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Stiffness profiles of earth dams based on the MASW technique

Profils de rigidité des barrages en terre basés sur la technique MASW

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ABSTRACT: Multichannel Analysis of Surface Waves (MASW) is a non-invasive seismic exploration method for evaluation of near-surface stiffness profiles. In recent years, MASW has been applied at a number of natural soil sites in Iceland. This study aims at extending its use to the analysis of earth dams. This paper discusses the application of MASW for characterization of the stiffness properties of three dams in the catchment area of the rivers Þjórsá and Tungnaá in Iceland's south central highlands; Sigalda dam, Sporðalda dam and Sultartangi dam. The experimentally evaluated stiffness profiles are compared with profiles obtained by empirical methods and, at the Sultartangi site, results of existing in-situ measurements of shear wave velocity. Overall, the stiffness profiles obtained by MASW are consistent with the empirically evaluated profiles and compare well with the available experimental results. In practical terms, the results of the study indicate that, if appropriately conducted, the MASW method can serve as a valuable tool to evaluate the stiffness properties of earth dams in Iceland.

RÉSUMÉ: L'analyse des ondes de surface (MASW) est une méthode d'exploration sismique permettant d'évaluer les profils de rigidité proche de la surface. Ces dernières années, la technique MASW a été appliqué sur plusieurs sites de sols naturels en Islande. Cette étude vise à étendre son utilisation aux barrages en terre. L'application de MASW pour la caractérisation des propriétés de rigidité de trois barrages situés dans les hauts plateaux du centre-sud de l'Islande, les barrages Sigalda, Sporðalda et Sultartangi, est examinée. Les profils de rigidité évalués expérimentalement sont comparés aux profils obtenus par des méthodes empiriques et, sur le site de Sultartangi, aux résultats de mesures in situ existantes de la vitesse des ondes de cisaillement. Les profils de rigidité obtenus par MASW sont cohérents avec les profils de rigidité évalués de manière empirique et se comparent bien aux résultats expérimentaux disponibles. En termes pratiques, les résultats de l'étude indiquent que, si elle est correctement menée, la méthode MASW peut constituer un outil précieux pour évaluer les propriétés de rigidité des barrages en terre en Islande.

Keywords: Earth dams; surface wave analysis; Multichannel Analysis of Surface Waves (MASW); small-strain shear stiffness; shear wave velocity

1 INTRODUCTION

Hydropower is the primary source of electricity in Iceland with more than 70% of the total production in 2017 being hydroelectricity (Orkustofnun 2018). Earth- and/or rock-filled dams form an indispensable part of the Icelandic hydropower system. Due to the volcanic activity in Iceland and a long history of frequent glacial outburst floods with fast build-up of sediments,

the fill materials used in these dams are quite different from the materials used in other countries. Seismic hazard is moderate to high in Iceland due to the Mid-Atlantic plate boundary that crosses the island. Hence, the dams in the Icelandic hydropower system can be exposed to high earthquake loads and must be designed to withstand large earthquakes without developing excessive deformations.

The small-strain shear stiffness is a key parameter for dynamic analysis of earth dams. It is further directly proportional to the shear wave velocity of the soil material (Kramer 1996)

$$G_{max} = \rho \cdot (V_S)^2 \quad (1)$$

where G_{max} (Pa) is small-strain shear stiffness, V_S (m/s) is shear wave velocity and ρ (kg/m^3) is material density.

Utilization of experimentally measured values of shear wave velocity is generally considered the most reliable way of assessing the in-situ value of G_{max} (Kramer 1996). Due to potential seepage hazard associated with borehole drilling, as well as excessive cost, the use of invasive methods for evaluating the V_S-profiles of earth dams is limited (Park and Kishida 2018). Non-invasive geophysical techniques can be an appealing choice as they are low-cost and neither require heavy machinery nor risk damaging the dam structure. In cases where measurements of shear wave velocity are not available, empirical formulas, e.g. in the form of Eq. (2), relating the small-strain shear stiffness to other material properties can be used

$$G_{max} = K \cdot (\sigma'_m)^n \quad (2)$$

where σ'_m (kPa) is the effective confining pressure and K, n are material dependent correlation parameters (Kramer 1996).

