Shear wave velocity as a tool for characterising undrained shear strength of Nordic clays

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Abstract. There has been increasing recent use of shear wave velocity ($V_s$) measurements in geotechnical engineering practice. This has been driven by advances in cost effective and efficient methods of determination of $V_s$. Traditionally $V_s$ measurements were used for seismic hazard assessment or dynamic analyses. However, they are being increasingly used for general site characterization studies, determination of strength and compressibility parameters by empirical correlation, assessment of sample disturbance effects and in the quality control of ground improvement schemes. This paper will briefly present the methods used to determine $V_s$ and give some examples of $V_s$ measurements in clays from Finland, Norway and Sweden. Despite similar depositional environments the range of $V_s$ profiles for these three countries is significantly different. Differences in the profiles appear to be consistent with differences in basic clay properties, e.g. water content, density or plasticity. Nevertheless, the relationship between $V_s$ and undrained shear strength ($s_u$) of clays appears to follow a similar trend for clays from Sweden, Finland and Norway. Correlations between $V_s$ and $s_u$ exist in the literature for Norwegian clays based on DSS tests. This paper studies the relationship between $V_s$ and $s_u$ from field vane test, which is commonly used in Finnish geotechnical practice. The proposed correlation is based on data from Sweden and Finland and is meant to be used for preliminary estimate of $s_u$ from $V_s$ in absence of test data or for validation of available test data.

1. Introduction
Over the last decades, shear wave velocity ($V_s$) measurements have gained popularity in geotechnical engineering practice. Advances in cost effective and efficient methods of determination of $V_s$ focused attention on this parameter, which is mainly used for seismic hazard assessment or dynamic analyses. However, its use can be extended to general site characterization studies, determination of strength and compressibility parameters by empirical correlation ([1],[2],[3]), assessment of sample disturbance effects ([4]) and in the quality control of ground improvement schemes ([5]).

Experimental results suggest that the range of $V_s$ profiles for clays from Norway and Sweden is significantly different (e.g., [6]). While clays from these countries have similar stress-histories (i.e. light overconsolidation subsequent to ageing effects and surface erosion), basic clay properties (i.e. water content, density, plasticity) can vary significantly. Moreover, clays from Finland generally show similar stress-histories and basic properties as clays from Sweden ([7]); while Norwegian clays exhibit lower water content and plasticity and higher density.
As described above, several authors have tried to link \( V_s \) to engineering properties of soils. Among others, [8] succeeded in finding correlations between undrained shear strength \( (s_u) \), preconsolidation stress \( (\sigma'_p) \) and \( V_s \) of Norwegian clays. The practical outcome is that \( V_s \) can be used for a preliminary estimate of engineering properties that require sampling and time-consuming laboratory tests or for evaluating possibly unreliable data.

L’Heureux and Long ([8]) proposed \( V_s \)-based correlations for anisotropic undrained shear strength from triaxial compression, extension and direct simple shear (DSS) tests. In Finland, strength anisotropy is seldom modelled in everyday geotechnical design. The undrained shear strength of clays in the measured direction is generally considered as representative of the average or mobilised shear strength at failure below embankments ([9],[10],[11],[12]) and it can be related to the \( s_u \) from DSS tests ([10]). Therefore, the FVT can provide a useful and meaningful parameter for several design situations. To the authors’ knowledge, no correlations exist between \( s_u \) from FVT and \( V_s \). Hence, this paper attempts to fill this gap and provide the engineers with a simple and practical tool to evaluate \( s_u,FVT \) from \( V_s \). On the other hand, given the popularity of FVT in Finland, these can be also used for preliminary evaluation of \( V_s \) for dynamic applications.

This paper will briefly present the methods used to determine \( V_s \) and give some examples of \( V_s \) measurements in clays from Finland, Norway and Sweden. Then, the relationship between undrained shear strength and \( V_s \) and the significance of \( s_u \) from FVT are discussed. Finally, a new correlation between \( V_s \) and \( s_u \) from FVT is derived from a dataset of clays from different sites in Sweden and Finland.

2. Shear wave velocity measurements

2.1. Invasive methods

Geophysical methods can be divided into two categories: invasive and non-invasive. Invasive methods require drilling into the ground. Common invasive methods include down-hole logging, cross-hole logging, suspension logging, seismic dilatometer (SDMT) and the seismic cone penetration test (SCPTC), see Figure 1a. In Scandinavia, most invasive testing is done with the SCPTU.

