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Depth-dependent empirical correlations for the shear wave velocity of Icelandic soils

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ABSTRACT: The geological characteristics of Icelandic soil sites are in many ways unusual. The soil deposits are geologically young, of volcanic origin, and have often been formed rapidly in catastrophic events, such as glacial outburst floods and sub-glacial volcanic eruptions. Hence, the local soils are largely comprised of normally consolidated basaltic granular materials, that frequently contain a mixture of different grain sizes ranging from silty sand to boulders. Furthermore, thick peat deposits exist in some locations. Surface wave measurements (SWMs) have been found well-suited for shear wave velocity (V_S) profiling of Icelandic soil sites, including gravelly sites and sites with partly cemented materials or mixed soils containing cobbles or boulders. This study presents the development of a set of empirical models to represent the V_S distribution as a function of depth for the three primary soil site categories in Iceland, as well as engineered fills. More specifically, listed in order of increasing soil stiffness, (i) peat and peaty soil sites, (ii) silty, sandy or gravelly soil sites, (iii) well-compacted engineered fills and earth dams, and (iv) cemented/conglomerated silty sand sites. In total, the empirical models were developed from active-source SWMs conducted at several tens of locations in the country. The resulting depth-dependent empirical correlations are, in absence of site-specific measurements, of value to assess soil stiffness parameters for the respective soil types for research and engineering design.

KEYWORDS: Shear wave velocity, surface wave analysis, empirical correlations, soil site categories, Iceland.

1 INTRODUCTION

The distribution of shear wave velocity (V_S) with depth is a key parameter in soil dynamics and geotechnical earthquake engineering. The soil site conditions in Iceland, being shaped by a combination of active volcanism and glaciations, are in many ways unusual (Erlingsson, 2019). The local soils are mostly normally consolidated coarse-grained basaltic aggregates (i.e., coarse silt, sand and coarser grains), often with highly irregularly shaped grains and intra-particle voids of varied shapes and sizes. The soils have been created by glacial erosion or weathering, or formed in volcanic eruptions, and transported by fluvial, glacial and aeolian processes, usually from the central highlands towards the coast. Notably, in large areas, thick deposits of loosely compacted sandy and gravelly materials have been built up in catastrophic events in the Holocene epoch, e.g., major outburst floods triggered by sub-glacial volcanic or geothermal activities. In addition, as is common in other countries in the northern latitudes, substantial deposits of peat exist in some parts of Iceland.

Surface wave measurements (SWMs) have been found well-suited for V_S profiling of Icelandic soil sites, including gravelly deposits and sites with partly cemented materials or mixed soils containing cobbles or boulders (e.g., glacial till). As part of earlier work undertaken by the authors, results of SWMs conducted at soil sites in Iceland have been organized and archived (Bessason & Erlingsson, 2011; Olafsdottir et al., 2023, 2024a). In addition to SWMs carried out as part of various research projects on seismic risk in Iceland, site-specific measurements of V_S have been conducted in relation to several major civil engineering projects in the country. Due to the need for specialized equipment and personnel, SWMs are, however, rarely conducted for smaller-scale construction and infrastructure projects. In such cases, indirect estimates of V_S obtained with empirical formulae, or knowledge drawn from measurements conducted at locations with comparable soil site characteristics, are of high value. The same applies for, e.g., future national- or regional-scale seismic microzonation efforts, where empirical V_S formulae for the primary types of surficial soil deposits would supplement direct measurements of V_S.

The shear strains induced by SWMs are well within the range where the soil response can be assumed as elastic. The resulting V_S profiles can therefore be used, together with information on the material density (ρ), to evaluate the in-situ variation of the small-strain shear modulus (G_{max}) with depth,

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

Prior work of the authors has indicated that in-situ values of G_{max} [Equation (1)] for the most-encountered types of Icelandic soil deposits may be adequately described by correlations that assume G_{max} to be directly proportional to the square root of the effective confining pressure (σ'_m),

$$G_{max} = K_{2,max} (\sigma'_m)^{0.5} \qquad (2)$$

where $K_{2,max}$ is an empirical coefficient (Erlingsson et al., 2022). However, the current lack of data on the soil principal properties and the expected location of the groundwater table at the respective SWM test sites, as needed for evaluation of σ'_m, remains a considerable source of uncertainty. For this reason, the use of regression forms that directly relate measured values of V_S to depth (z) may be favoured. Moreover, as the optimum value of $K_{2,max}$ for each category (i.e., the value of $K_{2,max}$ providing the best fit to the in-situ estimates of G_{max}) was found to increase with depth, alternative regression forms to that given by Equation (2) may be better suited to describe the depth-dependent shear stiffness characteristics of the local soils.