Multichannel Analysis of Surface Waves (MASW) is a non-invasive seismic exploration method for evaluation of near-surface shear wave velocity profiles. The use of MASW to study the dynamic properties of earthen dams and levees has been reported by several researchers (e.g. Karl et al. 2011, Cardarelli et al. 2014, Ha 2017, Rahimi et al. 2018, Park and Kishida 2018). In recent years, MASW has been applied at a number of natural soil sites in Iceland (Ólafsdóttir et al. 2019a, 2019b). This study aims at extending its use to the analysis of Icelandic earth dam structures. In order to gain practical experience in applying the MASW method to study the stiffness properties of earth- and rock-filled dams, in-situ measurements were conducted on the crests of three dams in Iceland; Sigalda dam, Sporðalda dam and Sultartangi dam. The Sporðalda and Sultartangi dams are rock-filled dams with a central core of moraine and/or loess (Silver et al. 1986), whereas the Sigalda dam has an impervious frontal facing of asphalt (Thorlaksson et al. 1978). The experimentally evaluated stiffness profiles were compared to profiles obtained by use of empirical methods in order to find appropriate formulas and parameter sets for empirical assessments of the stiffness properties of typical Icelandic earth dams. At the Sultartangi site, it was further possible to compare the results of the MASW measurements to the results of a SASW survey previously conducted at the site.

2 TEST SITES AND SURVEY PROCEDURE

The three dams studied in this work are located in the catchment area of the rivers Þjórsá and Tungnaá in Iceland's south central highlands (Figure 1) and are all part of the hydropower system operated the National Power Company of Iceland (Landsvirkjun). At each of the sites, an array of 24 vertical geophones with a natural frequency of 4.5 Hz was used for field measurements. The data acquisition and analysis were carried out by use of the open-source software MASWaves (Ólafsdóttir et al. 2018a, see also masw.hi.is).

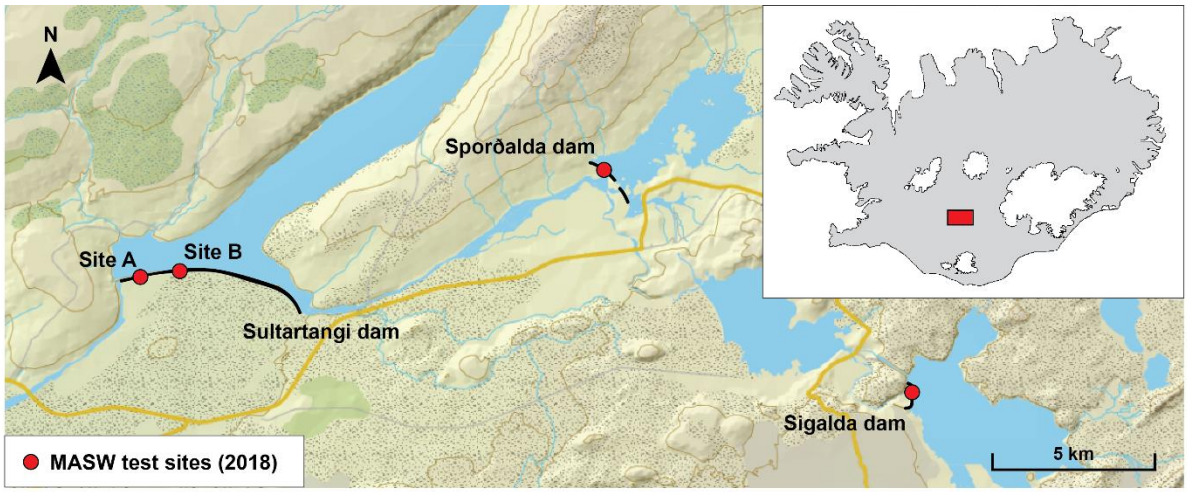


Figure 1. Location of MASW test sites at Sigalda dam, Sporðalda dam and Sultartangi dam. [The map is based on data from the National Land Survey of Iceland.]

At each of the four test locations (Figure 1), the seismic data were acquired along the dam crest with the survey profile aligned approximately along its middle line. For the Sporðalda and Sultartangi sites, the retrieved V_S-profiles are expected to be primarily representative of the core zone of the dams. However, the presence of the fill material may affect the results of the MASW survey, resulting in some kind of a composite V_S-profile for the two materials. As pointed out by Park and Kishida (2018), determination of the stiffness of the core material in an earth-core rock-filled dam can be difficult by means of a conventional MASW survey conducted on the dam crest. Due to the geometry of the dam, the acquired surface wave data might contain a combination of the response of the core and shell materials. A comparison of V_S-profiles obtained by MASW and downhole surveys for earth-core rock-filled dams in Korea, revealed that the V_S values obtained by MASW exceeded those from the borehole measurements at depths greater than 15–25 m, likely due to this effect (Park and Kishida 2018). Another recent survey on a Korean earth-core rock-filled dam, however, did not report such difference between results of MASW and borehole measurements (Ha 2017).