A standard cone penetrometer is equipped with one or more horizontally aligned seismic sensors. The seismic signals are only recorded during pauses in penetration, commonly every 0.5 or 1.0 m. A horizontal beam coupled to the ground surface by the weight of the testing vehicle is the source of the seismic energy. The beam is struck on end with a hammer to generate horizontally polarized vertically propagating shear waves that can be detected by the horizontal receiver within the cone penetrometer embedded below. The velocity is determined from the travel-time differences between recorded waves and the difference in the assumed travel path length for receiver depth. The SCPTU method was used for collecting shear wave velocity information at all the sites in Finland discussed here.

2.2. Non-invasive methods

Non-invasive geophysical methods include spectral analysis of surface waves (SASW), multichannel analysis of surface waves (MASW), seismic refraction, and seismic reflection. Of these the MASW method is the most used in geotechnical investigation in Scandinavia. This technique was introduced in the late 1990s by the Kansas Geological Survey, see [13], to address the problems associated with SASW. This method utilises the dispersion property of surface waves for the purpose of \( V_s \) profiling in 1D (depth) or 2D (depth and surface location) format. The entire procedure for MASW usually consists of four steps, see Figure 1b.

(1) Acquire field records by using a multichannel recording system and a receiver array deployed over a few to a few hundred meters of distance, like those used in conventional seismic reflection surveys. Typically, in geotechnical work the test configuration comprises twenty-four geophones spaced at 3 m centres over the survey length. An impulsive source (e.g. a sledgehammer) is used to generate the surface waves.
(2) Use is then made of the dispersive properties of the soil; i.e. longer wavelength signals reflect the deeper soils and shorter wavelengths represent the shallower soils, to produce a phase velocity versus wavelength relationship from the measured data.

(3) This phase velocity versus wavelength trace is converted to a dispersion curves (phase velocity versus frequency). Usually fundamental mode dispersion only is used.

(4) The dispersion curve is inverted to obtain 1D (depth) V\textsubscript{s} profiles (one profile from one curve). The inversion process involves the user specifying a synthetic ground profile (number of layers as well as the density, V\textsubscript{s} and Poisson ratio of each layer) and the software then iterates until the synthetic and field dispersion curves match. The software tool mostly used in Scandinavia for the purpose of inversion is Surfseis ([14]).

Some further details on the use and validation of the MASW technique in Norwegian clays can be found in L’Heureux and Long (2017).

Figure 1. Some V\textsubscript{s} measurement techniques (a) SCPTU and (b) MASW

3. V\textsubscript{s} measurements in Swedish clays

3.1. Typical Swedish site data

Some data from the classical Swedish research site at Lilla Mellösa are shown on Figure 2. This site has been used by the Swedish Geotechnical Institute (SGI) and others for research purposes since the mid 1940’s initially as part of a series of investigations for a new airport for Stockholm. For a full description of the site the reader is referred to Larsson and Matsson ([15]). The site is underlain by a thin dry crust followed by a deep sequence of soft organic clay. The organic content decreases with depth from about 5% to some 2% at 6 m to 7 m. There is a corresponding decrease in the water content from a maximum of 130% to 70% and an increase in the bulk density from 1.3 Mg/m\textsuperscript{3} to 1.8 Mg/m\textsuperscript{3}.

Several sets of shear wave velocity data are available for the site. A comparison between the V\textsubscript{s} profiles generated by SASW and SCPTU (3 separate campaigns) are shown on Figure 2c. The profiles are very similar and can be treated as identical for practical engineering purposes. This finding is consistent with others ([8]) in that it appears that it is possible to generate reliable and repeatable V\textsubscript{s} profiles using a variety of techniques.
3.2. Summary of all available Swedish $V_s$ profiles

A summary of all the available data from Sweden is shown on Figure 3. These data were obtained from the work of [3],[6],[15],[16],[17],[18],[19],[20],[21] using different non-invasive as well as invasive techniques.

**Figure 2.** Lilla Mellösa, Sweden, (a) water content, (b) bulk density and (c) $V_s$.

**Figure 3.** $V_s$ profiles for clays from Sweden and upper and lower range for clays from South Norway.
The data are in general very similar and fall into a relatively narrow band with \( V_s \) values typically increasing from 50 m/s at the surface to about 125 m/s at 20 m depth. Also shown on Figure 3 is the range of values obtained from a good number of sites in South Norway ([8]). The Norwegian data show a similar pattern with the values gradually increasing with depth. However, the measured values for Sweden are significantly lower than those from Norway. Also, the slope with depth of the Swedish profiles are not as steep as those of the Norwegian sites. Norwegian soils have lower water content and organic content and higher bulk density and silt content. There are also significant differences in the geological depositional environment in both cases.

