Correlations for undrained shear strength of Finnish soft clays.

芬兰软黏土不排水剪切强度的相关性

Marco D’Ignazio* Kok-Kwang Phoon† Siew Ann Tan Tim Tapani Länsivaara‡

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Abstract 摘要

The study focuses on the derivation of transformation models for undrained shear strength (s_u) of Finnish soft sensitive clays. Specific correlation equations for s_u of Finnish clays are presented in this work for the first time. Field and laboratory measurements from 24 test sites in Finland are exploited for this purpose and a multivariate database is constructed. The multivariate data consist of s_u from the field vane test, preconsolidation stress, vertical effective stress, liquid limit, plastic limit, natural water content, and sensitivity. The main objective is to evaluate the interdependence of s_u, consolidation stresses, and index parameters and provide a consistent framework for practical use. The new correlations are established through regression analyses. The constructed framework is further validated by another independent multivariate database of clays from Sweden and Norway as well as by empirical equations for Swedish and Norwegian clays. Existing correlations are evaluated for Finnish and Scandinavian clays. Finally, bias and uncertainties of the new correlations are presented.

Key Words: global transformation models, soft clays, multivariate database, undrained shear strength.

这项研究着重于芬兰软黏土不排水抗剪强度（s_u）转换模型的推导。芬兰黏土的特殊的相关方程是第一次在这项工作中提出。为此，利用了芬兰 24 个试验点的现场和实验室测量值，并建立了一个多元数据库。多元数据由现场叶片试验，预固结应力，垂直有效应力，液体极限，塑性极限，天然水含量和敏感性组成。主要目的是评估 s_u，固结应力和指标参数的相互依赖性，并为实际使用提供一致的框架。通过回归分析建立新的相关性。另一个来自瑞典和挪威的黏土的独立多元数据库以及瑞典和挪威黏土的经验公式进一步验证了构建的框架。对芬兰和斯堪的纳维亚黏土的现有相关性进行评估。最后，提出了新的相关性的偏差和不确定性。

关键词：全局转换模型，软黏土，多元数据库，不排水剪切强度。

M. D’Ignazio and T.T. Länsivaara.Department of Civil Engineering, Tampere University of Technology, Korkeakoulunkatu 5, 33720, Tampere, Finland.

†K.-K. Phoon and S.A. Tan.Department of Civil and Environmental Engineering, National University of Singapore, No. 1 Engineering Drive 2, 117576, Singapore.

‡**Corresponding author:** Marco D’Ignazio (emails: marco.dignazio@tut. ; marco.dignazio@ngi.no).

*Present address: Norwegian Geotechnical Institute (NGI), Sognsveien 72, N-0855 Oslo, Norway.

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1 Introduction 介绍

Soft sensitive clays are widespread in Scandinavia, especially on coastal areas. The high compressibility of these soils, along with their low undrained shear strength ($_su$) (even lower than 10 kPa near the ground surface), makes geotechnical design often rather challenging. Therefore, s_u needs to be carefully evaluated for a reliable assessment of the safety level.

柔软的黏土在斯堪的纳维亚半岛很普遍，特别是在沿海地区。这些土壤的高可压缩性以及较低的不排水抗剪强度（s_u）（甚至在地表附近甚至低于 10 kPa），使得岩土工程设计通常颇具挑战性。因此，需要对 s_u 进行仔细评估，以对安全级别进行可靠评估。

Scandinavian soft clays are typically slightly over consolidated. The overconsolidation is normally the result of the aging process (e.g., Bjerrum 1972). For quick clays, the remolded undrained shear strength (s_u^{re}) can be even less than 0.5 kPa and 50-100 times lower than the initially "intact" $_su$ (e.g., Rankka et al. 2004; Karlsrud and Hernandez-Martinez 2013).

斯堪的纳维亚软黏土通常略有过度固结。过度固结通常是老化过程的结果（例如Bjerrum 1972）。对于快黏土，重塑后的不排水抗剪强度（s_u^{re}）甚至可以小于 0.5 kPa，比最初的"完整" s_u 低 50-100 倍（例如，Rankka et al. 2004; Karlsrud and Hernandez-Martinez 2013）。

s_u can be evaluated from in situ as well as laboratory tests. In Scandinavia, the field vane (FV) test and piezocone cone penetration (CPTU) test are the most commonly used in situ tests. Laboratory tests include undrained triaxial compression (TXC) and direct simple shear (DSS) tests. For some special cases where s_u anisotropy needs to be assessed, triaxial extension (TXE) tests are also performed.

可以从原位以及实验室试验中评估 s_u。在斯堪的纳维亚半岛，现场十字板剪切试验（FV）和带孔压的静力触探试验（CPTU）是最常用的方法。实验室试验包括不排水三轴压缩（TXC）和直接单剪试验（DSS）试验。对于某些需要评估 s_u 各向异性的特殊情况，还执行三轴拉伸（TXE）试验。

In situations where s_u is not directly measured or measurements are considered to be unreliable, s_u is commonly evaluated from transformation models based on clay properties, such as vertical preconsolidation pressure (Cpl) (e.g., Mesri 1975; Jamiolkowski et al. 1985) or plasticity (e.g., Hansbo 1957; Chandler 1988). Such transformation models are typically empirical or semi-empirical, obtained by data fitting through regression analyses (e.g., Kulhawy and Mayne 1990). However, such models must be carefully applied and their limitations be recognized, as soil properties, soil behavior, and site geology may differ from the data source from where the transformation models are calibrated. As a direct consequence, predictions from these models may result in biases with respect to the actual property (s_u) values.

在无法直接测量 s_u 或认为测量结果不可靠的情况下，通常从基于黏土特性（例如垂直预固结压力（Cpl），例如Mesri 1975; Jamiolkowski et al. 1985）或可塑性的转化模型中评估 s_u（例如，Hansbo 1957; Chandler 1988）。这种转换模型通常是经验的或半经验的，通过回归分析的数据拟合获得（例如，Kulhawy and Mayne 1990）。但是，必须谨慎应用此类模型并认识到其局限性，因为土壤特性，土壤行为和站点地质可能与校准转换模型的数据源不同。直接的结果是，来自这些模型的预测可能导致相对于实际属性（s_u）值的偏差。

According to Phoon and Kulhawy (1999), uncertainty coming from transformation models can be customarily categorized as epistemic, meaning that it can be reduced by collecting a greater number of data or improving the available models. Therefore, "global" models, calibrated from data sets covering several sites and soil types, are preferred to "site-specific" models, which are restricted to a specific soil type or a specific site. Ching and Phoon (2012a,b, 2014a,b) presented global models based on soil data covering a large number of test sites from several countries. Ching and Phoon (2012a) pointed out how site-specific models are more accurate (or less uncertain) than global

根据Phoon and Kulhawy (1999)，来自转换模型的不确定性通常可以归类为与认知相关，这意味着可以通过收集更多数据或改进可用模型来减少不确定性。因此，从涵盖多个地点和土壤类型的数据集校准的"全局"模型优于"地点特定"模型，后者仅限于特定土壤类型或特定地点。Ching and Phoon (2012a, b, 2014a,b) 提出了基于土壤数据的全球模型，该数据涵盖了来自多个国家的大量试验地点。Ching and Phoon (2012a) 指出，尽管在应用

models, although bias can be significant when applied to another site. Instead, global models are less biased, although less precise (or more uncertain).

于其他站点时偏差可能会很明显，但特定于站点的模型如何比全局模型更准确（或不确定性更低）。取而代之的是，尽管精度较低（或更不确定），但全局模型的偏差较小。

Global transformation models for su of Swedish and Norwegian clays are available in the literature (Larsson and Mulabdic, 1991; Larsson et al., 2007; Karlsrud and Hernandez-Martinez, 2013). However, a comparable model calibrated using a sufficiently large soil research over the last decades, because of its practical database containing Finnish soft clay data is still missing. Therefore, the main objectives of the present paper are (i) to test existing transformation models for s_u for Finnish soft clays and (ii) to derive, for the first time, transformation models for s_u specific to Finnish soft clays using a large multivariate database consisting of FV data points from Finland. Another independent multivariate database of FV data points from Sweden and Norway is compiled and used for comparison and validation.

瑞典和挪威黏土的全球转换模型可在文献中找到 (Larsson and Mulabdic, 1991; Larsson et al., 2007; Karlsrud and Hernandez-Martinez, 2013)。但是，由于缺少包含芬兰软黏土数据的实用数据库，因此在过去几十年中使用足够大的土壤研究进行了校准的可比较模型仍然缺失。因此，本文的主要目标是（i）测试现有的芬兰软黏土的 s_u 转换模型，以及（ii）首次使用大型多元数据库导出特定于芬兰软黏土的 s_u 转换模型。由来自芬兰的 FV 数据点组成。来自瑞典和挪威的 FV 数据点的另一个独立的多元数据库已被编译并用于比较和验证。

The value of multivariate soil databases has been demonstrated by Ching and Phoon (2012a,b, 2013, 2014a,b) and Ching et al. (2014). Müller (2013), Müller et al. (2014, 2016) and Prästings et al. (2016) have demonstrated how uncertainties related to su can be reduced when multivariate soil data are available, showing the benefits of using multivariate analyses (e.g., Ching et al. 2010)in geotechnical engineering applications. Multivariate soil data-bases are, however, limited in the literature. A summary is given in Table 1. Ching and Phoon (2014a) proposed labeling a multivar-iate database as “soil type” / “number of parameters of interest” / “number of data points”. Based on this nomenclature, the two databases presented in this paper are (i) F-CLAY/7/216 for Finnish clays (where “F” stands for Finland) and (ii) S-CLAY/7/168 for Scan-dinavian clays (where “S” stands for Scandinavia). The seven parameters in these databases consisted of s_u from the FV test (s_U^{FV}), effective vertical stress (σ_v'), vertical preconsolidation pressure (σ_p'), natural water content (w), liquid limit (LL), plastic limit (PL),and sensitivity ($S_t = s_u/s_u^{re}$).

