Variability and Typical Value Distributions of Compressibility Properties of Fine-Grained Sediments in Finland

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Abstract: Most geotechnical design projects are characterized by soil data scarcity, which can be tackled by means of quantified prior knowledge and Bayesian methods. This paper aims to extend the prior knowledge on typical ranges of mean and coefficient of variation (COV) of compressibility properties of Finnish fine-grained sediments; another objective is to study whether the estimated geological sediment type affects the observed variability. The inherent variability of compressibility properties is estimated for 13 sediment layers. Lastly, the data for the estimation of typical mean is further extended, and the typical value distributions are constructed for the selected sediment types. The results indicate that neither the sediment type nor soil type affects the variability of fine-grained sediments; the COV values are rather consistent and fall into the typical range reported in the literature. On the other hand, the mean values and typical value distributions are clearly affected by the dominant soil type of the fine-grained sediment.

Keywords: Soil variability; coefficient of variation; prior knowledge; fine-grained soil; clay; silt.

1 Introduction

The determination of the characteristic value of a soil property plays a crucial role in geotechnical design. According to Eurocode 7 (CEN 2004, p. 27) "characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state." The cautiousness takes into account uncertainties, which include inherent soil variability, measurement error, transformation uncertainty and statistical uncertainty (Phoon and Kulhawy 1999). Of these, the inherent variability mainly arises from geological processes (Phoon and Kulhawy 1999), and it is often quantified via coefficient of variation, i.e., COV (the ratio of the standard deviation σ to the mean μ).

Although statistical methods could be used to consider this uncertainty in a systematic manner, "the curse of small sample size" (Phoon 2017, p. 12) limits their usage in the field of geotechnical engineering. Indeed, many geotechnical engineers supplement the sparse soil property data with their experience, engineering judgement, and other available 'prior knowledge'. However, this subjective approach may lead to inconsistency even with the same data (Bond and Harris 2008). One way to tackle this problem is to utilize Bayesian methods to integrate the scarce site-specific measurement data with prior knowledge in a rational and quantitative manner (e.g., Phoon and Kulhawy 1999; Wang et al. 2016; Phoon 2017; Wang 2017). The prior knowledge can be defined as a single normal distribution (e.g., Lee at al. 1983; Schneider 1999) or as a joint distribution which includes distributions for both the mean μ and standard deviation σ (e.g., Wang et al. 2016; Wang 2017).

The prior knowledge of a soil property is often relatively non-informative, such as typical ranges of mean and statistics. A set of non-informative prior knowledge can be represented by a joint uniform distribution, which defines ranges for both mean μ and standard deviation σ (e.g., Cao et al. 2016; Wang 2017). Many researchers have summarized typical ranges of mean and variability statistics, such as COV (e.g., Phoon and Kulhawy 1999; Cao et al. 2016). Hence, the geotechnical engineer may utilize these literature values as prior knowledge in order to supplement the site-specific soil data.

However, these summarized typical ranges might not apply to all regions. For example, in Finland and in other Northern countries the last ice age heavily shaped the properties of fine-grained sediments. Therefore, regional typical ranges might be more accurate. In the case of Finnish fine-grained soils, some typical value ranges are indeed available in the literature (e.g., Gardemeister 1975; Ronkainen 2012), but inherent variability (COV) has been studied very little (Slunga 1973; Löfman 2016). Moreover, quantified prior knowledge of compressibility properties is even more sparse than knowledge of strength properties. Thus, this paper aims to extend the prior knowledge on compressibility properties of Finnish fine-grained sediments. Specifically, this paper estimates the inherent variability of several clay and silt sediments, i.e., typical ranges of the mean and COV. The sediments are divided into geological sediment types in order to study whether the sedimentation conditions affect the observed variability. Lastly, the paper provides typical value distributions of compressibility properties for the selected sediment types.

Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR)
Editors: Jianye Ching, Dian-Qing Li and Jie Zhang

Published by Research Publishing, Singapore.
ISBN: 978-981-11-2725-0; doi:10.3850/978-981-11-2725-0_IS15-6-cd

2 Characteristics of Fine-Grained Sediments in Finland

2.1 Geological sediment types and their properties

The properties of Finnish fine-grained sediments differ mainly based on the evolutionary stages of the Baltic Sea (e.g., Sauramo 1958; Hyyppä 1963). Most of the oldest sediments were deposited in the Baltic Ice Lake during the late-glacial period around 10 000-12 000 years ago. These "BA" (Baltic Ice Lake) sediments are characterized by a stratified structure, such as silt layering in clayey soil (Sauramo 1923; Gardemeister 1975). On average, BA sediments have lower clay content (34 %) and higher silt content compared to the younger sediments (Gardemeister 1975).