Here we describe a set of empirical models to represent the V_S distribution as a function of depth for the three primary soil site categories in Iceland, as well as engineered fills and earth dam structures. More specifically, listed in order of increasing stiffness, the current work considers: (i) peat and peaty soil sites; (ii) silty, sandy or gravelly sites; (iii) well-compacted engineered fills and earth dams comprised of silty, sandy or gravelly soils; and (iv) cemented/conglomerated silty sand sites. SWMs of V_S for sites belonging to each of the four categories were collected from existing databases and published studies. Different empirical models, proposed in literature to describe the relationship between V_S and z, were evaluated against the in-situ V_S profiles to identify the optimal regression form for each soil site category.

2 SHEAR WAVE VELOCITY PROFILE DATA

Figure 1 presents the compiled dataset that was used to describe the variation of V_S with depth for the local soils. The natural deposits are classified based on their general site characteristics, obtained from available geotechnical data and geological maps, as peat and peaty soil sites (gray lines in Figure 1, 6 V_S profiles), deposits of silty, sandy or gravelly soils (blue, 50 profiles), and sites with deposits of conglomerated silty sand (green, 3 profiles). The V_S profiles of the earth dam structures are shown in red (6 profiles).

The collection of V_S profiles was obtained with active-source SWMs, i.e., Multichannel Analysis of Surface Waves (MASW) and Spectral Analysis of Surface Waves (SASW). Details on the data acquisition and analysis are given in Olafsdottir et al. (2024b) and Bessason & Erlingsson (2011). The surface wave inversion was in all cases conducted by modelling the sub-surface as a stack of horizontal layers above a half-space, each characterized by a constant value of V_S. A global search procedure was used to invert the MASW data and the resulting soil stiffness model given as a set of V_S profiles whose forward response matched the experimental site signature. In this work, the median of this set of 'accepted' V_S profiles was used to represent each test location with a single V_S-z estimate. An iterative trial-and-error search was used to invert the SASW data and the results taken as the resulting minimum-misfit V_S profile. As common practice for active-source SWMs, the maximum depth of the MASW- and SASW-retrieved V_S profiles (z_{max}) was evaluated based on the maximum measured wavelength, generally providing z_{max} in the range of 10−30 m.

Most of the V_S data was gathered in low-lying areas in South, South-West and North Iceland that are characterized by thick Holocene deposits of granular soils with surficial grain sizes ranging from silty sand to gravel. Hence, soil site category (ii) may be considered an 'umbrella term' for deposits of silty, sandy and gravelly soils. The granular deposits typically present an increase in V_S with depth from 50−150 m/s at surface level to around 300−400 m/s at 15−25 m depth. This trend is consistent with that indicated by a smaller V_S dataset used in prior work (Erlingsson et al., 2022) that only included V_S profiles obtained from MASW data. However, as shown in Figure 1, examples of both stiffer and softer granular soil profiles at these depths exist.

The V_S profiles of the tested peat and peaty formations [soil site category (i)] show considerably lower values, or 15−40 m/s close to surface with an increase to 50−85 m/s at 10−15 m depth. However, it should be noted that SWMs at peat sites have only been conducted in two areas in the capital region and at one location in the town of Selfoss. Therefore, further measurements are needed to better understand the variability of the stiffness properties of Icelandic peat formations with depth.

The surveyed earth dams [soil site category (iii)] all present a similar V_S-depth trend, with values ranging from 140−185 m/s at surface level to around 400−500 m/s at a depth of 15−25 m. Hence, they show values that at a given depth are approximately 100−150 m/s higher than the general trend indicated by the set of (uncompacted) granular soil deposits, i.e., category (ii).

Comparing the sets of V_S profiles for categories (ii) and (iii), the characteristic velocities of the naturally deposited granular soils show a significantly more variability with depth than those of the earth dam sites. This may, at least in part, be related to differences in grain-size distributions, sedimentary environments and compaction levels with depth that are expected within the set of category (ii) SWM test locations. However, detailed geotechnical investigations providing information on, e.g., primary geological units with depth are, in most cases, not available. Therefore, sub-dividing the category (ii) dataset based on, e.g. governing USCS classifications, was not attempted in the current work.