Ching and Phoon (2012a,b, 2013, 2014a, b) 和Ching et al. (2014) 证明了多元土壤数据库的价值。Müller et al. (2014, 2016) 和 Prästings et al. (2016) 证明了当获得多变量土壤数据时如何减少与 s_u 有关的不确定性，显示了在土力工程应用中使用多变量分析的好处（例如Ching et al. 2010）。然而，多元土壤数据库在文献中受到限制。表1给出了摘要。Ching and Phoon (2014a) 建议将一个多元数据库标记为“土壤类型” / “感兴趣参数的数量” / “数据点的数量”。基于此术语，本文介绍的两个数据库是（i）芬兰黏土的 F-CLAY/7/216（其中“F”代表芬兰）和（ii）斯堪的纳维亚语的 S-CLAY/7/168 黏土（其中“S”代表斯堪的纳维亚半岛）。这些数据库中的七个参数包括 FV 试验中的 s_u（s_U^{FV}），有效垂直应力（σ_v'），垂直预固结压力（σ_p'），天然水含量（w），液体极限（LL），塑性极限（PL），和灵敏度（$S_t = s_u/s_u^{re}$）。

The paper is organized as follows. Firstly, after a brief overview on existing transformation models for s_u, the compilation of F-CLAY/7/216 and S-CLAY/7/168 databases is presented. Secondly, 10 dimensionless parameters are derived from the seven basic parameters, resulting in two dimensionless databases. These dimensionless databases (labelled as F-CLAY/10/216 and S-CLAY/10/168) are compared to existing correlations in the literature. To develop more refined correlations for Finnish clays, outliers are removed from F-CLAY/10/216 according to systematic criteria based on soil nature,

本文的结构如下。首先，在对 s_u 的现有转换模型进行简要概述之后，介绍了 F-CLAY/7/216 和 S-CLAY/7/168 数据库的编译。其次，从七个基本参数中导出 10 个无量纲参数，从而形成两个无量纲数据库。将这些无量纲数据库（标记为 F-CLAY/10/216 和 S-CLAY/10/168）与文献中现有的相关性进行了比较。为了建立更精确的芬兰黏土相关性，根据土壤性质，机

Table 1: Summary of multivariate clay databases.
表 1: 多元黏土数据库概况。

Database	Reference	Parameters of interest	No. of data points	No. of sites or studies	Range of Properties OCR	PI	S_t
CLAY/5/345	Ching and Phoon (2012b)	$\mathrm{LI}, \mathrm{s_u}, \mathrm{s_u^{re}}, \sigma'_\mathrm{p}, \sigma'_\mathrm{v}$	345	37 sites	1∼4	-	Sensitive to quick clays
CLAY/7/6310	Ching and Phoon (2013)	s_u under seven different $\mathrm{s_u}$ test types	6310	164 studies	1∼10	Low to very high plasticity	Insensitive to quick clays
CLAY/6/535	Ching et al. (2014)	$s_u/\sigma'_v, \mathrm{OCR}, (\mathrm{q_t}-\mathrm{s_v})/\sigma'_\mathrm{v}, (q_t-u_2)/\sigma'_v, (u_2-u_0)/\sigma'_v, B_q$	535	40 sites	1∼6	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	Ching and Phoon (2014a)	$\mathrm{LL}, \mathrm{PI}, \mathrm{LI}, \sigma'_\mathrm{v}/\mathrm{P_a}, \sigma'_\mathrm{p}/\mathrm{P_a}, s_u/\sigma'_v, S_t, (q_t-\sigma_v)/\sigma'_v, (q_t-u_2)/\sigma'_v, B_q$	7490	251 studies	1∼10	Low to very high plasticity	Insensitive to quick clays

mechanical characteristics, and statistical considerations. New transformation models for su specific to Finnish clays are derived through regression analyses from the resulting F-CLAY/10/173 database. These new transformation models are compared with existing correlations for Scandinavian clays from the literature. Finally, the performance of the new models derived from F-CLAY/10/173 is evaluated by calculating the biases and uncertainties associated with S-CLAY/10/168.

械特性和统计考虑因素，根据系统标准从 F-CLAY/10/216 中删除异常值。通过对所得 F-CLAY/10/173 数据库进行回归分析得出了特定于芬兰黏土的新转换模型。从文献中将这些新的转换模型与斯堪的纳维亚黏土的现有相关性进行了比较。最后，通过计算与 S-CLAY/10/168 相关的偏差和不确定性来评估源自 F-CLAY/10/173 的新模型的性能。

2 Overview on existing transformation models for undrained shear strength 不排水抗剪强度的现有转换模型概述

The dependency of s_u on σ'_p and plasticity has been the object of research over the last decades, because of its practical usefulness. Skempton (1954) suggested a linear correlation between the normalized s_u determined from FV test (s_u^{FV}) and plasticity index (PI) for normally consolidated clays. Subsequently, Chandler (1988) indicated that the same correlation could be valid also for overconsolidated clays as shown in Equation 1, although attention must be paid when dealing with fissured, organic, sensitive or other special clays.

s_u 对 σ'_p 和可塑性的依赖性在过去几十年中一直是研究的对象，因为它具有实用性。Skempton (1954) 提出，通过 FV 试验确定的归一化 s_u（s_u^{FV}）与正常固结黏土的可塑性指数（PI）之间存在线性关系。随后，Chandler (1988) 指出，对于式1中所示的超固结黏土，同样的相关性也可能有效，尽管在处理裂隙，有机，敏感或其他特殊黏土时必须注意。

$$\frac{s_u^{\mathrm{FV}}}{\sigma'_p} \approx 0.11 + 0.0037\mathrm{PI} \tag{1}$$

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Hansbo (1957)suggested, for Scandinavian clays, that $s_u^{\mathrm{FV}}/\sigma_p'$ is directly proportional to LL. Larsson (1980), collected strength data points from FV test in Scandinavian clays and proposed a transformation model similar to Equation 1, as described by Equation 2

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Hansbo (1957) 提出，对于斯堪的纳维亚黏土，$s_u^{\mathrm{FV}}/\sigma_p'$ 与 LL 成正比。Larsson (1980) 从斯堪的纳维亚黏土的 FV 试验中收集了强度数据点，并提出了一个与式1类似的转换模型，如式2所述。

$$\frac{s_u^{\mathrm{FV}}}{\sigma_p'} \approx 0.08 + 0.0055\mathrm{PI} \tag{2}$$

According to Bjerrum (1972), s_u^{FV} needs to be converted into mobilized $s_u(s_u(\mathrm{mob}) \approx \mathrm{s_u^{FV}}\lambda)$. The parameter λ is a correction multiplier that accounts for rate effects as well as anisotropy, and it is thought to be dependent on the plasticity of the clay.

Mesri (1975, 1989) suggested a unique relationship for s_u(mob) of clays and silts, corresponding approximately to DSS condition (Equation 3), regardless of the plasticity of the clay.

根据Bjerrum (1972) 的说法，s_u^{FV} 需要转换扰动的 s_u（$s_u(\mathrm{mob}) \approx \mathrm{s_u^{FV}}\lambda$）。参数 λ 是一个校正倍数，它考虑了速率效应以及各向异性，并且被认为取决于黏土的可塑性。

Mesri (1975, 1989) 提出黏土和粉砂的 s_u(mob) 有独特的关系，与黏土的可塑性无关，大约相当于 DSS 条件（式3）。

$$\frac{s_u(\mathrm{mob})}{\sigma_p'} \approx 0.22 \tag{3}$$

However, according to Larsson (1980), Equation 3 tends to overestimate s_u in very low-plastic clays, while it underestimates s_u in high-plastic clays. For low overconsolidated clays with low to moderate PI, Jamiolkowski et al. (1985)recommended (Equation 4)

但是，根据Larsson (1980)，式3倾向于高估低塑性黏土中的 s_u，而低估了高塑性黏土中的 s_u。对于具有低至中等 PI 的低超固结黏土，Jamiolkowski et al. (1985) 推荐（式4）

$$\frac{s_u(\mathrm{mob})}{\sigma_v'} \approx (0.23 \pm 0.04)\mathrm{OCR}^{0.8} \tag{4}$$

The transformation model suggested by Jamiolkowski et al. (1985) is based on the stress history and normalized soil engineering properties (SHANSEP) framework (Equation 5) proposed by Ladd and Foott (1974). The SHANSEP framework is normally adopted to describe the variation of s_u with the overconsolidation ratio, $\mathrm{OCR}(= \sigma_p'/\sigma_v')$.

Jamiolkowski et al. (1985) 提出的转换模型基于Ladd and Foott (1974) 提出的应力历史和规范化土壤工程特性（SHANSEP）框架（式5）。通常采用 SHANSEP 框架描述 s_u 随超固结比 OCR（$= \sigma_p'/\sigma_v'$）的变化。

$$\frac{s_u}{\sigma_v'} = S(\mathrm{OCR^m}) \tag{5}$$

where S and m are constants dependent on material and test type. S represents the normalized s_u for normally consolidated state. The exponent m varies between 0.75 and 0.95 Jamiolkowski et al., 1985. A value of m equal to 0.8 is often assumed in practice. notethat $m = 1$ would reduce Equation 5 to eq (3) with $S = 0.22$.

studied the SHANSEP relation between su/v and OCR for inorganic Scandinavian clays. Data from undrainedTXC, DSS, and TXE tests were collected to assesssuanisotropy. Byassuming an

其中 S 和 m 是取决于材料和试验类型的常数。S 表示正常合并状态的归一化 s_u。指数 m 在 0.75 至 0.95 之间变化Jamiolkowski et al., 1985。在实践中通常假定 m 等于 0.8。注意，当 $S = 0.22$ 时，$m = 1$ 会将式5减小为式3。

研究了无机斯堪的纳维亚黏土中 s_u/σ_v' 与 OCR 之间的 SHANSEP 关系。从不排水的 TXC，DSS 和 TXE 试验中收集数据，以评估

averagemvalue equal to 0.8, it was shown how thenormally consolidated undrained shear strength ratio (S) is material dependent for DSS (eq (6)) and TXE, as it increases with in-creasing liquid limit; while it seems fairly constant for TXC.

各向异性。假设平均值为 0.8，表明随着固液极限的增加，正常固结不排水抗剪强度比（S）对于 DSS（式6）和 TXE 的影响与材料有关；

Karlsrud and Hernandez-Martinez (2013)studied the (su/v)-OCR relation for Norwegian soft clays from laboratory tests on high-quality block samples. Outcomes from this study indicate that s_u strongly correlates with natural water content (w) combined with OCR (Equation 7 for DSS strength). More specifically, peak strengths from TXC, DSS, and TXE test were observed to increase with increasingw. Possible reasons to explain this might be e.g., (i) the open structure typical of Norwegian clays Rosenqvist, 1953, 1966, which allows the soil to retain a quantity of pore water, typically above the liquid limit of the soil or (ii) the increasing rate effects with plasticity.

