MASWavesPy: A PYTHON PACKAGE FOR ANALYSIS OF MASW DATA

E.A. Olafsdottir[1], B. Bessason[1] and S. Erlingsson[1,2]

KEYWORDS

Surface wave analysis, MASW, Shear wave velocity, Open-source software

ABSTRACT

This paper presents MASWavesPy, an adaptable, open-source Python package to retrieve S-wave velocity (V_S) profiles from MASW-type active-source surface wave registrations. The data processing and forward modelling tools of MASWavesPy were validated by comparison with existing software. The analysis approach was then assessed by measurements at four geotechnical benchmark sites, where the retrieved V_S profiles were found to be consistent with existing in-situ and laboratory measurements.

1. INTRODUCTION

MASW (multichannel analysis of surface waves) is a non-invasive approach for in-situ evaluation of soil S-wave velocity (V_S) profiles. In the past two decades, surface wave methods (SWM), including MASW, have become increasingly more common in civil engineering practice as tools to retrieve the V_S distribution of soil sites down depths of a few tens of meters.

MASWavesPy is an open-source, adaptable Python package to process and analyze MASW-type active-source surface wave registrations and evaluate soil V_S profiles [1]. It presents an advancement of an earlier MATLAB tool created by the same authors [2,3] with more refined data processing and analysis methods for improved code usability and performance. Computationally intensive parts of the software are written in Cython for increased computational speed. The main aim of this paper is to present the new package and explain its main modules. The data processing and forward modelling tools of MASWavesPy are verified by comparison with existing software. The performance of the package as a whole is then assessed by measurements at four geotechnical benchmark sites in Norway, where V_S profiles obtained with MASWavesPy are compared with existing in-situ and laboratory data.

[1] Faculty of Civil and Environmental Engineering, University of Iceland
[2] VTI – The Swedish National Road and Transport Research Institute

2. METHOD

For MASW field testing (Fig. 1), a linear array of equally spaced receivers is placed on the soil surface and a vertical impact load is applied in-line with the receivers. The interval V_S profile of the underlying soil deposits is then retrieved by inverting the observed Rayleigh wave (R-wave) dispersion curve (DC). The inversion is conducted by modelling the subsurface as n homogeneous and isotropic linear elastic layers over a half-space. Each layer is described by its V_S, P-wave velocity (V_P) (or Poisson's ratio, ν), mass density (ρ) and thickness (h). In this work, the V_S and thickness of each layer are established by inverting the fundamental mode DC. Hence, the term 'dispersion curve' generally refers to its fundamental mode. In line with common practice [4], the values of V_P (or ν) and ρ for each layer are estimated based on available data and assigned fixed values during the inversion process.

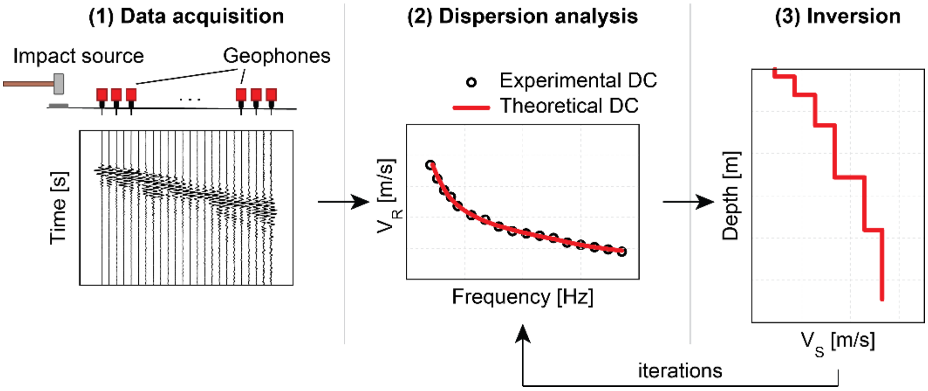

Figure 1. MASW surveying and analysis procedure. (1) Data acquisition: An impact load is applied on the soil surface and the wave propagation is recorded by an array of geophones. (2) Dispersion analysis: Data processing to retrieve the R-wave DC for the site. (3) Inversion: Evaluation of the V_S profile by inversion of the experimental DC.