Following the Baltic Ice Lake stage, the next sediments were deposited in the post-glacial, marine Yoldia Sea. These "YO" sediments often have a very high clay content (64 % on average) and weak stratification (Gardemeister 1975). The Yoldia Sea stage was followed by the Ancylus Lake ("AN") freshwater sediments and the marine Littorina Sea ("LI") sediments. The AN sediments and the youngest LI sediments share the same clay content (on average 40-42 %) and a homogeneous structure, but LI sediments contain higher amounts of organic material (Gardemeister 1975).

2.2 Special features of compressibility properties

Some of the Finnish fine-grained sediments are characterized by high compressibility. In particular, the marine YO and LI clay sediments were deposited in waters with higher salt content, and due to leaching processes, some of these clays are characterized by high compressibility and sensitivity (Bjerrum 1967). The over-consolidation ratio (OCR) of Finnish fine-grained sediments generally varies from 1 to 2 (Gardemeister 1975). In addition, Gardemeister (1975) observed overconsolidation as well in all the sediment types (OCR = 2-4).

Due to the high compressibility, most Finnish fine-grained soils do not have a linear compression curve in a semi-logarithmic scale. Hence, the non-linear tangent modulus method (Janbu 1963) has been preferred over linear methods, such as the compression index (C_c) concept. In the tangent modulus method, the vertical compressive strain ε_v is calculated using (Eq. 1) (Helenelund 1974):

$$\varepsilon_v = \begin{cases} \dfrac{1}{m\beta}\left[\left(\dfrac{\sigma_v'}{\sigma_{ref}}\right)^{\beta} - \left(\dfrac{\sigma_p'}{\sigma_{ref}}\right)^{\beta}\right] & for\ \beta \neq 0 \\ \dfrac{1}{m}\ln\left(\dfrac{\sigma_v'}{\sigma_p'}\right) & for\ \beta = 0 \end{cases} \tag{1}$$

where σ_{ref} is the reference stress (100 kN/m^2) and the stress increase is from preconsolidation stress σ'_p to final vertical effective stress σ'_v. Parameters m and β are defined from oedometer tests by means of curve fitting. If $\beta = 0$, where the stress-strain curve is linear in a semi-logarithmic scale as in the compression index concept, then the following applies: C_c is $[(1+e_0)\ln 10]/m$ (e_0 is the void ratio).

However, m and β are not physical compressibility properties, but rather mutually dependent curve-fitting parameters. Thus, the compression index C_c is more suitable for statistical analysis. Some of the data used in the construction of typical value distributions (Section 3.2) included only the parameters m and β; in those cases, C_c was approximated from m and β by assuming identical strains at a specified stress increase (Eq. 2):

$$C_c = \frac{(1+e_0)\dfrac{1}{m\beta}\left[\left(\dfrac{\sigma_v'}{\sigma_{ref}}\right)^{\beta} - \left(\dfrac{\sigma_p'}{\sigma_{ref}}\right)^{\beta}\right]}{\log_{10}\left(\dfrac{\sigma_v'}{\sigma_p'}\right)} \tag{2}$$

where the selected stress increase was from σ'_p to $\sigma'_v = 2\sigma'_p$ (if $\sigma'_p < 120$ kN/m^2) because (i) in standard oedometer test the stress is usually doubled, and (ii) in Finnish practice, C_c is often defined using two stress increments after σ'_p. In the case of $\sigma'_p \geq 120$ kN/m^2, a stress increase of 120 kN/m^2 was assumed; this assumption would correspond to a six-meter high embankment, which is in accordance with the typical design situations in Finland. Examples of this approximation are presented in Figure 1a (left).

The approximation was verified using datasets, which included both m and β and C_c. No significant bias was observed, and the scatter was reasonable (Figure 1b, right). The scatter is primarily caused by test results in which σ'_p is far from the closest stress-strain observation. Hence, the approximation performs best when the determined σ'_p is close to an observed oedometer test data point (as in Figure 1a, left).