Karlsrud and Hernandez-Martinez (2013) 通过高质量块状样品的实验室试验研究了挪威软黏土的 (s_u/σ'_v)-OCR 关系。这项研究的结果表明，它与天然水含量（w）和 OCR（DSS 强度的式7）密切相关。更具体地说，观察到来自 TXC，DSS 和 TXE 试验的峰值强度随 w 的增加而增加。解释这种情况的可能原因可能是，例如（i）挪威黏土Rosenqvist, 1953, 1966的典型的笔形结构，它可以使土壤保留一定数量的孔隙水，通常高于土壤的液位极限；或（ii）增速与可塑性的影响。

$$\frac{s_u^{\mathrm{DSS}}}{\sigma'_v} \approx (0.125 + 0.205\mathrm{LL}/1.17)\mathrm{OCR}^{0.8} \tag{6}$$

$$\frac{s_u^{\mathrm{DSS}}}{\sigma'_v} \approx (0.14 + 0.18w)\mathrm{OCR}^{0.35+0.77\mathrm{w}} \tag{7}$$

Ching and Phoon (2012b) proposed a global transformation model for s_u(mob) from FV and unconfined compression (UC) tests as a function of OCR and S_t. The model was built based on a large database of structured clays (CLAY/5/345) consisting of 345 clay data points from several locations all over the world (Equation 8).

Ching and Phoon (2012b) 提出了 FV 和无侧限压缩（UC）试验的 s_u(mob) 全局转换模型，该模型是 OCR 和 S_t 的函数。该模型是基于大型结构性黏土数据库（CLAY/5/345）由来自世界各地的 345 个黏土数据点组成（式8）。

$$\frac{s_u(\mathrm{mob})}{\sigma'_v} \approx 0.229\mathrm{OCR}^{0.823}\mathrm{S}_{\mathrm{t}}^{0.121} \tag{8}$$

3 Analysis of multivariate clay databases 多元黏土数据库分析

F-CLAY/7/216 and S-CLAY/7/168 F-CLAY/7/216 和 S-CLAY/7/168 数据库

The first clay database compiled in this study consists of 216 FV data points from 24 different test sites from Finland. Each data “point” contains multivariate information, i.e., information from different tests conducted in close proximity is available. The collected data points contain information on seven basic parameters measured at comparable depths and sampling locations: $s_{\mathrm{u}}^{\mathrm{FV}}, \sigma'_{\mathrm{v}}, \sigma'_{\mathrm{p}}, w, \mathrm{LL}, \mathrm{PL}$, and S_{t}.

这项研究中汇编的第一个黏土数据库包括来自芬兰 24 个不同试验点的 216 个 FV 数据点。每个数据“点”都包含多元信息，即，可以使用来自非常接近进行的不同试验的信息。收集的数据点包含有关在可比较的深度和采样位置处测量的七个基本参数的信息：$s_{\mathrm{u}}^{\mathrm{FV}}, \sigma'_{\mathrm{v}}, \sigma'_{\mathrm{p}}, w, \mathrm{LL}, \mathrm{PL}$ 和 S_{t}。

The standard FV test is normally carried out at high speed of rotation, inducing strain rates in the soil that are much higher than in conventional laboratory tests (e.g., triaxial tests, DSS tests). The main consequence is that s_u^{FV} is overestimated and, therefore, a correction is needed to convert s_u^{FV} into s_u(mob) (e.g., Bjerrum (1972)). The parameter s_u(mob) is defined as the undrained shear strength that is

标准 FV 试验通常在高速旋转下进行，导致土体中的应变率比传统的实验室试验（例如三轴试验，DSS 试验）高得多。主要结果是 s_u^{FV} 被高估了，因此需要更正以将 s_u^{FV} 转换为 s_u(mob)（例如Bjerrum (1972)）。s_u(mob) 定义为现场路堤或边坡全面失效时调动的未

mobilized in a full-scale failure of an embankment or slope in the field (Bjerrum, 1972; Mesri and Huvaj, 2007). s_u(mob) cannot be uniquely defined, as it is a function of failure mode, stress state, and strain rate, among others. In this study, the s_u^{FV} values are converted into s_u(mob) values through a correction factor λ, as reported in the Finnish Guidelines for stability analysis (Ratahallintokeskus, 2005). In this way, rate effects and anisotropy are implicitly accounted for. The strength correction factor used is expressed by Equation 9

排水抗剪强度（Bjerrum, 1972; Mesri and Huvaj, 2007)。s_u(mob) 不能被唯一定义，因为它是失效模式、应力状态和应变率等的函数。在这项研究中，s_u^{FV} 值通过校正因子 λ 转换为 s_u(mob) 值，如《芬兰稳定性分析指南》(Ratahallintokeskus, 2005) 所述。这样，就隐含地考虑了速率效应和各向异性。所使用的强度校正因子由式9表示。

$$\lambda = \frac{1.5}{1 + \mathrm{LL}} \tag{9}$$

According to Jamiolkowski et al. (1985) and Chandler (1988), s_u obtained from FV is somewhat comparable to s_u from DSS test results. It is common practice in Sweden to consider su from DSS tests as a reference value (e.g., Westerberg et al. (2015)). DSS tests may, however, be affected by some disturbance effects resulting from sampling as well as specimen preparation. In Finland, DSS tests are not in use and the FV test is normally assumed to provide reliable s_u values, despite some issues related to test equipment. As suggested by Mansikkamäki (2015), when casing is used to protect the vane during penetration into the ground, rod friction is minimized and, therefore, measured torque values are assumed to be less biased than when slip-coupling is used. FV data points from Finland collected in this study are mostly obtained using FV test equipment that includes casing. As a consequence, the results presented later will likely be representative of the best possible estimate of s_u^{FV} in Finnish current practice.

根据Jamiolkowski et al. (1985) 和Chandler (1988) 的研究，从 FV 中获得的 s_u 与 DSS 试验结果中的 s_u 具有一定的可比性。在瑞典，通常的做法是将来自 DSS 试验的 s_u 作为参考值（例如，Westerberg et al. (2015)）。然而，DSS 试验可能会受到取样以及样品制备所产生的一些干扰效应的影响。在芬兰，DSS 试验尚未使用，尽管存在一些与试验设备有关的问题，但通常认为 FV 试验可以提供可靠的 s_u 值。正如Mansikkamäki (2015) 所建议的那样，当套管用于保护叶片在插入地面时，杆件摩擦力被最小化，因此，假设测量的扭矩值比使用滑移耦合时的偏差小。本研究中从芬兰收集的 FV 数据点大多是使用包括套管的 FV 试验设备获得的。因此，后面介绍的结果很可能代表芬兰目前实践中对 s_u^{FV} 的最佳估计。

The database is compiled from data given in Gardemeister (1973), Lehtonen et al. (2015), together with data from recent soil investigations performed by Tampere University of Technology, Finland (J. Selänpää, personal communication, 2015). Gardemeister (1973) collected FV and oedometer tests performed at different construction sites in Finland. For the purpose of the present study, sites characterized by organic (organic content higher than 2%) and (or) silty soils have been discarded, because the focus of this study is on the strength of inorganic clays. Some low organic clays may, however, be present in the database.

该数据库是根据Gardemeister (1973) 和 Lehtonen et al. (2015) 提供的数据以及芬兰坦佩雷理工大学最近进行的土体调查数据汇编而成（J. Selänpää, personal communication, 2015）。Gardemeister (1973) 收集了在芬兰不同建筑工地进行的 FV 和固结试验。在本研究中，以有机土（有机含量高于 2%）和（或）淤泥质土为特征的场地已被舍弃，因为本研究的重点是无机黏土的强度。然而，数据库中可能存在一些低有机黏土。

This database is labeled as F-CLAY/7/216 following the nomenclature proposed by 2014a. F-CLAY/7/216 is a new database that would contribute to the list of multivariate soil databases shown in Table 1. The basic statistics of the seven clay parameters in F-CLAY/7/216 are listed in Table 2. The parameters σ'_v and σ'_p are normalized to the atmospheric pressure, P_a (P_a = 101.3 kPa). The numbers of available data points (n) are reported in the second column. The statistics shown are the mean value, coefficient of variation (COV), minimum value

根据2014a提出的命名法，该数据库被标记为 F-CLAY/7/216。F-CLAY/7/216 是一个新的数据库，将为表1所示的多变量土体数据库列表做出贡献。F-CLAY/7/216 中 7 个黏土参数的基本统计量列于表2中。参数 σ'_v 和 σ'_p 已归一化为大气压，P_a（P_a = 101.3 kPa）。可用数据点的数量 (n) 在第二栏中显示。显示的统计数据为平均值、变异系数 (COV)、最

(Min) and maximum value (Max). Clay properties cover a wide range of S_t values varying from 2 (insensitive clays) to 64 (quick clays), and a wide range of PI values (2∼95) and w values (25∼150).

小值 (Min) 和最大值 (Max)。黏土特性涵盖了从 2（不敏感黏土）到 64（流黏土）的广泛 S_t 值，以及广泛的 PI 值（2∼95）和 w 值（25∼150）。

A second independent database consisting of 168 FV data points from Sweden and Norway is extracted from the existing global CLAY/10/7490 database (Ching and Phoon, 2014a). This database is labelled as S-CLAY/7/168 and it contains multivariate information on the same soil parameters as in F-CLAY/7/216. The purpose of S-CLAY/7/168 is to act as an independent set of data to be used for comparison with F-CLAY/7/216 in subsequent analyses. The geographical coverage of S-CLAY/7/168 is restricted to Sweden (12 sites) and Norway (seven sites). Full information on all seven parameters is available for only 59 data points. Fortunately, for the remaining 109 data points, information on all six parameters with the exception of S_t is known. The practical implication here is that the effect of S_t on s_u correlations is more difficult to discern in the case of S-CLAY/7/168. Basic statistics of the seven clay parameters in S-CLAY/7/168 are reported in Table 3. The multivariate clay data contained in F-CLAY/7/216 and S-CLAY/7/168 are listed in Appendix A.

从现有的全球 CLAY/10/7490 数据库 (Ching and Phoon, 2014a) 中提取了第二个独立的数据库，其中包括来自瑞典和挪威的 168 个 FV 数据点。该数据库被标记为 S-CLAY/7/168，包含了与 F-CLAY/7/216 数据库相同的土体参数的多变量信息。S-CLAY/7/168 的目的是作为一套独立的数据，用于在随后的分析中与 F-CLAY/7/216 进行比较。S-CLAY/7/168 的地理范围仅限于瑞典（12 个地点）和挪威（7 个地点）。只有 59 个数据点有关于所有七个参数的完整信息。幸运的是，对于其余的 109 个数据点，除了 S_t 以外，所有六个参数的信息都是已知的。这里的实际意义是，在 S-CLAY/7/168 的情况下，S_t 对 s_u 相关性的影响更难辨别。表3为 S-CLAY/7/168 中 7 个黏土参数的基本统计。F-CLAY/7/216 和 S-CLAY/7/168 中包含的多变量黏土数据列于附录A中。

Figure 1 shows how the data points are positioned in the plasticity chart to provide a broad physical overview of the databases. Figure 2 suggests that w tends to increase for increasing LL, and that w is higher than LL for the majority of the data points.