A single shot gather may be sufficient to retrieve the V_S-depth distribution at a given site. However, to get a quality assessment of the V_S profile it is, in the authors' experience, important to collect multiple records with several impact locations (source offsets) and, in some cases, two or more receiver array lengths. This aligns with prior studies that advice collecting repeated forward and reverse shots to better assess the experimental DC and, consequently, the V_S profile [4-6]. The benefits of using multiple source-receiver configurations include mitigation of near- and far-field effects, the possibility of assessing DC uncertainty, and an extended DC frequency range providing both an improved survey resolution close to surface and an increased surveying depth.

MASWavesPy program structure

MASWavesPy is designed for processing and analyzing surface wave datasets that consist of multiple shot gathers. The package contains four main analysis modules (`wavefield`, `dispersion`, `combination`, and `inversion`) and two supplementary modules (`dataset` and `select_dc`). MASWavesPy can be installed from the Python Package Index (PyPi) using the command `pip install maswavespy`. Its code, together with a quick start guide and sample data, can also be downloaded from Github (see further https://pypi.org/project/maswavespy/). The implementation described below refers to version v.1.0 (released 02.24). A more comprehensive description of the computational procedure is given in Olafsdottir et al. [1].

The `wavefield` module imports shot gathers as `RecordMC` objects (one object for each shot gather) and transforms each seismic record into the frequency-phase velocity (f–V_R) domain by using the phase shift method [7]. A DC obtained from a single shot gather is here referred to as an elementary DC. The supplementary `dataset` module can be used to batch import surface wave datasets, containing multiple shot gathers, as a `Dataset` object.

The `dispersion` module includes methods to visualize the f–V_R spectrum and identify the corresponding elementary DC. An `ElementDC` object stores the f–V_R domain representation of a given `RecordMC` and the identified elementary DC. In the f–V_R domain, the propagation of the fundamental R-wave mode (and higher modes, if excited) is revealed by the spectral amplitude maxima. Hence, the experimental DC is extracted by picking the relevant amplitude maxima over a range of frequencies. The `select_dc` module provides an easy-to-use graphical user interface (GUI) to aid the DC extraction. It also includes a function to automatically identify the absolute amplitude maxima at each frequency. It should, however, be noted that manual inspection of the spectral image, and the trend shown by the amplitude maxima with frequency, is a crucial aspect of the DC identification. Sometimes, the fundamental mode may be associated with a local maximum of the spectral image or masked by a higher mode or disturbances in the seismic data.

The `combination` module provides methods to combine elementary DCs, obtained from multiple shot gathers, into a composite DC with upper and lower boundaries [8]. It is, therefore, specifically intended for processing surface wave datasets. It further provides tools to assess the variation within the set of picked elementary DCs with wavelength or frequency. A `Dataset` object contains multiple `RecordMC` and `ElementDC` objects (one pair for each imported shot gather) and provides a routine for initializing a `CombineDCs` object for the set of records or a given subset of processed records.

Lastly, the `inversion` module provides routines to assess the V_S profile of the surveyed site by inverting the composite DC (as is recommended) or a particular elementary DC. The inversion methods, including methods for post-processing and visualizing the inversion results, are defined on an `InvertDC` object that is initialized using a given DC. The fast delta matrix algorithm [9] is used for forward modelling (i.e., computation of theoretical DCs) and a Monte-Carlo global search algorithm [3] for searching the solution space for the optimal set of model parameters (V_S and h for each layer). A detailed description of the inversion process and recommended practices, e.g., related to model parameterization, is provided in Olafsdottir et al. [1,3].

3. EVALUATION OF MASWavesPy

Comparison with other computational methods

The wavefield transformation and DC extraction methods of MASWavesPy were verified by comparing their results with those of the Active FK toolbox of Geopsy [10]. Figure 2 shows spectral images that were obtained with the two programs using data from three locations in Iceland (one 24-channel shot gather for each site). The three sites are characterized by sediments of Holocene granular materials but have different surficial grain size distributions (silty sand to sandy gravel) and surficial compaction levels.