2.1 Sigalda dam

The Sigalda dam is a 0.93 km long asphalt face rock-fill dam, founded on moberg and postglacial lava flows (Thorlaksson et al. 1978). The dam was built in the 1970s as a part of the Sigalda hydropower scheme and forms the 14 km^2 Krókslón reservoir (Gunnarsdóttir 2016). The maximum height of the embankment is 40 m (Thorlaksson et al. 1978). The fill material of the dam consists of reworked moberg, breccia, tuff and sand, and is classified as well-graded gravel (GW) according to the Unified Soil Classification System (USCS). The unit weight of the fill material has been evaluated as 20.6 kN/m^3 and its friction angle as 38° (Thorlaksson et al. 1978, Silver et al. 1986). Due to the presence of the impervious upstream asphalt cladding, the fill material is assumed to be unsaturated.

2.2 Sporðalda dam

The Sporðalda dam was built between 2011 and 2013 as a part of the Búðarháls power station project and forms the 7 km^2 Sporðalda reservoir (Gunnarsdóttir 2016). The Sporðalda dam is an earth- and rock-fill dam with a central core of moraine with a unit weight of around 23 kN/m^3. The dam consists of two separate parts. The

north-western part is 1105 m long and 28.0 m high at its highest cross section, whereas the dam's south-eastern part is 315 m long and with a maximum height of 27.6 m. The MASW survey was conducted on the crest of the north-western part of the dam (Figure 1). The height of the embankment within the investigated section is around 25 m.

2.3 Sultartangi dam

The Sultartangi dam is the longest dam in Iceland with a total length of 6.1 km. It was built between 1982 and 1984 (Gunnarsdóttir 2016). In the late 1990s, the crest of the dam was raised by a meter in conjunction with the construction of the Sultartangi power station. After completion of the second construction phase, the maximum height of the dam is 23 m (Landsvirkjun 2011).

The Sultartangi dam is an earth- and rock-fill dam with a central core of moraine and loess. MASW field measurements were conducted at two locations on the crest of the western part of the dam, where the height of the dam is the most and its central core is primarily made of loess. The unit weight of the core material has been evaluated as 16.9 kN/m^3 and the saturated unit weight as 18.1 kN/m^3 (Silver et al. 1986). The location of the two test sites on the crest of the Sultartangi dam is shown in Figure 1. The distance between the survey locations (measured midpoint-to-midpoint) is around 1.1 km.

3 MASW MEASUREMENTS

The data acquisition was conducted using two to three survey profiles with the same midpoint but different lengths, 11.5 m, 23 m and/or 46 m. A 6.3 kg sledgehammer, struck on a 15 cm-diameter metallic base plate, was used as an impact source with shots taken at offsets in the range of 3 m to 10 m from one end of the receiver spread. Furthermore, for each measurement profile configuration, four to five multichannel records were acquired. The records were later stacked for enhanced data quality, prior to identification of experimental dispersion curves and commencement of the inversion analysis (Ólafsdóttir et al. 2018a, 2018b).

3.1 Measurements at Sigalda dam

The results of the MASW measurements conducted on the crest of the Sigalda dam are presented in Figure 2. Figures 2a-c show stacked dispersion images obtained from data acquired by using receiver spreads of different lengths; i.e. 11.5 m, 23 m and 46 m. By lengthening the receiver spread, the high-amplitude peaks appeared sharper and better separation of overtones was observed. This is in agreement with trends observed in data gathered at various natural test sites in Iceland (Ólafsdóttir et al. 2018b). Below a frequency of approximately 30 Hz, the high-amplitude band is believed to correspond to the fundamental mode of the Rayleigh wave propagation. However, between 30 Hz and 40 Hz, where the spectral images in Figures 2a, b show an abrupt upward bend, the peak energy may be jumping to a higher mode or propagating at an effective mode. This suspicion is strengthened by the dispersion image in Figure 2c, where the high-amplitude band splits into two separate parts at a frequency of around 35 Hz.