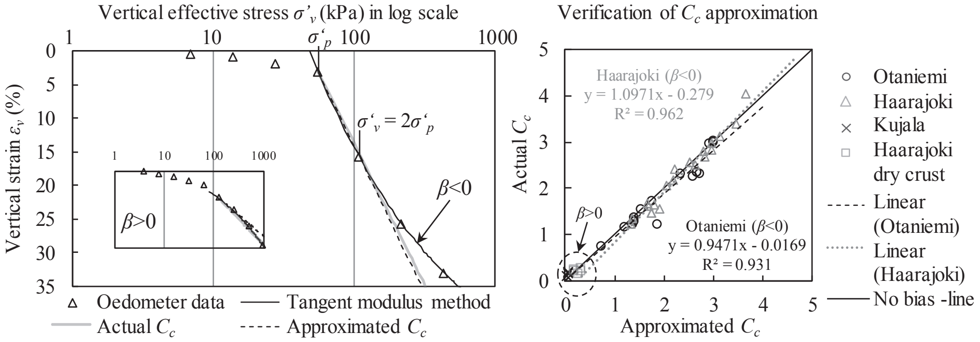


Figure 1a-1b. Examples of the approximation of compression index (left) and verification of the approximation (right).

3 Prior Knowledge on Compressibility Properties of Finnish Fine-Grained Sediments

3.1 Typical ranges of mean and variability (COV) of compressibility properties

The inherent variability of unit weight γ, compression index C_c and swelling index C_s was estimated for 13 fine-grained sediment layers at seven sites. All sites except one are located in the Southern coast of Finland; Murro site is located in Seinäjoki, on the Western coast of Finland. Almost all the soil specimens from the studied sites have been tested at Aalto University. Regarding a few specimens from Kujala, the unit weight was determined at Tampere University of Technology. The compressibility indexes were determined from incrementally loaded oedometer test results.

The inherent variability was estimated using total variability analysis, without taking into account measurement error or statistical uncertainty. According to Phoon and Kulhawy (1999), the total variability might be greater than the inherent soil variability, if (i) soil data from different geological units are mixed, (ii) equipment and procedural controls are insufficient, (iii) trends in the soil data are not removed, and (iv) soil data are taken over a long time period. These effects were minimized as follows: (i) layer boundaries were defined based on visual assessment of soil property variability and knowledge of sediment type (when available), (ii) all specimens have been taken and tested by competent university personnel or under their supervision, (iii) care was taken not to include soil layers with visible spatial trend, and (iv) soil data from only one site (Otaniemi) contains data from a longer time period.

The quality of the oedometer tests was ensured by discarding tests with reported specimen disturbance or OCR < 0.95. The latter would indicate specimen disturbance especially in silty soils (Gardemeister 1975) (or, alternatively, actual underconsolidation). However, it should be noted that the data include specimens taken with different piston samplers, and the oedometer test conditions vary to some degree; namely, different stress increments, specimen sizes and test operators. These factors might add to the observed variability.

The soil layers selected for the variability analysis were divided into geological sediment types. For most layers, the assessed geological sediment type was available in the literature (Ojala et al. 2007; Koskinen 2014). For the others, the sediment type was estimated. Otaniemi no. 1 layer and Haarajoki test embankment clay layers were evaluated to represent YO sediments because of their high clay content. Silty clay layers at Kujala sites (located in the City of Lahti) were estimated to represent BA sediments based on an adjacent site studied by Gardemeister (1973). For one profile in Suurpelto, sediment types were estimated based on a nearby profile (Ojala et al. 2007). The Suurpelto layers include three points within a 400-meter study line, and therefore the layer depths somewhat overlap (due to different deposit thicknesses). All the other studied layers consist of soil profiles located within 20-meter distance from each other. For two soil layers −POKO no. 2 layer and Tolsa (a site located in Kirkkonummi)−probable sediment type could not be estimated. Table 1 presents the classification properties and the estimated geological sediment types of the studied layers.

Soil types in Table 1 represent the "GEO" classification system (Korhonen et al. 1974) that is commonly used in Finland. In the GEO system, "fat" clays have a clay content of over 50 %, "lean" clays have a clay content of 30-50 % and clayey silts have a clay content of 10-30 %. "Organic" clays contain 2-6 % of organic material. The dominant soil types in the studied sediments follow the typical characteristics described by Gardemeister (1975): LI sediments contain mostly organic clays and silts, YO sediments fat clays and BA sediments lean clays and clayey silts.