The three survey locations characterized by deposits of conglomerated silty sand [soil site category (iv)] present even higher values of V_S than those of the engineered fills, i.e., around 200 m/s close to surface level and exceeding 700 m/s at 9−12 m depth. However, as shown in Figure 1, there is a large inter-site variation in the predicted V_S values, especially at depths exceeding 6 m. Further measurements at conglomerated silty sand sites are, therefore, required to better understand the range of V_S values that may be expected for such conditions.

3 REGRESSION ANALYSIS

The velocity profiles in Figure 1 were discretized by expressing each layer (apart from the surficial layer) with five uniformly distributed points $(V_{S,i}, z_{ij})$, $j \in \{0,1,\ldots,4\}$. Here, $V_{S,i}$ denotes the V_S of the i-th layer, z_{i0} is the depth at the top of the i-th layer and z_{i4} is the depth to the bottom of the i-th layer. For the surficial layer, points where $z_{ij} < 0.1$ m were not included in the regression analysis. The underlying half-space was discretized in the same manner as described above, with z_{i4} taken as the survey investigation depth (z_{max}).

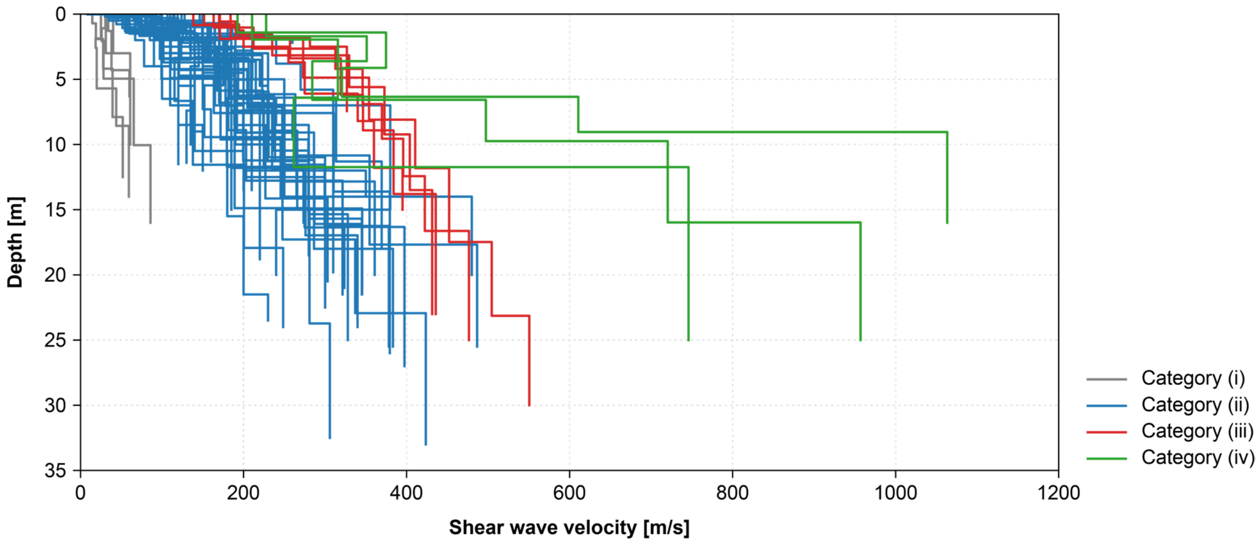

Figure 1. Collection of shear wave velocity (V_S) profiles used in this work. The survey locations are divided into four categories based on general site characteristics. Category (i): Peat and peaty soil sites. Category (ii): Silty, sandy or gravelly soil sites. Category (iii): Well-compacted engineered fills and earth dams. Category (iv): Cemented/conglomerated silty sand sites. V_S profiles from Skúlason Kaldal (2007), Bessason & Erlingsson (2011), Björnsson (2011), Olafsdottir et al. (2019), Erlingsson et al. (2022), Olafsdottir et al. (2024a) and Olafsdottir et al. (2025).

Different polynomial- and exponential-type models have been proposed in literature to describe the variation of soil V_S with depth (e.g., Campbell & Duke, 1976; Campbell et al., 1979; Lee, 1992; Wang & Wang, 2016). Four functional forms, given by Equations (3)–(6), were fitted to the set of discretized V_S profiles for each soil site category using linear [Equations (3), (5)] or non-linear [Equations (4), (6)] least squares regression,

$$V_S(z) = a + bz \quad (3)$$

$$V_S(z) = a + bz + cz^2 \quad (4)$$

$$V_S(z) = a \cdot z^b \quad (5)$$

$$V_S(z) = a \cdot (z + b)^c \quad (6)$$

where a, b and c denote the regression coefficients.