图1显示了如何在可塑性图表中定位数据点以提供数据库的广泛物理概览。图2表明 w 倾向于随着 LL 的增加而增加，并且对于大多数数据点而言，w 高于 LL。

Dimensionless databases: F-CLAY/10/216 and S-CLAY/10/168 无量纲数据库：F-CLAY/10/216 和 S-CLAY/10/168

Ten dimensionless soil parameters are of primary interest in this study. They are derived from the seven basic clay parameters appearing in F-CLAY/7/216 and S-CLAY/7/168 and they can be categorized into two groups:

1. Index properties, including natural water content (w), liquid limit (LL), plasticity index (PI), and liquidity index (LI).
2. Stresses and strengths, including OCR, normalized s_u(mob) against vertical effective stress $[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}]$ and preconsolidation pressure $[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}]$, normalized s_u^FV against vertical effective stress $(s_\mathrm{u}^\mathrm{FV}/\sigma'_\mathrm{v})$ and preconsolidation pressure $(s_\mathrm{u}^\mathrm{FV}/\sigma'_\mathrm{p})$, and sensitivity $(S_\mathrm{t} = s_\mathrm{u}/s_\mathrm{u}^\mathrm{re})$.

10 个无量纲土体参数是本研究的主要内容。它们来自 F-CLAY/7/216 和 S-CLAY/7/168 的七个基本黏土参数，可分为两组：

1. 指数属性，包括天然水含量（w），液限（LL），塑性指数（PI）和液性指数（LI）。
2. 应力和强度，包括 OCR，针对垂直有效应力 $[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}]$ 的归一化 s_u(mob) 和预固结压力 $[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}]$，针对垂直有效应力 $(s_\mathrm{u}^\mathrm{FV}/\sigma'_\mathrm{v})$ 的归一化 s_u^FV，预固结压力 $(s_\mathrm{u}^\mathrm{FV}/\sigma'_\mathrm{p})$ 和灵敏度 $(S_\mathrm{t} = s_\mathrm{u}/s_\mathrm{u}^\mathrm{re})$。

Figure 3(a) shows the $s_u(\mathrm{mob})/\sigma'_v$ values plotted against OCR for F-CLAY/10/216 and S-CLAY/10/168. The trend described by the

图3(a)显示了针对 F-CLAY/10/216 和 S-CLAY/10/168 对 OCR 的 $s_u(\mathrm{mob})/\sigma'_v$ 值。相

Table 2: Basic statistics of the seven basic parameters in F-CLAY/7/216.
表 2: 数据库 F-CLAY/7/216 中七个基本参数的基本统计信息。

Variable	n	Mean	COV	Min	Max
s_u^{FV}(kPa)	216	21.443	0.501	5	75
σ'_v/P_a	216	0.464	0.485	0.074	1.609
σ'_p/P_a	216	0.948	0.515	0.251	2.884
LL	216	66.284	0.298	22.0	125.0
PL	216	27.740	0.204	10.0	50.0
w	216	76.340	0.268	25.0	150.0
S_t	216	17.447	0.789	2.0	64.0

Table 3: Basic statistics of the seven basic parameters in S-CLAY/7/168.
表 3: 数据库 S-CLAY/7/168 中七个基本参数的基本统计信息。

Variable	n	Mean	COV	Min	Max
s_u^{FV}(kPa)	168	16.346	0.505	5.62	48.75
σ'_v/P_a	168	0.503	0.632	0.068	2.101
σ'_p/P_a	168	0.786	0.726	0.15	3.116
LL	168	71.055	0.396	22.77	201.81
PL	168	29.448	0.344	2.73	73.92
w	168	76.631	0.347	17.27	180.11
S_t	59	12.068	0.779	3.0	42.5

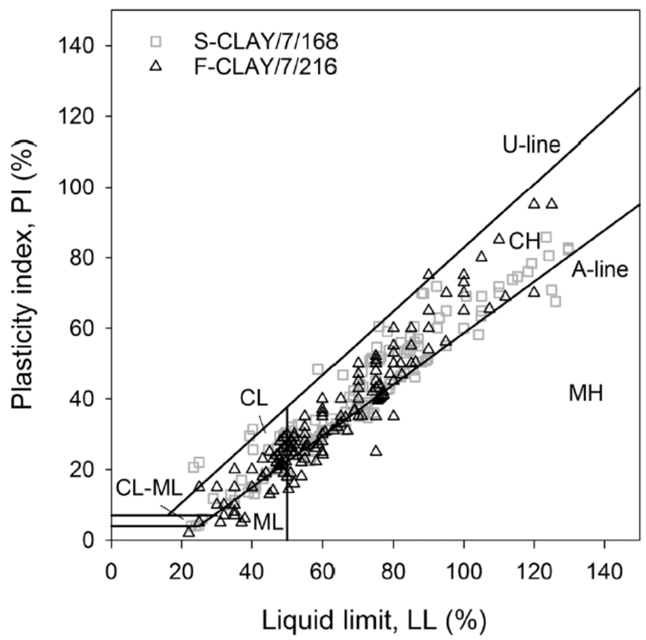


Figure 1: Plasticity chart
图 1: 塑性图

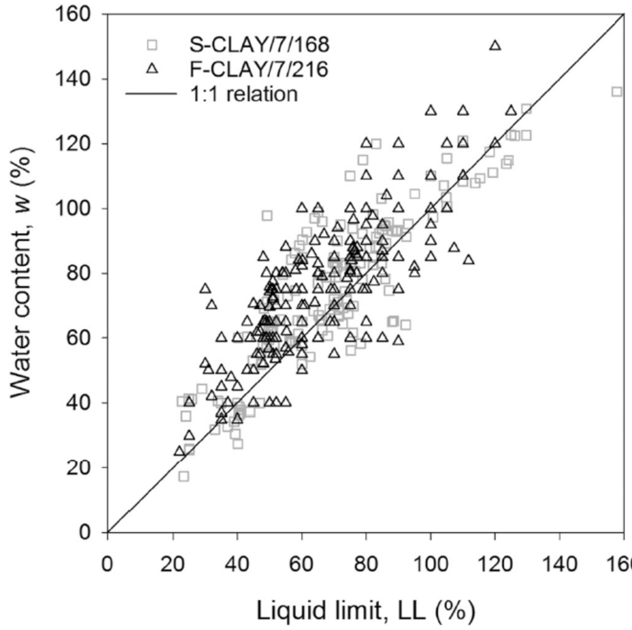


Figure 2: Water content (w) versus liquid limit (LL) for F-CLAY/7/216 and S-CLAY/7/168
图 2: F-CLAY/7/216 和 S-CLAY/7/168 的含水量（w）与液限（LL）

$s_{\mathrm{u}}(\mathrm{mob})/\sigma'_{\mathrm{v}}$ points vs. OCR seem on average higher for Finnish clays s than for Scandinavian clays. The reason for such a discrepancy could lie in the definition of σ'_{p} used to estimate OCR. Indeed, σ'_{p} is normally determined through an oedometer test and it is strongly affected by the strain rate used in the test (e.g., Leroueil et al. (1983, 1985)). As suggested by Leroueil et al. (1985) and Leroueil (1988, 1996), constant rate of strain (CRS) oedometer tests provide stress-strain curves that normally differ from those provided by conventional 24 h incrementally loaded (IL) oedometer tests. The main reason for such differences can

对于 OCR$s_{\mathrm{u}}(\mathrm{mob})/\sigma'_{\mathrm{v}}$ 点所描述的趋势，芬兰黏土似乎比斯堪的纳维亚黏土平均值较高。出现这种差异的原因可能在于用于估计 OCR 的 σ'_{p} 的定义。实际上，σ'_{p} 通常是通过固结试验确定的，并且受试验中使用的应变率的强烈影响（例如Leroueil et al. (1983, 1985)）。如Leroueil et al. (1985) 和Leroueil (1988, 1996) 所建议，恒定应变率（CRS）固结试验提供的应力-应变曲线通常不同于传统的 24 小时增

be found in the different rate of loading (or rate of straining) applied during the test. According to Leroueil (1996), the strain rate in IL test after 24 h is between $1\times 10^{-7}\mathrm{s}^{-1}$ for highly compressible clays and $5\times 10^{-8}\mathrm{s}^{-1}$ for low compressible clays. The strain rate in CRS tests is normally between $1\times 10^{-6} - 4\times 10^{-6}\mathrm{s}^{-1}$. As a consequence, σ'_p is larger in CRS than in the 24h IL test (Leroueil, 1996). More specifically, Leroueil (1996) suggests that σ'_p obtained from the CRS oedometer test is typically 25% larger than that deduced from the IL test. For Finnish clays, Kolisoja et al. (1989) reported, for one site in Finland, the ratio $\sigma'_\mathrm{pCRS}/\sigma'_\mathrm{pIL}$ to be equal to 1.16. Hoikkala (1991) observed the same ratio to be equal to 1.3 for three different sites in Finland. Länsivaara (1999), based on the data collected by Leroueil (1996) on several types of clays, suggested $\sigma'_\mathrm{pCRS}/\sigma'_\mathrm{pIL} = 1.27$. Karlsrud and Hernandez-Martinez (2013) observed, for oedometer tests conducted on block samples of Norwegian clays, that σ'_p values derived from the IL tests were 10% – 18% lower than for the CRS tests.