Figure 2 presents the mean and COV values for unit weight γ, compression index C_c and swelling index C_s. The value of COV was determined via arithmetic mean and sample standard deviation. For datasets with a very small sample size (here $N < 8$), determination of COV is not meaningful (e.g., Schneider 1999); these results are marked with COV = 0 %. The ranges of mean and COV together with literature values are tabulated in Table 2.

Table 1. Estimated sediment types and classification properties of the studied sites (assessment of inherent variability).

Site name and layer number	Sediment	Layer depth (m)	Soil types (Cl = clay, Si = silt, clSi = clayey silt)	Clay content (%)	Organic content (%)	Water content (%)	Plasticity index (%)	Sensitivity (-)	OCR (-)
Murro no. 1	LI[1]	3-7	Organic Cl + Si	26-30	2.4-4.1	76-100	49-62	8-9	1.0-1.1
Murro no. 2	LI[1]	7-23	Org. Si, clSi + Lean Cl	18-42	0.8-3.7	45-76	19-52	4-12	1.0-1.2
Suurpelto no. 1	LI[2]	4-10	Organic Cl	45-47	7.7-7.8	125-171	≈106	7-9	1.1-1.6
Suurpelto no. 2	AN[2]	8-14	Fat Cl (+ organic Cl)	42-58	0.6-2.5	72-113	38-49	8-13	1.0-1.6
Otaniemi no. 1	YO	3-4	Fat Cl	75-78	0.4-0.6	103-143	55-65	≈10	1.0-1.4
Otaniemi no. 2	YO[1]	4-6	Fat Cl	77-78	0.4-0.6	75-107	≈38	≈8	1.0-1.9
POKO no. 1	YO[1]	8-11	Fat Cl	62-79	0.5-1.2	76-92	35-58	9-14	1.0-1.4
Haarajoki no. 1	YO	2-7	Fat Cl (+ organic Cl)	66-89	1.4-2.2	80-124	47-59	23-46	1.5-3.5
Haarajoki no. 2	YO	7-10	Fat Cl (+ organic Cl)	68-74	1.8-2.0	76-94	38-41	22-44	1.3-2.3
Kujala no. 1	BA	6-9	Lean Cl + clSi	24-34	0.0	29-49	11-14	10-44	1.2-2.5
Kujala no. 2	BA	11-16	Lean Cl + clSi	24-34	0.0	37-50	19-20	8-58	1.1-1.3
POKO no. 2	-	5-8	Fat Cl + Lean Cl	40-59	1.4-2.1	85-109	40-49	21-47	1.0-2.7
Tolsa	-	2-4	Fat Cl + Lean Cl	50-58	0.0	51-71	24-26	11-30	1.4-3.0

[1] Koskinen (2014)

[2] Ojala et al. (2007)

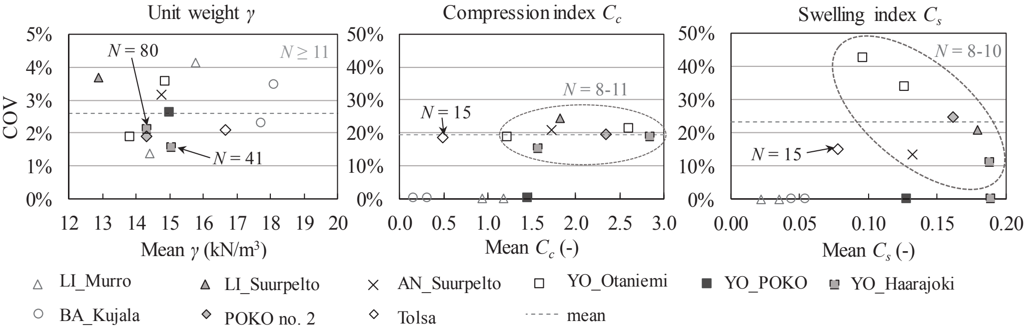


Figure 2. Inherent variability (COV) and mean values of different sediments. Samples with N<8 are marked as COV = 0 %.