The estimated V_S-profile for the Sigalda dam site is presented in Figure 2d. The corresponding theoretical dispersion curve is compared to the observed dispersion characteristics in Figures 2a-c. For inversion of the experimental data, a constant Poisson's ratio of 0.3 was assumed for the fill material. Due to the presence of the asphalt cladding on the upstream side of the dam, the inversion was conducted based on the assumption that the fill material was unsaturated.

Overall, the results presented in Figure 2 indicate a relatively gradual increase in V_S (stiffness) down to the maximum investigated depth of 25 m. The results of the survey are further presented in the form of $\bar{V}_{S,z}$ in Figure 2e,

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

where $\bar{V}_{S,z}$ (m/s) is the average shear wave velocity of the uppermost z meters, and $V_{S,j}$ (m/s) and h_j (m) denote the shear wave velocity and thickness of the j-th layer for a total of N layers down to depth z (CEN 2004).

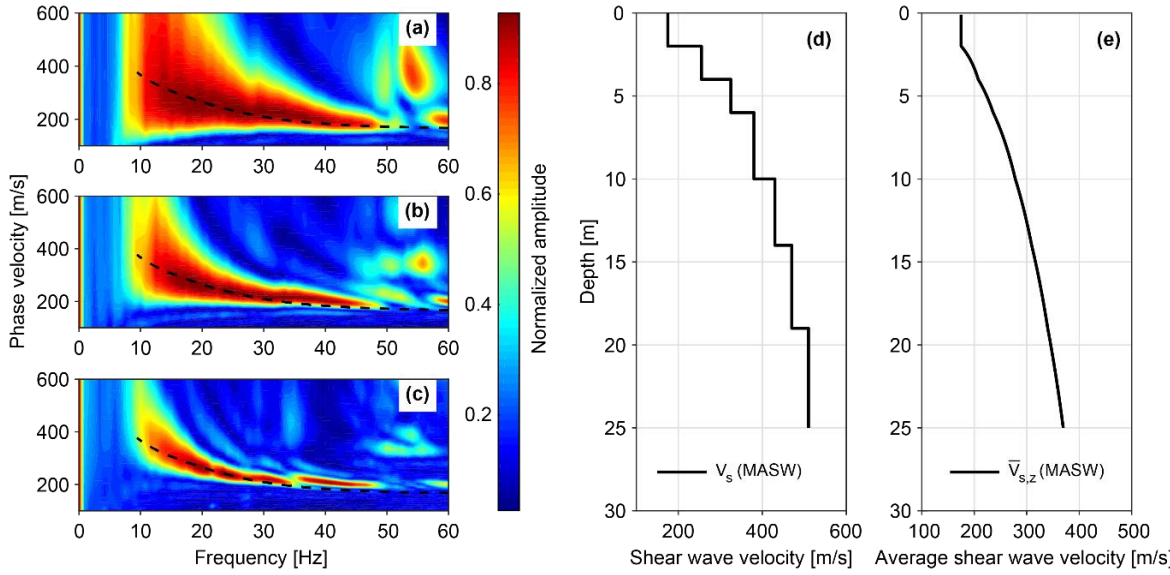


Figure 2. Results of MASW surveys at the crest of Sigalda dam. Dispersion images obtained by profiles of length (a) 11.5 m, (b) 23 m and (c) 46 m. Estimated (d) shear wave velocity (V_S) and (e) average V_S ($\bar{V}_{S,z}$) profiles for the Sigalda site. The dispersion curve corresponding to the V_S-profile in (d) is shown by a dashed line in (a)-(c).

3.2 Measurements at Sporðalda dam

The results of the MASW measurements conducted on the crest of the Sporðalda dam are illustrated in Figure 3. Figures 3a, b show stacked dispersion spectra of records acquired using receiver spreads of length 11.5 m and 23 m, respectively. As compared to the dispersion images obtained for the Sigalda dam site (Figures 2a-c), the spectra presented in Figure 3 do not display an equally continuous peak energy band. The fact that the Sporðalda dam has a central core, whereas the Sigalda dam is comprised of a relatively uniform soil material, is considered likely to contribute to this observed difference.