In addition to graphical comparison between the measured and predicted V_S values for each category and V_S-z model, the coefficient of determination (R^2) was used as a measure of the compatibility between the currently available V_S data for a given soil site category and each regression form. The depth-dependent model estimates of V_S are supplemented by the corresponding 84% prediction interval computed by the delta method (Pelletier, 2024; Chiquet et al., n.d.).

4 RESULTS AND DISCUSSION

4.1 *Development of parametric equations for V_S*

Figure 2 compares the SWM derived values of V_S for each of the four soil site categories and the corresponding values estimated using the linear and non-linear regression forms given by Equations (3)–(6). For further evaluation of the predictive performance of the different regression forms, Figure 3 quantifies the differences between the measured and model-predicted values of V_S for each category and regression form as a function of depth, adopting the formula used by McGann et al. (2015) for comparison of V_S prediction models,

$$\epsilon = \frac{\ln(y_i) - \ln(\overline{y}_i)}{s_{Y|x}} \quad (7)$$

where ϵ denotes the residual values, y_i and $\overline{y}_i$ are the measured and predicted V_S values of the i-th datapoint, respectively, and $s_{Y|x}$ is an estimate of the conditional standard deviation. The number of datapoints is denoted by N.

$$s_{Y|x} = \sqrt{\frac{\Sigma\left(\ln(y_i) - \ln(\overline{y}_i)\right)^2}{N-4}} \quad (8)$$

