is expected to be approximately 2.5 m below the ground surface (Blaker et al. 2016).

Figure 1. Location of MASW test sites in Southern and Central Norway. [The map is based on data from the Norwegian Mapping Authority. ©Kartverket]

3.1.1 MASW measurements at Halden

A 23 m survey profile was used for the MASW measurements at the Halden site. The profile was positioned in the south-western part of the testing area, where the depth to bedrock is expected to be the greatest, and as close as possible to previous relevant work at the site. The impact load was a sledgehammer blow that was applied at a distance of 3-5 m from each end of the receiver spread. Due to logistical constrains, as well as the varying depth to bedrock within the area, the use of a longer measurement profile or a longer source offset was not attempted.

A typical dispersion image for the site is shown in Figure 2a. The image shows a clear higher mode above 35 Hz which might be due to the fact that the site is far from a 1D structure. The experimental dispersion curves obtained by using different source offsets were in good agreement as indicated by a coefficient of variation (CV) below 5% at each frequency (Table 1). In line with previous findings (Ólafsdóttir et al. 2018c), the lowest frequency components displayed more variability than components in the higher frequency range. Analysis of shots applied from both ends of the profile indicated comparable dispersion characteristics. The composite dispersion curve for the Halden site is shown in Figure 3, along with its upper and lower boundary curves corresponding to plus-minus one standard deviation of the composite (mean) curve.

3.2 Onsøy

The Onsøy test area is characterized by thick deposits of uniform dark-gray silty clay (Lunne et al. 2003). Extensive work has been carried out to study the properties of the Onsøy clay. Beginning in the 1960s, surveys have been conducted within an area in the northern part of the town Gressvik. Two sites within the area have been studied, referred to as Onsøy 1 and 2, located within 300 m of each other. Results of laboratory and in-situ measurements suggest that the nature of the clay deposits is essentially identical at the two sites (Long and Donohue 2007; Lunne et al. 2003).

The Onsøy clay has been classified as normally to lightly overconsolidated, of high to very high plasticity and of medium sensitivity. Measurements indicate that it has a unit weight of around 16 kN/m^3, an in-situ void ratio of 1.4-1.9 and a water content in the range of 50% to 70%. Below a thin surficial crust, the material is considered fully saturated (Lunne et al. 2003).

3.2.1 MASW measurements at Onsøy

A MASW survey was conducted at the Onsøy 1 location using two survey profiles with the same midpoint and direction but different lengths, i.e. 23 m and 46 m. A sledgehammer was used as an impact source with shots taken at various offsets from one end of each receiver spread (Table 1). Overall, the fundamental mode of the dispersion curve was identified in the range of 3.6-45.0 Hz. Based on combination of curves from many shots, the CV values were in the range of 0.1-5.8%, indicating little spread in the data. The combined dispersion curve for the site, along with its boundary curves, is shown in Figure 3.

3.3 Tiller-Flotten

The Tiller-Flotten site is located in an agricultural area 10 km south of the city center of Trondheim. The site is located on thick deposits of marine clay and the depth to bedrock is expected to be around 55 m (L'Heureux et al. 2019).

The soil profile at the Tiller-Flotten site is characterized by an overconsolidated non-sensitive clay down to 7 m below the terrain. Below this, the clay is highly sensitive and quick (i.e. remoulded undrained shear strength below 0.5 kPa) down to a depth of at least 30 m. The groundwater table is considered to be located below the surficial crust, but the groundwater pressures are far below hydrostatic conditions due to drainage to the Nidelva river (L'Heureux et al. 2019). The bulk unit weight of the soil at the site varies between 17.0-18.0 kN/m^3 with depth. The water content is in the range of 40-50% (L'Heureux et al. 2019; Gella 2017).