The shear wave velocity profile estimated for the Sporðalda dam site is shown in Figure 3c. The corresponding theoretical dispersion curve is compared to the experimental data in Figures 3a, b. The $\bar{V}_{S,z}$-profile for the site [Eq. (3)], is further visualized in Figure 3d.

For inversion of experimental Rayleigh wave dispersion curves, an estimated location of the groundwater table at the survey site is required. The depth to groundwater varies greatly within an earth dam structure. Furthermore, the level of groundwater is correlated to, e.g., the water level in the reservoir that the dam forms. Hence, considering a survey carried out on the crest of an earth dam, obtaining a clear-cut estimate of the location of the groundwater table is impossible. For inversion of the dispersion data acquired at the crest of the Sporðalda dam, the groundwater table within its central core was set at an average depth of approximately 10 m, i.e. at around 2/5 of the height of the dam as measured from the top of the structure. Furthermore, a Poisson's ratio of 0.3 was estimated for the soil layers above the

assumed groundwater table. For comparison purposes, the inversion process was repeated, assuming the same layer structure as shown in Figure 3c, based on the following two assumptions; (i) the average groundwater table is located at a depth of approximately 2 m, and (ii) the dam is unsaturated. Raising the groundwater table lead to a decrease in estimated shear wave velocities, below the depth of 2 m, in the order of 5-10%. Increasing the depth to groundwater did not have a significant effect on the estimated shear wave velocity values.

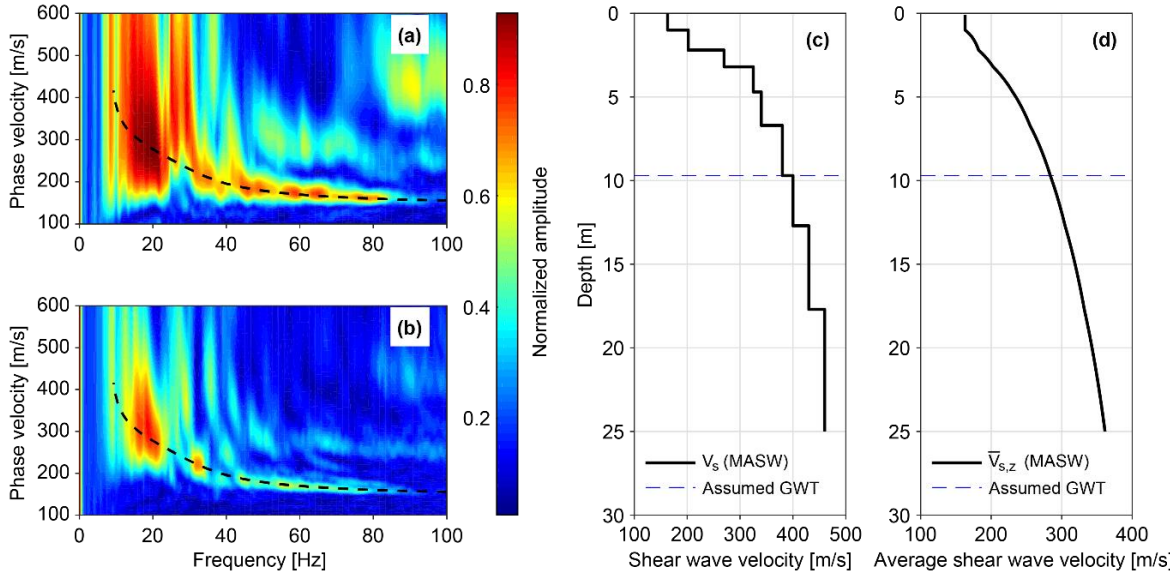


Figure 3. Results of MASW measurements conducted at the crest of the Sporðalda dam. Dispersion images obtained by using survey profiles of length (a) 11.5 m and (b) 23 m. Estimated (c) shear wave velocity (V_S) and (d) average shear wave velocity ($\bar{V}_{S,z}$) profiles for the Sporðalda dam site. The theoretical dispersion curve corresponding to the V_S-profile in (c) is shown by a black dashed line in (a) and (b). The assumed location of the groundwater table (GWT) within the central core of the dam is shown using a blue dashed line in (c) and (d).