For total unit weight γ, COV of inherent variability is only 1-4 %, which is smaller than the reported typical range of 3-20 % (Table 2). On the other hand, the variability of compressibility indexes C_c and C_s is mostly within the reported ranges. COV of C_c is quite consistent, with mean COV being at 19 %. In contrast, swelling index C_s has greater scatter around the mean of 23 %. Besides sedimentation and structure effects, the test conditions might add to the greater variability of C_s. Namely, the largest COV values of the Otaniemi layers are probably caused by varying unloading stresses; some specimens have been unloaded below their effective in-situ stress. The mean values of compression index C_c are much larger than the literature values due to reasons discussed in Section 2.2.

Table 2. Ranges of mean and COV of inherent variability (N = the range of sample size. Samples with N<8 are excluded).

Data	(Total) unit weight γ			Compression index C_c			Swelling index C_s		
	Mean μ (kN/m³)	COV (%)	N	Mean μ (-)	COV (%)	N	Mean μ (-)	COV (%)	N
This study	12.9-18.1	1-4	11-80	0.493-2.85	15-24	8-15	0.0775-0.189	11-43	8-15
Literature	13-24[1]	3-20[1]	-	0.18-0.996[1]	14-47[1]	-	0.123-0.168[2]	17-31[2]	-

[1] Cao et al. (2016) (summary, fine-grained soils)

[2] Löfman (2016) (Perniö clay)

According to Figure 2, neither sediment type nor dominant soil type seems to affect the inherent variability (COV) of unit weight or compressibility indexes. On the other hand, their typical characteristics are visible in the mean values. For example, one LI sediment (Suurpelto) contains a high amount of organic material, which leads to the small unit weight (12.9 kN/m³). Similarly, silty BA sediments have on average lower water content than the other, more clayey sediments, thus resulting in higher γ and lower C_c. All in all, the positive correlation between water content and compression indexes (e.g., Janbu 1963; Löfman 2016) is evident in the mean values.

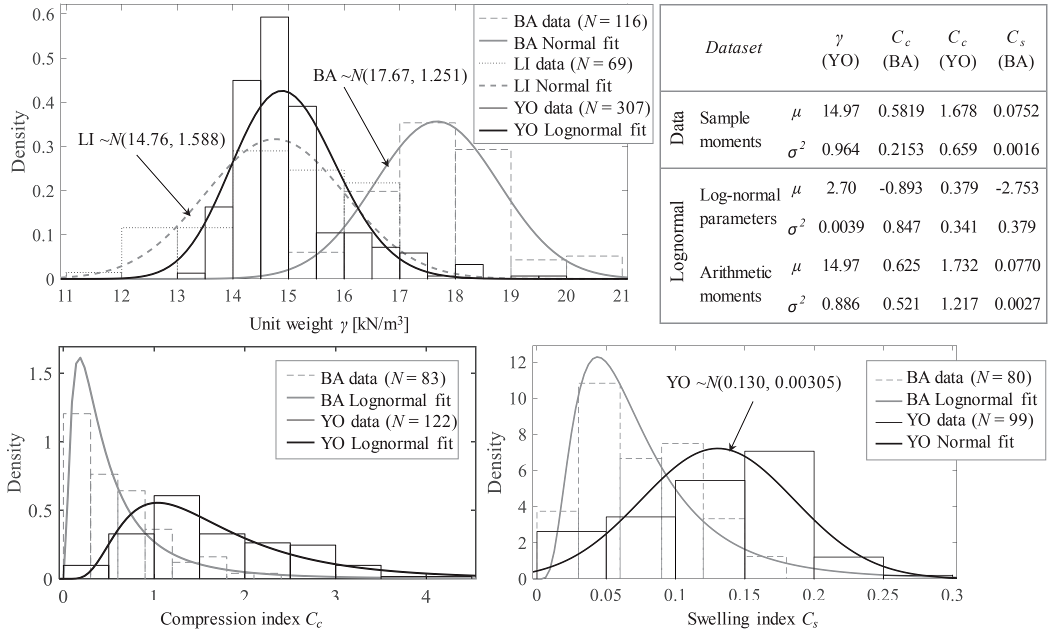
3.2 Typical value distributions of compressibility properties for the selected sediment types

In this analysis, the typical value distributions of compressibility properties were constructed for the selected sediment types. The dataset used in the previous section was extended to include other sites with estimated geological sediment types, but with too few samples for the variability analysis. The sites with no sediment information (POKO no. 2 and Tolsa) were excluded. These typical value distributions can be used to enhance the typical range of the mean, i.e., to construct more informative prior distributions of the mean.