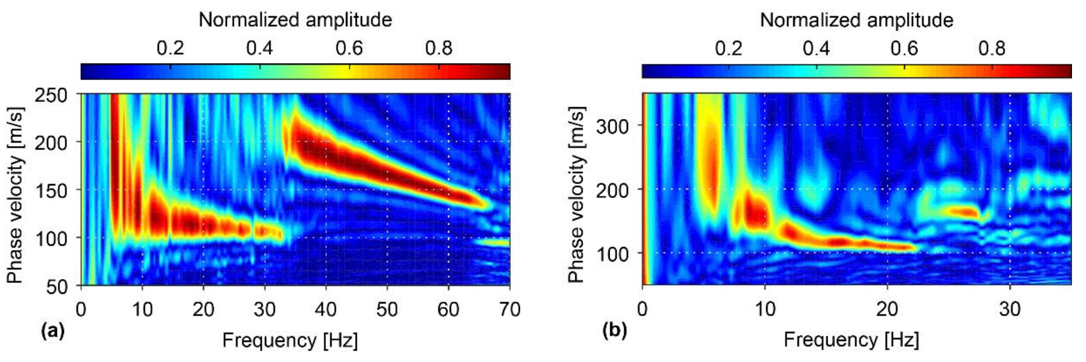

Figure 2. Dispersion images of data from the (a) Halden and (b) Tiller-Flotten sites.

Table 1. Overview of MASW test parameters at the Halden, Onsøy and Tiller-Flotten test sites.

		Halden	Onsøy	Tiller-Flotten
Data acquisition				
Characteristic soil type		Silt	Soft clay	Quick clay
Number of geophones	[-]	24	24	24
Geophone spacing (source offsets)	[m]	1 (3-5)	1 (3-15) 2 (3-20)	2 (3-30)
Sampling rate	[Hz]	1000	1000	1000
Recording time	[s]	2.0	2.2	2.0
Dispersion analysis				
Dispersion curve frequency range	[Hz]	5.5-35.8	3.6-45.0	4.1-27.6
Coefficient of variation (CV)	[%]			
- Range		0.1-4.8	0.1-5.8	0.2-10.8
- Below 10 Hz, maximum value		4.8	5.8	10.8
- Above 10 Hz, maximum value		1.3	2.1	3.2
- Average (all frequencies)		1.0	1.0	2.5
Inversion analysis				
Estimated investigation depth (γ=0.5, Eq. (1))	[m]	14.5	16.0	25.0

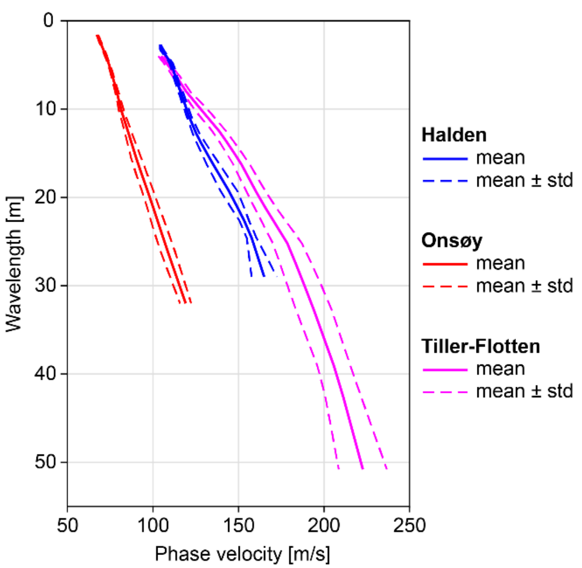

Figure 3. Composite experimental dispersion curves for the Halden, Onsøy and Tiller-Flotten test sites.

3.3.1 MASW measurements at Tiller-Flotten

The MASW measurement was conducted at the Tiller-Flotten site by using a 46 m long survey profile. A sledgehammer blow, applied at a distance of 3-30 m from one end of the profile, was used as an impact load. A dispersion image visualizing the dispersion properties of the soil materials at the site is presented in Figure 2b. As indicated by the CV values in Table 1, the dispersion curve data points for the Tiller-Flotten site were notably more scattered below a frequency of 10 Hz than the data acquired at the other two sites. However, at higher frequencies, the scatter within the experimental data from the site decreased. The composite dispersion curve for the Tiller-Flotten site, along with its estimated boundary curves, is shown in Figure 3.