3.3 Measurements at Sultartangi dam

MASW surveys were carried out at two locations on the crest of the Sultartangi dam, here referred to as 'site A' and 'site B' (Figure 1). The results of the MASW measurements at the two sites are presented in Figure 4. Figures 4a, b show stacked dispersion images obtained from data acquired at site A using receiver spreads of length 11.5 m and 23 m, respectively. Furthermore, the theoretical dispersion curve, corresponding to the estimated V_S-profile for site A (Figure 4c), is compared to the experimental spectra in Figures 4a, b. The dispersion images obtained for Sultartangi site B indicated comparable dispersion characteristics. The V_S-profile for site B is shown in Figure 4c using a red solid line. The $\bar{V}_{S,z}$-profiles for the two Sultartangi test sites, obtained by Eq. (3), are further compared in Figure 4d.

For analysis of the surface wave records acquired on the crest of the Sultartangi dam, the average depth to groundwater was estimated as 9 m (around 2/5 of the height of the structure as measured from its top). As observed for the Sporðalda dam test site, raising the assumed groundwater table to 2 m below the crest of the dam resulted in a decrease in estimated shear wave velocity values, below 2 m depth, of the order of 5-10%. The effects of lowering the groundwater table (i.e. below 9 m) were insignificant.

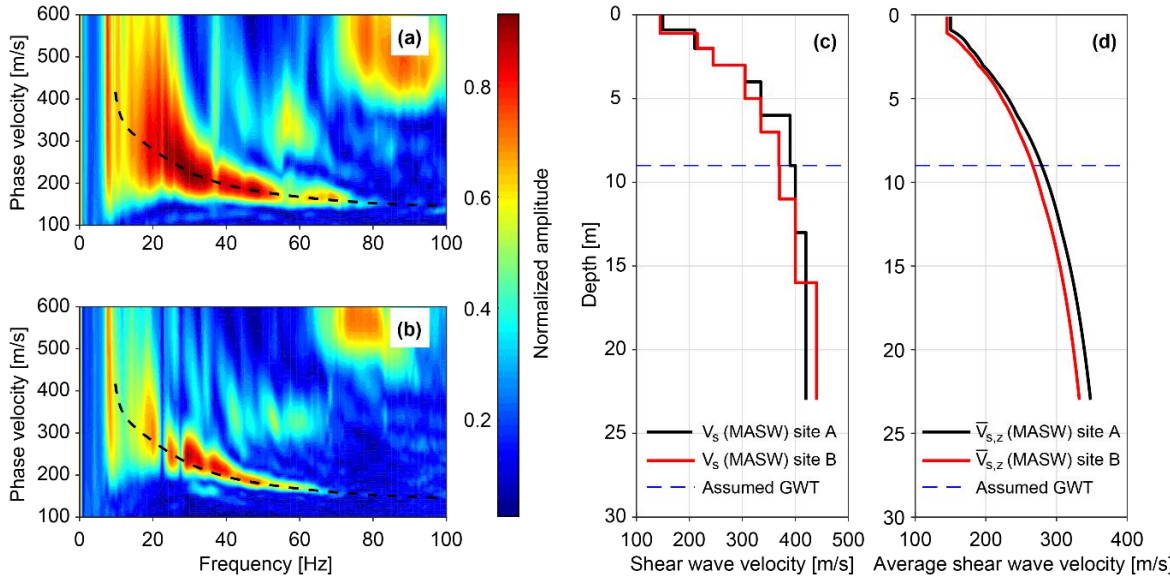


Figure 4. Results of MASW measurements conducted at two locations on the crest of the Sultartangi dam (site A and site B). Dispersion images obtained at Sultartangi site A by using survey profiles of length (a) 11.5 m and (b) 23 m. Estimated (c) shear wave velocity (V_S) and (d) average shear wave velocity ($\bar{V}_{S,z}$) profiles for the two Sultartangi dam test sites. The theoretical dispersion curve corresponding to the V_S-profile for site A is shown using a black dashed line in (a) and (b). The assumed location of the groundwater table (GWT) within the central core of the dam is shown using a blue dashed line in (c) and (d).

4 COMPARISON

Substantial research has been carried out to develop and evaluate empirical correlations between the small-strain shear stiffness (G_{max}) of soil and other material parameters, most importantly the effective confining pressure (σ'_m) and the void ratio (e). A common feature of such correlations is that G_{max} is assumed to be proportional to the square root of σ'_m (Kramer 1996), i.e. that the stress exponent in Eq. (2) is taken as $n = 0.5$.