Most of the added data are from sites located in Vantaa, near the City of Helsinki. Saarelainen (1978) divided the Vantaa soil profiles (City of Vantaa 1976) into geological sediments based on i) visual characteristics (such as color, stratification and consistency) of dry specimens, ii) typical clay contents and organic contents of each sediment (Gardemeister 1975) and iii) previous geological analysis of soil profiles in Vantaa. Besides the Vantaa sites, the added data included four sites from Gardemeister (1973): Saimaa canal, Lahti, Riihimäki and Ryttylä. Gardemeister (1973; 1975) divided the soil specimens into sediment types based mainly on pollen analysis, but he also utilized the measured salinity of pore water. Lastly, Taasia site was included (Lojander 1985). Most of the additional datasets required the approximation of the compression index C_c (Eq. 2).

Figure 3 presents the histograms and the fitted (normal or lognormal) typical value distributions for unit weight γ and compressibility indexes C_c and C_s. The analysis was performed using the Distribution Fitter App in MATLAB®. The normal distribution parameters are presented within figures using the notation $N(\mu, \sigma^2)$, where σ^2 is the variance. The lognormal distribution parameters are tabulated in the right upper corner. Some sediment types (AN all together and LI partly) were excluded from the analysis due to small sample size.

The typical value distributions of the compressibility properties clearly differ depending on the geological sediment type. As discussed in the previous section, this result is probably caused by the dominant soil types in the sediment types; BA sediments contain mostly lean clays and silts whereas YO sediments contain mostly fat clays, the latter thus resulting in higher water contents and higher compressibility.



	Dataset		γ (YO)	C_c (BA)	C_c (YO)	C_s (BA)
Data	Sample moments	μ	14.97	0.5819	1.678	0.0752
		σ^2	0.964	0.2153	0.659	0.0016
Lognormal	Log-normal parameters	μ	2.70	-0.893	0.379	-2.753
		σ^2	0.0039	0.847	0.341	0.379
	Arithmetic moments	μ	14.97	0.625	1.732	0.0770
		σ^2	0.886	0.521	1.217	0.0027

Figure 3. Typical value distributions of unit weight and compressibility indexes for the selected sediment types.

4 Conclusions

This paper enhanced the prior knowledge on unit weight and compression indexes of Finnish fine-grained sediments. The results indicate that neither the geological sediment type nor the dominant soil type affects the inherent variability (COV) of the studied soil properties. On the other hand, the dominant soil types (for instance, clays versus silty soils) clearly affect the mean values and the typical value distributions.

Yet it should be noted that the assigned geological sediment types include some uncertainty, and they should be considered as estimations only. Furthermore, the actual inherent variability of compression indexes might be smaller than reported here, since measurement error was not considered. In addition, the sample sizes were quite small, which contributes to statistical uncertainty.

Overall, the COV values of the compressibility properties were rather consistent and fell into the typical ranges reported in the literature. However, the typical mean values depend on properties like water content, meaning that the category of fine-grained soils is too broad for Finnish sediments. Thus, instead of relying on non-informative prior ranges only, more specific, informative prior distributions or empirical correlations should be utilized when relevant information (e.g., water content) is available.

Acknowledgments

This study was a part of a project funded by the Finnish Transport Infrastructure Agency. Most of the data used in the variability analysis have been produced by the geotechnical research group of the Department of Civil Engineering, Aalto University (previously Helsinki University of Technology) and collected into tabulated form by Rita Rekonen as a part of a project funded by the Finnish Road Administration.

References

Bjerrum, L. (1967). Engineering geology of normally consolidated marine clays as related to settlements of buildings. *Geotechnique*, 17(2), 83-119.

Bond, A. and A. Harris. (2008). *Decoding Eurocode 7*, Taylor and Francis, London.

Cao, Z., Wang, Y., and Li, D. (2016). Quantification of prior knowledge in geotechnical site characterization. *Engineering Geology*, 203, 107-116.

CEN. (2004). EN 1997-1:2004: *Eurocode 7: Geotechnical Design. Part 1: General rules*, European Committee for Standardization, Brussels.

City of Vantaa. (1976). *Hienorakeisten Maalajien Geoteknisten Ominaisuuksien Tutkimus*, City of Vantaa, Building Board, Municipal Infrastructure Planning Unit, Report M/1/1976, Vantaa.