4. \( V_s \) measurements in clays from Finland

Only limited data is available for \( V_s \) profiles from sites in Finland. SCPTU data has been published for the soft clay sites at Perniö, Lempäälä and Masku from Southern Finland ([22],[25],[23],[24]).

![Figure 4. \( V_s \) profiles for soft clays from Finland](image)

The profiles are shown on Figure 4 are compared to the range of values for Swedish clays from Figure 3 above. Two profiles from each site are shown and in general they are very similar. Overall the range of values measured for the sites in Finland are very like those from Sweden and fall within the range of values measured for the Swedish clays. One possible reason leading to consistent \( V_s \) versus depth profiles is to be found in the similarities between the basic clay properties (water content, bulk density and plasticity). From a large multivariate clay database [7] concluded that basic properties of Finnish and Swedish clays fall within a similar range, while Norwegian clays generally show lower water contents and plasticity and higher density. Figure 5 shows water content, density and \( V_s \) profiles for Perniö clay from South-West Finland. The water content is in the range 70 % to 110% and the density is about 1.5 Mg/m\(^3\), in line with the Lilla Mellösa site shown in Figure 2.
5. Correlations between $V_s$ and undrained shear strength from the field vane

5.1. Relevance and importance of $s_u$ from field vane

A good number of correlation equations have been published between undrained shear strength ($s_u$) from various laboratory methods and $V_s$. For example [8] suggested some relationships for Norwegian clays and [6] developed a similar set of relationships for Swedish clays. It was found from these two studies that although the same form of equations applied, the relationships were not identical, and it is necessary to develop local correlations and not rely on correlations developed for soils elsewhere.

Here the focus is on $s_u$ from the field vane (FVT) given its widespread use and importance in Finland. Although $s_u$ is one of the most used and useful property in soil mechanics, it is a difficult parameter. There is no one unique value for $s_u$ for a particular soil element. It depends on, amongst many factors, anisotropy, test type, effective stress, stress history, rate of loading and temperature effects. The influence of anisotropy / test type is shown for an infinite slope stability problem and for an embankment on soft ground. The soil along the potential sliding surface in the infinite slope stability problem is mostly in direct simple shear (DSS). In contrast that beneath the embankment is partly in compression (anisotropically consolidated undrained tests - CAUC) and partly in extension (CAUE). These concepts are illustrated in Figure 6.

Figure 5. Perniö, Finland (a) water content, (b) bulk density and (c) $V_s$.

Figure 6. Influence of anisotropy and test type on $s_u$ ([27]).
It has been shown that $s_u$ from DSS often represents the average value of $s_u$ for a given problem ([11],[26]) and thus can be used in design as the “mobilised” $s_u$. It has also been shown for a variety of clays, e.g. Norwegian ([25],[26]), Finnish ([10]) and Swedish ([3]) that $s_u$ from DSS testing often yields a similar value numerically as $s_u$ from the field vane, thus confirming the usefulness of the field vane technique.

5.2. Relationship between $s_u$ from field vane and DSS for Norwegian clays

The relationship between $s_u$ from field vane and $s_u$ from DSS for Norwegian clays is shown on Figure 7a. There seems to be a particularly good fit between $V_s$ and $s_u,DSS$ compared to similar relationships with CAUC and CAUE results. Perhaps this is not surprising given the mode of soil deformation is the same in the two sets of tests ([8]). It was found that:

$$s_u,DSS = 0.027 V_s^{1.39} \text{ with } R^2 = 0.87$$  \hspace{1cm} (1)

The relationship between $s_u$ from field vane and $s_u$ from DSS for Norwegian clays is shown on Figure 7b. Although there is more scatter than for the DSS tests the relationship between the two sets of parameters is clear. The best fit power function relationship between the two sets of data has an $R^2$ value of 0.66. Also shown on Figure 7b is the best fit trend line for the DSS test results from Figure 7a. There is a reasonably good fit between the DSS trendline and the field vane data. This confirms the good relationship between these two test types as has been found elsewhere.

**Figure 7.** (a) $s_u,DSS$ versus $V_s$ for Norwegian clays ([8]) and (b) $s_u,FVT$ versus $V_s$ for Norwegian clays.
5.3. Relationship between $s_u$ field vane and $V_s$ for Finnish clays

As for the Norwegian clays, an attempt is made to study the relationship between $s_{u,FVT}$ and $V_s$ in Finnish and Swedish clays. FVT data is collected from [7] and [22], while $V_s$ measurements for the sites where FVT is available is collected from [3] and [22].