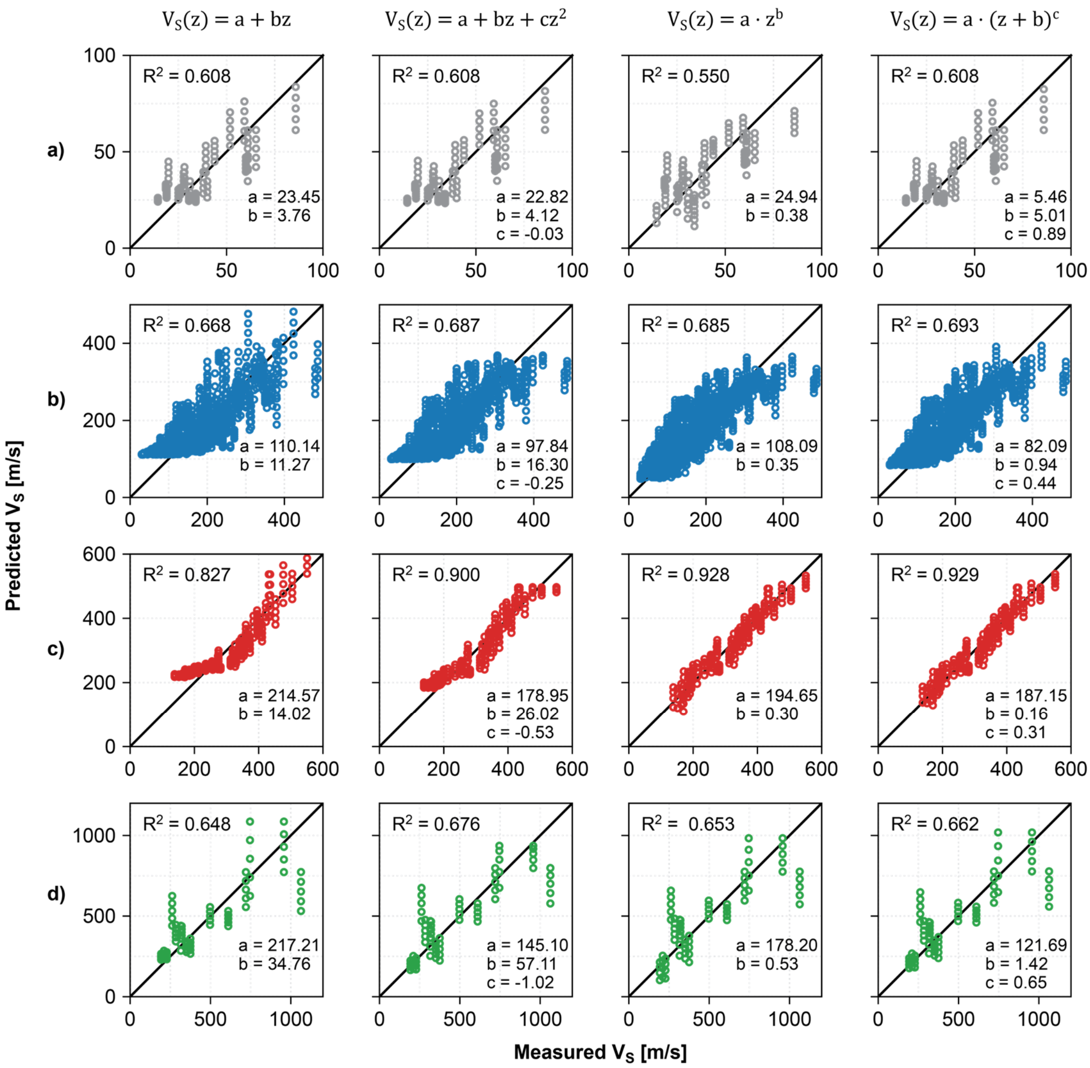

Figure 2. Comparison of measured and predicted V_S values for (a) peat and peaty soil sites [category (i)]; (b) silty, sandy or gravelly soil sites [category (ii)]; (c) well-compacted engineered fills and earth dams [category (iii)]; (d) cemented/conglomerated silty sand sites [category (iv)]. The model-predictions were obtained using the regression forms of Equation (3) (first column), Equation (4) (second column), Equation (5) (third column), and Equation (6) (fourth column).