Gardemeister, R. (1973). *Hienorakeisten maalajien geologisia ja geoteknisiä ominaisuuksia*, Geotechnical Laboratory, Bulletin 8, Technical Research Centre of Finland, Otaniemi.

Gardemeister, R. (1975). *On Engineering-Geological Properties of Fine-Grained Sediments in Finland*, Technical Research Centre of Finland, Building Technology and Community Development, Helsinki.

Helenelund, K. V. (1974). Maamekaaniset perusteet, *Chapter 3 in Pohjarakennus RIL 95, J. Hartikainen (ed.)*, Suomen Rakennusinsinöörien Liitto, Helsinki.

Hyyppä, E. (1963). On the late-quaternary history of the Baltic sea. *Fennia*, 89(1), Helsinki.

Janbu, N. (1963). Soil compressibility as determined by oedometer and triaxial tests. *Proceedings of European Conference on Soil Mechanics and Foundation Engineering*, Wiesbaden, 1, 19-25.

Korhonen, K. H., Gardemeister, R, and Tammirinne, M. (1974). *Geotekninen Maaluokitus*, laboratory of geotechnics, Bulletin 14, Technical Research Centre of Finland, Otaniemi.

Koskinen, M. (2014). *Plastic Anisotropy and Destructuration of Soft Finnish Clays*, Doctoral Dissertation, Aalto University, School of Engineering, Helsinki.

Lee, I. K., White, W. and Ingles, O. G. (1983). *Geotechnical Engineering*, Pitman, Boston, 75-76.

Lojander, M. (1985). 5.45 Pehmeän savialueen laskentamalli. *Chapter 5.45 in RIL 157-1 Geomekaniikka I, H. Mäkelä (ed.)*, Suomen Rakennusinsinöörien Liitto, Helsinki.

Löfman, M. (2016). *Perniön Saven Parametrien Luotettavuuden ja Saven eri Ominaisuuksien Välisten Korrelaatioiden Arviointi*, master thesis, Aalto University School of Engineering, Espoo. 121+27 pp.

Ojala, A. E. K., Ikävalko, O., Palmu, J. P., Vanhala, H., Valjus, T., Suppala, I., Salminen, R., Lintinen, P., and Huotari, T. (2007). *Espoon Suurpellon Alueen Maaperän Ominaispiirteet*, Geological Survey of Finland, Espoo.

Phoon, K. K. (2017). Role of reliability calculations in geotechnical design. *Georisk*, 11(1), 4-21.

Phoon, K. K. and Kulhawy, F. H. (1999). Characterization of geotechnical variability. *Can. Geotech. J.,* 36(4), 612-624.

Ronkainen, N. (2012). *Suomen Maalajien Ominaisuuksia*, Finnish Environment Institute.

Saarelainen, S. (1978). *Vantaan Savialueiden Painumisominaisuuksista*, Report M/1/1978, Vantaa.

Sauramo, M. (1923). Studies on Quaternary varve sediments in southern Finland. *Bulletin Commission Géologique Finlande 60*, Helsinki.

Sauramo, M. (1958). Die Geschichte der Ostsee. *Annales Academiae Scientiarum Fennicae, Series A, III*, 51, Helsinki.

Schneider, H. R. (1999). Determination of characteristic soil properties. *Proc. of the 12th European Conf. on Soil mechanics and Geotechnical Eng*., Amsterdam, 7-10 June 1999), Vol. 1, Barends et al. (eds.), A.A.Balkema, Rotterdam, 273-281.

Slunga, E. (1973). Maaluiskan vakavuus kerrallisessa koheesiomaassa. *Tutkimus Saimaan kanavan rakennustyön aikana tapahtuneista sortumista*, Geotechnical Laboratory, Bulletin 11, Technical Research Centre of Finland, Otaniemi.

Wang, Y., Cao, Z., and Li, D. (2016). Bayesian perspective on geotechnical variability and site characterization. *Engineering Geology*, 203, 117-125.

Wang, Y. (2017). Selection of characteristic values for rock and soil properties using Bayesian statistics and prior knowledge. *Discussion of Statistical/Reliability Methods for Eurocodes*, Chapter 5 in Joint TC205/TC304 Working Group on, Final Report (September 2017), ISSMGE.