The model of Seed and Idriss [Eq. (4)] is a well-known correlation for predicting the small-strain shear modulus of granular soils,

$$G_{max} = 1000 \cdot K_{2,max}\sqrt{\sigma'_m} \qquad (4)$$

where $K_{2,max}$ (kPa$^{0.5}$) is an empirical coefficient (Gazetas 1991, Kramer 1996). For evaluation of σ'_m, the unit weight (γ and/or γ_{sat}) and the friction angle (ϕ') of the material are required. The effects of the void ratio are taken into account by the parameter $K_{2,max}$. Suggested values of $K_{2,max}$ for several groups of granular soils (Gazetas 1991) are provided in Table 1.

Table 1. Suggested values of the coefficient $K_{2,max}$ in Eq. (4) for granular soil materials.

Soil type	$\boldsymbol{K_{2,max}}$ [(kPa)$^{0.5}$]
Loose sand	8
Dense sand	12
Very dense sand	16
Very dense sand and gravel	25-40

Figure 5 shows the small-strain shear stiffness profiles for the Sigalda dam, Sporðalda dam and Sultartangi dam test sites, respectively, as obtained from the results of the MASW surveys. Figure 5 further compares empirically estimated stiffness profiles for the three sites to the

measured (MASW) profiles. The empirical profiles are obtained from the correlation of Seed and Idriss [Eq. (4)] using several values of the parameter $K_{2,max}$ within the range recommended for very dense sand and gravel (Table 1). For computation of the empirical profiles, a friction angle of 40° was assumed for the Sporðalda and Sultartangi sites. For simplification of the modelling, the material parameters were assumed to be independent of depth.

The results presented in Figure 5 indicate that the experimentally evaluated small-strain shear stiffness profiles can in general be fitted adequately well with empirical curves that assume the small-strain stiffness to be directly proportional to the square-root of the effective confining pressure ($\sqrt{\sigma'_m}$). A value of $K_{2,max}$ in the range of 30-35 seems to provide the best fit between the experimental and empirical stiffness profiles for the Sigalda and Sporðalda dams. However, for the two test sites on the crest of the Sultartangi dam (where the central core was primarily made of loess), a slightly lower value of $K_{2,max}$, or between 25-30, appears to provide the closest match between the experimental and empirical results.

4.1 Comparison of MASW and SASW measurement results

Spectral Analysis of Surface Waves (SASW) measurements were conducted on the crest of the Sultartangi dam in 1984 (Silver et al. 1986). Figure 6a presents a comparison of the shear wave velocity profiles obtained as a result of the 1984 SASW measurements and the 2018 MASW measurements. As the layer thicknesses of the three soil layer models shown in Figure 6a (i.e. MASW Sultartangi dam - site A, MASW Sultartangi dam - site B and SASW Sultartangi) differ, the estimated shear wave velocity values are further compared in terms of the $\overline{V}_{S,z}$-profiles [Eq. (3)] for the sites in Figure 6b.

In general, the SASW shear wave velocity profile agrees well with the profiles estimated for the Sultartangi dam test sites by using the MASW method. The results of the SASW survey predict somewhat higher values of V_S for the upper-most soil layers. However, below a depth of 2-3 m, the results of the SASW measurements indicate a slightly less stiff soil profile than the MASW survey, particularly at site A.