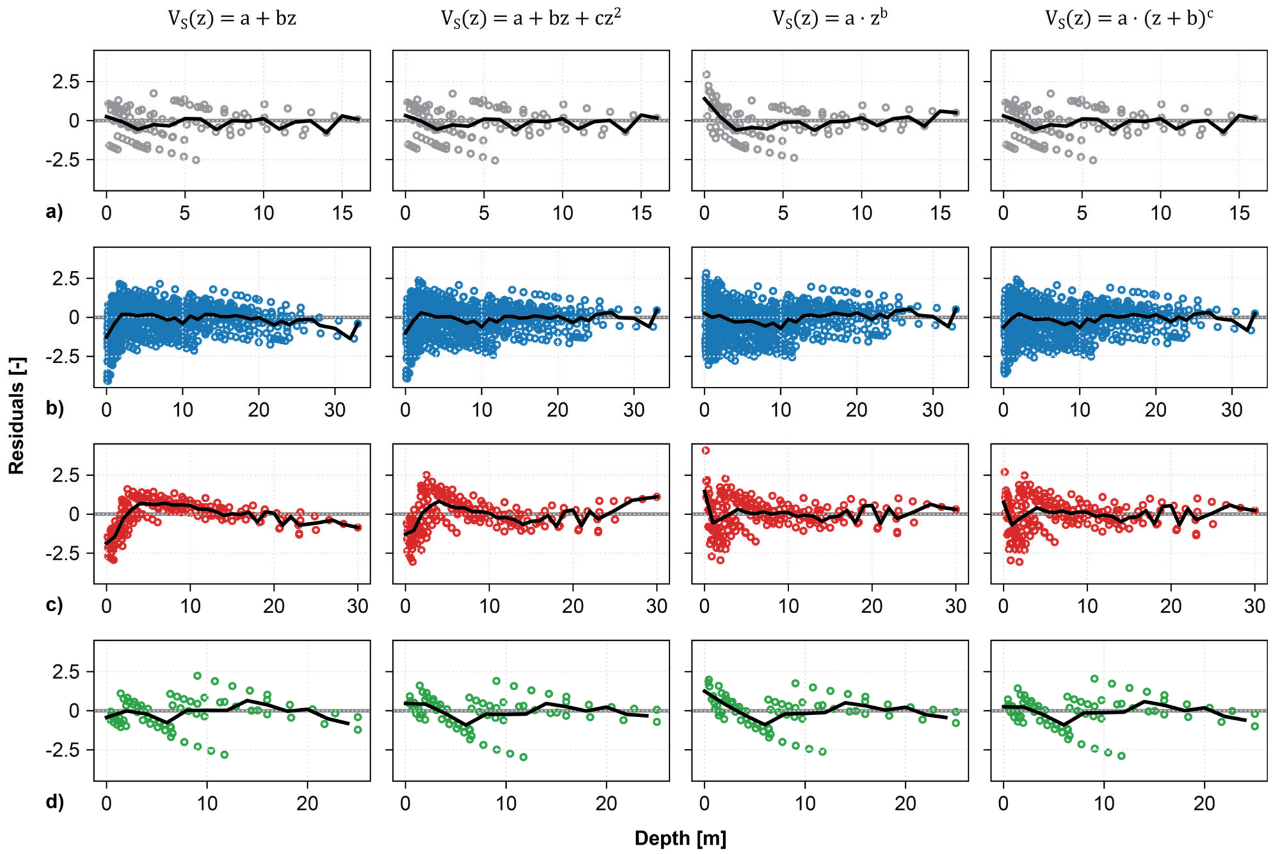

Figure 3. Variation of prediction residuals (ϵ) with depth for (a) peat and peaty soil sites [category (i)]; (b) silty, sandy or gravelly soil sites [category (ii)]; (c) well-compacted engineered fills and earth dams [category (iii)]; (d) cemented/conglomerated silty sand sites [category (iv)]. The model-predictions were obtained using the regression forms of Equation (3) (first column), Equation (4) (second column), Equation (5) (third column), and Equation (6) (fourth column).

Hence, a negative value of the residual ϵ indicates an overprediction of the measured V_S value at a given depth, whilst a positive value indicates an underprediction. The mean residual, computed by binning the individual ϵ values into 1 m wide depth-bins, is shown with a black solid line in Figure 3.

4.1.1 *Peat and peaty soil sites, category (i)*

As shown in Figure 2a, the regression forms given by Equations (3), (4) and (6) produce values of V_S for the peat and peaty soil sites that are visually near identical (same R^2). This can further be seen by the results in Figure 3a, where the prediction residuals with depth for these three models are found to be nearly identical.

Considering the associated model parameters, the values given by the regression analysis for the coefficient of z^2 in Equation (4) and the exponent in Equation (6) are -0.03 and 0.89, respectively. Hence, for site category (i), neither the inclusion of the second order term in Equation (4) nor the exponential in Equation (6) was found to describe the measured variation in V_S with depth any better than the assumption of a linear relationship between V_S and z as described by Equation (3). Based on the currently available, albeit limited, data, the linear regression model is therefore recommended for the peat and peaty soil sites.

4.1.2 *Silty, sandy or gravelly sites, category (ii)*

For the sites characterized by natural deposits of granular materials, Equations (4), (5) and (6), provide a similar fit to the observed V_S values, although Equation (6) provides the highest R^2 value by a small margin.

The results in Figure 2b and Figure 3b show that out of the three aforementioned regression forms, Equation (5), which assumes a linear relationship between V_S and z in log-log space and that V_S vanishes at the surface, provides a slightly improved fit to the surficial-layer V_S ($V_{S,0}$) for the softest granular soil sites, i.e., where $V_{S,0} < \sim 70$ m/s. The second-order polynomial regression model [Equation (4)] overpredicts V_S close to surface for many of the tested sites, as indicated by the negative mean residual at shallow depths ($z < \sim 1.5$ m). The improved exponential-type regression form of Campbell et al. (1979), given by Equation (6), provides estimates of the surficial V_S in-between the other two. At depths exceeding ~1 m, the two exponential regression models, Equations (5) and (6), produce comparable values of V_S that are consistent with the general trend indicated by the set of measured V_S profiles. However, as shown by the corresponding residual plots and mean residuals in Figure 3b, using Equation (5) leads to, on average, a slightly larger overprediction of the measured V_S values at 2.5−12.5 m depth and a slightly larger underprediction at depths >15 m, as compared to the predictions obtained with Equation (6).

In view of the above, Equation (6) is recommended to describe the general V_S-z trend for deposits of silty, sandy or gravelly soils. However, the simpler power-law relation given by Equation (5), which may be favored in some applications despite not accounting for the asymptotic behavior of V_S near the surface, may also be used to adequately describe the velocity-depth distribution for soil site category (ii).

4.1.3 *Well-compacted engineered fills and earth dams, category (iii)*

For the well-compacted engineered fills, the results in Figure 2c and Figure 3c show that the exponential-type regression forms, Equations (5) and (6), provide a considerably better fit to the available V_S data than the first- and second-order polynomials.

The two exponential models produce nearly identical residual distributions for $z > 1$ m (Figure 3c). However, near the surface, Equation (5) underestimates the measured V_S values to a larger extent which, given that it assumes V_S to vanish at the surface, may be expected.