4 V_S-PROFILE ESTIMATES

4.1 Halden

Several techniques have been used to evaluate the V_S of the soil materials at the Halden site. SCPT and SDMT measurements were carried out at the site as a part of the NGTS project (NGI 2018; Blaker et al. 2016) and are used for comparison in this work. The V_S of the Halden silt has further been assessed by bender element tests performed on triaxial and direct simple shear specimens (Blaker et al. 2019; NGI 2018).

The results of the MASW survey at the Halden site are presented in Figure 4, along with results of other measurements previously conducted at the site. The lowest misfit MASW V_S-profile is shown using a red line. As an indication of the uncertainty associated with the 'best-fitting' V_S-profile, tested models whose theoretical dispersion curves fall between the upper/lower boundaries of the experimental curve (Figure 3) are shown using gray lines in Figure 4a.

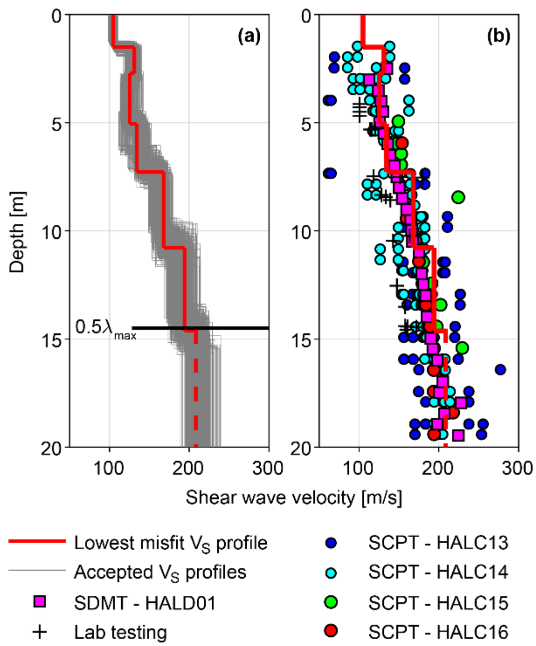

Figure 4. a) Results of the MASW measurement at the Halden site. b) Comparison with results of SCPT, SDMT and laboratory measurements previously conducted at the site.

The V_S-profiles in Figure 4b indicate a very good agreement between the results of the MASW and SDMT measurements. The SCPT data are slightly scattered. However, the results of the MASW measurement are very comparable with the general V_S trend obtained by the SCPT. The laboratory measurements tended to provide slightly lower values of V_S than were obtained with the in-situ techniques. Based on the wavelengths covered by the composite dispersion curve, the investigation depth of the MASW survey was estimated as 14.5 m. However, the MASW V_S-profile is very comparable to the borehole data below this level, indicating that the results of the MASW measurement might be fully reliable down to a greater depth than $0.5\lambda_{max}$ at the Halden site.

4.2 Onsøy

The results of the MASW survey conducted at the Onsøy site are presented in Figure 5. Based on the range of wavelengths covered by the combined dispersion curve, the estimated investigation depth was around 16 m.

The V_S of the Onsøy clay has previously been evaluated with a few different techniques. SCPT measurements were conducted in the area in 1984 (Eidsmoen et al. 1985; Lunne et al. 2003) and 2004 (Landon 2007; Bazin et al. 2016), and MASW measurements were carried out at the Onsøy 2 site (Long and Donohue 2007) using two profile orientations. Results of laboratory measurements carried out on block samples of Onsøy clay are also available (Bazin et al. 2016).