Often, FVT and $V_s$ measurements are not taken at the same exact depth. However, the average depth discrepancy between different measurements was found in the order of ±0.5 m. For greater depth intervals, average $s_{u,FVT}$ and $V_s$ values are selected based on engineering judgment. In general, both $s_{u,FVT}$ and $V_s$ are found to increase almost linearly with depth for all the sites, with $s_{u,FVT}$ showing less scatter. While single $s_{u,FVT}$ and $V_s$ soundings are available for Swedish clays, low (LE) and high estimate (HE) values are selected for the Finnish sites where multiple verticals were tested ([22]). These ranges are used directly in the analyses.

Figure 8a illustrates the relationship between $s_{u,FVT}$ and $V_s$ of Swedish and Finnish clays. The mean trend of the data is consistent with Equation (1) for $s_{u,DSS}$ of Norwegian clays. Moreover, from the regression analysis it was found that:

$$s_{u,FVT} = 0.062V_s^{1.23} \text{ with } R^2 = 0.69$$  \hspace{1cm} (2)

For comparison, the Norwegian FVT data from Figure 7b is added to Figure 8b. There seems to be a reasonably good fit between the DSS trendline for Norwegian clays and the field vane data. This would suggest that the positive relationship between $s_{u,DSS}$ and $s_{u,FVT}$ is also valid for clays from Sweden and Finland, as suggested by Figure 8a. However, additional DSS data is needed to draw further conclusions on the DSS-FVT relationship in Finnish and Swedish clays.

Figure 8. $s_{u,FVT}$ versus $V_s$ for (a) Swedish and Finnish clays and (b) Swedish and Finnish clays compared to Norwegian clays
6. Summary and conclusions

This paper discusses the use of shear wave velocity ($V_s$) to model engineering properties of clays, focusing on the undrained shear strength of soft clays from Sweden, Finland and Norway. Consistency was found between $V_s$ profiles with depth from shallow deposits of soft clays from Sweden and Finland. This is possibly due to similarities in stress-history and basic clay properties. On contrary, $V_s$ appears to be consistently higher in Norwegian clays, where both water content and plasticity are generally lower, and density is higher than Sweden and Finland. Nevertheless, the relationship between undrained shear strength from field vane ($s_u,FVT$) and $V_s$ follow a reasonably similar trend for all three countries, with $s_u,FVT$ increasing with increasing $V_s$. The best-fit power regression line for Finland and Sweden data presented in this paper gives $R^2 = 0.69$. Further, a previously published correlation for Norwegian clays suggests $s_u,FVT$ to be in the same order of $s_u,DSS$. Given that $s_u,DSS$ governs most of the classical undrained geotechnical design situations, this result is of practical interest and it points out the significance of field vane test results.

The correlation proposed in this paper is meant to be used in situations where site-specific measurements of $s_u$ are not available. Therefore, its application should be restricted to preliminary analyses; or it can be used to verify or validate data that is suspected to be unreliable. The relationship can further be used to estimate $V_s$ for dynamic analyses from the available field vane measurements.

Future studies should focus on building a multivariate database of high-quality data from well-investigated sites, not only limited to Sweden, Finland and Norway, with the aim to improve the proposed correlation and reduce uncertainties by evaluating the influence of basic clay properties and stress-history on the $s_u,V_s$ relationship.

References

[1] Andersen K H 2004 Cyclic clay data for foundation design of structures subjected to wave loading. Proceedings of the international conference of cyclic behaviour of soils and liquefaction phenomena AA Balkema Publishers, Bochum 371-387

[2] Andersen K H 2015 Cyclic soil parameters for offshore foundation design. The 3rd ISSMGE McClelland Lecture. Frontiers in Offshore Geotechnics III, ISFOG'2015, Meyer (Ed). Taylor & Francis Group, London, ISBN: 978-1-138-02848-7. Proc., 5-82. Revised version in: http://www.issmge.org/committees/technical-committees/applications/offshore and click on “Additional Information”

[3] Larsson R and Mulabdić M 1991 Shear moduli in Scandinavian clays. Swedish Geotechnical Institute.

[4] Landon M E, DeGroot D J and Sheahan T C 2007 Nondestructive sample quality assessment of a soft clay using shear wave velocity. Journal of Geotech. and Geoenv. Eng. 133(4) 424-432.

[5] Donohue S and Long M 2008 Ground improvement assessment of glacial till using shear wave velocity. In 3rd International Conference on Geotechnical and Geophysical Site Characterization - ISC’3, Volume 1: Taipei, Taylor and Francis, 825 - 830.