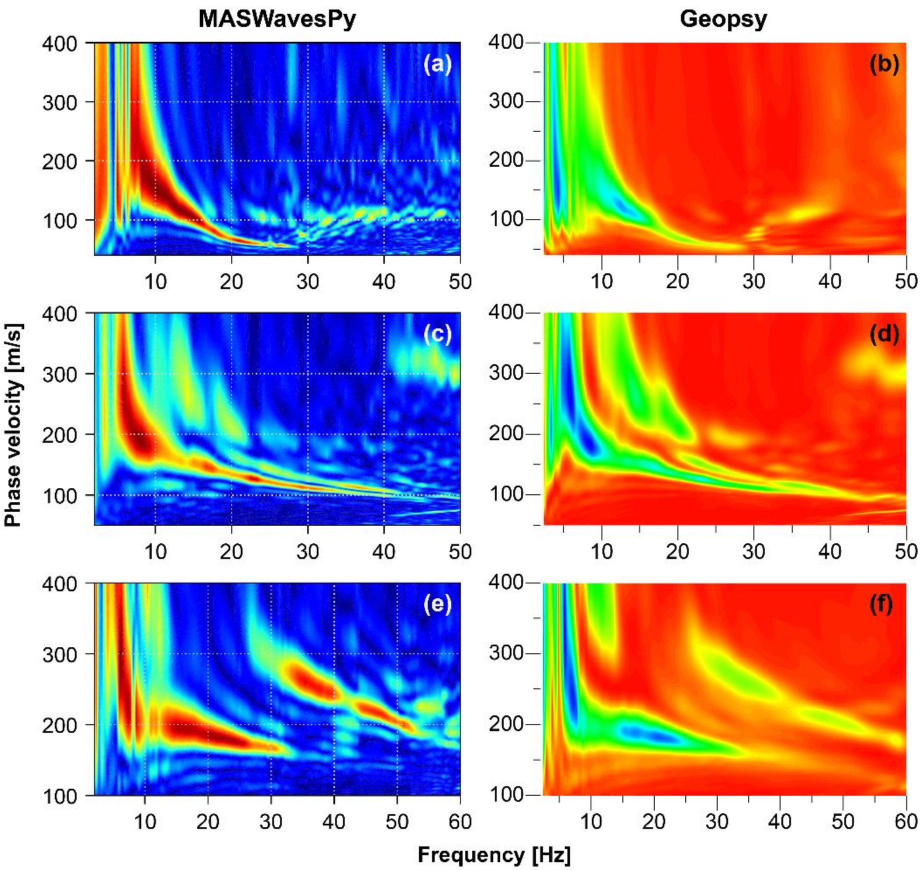

Figure 2. Spectral images obtained with MASWavesPy (left column) and Geopsy (right column). (a,b) Site I. (c,d) Site II. (e,f) Site III.

The corresponding elementary DCs are given in Fig. 3, where they are presented in the phase velocity-wavelength (V_R–λ) domain. Also shown is the composite DC for each site with experimental boundaries defined as one standard deviation of the mean curve. Each composite DC was retrieved using a variety of receiver array lengths and source offsets. Therefore, its wavelength range is wider than that of the two elementary DCs.