量加载（IL）固结试验提供的应力-应变曲线。这种差异的主要原因可以在试验过程中施加的不同加载速率（或应变速率）中找到。根据Leroueil (1996) 的研究，对于高度可压缩的黏土 IL 试验 24 小时后的应变率在 $1\times 10^{-7}\mathrm{s}^{-1}$ 之间，而低压缩性黏土为 $5\times 10^{-8}\mathrm{s}^{-1}$。CRS 试验中的应变率通常在 1×10^{-6} 到 $4\times 10^{-6}\mathrm{s}^{-1}$ 之间。因此，CRS 中的 σ'_p 比 24 小时的 IL 试验中的要大 (Leroueil, 1996)。更具体地说，Leroueil (1996) 提出，从 CRS 固结试验获得的 σ'_p 通常比从 IL 试验得出的值大 25%。对于芬兰黏土，Kolisoja et al. (1989) 报告，对于芬兰的一个站点，比率 $\sigma'_\mathrm{pCRS}/\sigma'_\mathrm{pIL}$ 等于 1.16。Hoikkala (1991) 观察到芬兰三个不同地点的比率均等于 1.3。Länsivaara (1999) 根据 Leroueil (1996) 收集的关于几种类型黏土的数据，提出了 $\sigma'_\mathrm{pCRS}/\sigma'_\mathrm{pIL} = 1.27$。Karlsrud and Hernandez-Martinez (2013) 在对挪威黏土块状样品进行的固结试验中观察到，来自 IL 试验的 σ'_p 值比 CRS 试验低 10% – 18%。

Upon examination of the original sources (listed in Table *A*1 of Ching and Phoon (2014a)) from where data contained in S-CLAY/7/168 have been collected, it seems that σ'_p points were mostly measured from CRS oedometer tests. F-CLAY/7/216 contains only 56 σ'_pCRS points, while the remaining 162 points are from 24h IL tests (σ'_pI) (Figure 3(a)). Therefore, to make data suitable for comparison, σ'_pIL is increased by 27% for all data points as a first-order correction following the proposal by Länsivaara (1999) (Figure 3(b)). By applying $\sigma'_\mathrm{pCRS}/\sigma'_\mathrm{pIl} = 1.27$ to all $162\sigma'_\mathrm{pIL}$ values from Finland, the strength points from F-CLAY/10/216 seem to better adapt to the $s_y(\mathrm{mob})/\sigma'_\mathrm{v} -$ OCR trend shown by those contained in S-CLAY/10/168 (Figure 3(b)). It is plausible that the difference between F-CLAY/7/216 and S-CLAY/10/168 in the $s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}$ versus OCR plot is primarily caused by the difference between the CRS and IL test, rather than the difference between clay types, as also indicated by Figure 1 and Figure 1.

在检查原始来源（列于Ching and Phoon (2014a) 的表 A1）后，从中收集了 S-CLAY/7/168 的数据，似乎 σ'_p 点主要是通过 CRS 固结试验测得的。F-CLAY/7/216 仅包含 56 个 σ'_pCRS 点，其余 162 个点来自 24 小时 IL 试验 (σ'_pI)（图3(a)）。因此，为了使数据适合比较，按照Länsivaara (1999) 的建议（图3(b)），对所有数据点的 σ'_pIL 增加 27% 作为一阶校正。通过对芬兰的所有 162 个 σ'_pIL 值应用 $\sigma'_\mathrm{pCRS}/\sigma'_\mathrm{pIl} = 1.27$，F-CLAY/10/216 的数据点似乎要比 S-CLAY/10/168（图 3(b)）的数据点更好地适应 $s_y(\mathrm{mob})/\sigma'_\mathrm{v} -$ OCR 显示的趋势。$s_y(\mathrm{mob})/\sigma'_\mathrm{v} -$ OCR 图中的 F-CLAY/10/216 和 S-CLAY/10/168 之间的差异可能主要是由 CRS 和 IL 试验之间的差异引起的，而不是由黏土类型之间的差异，也正如图 1和图 2所示。

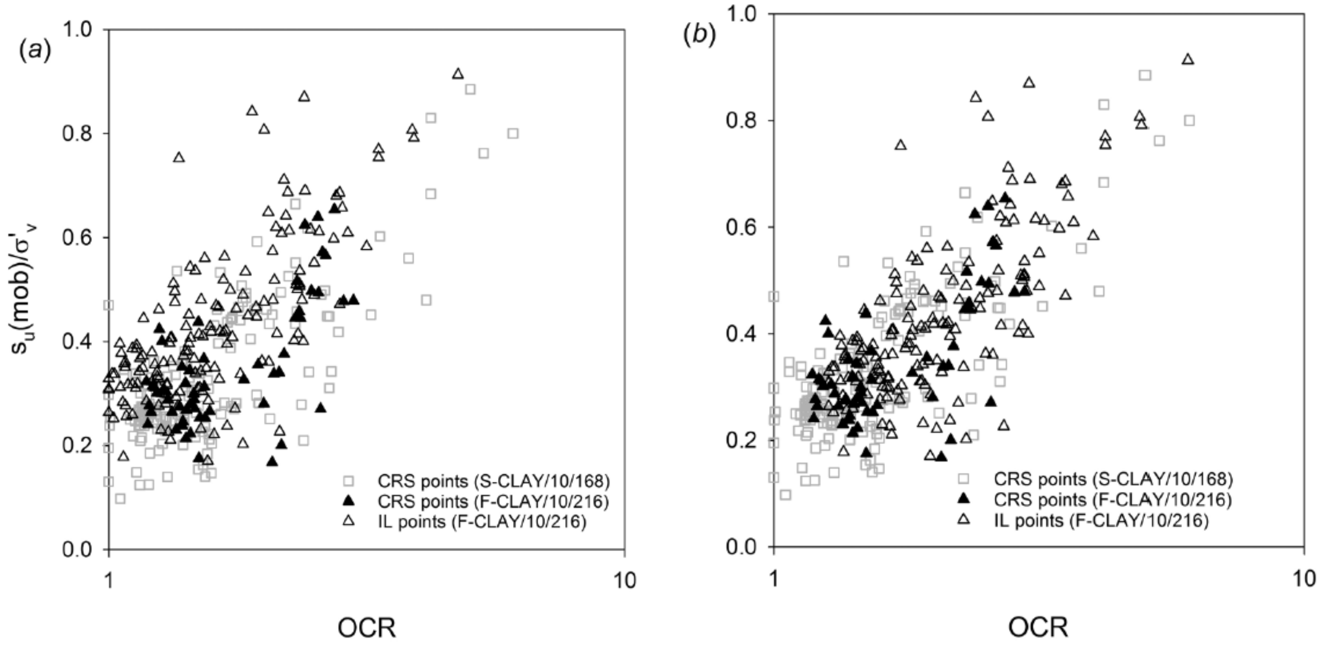
The basic statistics of the 10 dimensionless parameters are listed in Table 4 and Table 5 for the dimensionless databases, labeled as F-CLAY/10/216 and S-CLAY/10/168, respectively.

表4和表5中列出了针对无量纲数据库的 10 个无量纲参数的基本统计信息，分别标记为 F-CLAY/10/216 和 S-CLAY/10/168。

Comparison with existing transformation models 与现有转换模型的比较

The 384 clay data points constituting F-CLAY/10/216 and S-

将构成 F-CLAY/10/216 数据库和



(a) raw data point

(b) data points corrected to σ'_p from CRS oedometer test using $\sigma'_{pCRS}/\sigma'_{pIL} = 1.27$

Figure 3: $s_u(\text{mob})/\sigma'_v$ against OCR
图 3: $s_u(\text{mob})/\sigma'_v$ 与 OCR 的关系

Table 4: Basic statistics of 10 dimensionless soil parameters in F-CLAY/10/216, derived from the seven basic parameters in F-CLAY/7/216.
表 4: 从 F-CLAY/7/216 中的七个基本参数得出的 F-CLAY/10/216 中 10 个无量纲土体参数的基本统计信息

Variable	n	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	168	0.329	0.417	0.098	0.885
$s_u(\text{mob})/\sigma'_p$	168	0.21	0.269	0.088	0.470
s_u^{FV}/σ'_v	168	0.386	0.469	0.098	0.974
s_u^{FV}/σ'_p	168	0.244	0.311	0.088	0.490
OCR	168	1.664	0.476	1.00	6.07
LL	168	71.06	0.396	22.77	201.81
PI	168	41.61	0.496	3.91	127.89
w	168	76.63	0.347	17.27	180.11
LI	168	1.267	0.507	0.60	5.50
St	59	12.068	0.779	3.00	42.50

Table 5: Basic statistics of 10 dimensionless soil parameters in F-CLAY/10/168, derived from the seven basic parameters in F-CLAY/7/168
表 5: 从 F-CLAY/7/168 中的七个基本参数得出的 F-CLAY/10/168 中 10 个无量纲土体参数的基本统计信息

Variable	n	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	216	0.458	0.715	0.167	2.754
$s_u(\text{mob})/\sigma'_p$	216	0.209	0.281	0.081	0.469
s_u^{FV}/σ'_v	216	0.513	0.712	0.176	2.938
s_u^{FV}/σ'_p	216	0.234	0.293	0.083	0.594
OCR	216	2.17	0.467	1.18	7.50
LL	216	66.284	0.298	22.0	125.0
PI	216	38.545	0.482	2.0	95.0
w	216	76.34	0.268	25.0	150.0
LI	216	1.443	0.459	0.425	4.800
S_t	216	17.447	0.789	2.0	64.0

CLAY/10/168 databases are compared with transformation models proposed in the literature to check their consistency. It is worth pointing out that transformation models are generally derived based on certain types of clays and geographical locations. The basis for

S-CLAY/10/168 数据库的 384 个黏土数据点与文献中提出的转换模型进行比较，以检查其一致性。值得指出的是，转换模型通常是基于某些类型的黏土和地理位置得出的。

these models is usually empirical. Very often, for such models we do not know the basic statistics (such as those reported in Table 4 and Table 5).

The 10 transformation models analyzed are labeled using the following template: "primary input parameter" - "target parameter" - "secondary input parameter". They are categorized into four types (see e.g., Table 6):

Type A: Models for S_t, including two LI $-$ (s_u^{re}/P_a) models and two LI $-$ (S_t) models.

Type B: Models for effective stress, including one LI $-\left(\sigma_p'/P_a\right)-S_t$ model. Basic statistics of $\sigma_p'/\mathrm{P_a}$ are reported in Table 2 and Table 3 and not included in the dimensionless databases, as s_u^{FV} and $s_u(\mathrm{mob})$ are the parameters of primary interest for this study.

Type C: Models for shear strength, including one PI $-$ $\left[\mathrm{s_u(mob)}/\sigma_p'\right]$ model, one OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ model, and one OCR $-$ $[\mathrm{s_u(mob)}/\sigma_v'] - S_t$ model.

Type D: Models for shear strength, including two PI $-$ $\left(s_u^{FV}/\sigma_p'\right)$ one LL $-$ $\left(s_u^{FV}/\sigma_p'\right)$. These three models are compared to uncorrected s_u^{FV}(λ correction factor is not applied), being originally derived from uncorrected measurements.

Many of the transformation models are derived empirically using regression analyses. Only the LI $-$ (s_u^{re}/P_a) model by Wroth and Wood (1978) represents an exception. It is derived theoretically from the modified Cam clay model. The LI $-$ $\left(\sigma_p'/\mathrm{P_a}\right)$ $-$ S_t and OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ $-$ S_t models proposed by Ching and Phoon (2012b) are derived from sensitive structured clay data. The LI $-$ S_t model by Bjerrum (1954) is based on Norwegian marine clay data.

Figure 4-Figure 10 show the comparison between databases and transformation models. For the LI $-$ $\left(\sigma_p'/P_a\right)$ $-$ S_t and OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ $-$ S_t models by Ching and Phoon (2012b), data points are divided into two groups according to S_t values. The two groups are based on the distinction between "low to medium sensitive" ($S_t < 15$) and "highly sensitive" ($S_t > 15$) clays suggested by Karlsrud and Hernandez-Martinez (2013) for Norwegian clays.

The OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ transformation model by Jamiolkowski et al. (1985) provides a reasonable average fit to the data. For OCR < 8, $s_u(\mathrm{mob})/\sigma_v'$ seems to be strongly dependent on OCR (Figure 4). A deviation from the trend line in Figure 4 is visible at OCR values greater than 5. However, data points with OCR > 5 belong to layers located in proximity of the ground surface (above 1.50 m) where the clay might be fissured and (or) partially saturated. Therefore, the interest for those points is limited, because the focus of this study is on intact clays.

这些模型的基础通常是经验性的。通常，对于此类模型，我们不了解基本统计信息（例如表4和表5中报告的统计信息）。

使用以下模板标记分析的 10 个转换模型：“主要输入参数” - “目标参数” “次要输入参数”。它们分为四种类型（例如，参见表6）：

A 类：S_t 的模型，包括两个 LI $-$ (s_u^{re}/P_a) 模型和两个 LI $-$ (S_t) 模型。

B 类：有效应力的模型，包括一个 LI $-$ $\left(\sigma_p'/P_a\right)$ $-$ S_t 模型。$\sigma_p'/\mathrm{P_a}$ 的基本统计数据在表2和表3中报告，并且不包含在无量纲数据库中，因为 s_u^{FV} 和 $s_u(\mathrm{mob})$ 是这项研究的主要参数。

C 类：剪切强度的模型，包括一个 PI $-$ $\left[\mathrm{s_u(mob)}/\sigma_p'\right]$，一个 OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ 模型和一个 OCR $-$ $[\mathrm{s_u(mob)}/\sigma_v']$ $-$ S_t 模型。

D 类：剪切强度的模型，包括两个 PI $-$ $\left(s_u^{FV}/\sigma_p'\right)$，一个 LL $-$ $\left(s_u^{FV}/\sigma_p'\right)$ 模型。将这三个模型与未经修正的 s_u^{FV}（λ 修正因子未应用）进行比较，该模型最初是由未经修正的测量得出的。

许多转换模型是使用回归分析根据经验得出的。只有Wroth and Wood (1978) 的 LI $-$ (s_u^{re}/P_a) 模型代表例外。它是从理论上从改进的 Cam clay 模型得出的。Ching and Phoon (2012b) 提出的 LI $-$ $\left(\sigma_p'/\mathrm{P_a}\right)$ $-$ S_t 和 OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ $-$ S_t 模型是从敏感的结构化黏土数据中得出的。Bjerrum (1954) 的 LI $-$ S_t 模型基于挪威海洋黏土数据。

图 4-图 10显示了数据库和转换模型之间的比较。对于Ching and Phoon (2012b) 的 LI $-$ $\left(\sigma_p'/P_a\right)$ $-$ S_t 和 OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ $-$ S_t 模型，数据点根据 S_t 值被分为两组。两组基于Karlsrud and Hernandez-Martinez (2013) 对挪威黏土提出的“中低敏感度”（$S_t < 15$）和“高敏感度”（$S_t > 15$）黏土的区别。

Jamiolkowski et al. (1985) 的 OCR $-$ $[s_u(\mathrm{mob})/\sigma_v']$ 转换模型。提供了一个合理的平均拟合数据。对于 OCR < 8，$s_u(\mathrm{mob})/\sigma_v'$ 似乎与 OCR 密切相关（图4）。在 OCR>5 时，可以看到与图4中趋势线的偏离。但是，OCR>5 的数据点属于位于地面附近（1.50 m 以上）的层，黏土可能会开裂，且（或）部分饱和。因此，我们对这些观点的研究兴趣是有限的，因

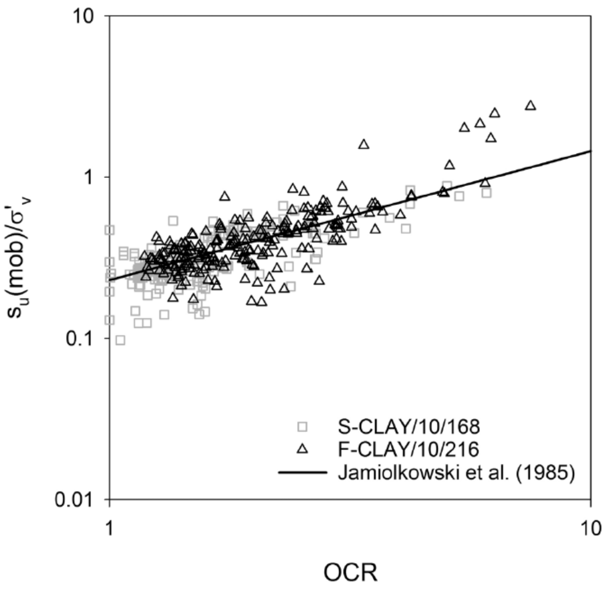


Figure 4: OCR $- [s_u(mob)/\sigma'_v]$ model proposed by Jamiolkowski et al. (1985)

图 4: Jamiolkowski et al. (1985) 提出的 OCR $- [s_u(mob)/\sigma'_v]$ 模型

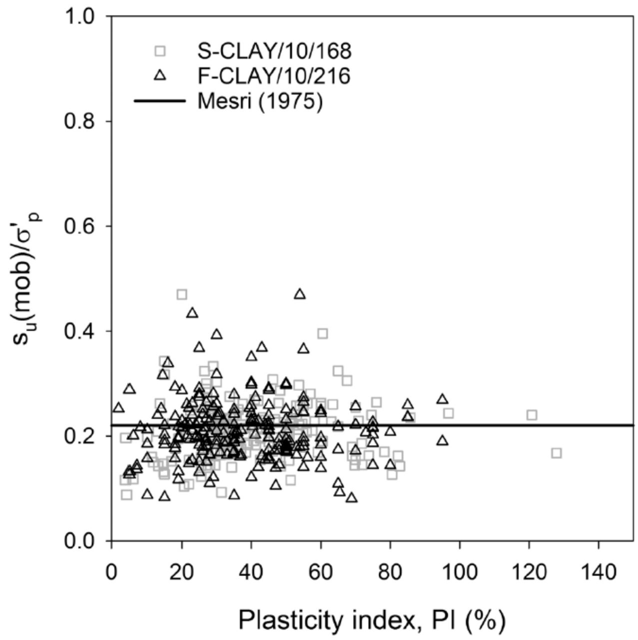
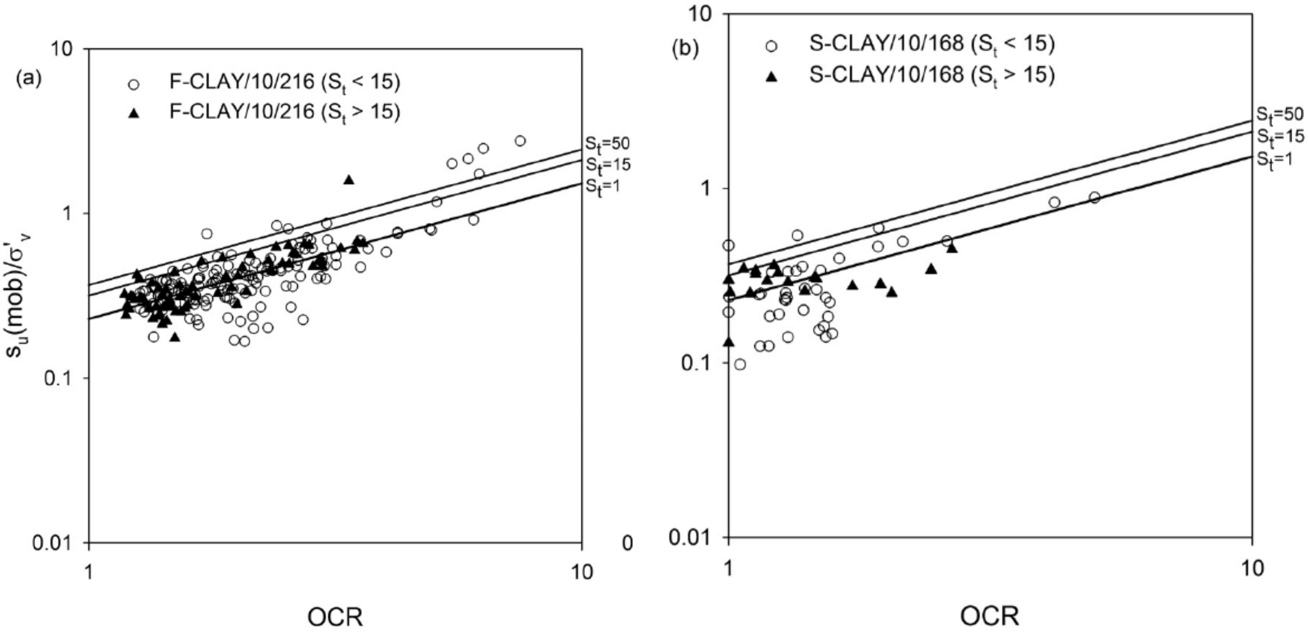


Figure 5: PI $- [s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}]$ model proposed by Mesri (1975, 1989)

图 5: Mesri (1975, 1989) 提出的 PI $- [s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}]$ 模型



(a) F-CLAY/10/216

(b) S-CLAY/10/168

Figure 6: OCR $- [\mathrm{s_u}(\mathrm{mob})/\sigma'_\mathrm{v}] - S_\mathrm{t}$ model proposed by Ching and Phoon (2012b)

图 6: Ching and Phoon (2012b) 提出的 OCR $- [\mathrm{s_u}(\mathrm{mob})/\sigma'_\mathrm{v}] - S_\mathrm{t}$ 模型

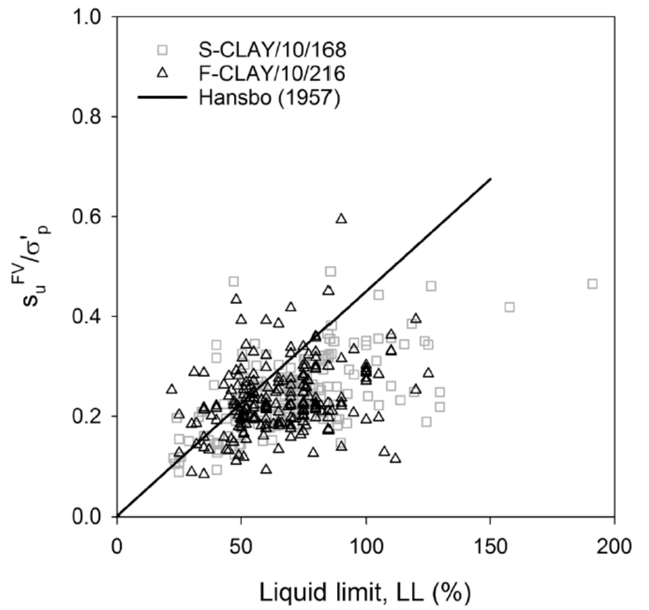


Figure 7: LL – $\left(s_{\mathrm{u}}^{\mathrm{FV}}/\sigma'_{\mathrm{p}}\right)$ model proposed by Hansbo (1957)
图 7: Hansbo (1957) 提出的 LL – $\left(s_{\mathrm{u}}^{\mathrm{FV}}/\sigma'_{\mathrm{p}}\right)$ 模型