Consistent with the findings for category (ii) (refer to Section 4.1.2), the improved exponential regression form described by Equation (6) is, in the following, taken to model the depth-dependence of V_S for the well-compacted granular soils. The results of the regression analysis, however, indicate that the simpler power-law relation, Equation (5), can also be used to sufficiently describe the V_S-z relation, although it should be used with caution at very shallow depths (or for thin fills).

4.1.4 *Cemented/conglomerated silty sand sites, category (iv)*

Lastly, for the SWM survey locations characterized by deposits of conglomerated silty sand, the second-order polynomial regression form given by Equation (4) is found to provide the highest value of the coefficient of determination, R^2. However, V_S measurements have only been conducted at a few category (iv) sites that show a large inter-site variability. This leads to wide V_S-z prediction intervals with depth (refer to Figure 4d). Hence, additional SWMs at category (iv) locations are required to better understand the expected V_S-z distribution for such conditions.

4.2 *Summary of recommended V_S-z correlations*

Table 1 provides an overview of the functional forms and the associated regression parameters that were found to yield the best fit to the discretized V_S profiles for each of the four soil site categories. Figure 4 compares the developed regressions to the corresponding set of measured V_S profiles. The shaded areas indicate the 84% prediction intervals of each parametric model.

The maximum depth listed in Table 1 for each of the parametric V_S models, i.e., 16 m for category (i), 33 m for category (ii), 30 m for category (iii), and 25 m for category (iv), is equal to the maximum investigation depth of the set of SWMs used in the current analysis. Hence, it is not recommended to use the set of regressions to predict values of V_S at depths greater than those listed in Table 1. Furthermore, as the number of datapoints generally decreases with depth, it is suggested that the parametric V_S equations are used with caution for depths close to the maximum depth for each category.

Each SWM test site is, in the current work, represented by a single estimate of its V_S profile, either the median of a range of 'acceptable' solutions (MASW) or the lowest-misfit profile obtained with a trial-and-error search (SASW). It is well known that the surface wave inversion conducted as part of SWMs is highly non-unique. Hence, by representing each site with a deterministic estimate of its characteristic V_S-z distribution, the uncertainties associated with the inversion non-uniqueness are not accounted for by the prediction intervals shown in Figure 4. The effects of the inversion non-uniqueness on the parametric regression models given in Table 1, which are intended to describe the mean V_S-z behaviour for each category of soil sites, are, however, expected to be reduced. Alternative 'acceptable' V_S-z profiles for a particular site would presumably both show higher and lower values of V_S for any given soil layer.

Table 1. Overview of recommended V_S-z correlations for the four considered soil site categories.

Soil site category	Parametric V_S profile, functional form	Regression parameters a	b	c	Number of measured V_s profiles	Number of data-points N	R^2	Max. depth [m]
(i) Peat and peaty soil sites (natural deposits)	$V_S(z) = a + bz$	23.45	3.76	-	6	109	0.608	16
(ii) Silty, sandy or gravelly soil sites (natural deposits)	$V_S(z) = a \cdot (z + b)^c$ (*) $V_S(z) = a \cdot z^b$	82.09 108.09	0.94 0.35	0.44 -	50	1300	0.693 0.685	33
(iii) Well-compacted silty, sandy or gravelly fills (engineered fills and earth dams)	$V_S(z) = a \cdot (z + b)^c$ (*) $V_S(z) = a \cdot z^b$	187.15 194.65	0.16 0.30	0.31 -	6	194	0.929 0.928	30
(iv) Cemented/conglomerated silty sand (natural deposits)	$V_S(z) = a + bz + cz^2$	145.10	57.11	-1.02	3	72	0.676	25

(*) Shown in Figure 4.