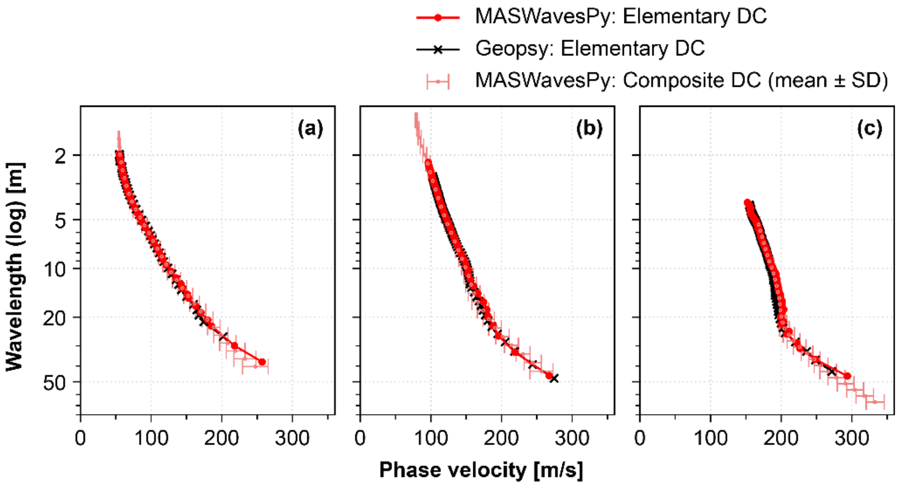

Figure 3. Comparison of experimental DCs obtained with MASWavesPy and Geopsy for (a) site I, (b) site II, and (c) site III. The elementary DCs are extracted from the spectral images shown in Fig. 2. The composite DC (obtained with MASWavesPy) for each site is shown with upper and lower boundaries corresponding to one standard deviation (SD) of the mean curve.

As shown in Figs. 2 and 3, there is a good agreement between Geopsy and MASWavesPy. Each pair of spectral images shows the same dispersion characteristics. The extracted DCs also agree well, with the observed inter-code differences being smaller than, or comparable to, the estimated uncertainty of the composite DC. The fundamental R-wave mode dominated the surface wave signal at sites I and II. At site III, a higher mode was found to dominate at frequencies exceeding 30 Hz (Figs. 2ef), therefore limiting the maximum frequency (minimum wavelength) of the extracted DCs (Fig. 3c). For site II, the spectral imaging routines of both programs revealed higher mode propagation between approximately 12 Hz and 40 Hz (Figs. 2cd). The effects of this on the identification of the fundamental mode DC were though minimal (Fig. 3b).

The forward modelling tool of MASWavesPy was evaluated by comparing its results to those of the gpdc module in Geopsy [10]. Figure 4 shows theoretical dispersion curves (TDCs) that were obtained using the two programs for three soil layer models of varying complexity (Table 1). The models, initially defined by Tokimatsu et al. [11], all present values of V_S that are consistent with those commonly measured in the upper-most 15–20 m at granular soil sites. Model A represents a normally dispersive soil profile. The S-wave velocity varies more irregularly in models B and C, with a stiff surficial layer in model B and a low-velocity layer at depths of 6–14 m in model C. The TDCs were computed over a frequency range of 3–100 Hz, as commonly retrieved in active-source surveys. As shown in Fig. 4, the results show excellent agreement between the two programs, with the TDCs in all cases being nearly identical.

Table 1. Definition of soil layer models A, B and C.

Layer	h [m] (All)	V_P [m/s] (All)	ρ [kg/m^3] (All)	V_S [m/s] Model A	Model B	Model C
1	2.0	360	1800	80	180	80
2	4.0	1000	1800	120	120	180
3	8.0	1400	1800	180	180	120
4	(infinite)	1400	1800	360	360	360

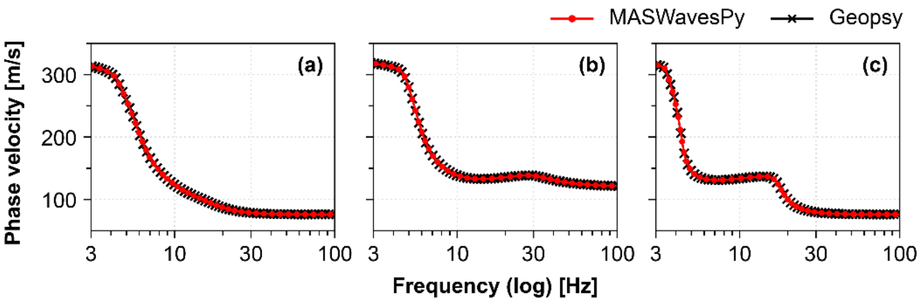

Figure 4. Comparison of theoretical dispersion curves computed with MASWavesPy and Geopsy for (a) model A, (b) model B, and (c) model C.