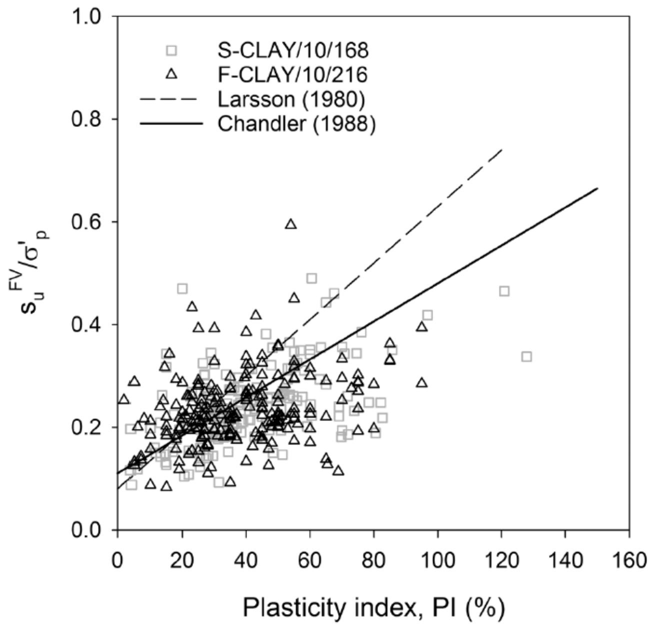


Figure 8: PI – $\left(s_{\mathrm{u}}^{\mathrm{FV}}/\sigma'_{\mathrm{p}}\right)$ model proposed by Larsson (1980); Chandler (1988)
图 8: Larsson (1980); Chandler (1988) 提出的 PI – $\left(s_{\mathrm{u}}^{\mathrm{FV}}/\sigma'_{\mathrm{p}}\right)$ 模型

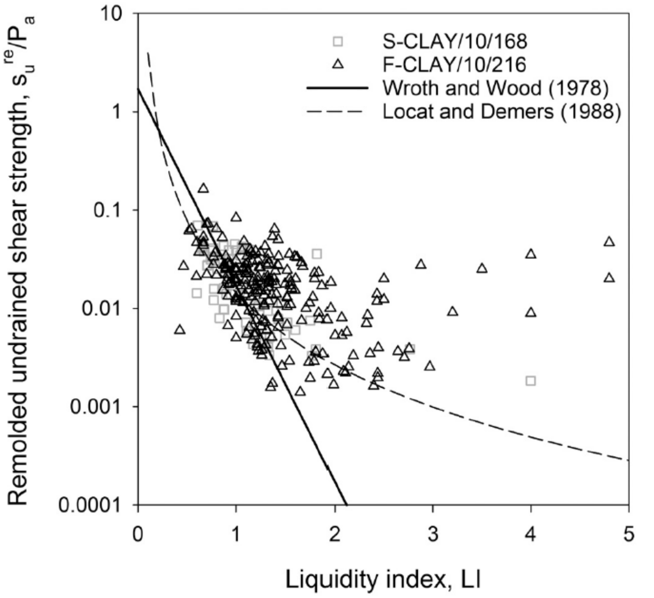


Figure 9: LI – $\left(s_{\mathrm{u}}^{\mathrm{re}}/P_{\mathrm{a}}\right)$ models
图 9: LI – $\left(s_{\mathrm{u}}^{\mathrm{re}}/P_{\mathrm{a}}\right)$ 模型

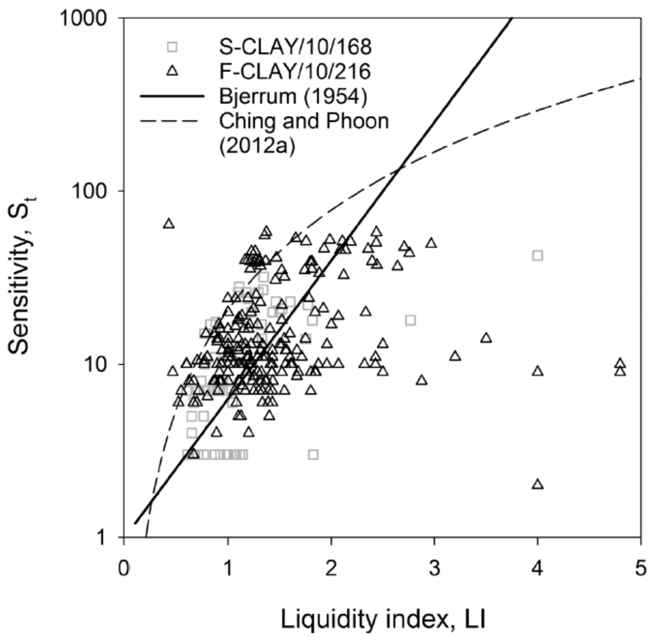
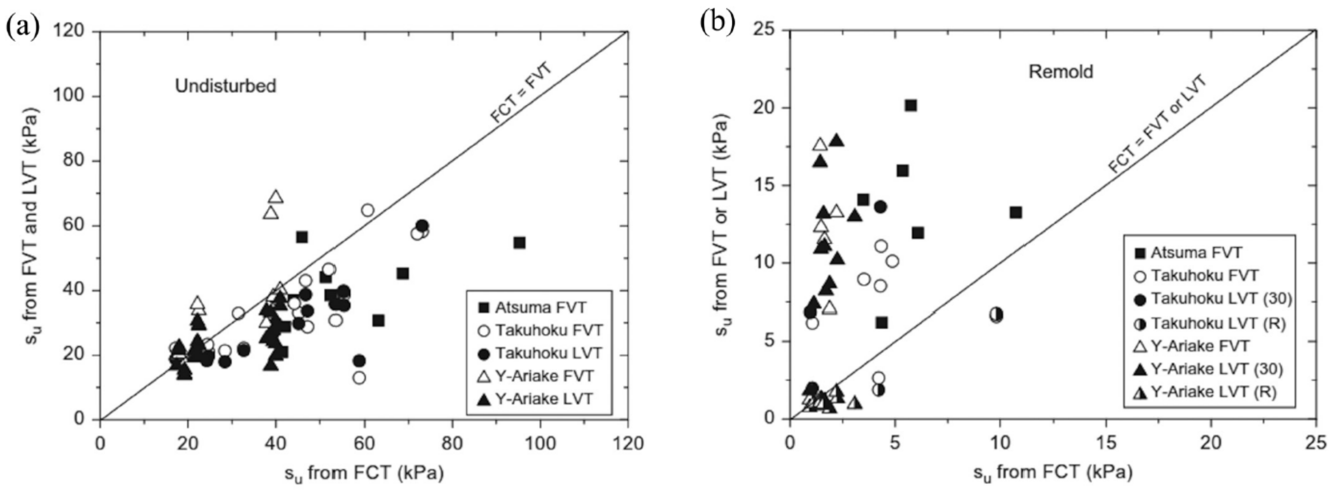


Figure 10: LI – S_{t} models
图 10: LI – S_{t} 模型

Table 6: Transformation models in literature and their calibration results for F-CLAY/10/216
表 6: 文献中的转换模型及其对 F-CLAY/10/216 的校准结果

Type	Relationship	Literature	n	Transformation model	Comprasion Figure	Calibration Fit to trend?	Bias factor,b	COV of $\varepsilon=\delta$
A	$\mathrm{LI}-\mathrm{s_u^{re}/P_a}$	Wroth and Wood (1978)	899	$s_u^{re}/P_a \approx 1.7^{-4.6\mathrm{LI}}$	Fig.9	NO	–	–
		Locat and Demers (1988)	899	$s_u^{re}/P_a \approx 0.0144\mathrm{LI}^{-2.44}$	Fig.9	YES	4.05	3.02
	$\mathrm{LI}-\mathrm{S_t}$	Bjerrum (1954)	1279	$S_t \approx 10^{0.8\mathrm{LI}}$	Fig.10	YES	1.56	1.40
		Ching and Phoon (2012b)	1279	$S_t \approx 20.726\mathrm{LI}^{1.910}$	Fig.10	NO	0.57	1.94
B	$\mathrm{LI}-(\sigma'_\mathrm{p}/\mathrm{P_a})-\mathrm{S_t}(\text{for } \mathrm{S_t}<15)$	Ching and Phoon (2012b)	694	$\sigma'_p/P_a \approx 0.235\mathrm{LI}^{-1.139}\mathrm{S_t^{0.536}}$	Fig.12(a)	YES	2.02	0.94
	$\mathrm{LI}-(\sigma'_\mathrm{p}/\mathrm{P_a})-\mathrm{S_t}(\text{for } \mathrm{S_t}>15)$	Ching and Phoon (2012b)	492	$\sigma'_p/P_a \approx 0.235\mathrm{LI}^{-1.139}\mathrm{S_t^{0.536}}$	Fig.12(a)	YES	0.95	0.47
C	$\mathrm{PI}-\mathrm{s_u(mob)}/\sigma'_\mathrm{p}$	Mesri (1975, 1989)	1072	$s_u(\mathrm{mob})/\sigma'_\mathrm{p} \approx 0.22$	Fig.5	YES	0.95	0.28
	$\mathrm{OCR}-\mathrm{s_u(mob)}/\sigma'_\mathrm{v}$	Jamiolkowski et al. (1985)	1155	$s_u(\mathrm{mob})/\sigma'_\mathrm{v} \approx 0.23\mathrm{OCR}^{0.8}$	Fig.6	YES	1.06	0.30
	$\mathrm{OCR}-\mathrm{s_u(mob)}/\sigma'_\mathrm{v}-\mathrm{S_t}$	Ching and Phoon (2012b)	1402	$s_u(\mathrm{mob})/\sigma'_\mathrm{p} \approx 0.229\mathrm{OCR}^{0.823}\mathrm{S_t^{0.121}}$	Fig.6(a)	YES	0.77	0.32
D	$\mathrm{LL}-(\mathrm{s_u^{FV}}/\sigma'_\mathrm{p})$	Hansbo (1957)	423	$s_u^{FV}/\sigma'_p \approx 0.45\mathrm{LI}$	Fig.7	YES	0.84	0.38
	$\mathrm{PI}-(\mathrm{s_u^{FV}}/\sigma'_\mathrm{p})$	Larsson (1980)	428	$s_u^{FV}/\sigma'_p \approx 0.08+0.0055\mathrm{PI}$	Fig.8	YES	0.89	0.43
		Chandler (1988)	423	$s_u^{FV}/\sigma'_p \approx 0.11+0.0037\mathrm{PI}$	Fig.8	YES	0.97	0.35



(a) undisturbed (b) remolded conditions (Tanaka et al., 2012)

Figure 11: Comparison of strengths measured by FC, FV, and LVT
图 11: 通过 FC，FV 和 LVT 测量的强度比较

The $\mathrm{PI}-[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}]$ model by Mesri (1975, 1989) takes out the dependency of $s_\mathrm{u}(\mathrm{mob})$ on PI, stating that $s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}$ is constant and equal to 0.22. From Figure 5, s_u (mob) $/\sigma'_\mathrm{p}$ seems independent of PI, thus confirming the suggestion given by Mesri.