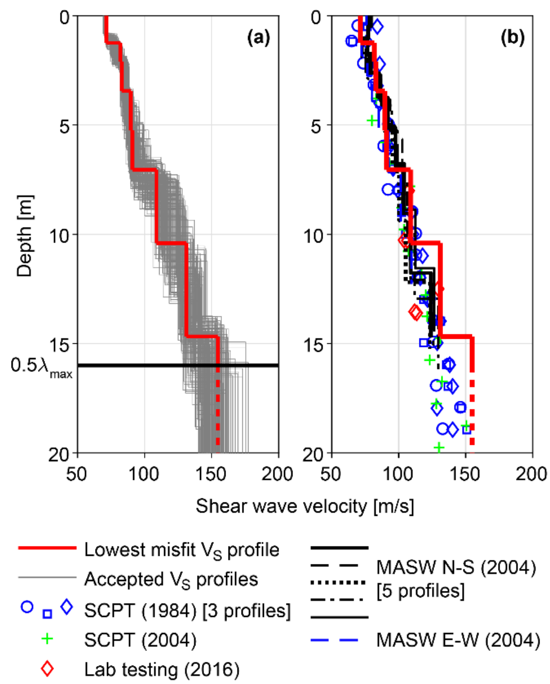

Figure 5. a) Results of the MASW measurement at the Onsøy site. b) Comparison with results of SCPT, MASW and laboratory measurements previously conducted in the Onsøy area.

Overall, there is a good agreement between the 2018 MASW V_S-profile and the previously evaluated V_S-profiles for the site. Below a depth of about 10 m, the 2018 MASW V_S-profile though tends to indicate slightly higher V_S values than the other profiles. The investigation depth of the 2018 survey and the previous MASW surveys at the site is comparable, or generally 15-16 m. However, SCPT data was, on both occasions, collected down to a depth of around 20 m.

4.3 Tiller-Flotten

The results of the MASW survey at the Tiller-Flotten site are presented in Figure 6. Based on a λ_{max} of 50 m, the investigation depth of the survey is estimated as 17-25 m. A V_S-profile obtained by SDMT, covering depths of 5-20 m, is available for the site. At depths of 5-18 m, there is generally good agreement between the results obtained by MASW and SDMT. However, between 18-20 m, the MASW survey resulted in slightly higher values of V_S than were obtained for the same depth interval by SDMT.

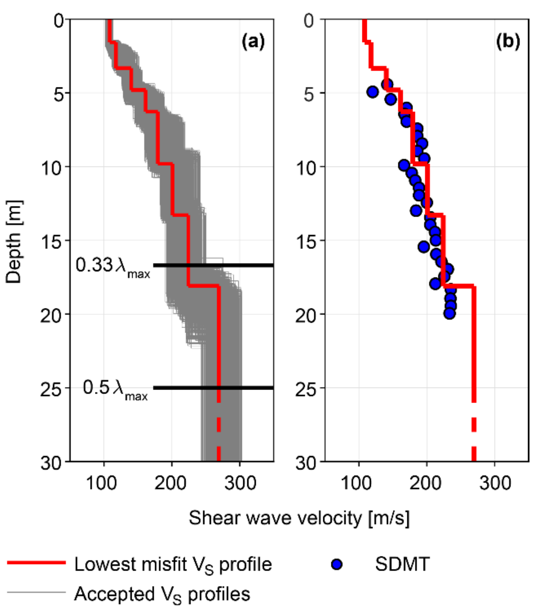

Figure 6. a) Results of the MASW measurement at the Tiller-Flotten test site. b) Comparison with results of SCPT soundings conducted at the site.

As compared to the other sites, there is more uncertainty associated with the estimation of the composite dispersion curve for the Tiller-Flotten site, most notably in the lowest-frequency range. This results in a substantial spread within the set of 'accepted V_S-profiles' in Figure 6a (i.e., profiles whose theoretical dispersion curves fall within the boundaries of the composite curve). Hence, for the Tiller-Flotten site, the maximum reliable depth of the MASW survey is considered to be closer to $0.33\lambda_{max}$ than $0.5\lambda_{max}$ (Eq. (1)).

5 CONCLUSIONS

MASWaves (masw.hi.is) is a new open-source software for acquiring, processing and analyzing MASW data. The objective of this work was to benchmark results obtained by MASWaves against ground-truth data from three geotechnical research sites in Norway, characterized by soft clay, quick clay and silt, respectively.

Overall, the results show that the V_S-profiles obtained by using MASWaves correspond well to profiles measured by invasive techniques, 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 gathered at the Norwegian research sites.

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