Comparison with invasive and non-invasive measurements of V_S

For further evaluation of the package, velocity profiles obtained using MASWavesPy were compared with results of invasive, non-invasive, and laboratory-scale measurements of V_S at four well-established geotechnical research sites in Norway. The Halden, Øysand and Tiller-Flotten sites were developed in the Norwegian GeoTest Site (NGTS) project [12]. The research site at Onsøy was established in the late 1960s [13]. The four sites are characterized by deposits of silt, soft clay, silty sand, and quick clay [12-16]. They are, therefore, considered representative of soft soil conditions commonly encountered in engineering practice.

The MASW data was acquired using a set of 24 vertical 4.5 Hz geophones with the receiver arrays placed as close as possible to the relevant invasive measurements. However, some differences may be expected in the V_S assessments as the invasive tests are point measurements whilst SWMs average the soil stiffness properties over a larger area. A certain degree of variability is further associated with inverted V_S profiles, e.g., resulting from the nonuniqueness of the R-wave DC inversion and the choice of layering parameterization. The MASWavesPy data processing and analysis is described in Olafsdottir et al. [1]. An example illustrating the analysis process is given in Fig. 5, showing data and results from Tiller-Flotten.

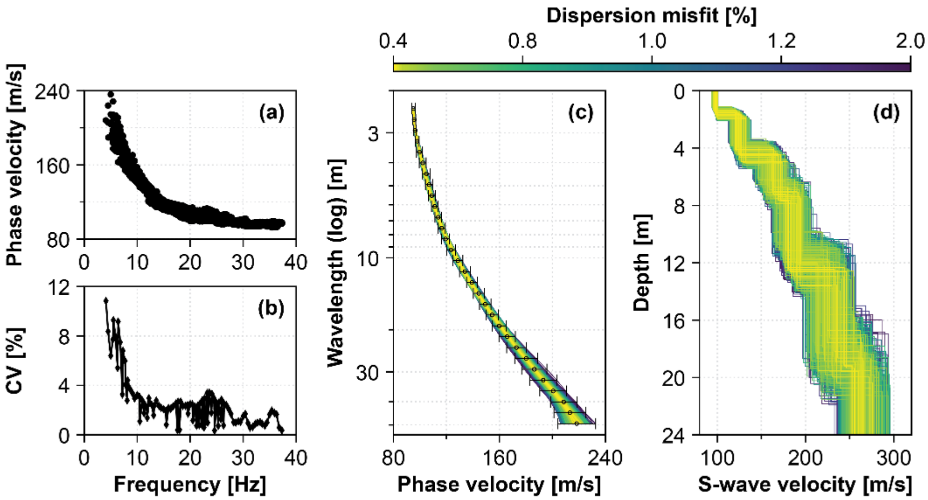

Figure 5. MASW survey at the Tiller-Flotten geotechnical research site. (a) Set of elementary DCs retrieved by processing repeated shot gathers collected at the site. (b) Coefficient of variation (CV) of the identified elementary DCs. (c,d) Sampled V_S profiles whose TDCs fall within one standard deviation (SD) of the composite DC at all wavelengths. The V_S profiles and associated TDCs are color-coded by dispersion misfit values. In (c), the composite DC (mean ± SD) is shown in black.

Figure 6 compares the resulting velocity profiles with the independent assessments of V_S for each of the four sites. The MASWavesPy results are summarized by the median of the set of sampled V_S models whose TDCs fall within one standard deviation of the composite DC. The lowest misfit V_S profile for each site is also shown. The comparison in Fig. 6 reveals that the V_S profiles obtained with MASWavesPy are, overall, consistent with those established with invasive techniques (SCPT and SDMT) and MASW surveys conducted with other hardware and software. They further show comparable values as the laboratory assessments of V_S available for the Halden, Onsøy and Øysand sites.

4. CONCLUSIONS

This paper presents MASWavesPy, an adaptable, open-source Python package to establish soil V_S profiles from MASW-type surface wave data. It is based on an earlier MATLAB tool created by the same authors, with more refined data processing and analysis methods for improved code usability. Furthermore, efforts were made to improve the computational performance of the forward modelling to decrease the run-time of global search approaches in the inversion.