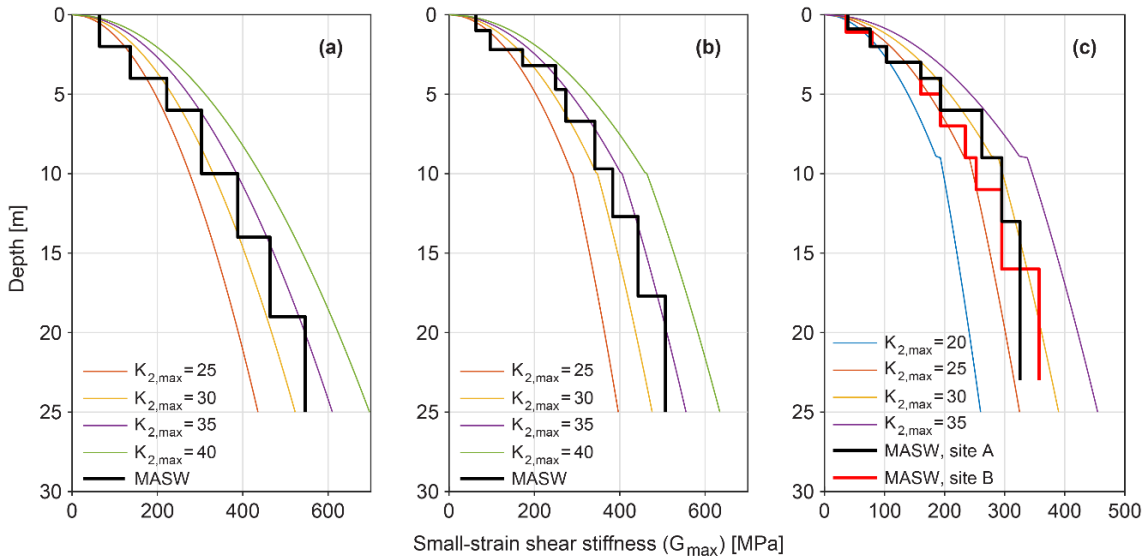


Figure 5. Comparison of empirical and experimental stiffness profiles for the (a) Sigalda dam site, (b) Sporðalda dam site and (c) Sultartangi dam sites. The empirical profiles are obtained by to the model of Seed and Idriss.

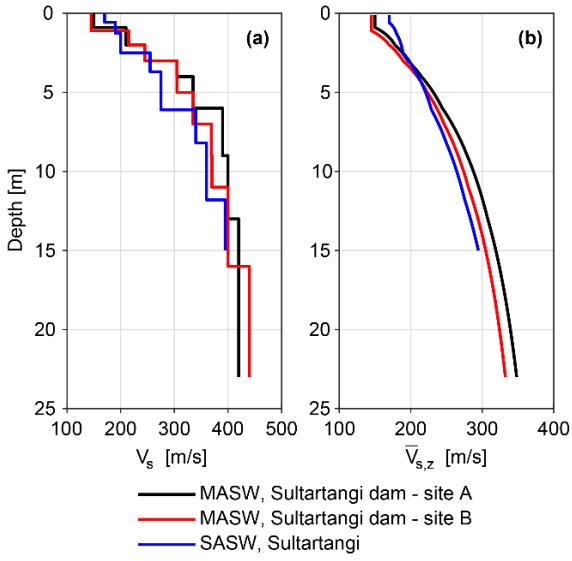


Figure 6. Comparison of (a) shear wave velocity (V_S) profiles and (b) average shear wave velocity ($\bar{V}_{S,z}$) profiles obtained at the crest of the Sultartangi dam by use of the SASW and MASW methods.

5 CONCLUSIONS

In this study, the surface wave analysis method MASW was successfully applied to evaluate the near-surface shear wave velocity/stiffness profiles of three dams in Iceland's south central highlands; Sigalda dam, Sporðalda dam and Sultartangi dam, with measurements conducted at one or two locations on the crest of each dam. The experimentally evaluated stiffness profiles were compared with profiles obtained by empirical methods and, at the Sultartangi dam site, results of existing in-situ measurements of shear wave velocity. Overall, the stiffness profiles obtained by MASW were consistent with the empirically evaluated profiles and compared well with the available experimental results. Particularly, the correlation of Seed and Idriss [Eq. (4)] with $K_{2,max}$ in the range of 25-35, depending on the type of soil material used for construction of the dam, seems to provide a good fit between the experimental and empirical profiles.

The small-strain shear stiffness is a fundamental parameter required for dynamic analysis of earth dams. Direct measurements of shear wave velocity are usually considered the most reliable way of assessing the in-situ value of G_{max}. However, at sites where measurements of V_S are not available, the use of empirical correlations, relating G_{max} to other material properties, can provide valuable estimations. Many such correlations have been developed in the past, utilizing field data collected in different parts of the world. Nonetheless, due to the unique characteristics of Icelandic soils, existing models should be evaluated against results of in-situ measurements prior to their use.

In practical terms, the results of the study indicate that, if appropriately conducted, the MASW method can serve as a valuable tool to evaluate the stiffness properties of earth dams in Iceland. At sites where in-situ values of V_S have not been obtained, the correlation of Seed and Idriss can be considered as a possible alternative to field measurements. However, comparison of experimentally and empirically estimated stiffness profiles from other dam sites is considered necessary for further verifying its applicability, and for making specific recommendations regarding appropriate values of the parameter $K_{2,max}$.

6 ACKNOWLEDGEMENTS

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