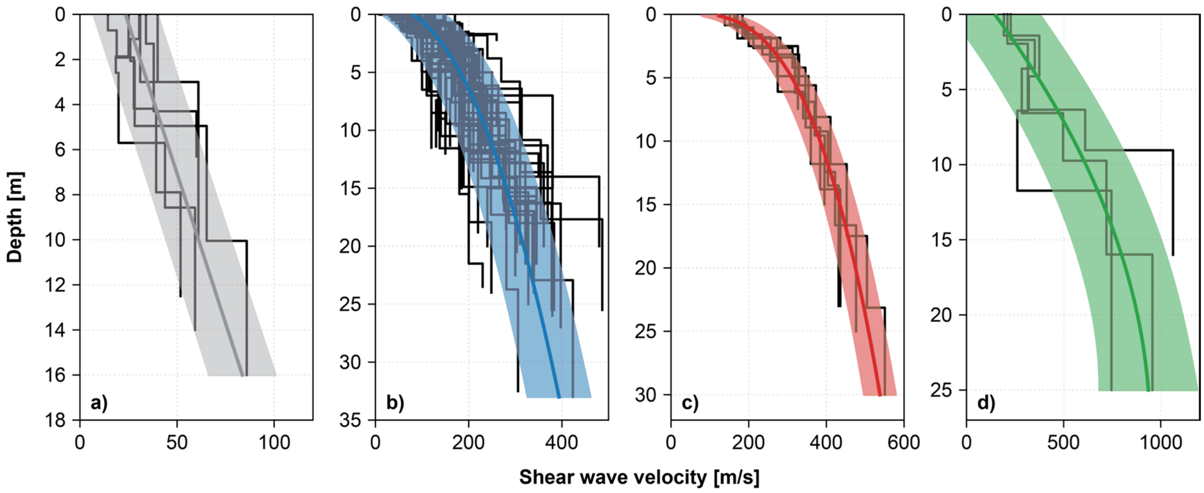

Figure 4. Comparison of measured V_S profiles (black lines) and depth-dependent V_S correlations (colored lines, Table 1) for each of the four soil site categories; (a) peat and peaty soil sites [category (i)]; (b) silty, sandy or gravelly soil sites [category (ii)]; (c) well-compacted engineered fills and earth dams [category (iii)]; (d) cemented/conglomerated silty sand sites [category (iv)]. The shaded areas in each subplot indicate the 84% prediction interval of the corresponding empirical correlation.

5 SUMMARY AND CONCLUDING REMARKS

Linear- and non-linear regression analysis was used to develop a set of empirical correlations to describe the V_S distribution with depth of the four primary categories of soil deposits in Iceland; (i) peat and peaty soil sites; (ii) silty, sandy or gravelly soil sites; (iii) well-compacted engineered fills and earth dams; and (iv) cemented/conglomerated silty sand sites. The resulting depth-dependent V_S models are, in absence of site-specific measurements, of value to assess soil stiffness parameters for the respective soil types for geotechnical engineering design. In addition, the empirical regressions may, e.g., be used to evaluate the consistency between geotechnical surveys and seismic geophysical measurements, as well as to provide an order-of-magnitude check of V_S (or G_{max}) values measured using in-situ or laboratory techniques.

Exponential- and polynomial-type models were fitted to a set of discretized SWM-derived V_S profiles for each of the four soil site categories. For the granular deposits [category (ii)] and engineered fills [category (iii)], the exponential regression forms were found to provide the best fit to the set of measured V_S profiles. For the peat and peaty soil sites [category (i)], the measured V_S values were found to be adequately modelled by a linear relation between V_S and z. A second-order polynomial relation was found to yield the best fit to the measured data for the conglomerated silty sand sites [category (iv)]. Table 1 summarizes the V_S-z correlations that, based on the current dataset, are recommended for each of the four categories. It should, however, be noted that the number of measured V_S profiles in categories (i) and (iv) is small. Furthermore, the measured profiles for category (iv) show a large inter-site variability. Therefore, additional in-situ V_S measurements are necessary to more confidently assess the suitability of the different regression forms (and the values of the regression parameters) for categories (i) and (iv).

It is well-recognized that soil V_S generally increases with increased confining pressure. Regression forms modelling V_S as a function of depth account for overburden pressure by considering z as a proxy variable. However, other factors affecting V_S (some of them interrelated), e.g., porosity, degree of compaction, cementation and geologic age, are ignored. By dividing the surveyed sites into four main categories, this work attempts to account for the effects of the governing soil type and the presence of cementation, although in a simplified manner. However, further efforts should be aimed at sub-dividing the granular soil site category by, e.g., principal USCS classifications or sedimentary environments (glaciofluvial sediments, littoral sediments, aeolian sediments, glacial till, etc.), to better account for the soil type whilst still providing a set of equations that are easy-to-implement in case of limited geotechnical data. Future work may also be directed towards extending the applicable depth of the V_S regressions for the granular soil sites. The thickness of the granular deposits in many of the surveyed areas is known to exceed 25−35 m. However, only a limited number of V_S profiles that reach those depths are currently available.

6 ACKNOWLEDGEMENTS

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