The wavefield transformation, DC extraction and forward modelling tools of MASWavesPy were verified by comparing their results with those of Geopsy, a widely known software for active-source and ambient vibration processing. The performance of the package as a whole was subsequently assessed by measurements at four geotechnical benchmark sites in Norway, where velocity profiles obtained with MASWavesPy were found to be consistent with those previously obtained at the same locations with a variety of in-situ and laboratory techniques.

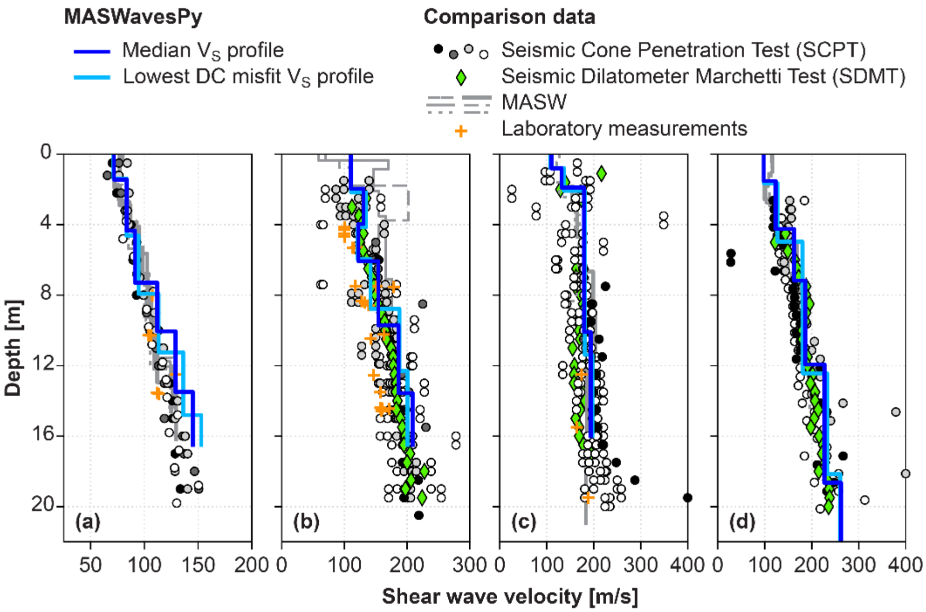

Figure 6. Comparison of inverted V_S profiles (MASWavesPy) and results of invasive, non-invasive and laboratory measurements of V_S for (a) Onsøy, (b) Halden, (c) Øysand, and (d) Tiller-Flotten. SCPT, SDMT, MASW and laboratory results from Blaker et al. [14], Quinteros et al. [15], L'Heureux, Lindgård, and Emdal [16], Long and Donohue [17], Bazin et al. [18], NGI [19], and NGTS data. Figure altered from Olafsdottir et al. [1].

ACKNOWLEDGEMENTS

This work was supported by the Icelandic Research Fund (grants no. 206793-053, 218149-053), the Icelandic Road and Coastal Administration, the Energy Research Fund of the National Power Company of Iceland, and the University of Iceland Research Fund (grant no. 94242). The authors thank the organizers of the NGTS project (www.geotestsite.no) for assistance prior to and during the data acquisition at the Norwegian research sites, and for providing access to results of in-situ and laboratory measurements conducted at the sites.

REFERENCES

[1] E. A. Olafsdottir, B. Bessason, S. Erlingsson and A. M. Kaynia: A Tool for Processing and Inversion of MASW Data and a Study of Inter-Session Variability of MASW. Geotechnical Testing Journal, vol. 47, no. 5, 2024. doi:10.1520/GTJ20230380

[2] E. A. Olafsdottir, S. Erlingsson and B. Bessason: Tool for analysis of multichannel analysis of surface waves (MASW) field data and evaluation of shear wave velocity profiles of soils. Canadian Geotechnical Journal, vol. 55, no. 2, pp. 217–233, 2018. doi:10.1139/cgj-2016-0302