[6] Long M, Wood T and L’Heureux J S 2017 Relationship between shear wave velocity and geotechnical parameters for Norwegian and Swedish sensitive clays. In 2nd International Workshop on Landslides in Sensitive Clays (IWLSC), Chapter 6 in Landslides in Sensitive Clays, Advances in Natural and Technological Hazards Research 46: Trondheim, Norway, Springer International Publishing AG, p. 67 - 76

[7] D’Ignazio M, Phoon K K, Tan S A and Länsivaara T T 2016 Correlations for undrained shear strength of Finnish soft clays Can. Geotech. J. 53(10) 1628–1645

[8] L’Heureux J S and Long 2017. Relationship between shear wave velocity and geotechnical parameters for Norwegian clays. Journal of Geotech. and Geoenv. Eng. 04017013-04017011 – 04017013-04017020

[9] D’Ignazio M 2016 Undrained shear strength of Finnish clays for stability analyses of
embankments. Ph.D. Thesis, Tampere University of Technology, Finland. ISBN 978-952-15-3804-9

[10] D’Ignazio M, Länsivaara T T and Jostad H P 2017 Failure in anisotropic sensitive clays: finite element study of Perniö failure test Can. Geotech. J. 54(7) 1013-1033. DOI: 10.1139/cgj-2015-0313

[11] Leroueil S, Magnan J P and Tavenas F 1990 Embankments on soft clays (Translation by D. Muir Wood) England, Ellis Horwood Ltd.

[12] Terzaghi K, Peck R B and Mesri G 1996 Soil mechanics in engineering practice. New York, John Wiley

[13] Park C B, Miller D M and Xia J 1999 Multichannel analysis of surface waves. Geophysics 64(3) 800 – 808

[14] Park C B and Brohammer M 2003 "SurfSeis." Multichannel Analysis of Surface Waves. User Manual 1

[15] Larsson R and Mattsson H 2003 Settlement and shear strength increase below embankments. Swedish Geotechnical Institute

[16] Andréasson B 1981 Dynamic deformation characteristics of a soft clay. International conference on recent advances in geotechnical earthquake engineering and soil dynamics, Volume 1: St. Louis, MO, April-May, 1981. Vol. 1 p. 65 - 70.

[17] Comina C Krawczyk C M, Polom, U and Socco L V 2017 Integration of SH seismic reflection and Love-wave dispersion data for shear wave velocity determination over quick clays. Geophysical Journal International 210 1922-1931.

[18] Kania A, Madshus C and Zackrissom P 2000 Ground vibration from high-speed trains: prediction and counter measure. Journal of Geotech. and Geoenviron. Eng. 126(6) 531-537

[19] Wood T 2015 Re-appraisal of the dilatometer for in-situ assessment of geotechnical properties of Swedish glacio-marine clays, DMT 2015 3rd International Conference on the Flat Dilatometer: Rome, Italy, June.

[20] Svensson M and Möller B 2001 Geophysics in soil mechanics - in situ shear moduli determined by SASW-technique and more traditional geotechnical methods. Swedish Geotechnical Institute

[21] Granskär J 2018 Evaluation of SCPT-surveys as method for accessing dynamic modulus. MSc Thesis Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering

[22] Di Buò B, D’Ignazio M, Selännpää J and Länsivaara T 2016 Preliminary results from a study aiming to improve ground investigation data. 17th Nordic Geotechnical Meeting, NGM 2016, Reykjavik, Iceland, p. 187 - 197.

[23] Di Buò B, Selännpää J, Länsivaara T and D’Ignazio M 2018 Evaluation of existing CPTu-based correlations fo rthe deformation properties of Finnish soft clays. In Hicks, Pisanó and Peuchen eds. CPT18: Delft, The Netherlands, p. 185 - 191.

[24] Di Buò B, D’Ignazio M, Selännpää J, Haikola M, Länsivaara T and Di Sante M 2019 Investigation and geotechnical characterisation of Perniö clay, Finland. AIMS Geosciences 5(3): 591 – 616

[25] Lunne T, Berre T, Andersen K H, Strandvik S and Sjursen M 2006 Effects of sample disturbance and consolidation procedures on measured shear strength of soft marine Norwegian clays Can. Geotech. J. 43(7) 726-750

[26] Lunne T, Long M and Forsberg C F 2003 Characterisation and engineering properties of Onsøy clay. In Proceedings International Workshop on Characterisation and Engineering Properties of Natural Soils, Singapore, 2003, Volume 1, Balkema, Rotterdam, p. 395-427.

[27] Long M 2020 2nd Hanrahan memorial lecture - Irish compressible soils. Quarterly Journal of Engineering Geology (QJEGH)