[3] E. A. Olafsdottir, S. Erlingsson and B. Bessason: Open-Source MASW Inversion Tool Aimed at Shear Wave Velocity Profiling for Soil Site Explorations. Geosciences, vol. 10, no. 8, 2020. doi:10.3390/geosciences10080322

[4] S. Foti et al.: Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project. Bulletin of Earthquake Engineering, vol. 16, no. 6, pp. 2367–2420, 2018. doi:10.1007/s10518-017-0206-7

[5] C. M. Wood and B. R. Cox: A comparison of MASW dispersion uncertainty and bias for impact and harmonic sources. Proc. of GeoCongress 2012, pp. 2756–2765, 2012. doi:10.1061/9780784412121.282

[6] J. P. Vantassel and B. R. Cox: SWprocess: a workflow for developing robust estimates of surface wave dispersion uncertainty. Journal of Seismology, vol. 26, pp. 731–756, 2022. doi:10.1007/s10950-021-10035-y

[7] C. B. Park, R. D. Miller and J. Xia: Imaging dispersion curves of surface waves on multi-channel record. SEG Technical Program Expanded Abstracts 1998, pp. 1377–1380, 1998. doi:10.1190/1.1820161

[8] E. A. Olafsdottir, B. Bessason and S. Erlingsson: Combination of dispersion curves from MASW measurements. Soil Dynamics and Earthquake Engineering, vol. 113, pp. 473–487, 2018. doi:10.1016/j.soildyn.2018.05.025

[9] P. W. Buchen and R. Ben-Hador: Free-mode surface-wave computations. Geophysical Journal International, vol. 124, no. 3, pp. 869–887, 1996. doi:10.1111/j.1365-246X.1996.tb05642.x

[10] M. Wathelet et al.: Geopsy: a user-friendly open-source tool set for ambient vibration processing. Seismological Research Letters, vol. 91, no. 3, pp. 1878–1889, 2020. doi:10.1785/0220190360

[11] K. Tokimatsu, S. Tamura and H. Kojima: Effects of multiple modes on Rayleigh wave dispersion characteristics. Journal of Geotechnical Engineering, vol. 118, no. 10, pp. 1529–1543, 1992. doi:10.1061/(ASCE)0733-9410(1992)118:10(1529)

[12] J.-S. L'Heureux et al.: Norway's National GeoTest Site Research Infrastructure (NGTS). Proc. of the 19th Int. Conf. on Soil Mechanics and Geotechnical Engineering, pp. 611–614, 2017.

[13] T. Lunne, M. Long and C. F. Forsberg: Characterisation and engineering properties of Onsøy clay. Characterisation and Engineering Properties of Natural Soils, vol. 1, pp. 395–428, 2003.

[14] Ø. Blaker et al.: Halden research site: geotechnical characterization of a post glacial silt. AIMS Geosciences, vol. 5, no. 2, pp. 184–234, 2019. doi:10.3934/geosci.2019.2.184

[15] S. Quinteros et al.: Øysand research site: Geotechnical characterisation of deltaic sandy-silty soils. AIMS Geosciences, vol. 5, no. 4, pp. 750–783, 2019. doi:10.3934/geosci.2019.4.750

[16] J.-S. L'Heureux, A. Lindgård and A. Emdal: The Tiller-Flotten research site: Geotechnical characterization of a very sensitive clay deposit. AIMS Geosciences, vol. 5, no. 4, pp. 831–867, 2019. doi:10.3934/geosci.2019.4.831

[17] M. Long and S. Donohue: In situ shear wave velocity from multichannel analysis of surface waves (MASW) tests at eight Norwegian research sites. Canadian Geotechnical Journal, vol. 44, no. 5, pp. 533–544, 2007. doi:10.1139/t07-013

[18] S. Bazin et al.: Geophysical characterisation of marine and quick clay sites: field and laboratory tests. Proc. of the 5th Int. Conf. on Geotechnical and Geophysical Site Characterisation, vol. 2, pp. 831–836, 2016.

[19] NGI: Field and laboratory test results Halden. Norwegian GeoTest Sites (NGTS). Factual report 20160154-04-R, Norwegian Geotechnical Institute (NGI), 2018.