The dependency of s_u on $\mathrm{S_t}$ predicted by the $\mathrm{OCR}-[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}]-S_\mathrm{t}$ model by Ching and Phoon (2012b), is not visible from the collected data points (Figure 6). However, the majority of the F-CLAY/10/216 data points for $S_\mathrm{t}<15$ are located between the $s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}-\mathrm{OCR}$ trend lines for $S_\mathrm{t}=1$ and $S_\mathrm{t}=15$ (Figure 6(a)).

It is quite difficult to observe a well-defined trend for the data

为本研究的重点是完整的黏土。

Mesri (1975, 1989) 的 $\mathrm{PI}-[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}]$ 模型去除了 $s_\mathrm{u}(\mathrm{mob})$ 对 PI 的依赖性，并指出 $s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}$ 是常数且等于 0.22。从图5可以看出，$s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{p}$ 似乎与 PI 无关，从而证实了 Mesri 的建议。

从Ching and Phoon (2012b) 的 $\mathrm{OCR}-[s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}]-S_\mathrm{t}$ 模型所预测收集的数据点中看不到对 s_u 对于 $\mathrm{S_t}$ 的依赖性（图6）。但是，$S_\mathrm{t}<15$ 的大多数 F-CLAY/10/216 数据点位于 $S_\mathrm{t}=1$ 和 $S_\mathrm{t}=15$ 的 $s_\mathrm{u}(\mathrm{mob})/\sigma'_\mathrm{v}-\mathrm{OCR}$ 趋势线之间（图6(a)）。

Hansbo (1957) 的 $\mathrm{LL}-(s_\mathrm{u}^\mathrm{F}/\sigma'_\mathrm{p})$ 模型很

points to the $\mathrm{LL}-\left(s_u^{\mathrm{F}}/\sigma'_p\right)$ model by Hansbo (1957) (Figure 7). Both databases seem to better adapt to the mean trend suggested by the $\mathrm{PI}-\left(s_u^{\mathrm{FV}}/\sigma'_p\right)$ models (Figure 8), although high scatter can be observed along the trend lines suggested by Larsson (1980) and Chandler (1988) (after Skempton (1954)).

难观察到一个指向的数据点的清晰的趋势（图7）。尽管我们可以沿着Larsson (1980) 和 Chandler (1988)（在Skempton (1954) 之后）提出的趋势线观察到数据点高度分散，但两个数据库似乎都更好地适应了 $\mathrm{PI}-\left(s_u^{\mathrm{FV}}/\sigma'_p\right)$ 模型建议的平均趋势（图8）。

Data points seem to depart from the $\mathrm{LI}-\left(s_u^{\mathrm{re}}/P_a\right)$ model by Wroth and Wood (1978) for LI values greater than 1 (Figure 9). However, the transformation model by Locat and Demers (1988) seems able to reproduce the trend observed for LI < 2 (Figure 9). For LI > 2, the data points deviate from the existing transformation models. The authors believe that S_t was determined from the FV test for some of the Finnish data points (from Gardemeister (1973)). The FV test is known to produce higher s_u^{re} values than the conventional fall cone (FC) test. Tanaka et al. (2012) demonstrated how s_u^{re} determined from the FV test and the laboratory vane test (LVT) is as much as tenfold larger than s_u^{re} determined using the FC test (Fig. 10b). This was attributed to the different remolding methods, as the turning of the vane is not equivalent to the remolded state for the FC test, which is obtained by kneading by hand. Hence, the actual s_u^{re} may be lower than that shown in Fig. 9, which consequently produces a higher S_t. However, there are only 29 points with LI > 2. The conclusions of this study will be largely unaffected, because 29 points only constitute 13.4% of the total number of points. Based on the experimental results presented by Tanaka et al. (2012), the authors would like to further suggest that while undisturbed s_u values from FV and FC can be mixed (as shown in Figure 11(a)), s_u^{re} or derived parameters (S_t) between FV and FC should be treated separately (as suggested by Figure 11(b)).

Wroth and Wood (1978) 对于 LI 值大于 1 的数据点似乎偏离了 $\mathrm{LI}-\left(s_u^{\mathrm{re}}/P_a\right)$ 模型（图9）。但是，Locat and Demers (1988) 的转换模型似乎能够重现对于 LI<2 观察到的趋势（图9）。对于 LI>2，数据点偏离现有的转换模型。作者认为，S_t 是通过 FV 试验确定的一些芬兰数据点（来自Gardemeister (1973)）。已知 FV 试验会产生比传统的落锥（FC）试验更高的输出值。Tanaka et al. (2012) 证明了通过 FV 试验确定的结果和实验室叶片试验（LVT）的结果是使用 FC 试验确定的结果的十倍之多（图11(b)）。这归因于不同的重塑方法，因为叶片的旋转不等同于通过手动捏合获得的 FC 试验的重塑状态。因此，实际的结果可能会低于图9所示的结果，因此会产生更高的 S_t。但是，LI>2 的数据点仅有 29 个。该研究的结论将在很大程度上不受影响，因为仅 29 个数据点占总数据点的 13.4%。基于Tanaka et al. (2012) 提出的实验结果，作者想进一步建议，尽管可以混合 FV 和 FC 的不受干扰的 s_u 值（如图11(a)所示），但 FV 和 FC 之间的 s_u^{re} 或派生参数（S_t）应分开对待（如图11(b)建议）。

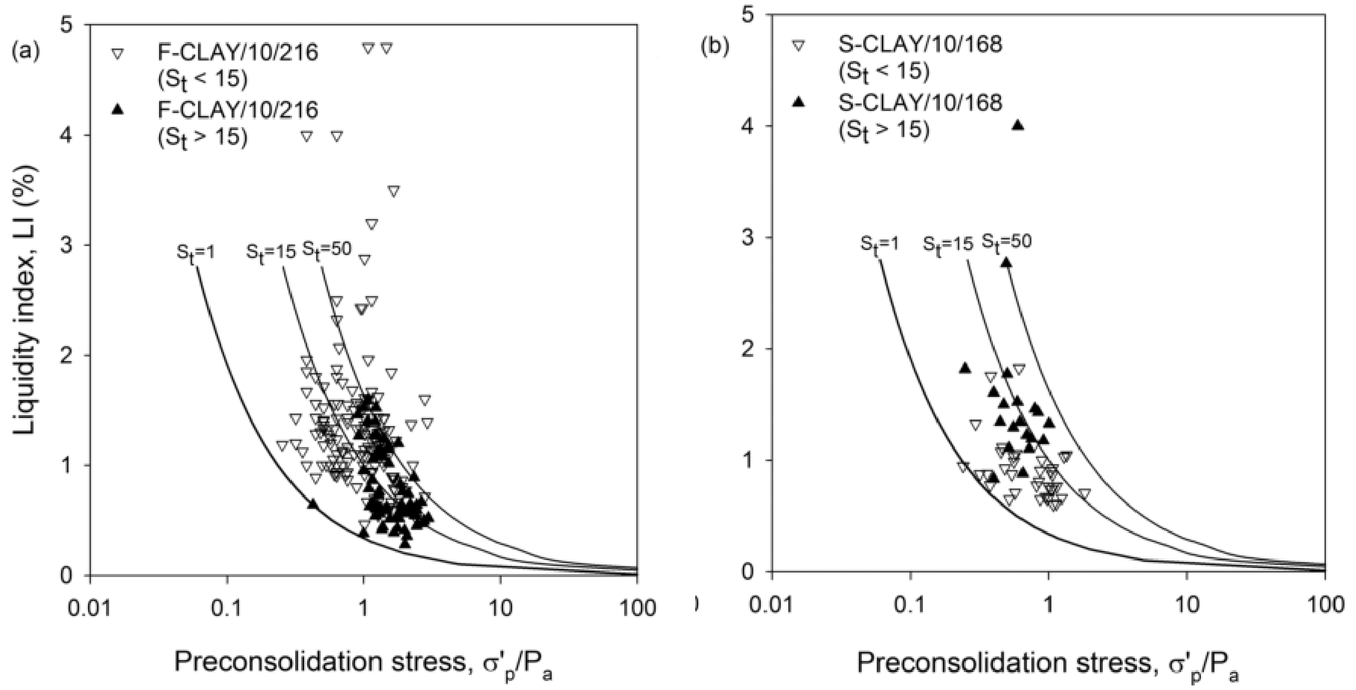
The $\mathrm{LI}-(S_t)$ model by Bjerrum (1954) can reasonably describe the data points for LI < 2, despite the high scatter observed (Figure 10). In contrast, the global model by Ching and Phoon (2012a) seems to provide an upper bound rather than an average fit to the databases (Figure 10).

尽管观察到高度分散（图10），但Bjerrum (1954) 的 $\mathrm{LI}-(S_t)$ 模型可以合理地描述 LI<2 的数据点。相比之下，Ching and Phoon (2012b) 的全局模型似乎为数据库提供了上限，而不是平均拟合（图10）。

The $\mathrm{LI}-\left(\sigma'_p/P_a\right)-S_t$ model by Ching and Phoon (2012b) does not seem to fit the data points in F-CLAY/10/216 for $S_t < 15$ (Figure 12(a)). The $\mathrm{LI}-\left(\sigma'_p/\mathrm{P_a}\right)-S_t$ transformation model appears to provide a better description of the highly sensitive clays ($S_t > 15$) in F-CLAY/10/216 as the majority of the points are contained in the interval between the $\mathrm{LI}-\left(\sigma'_p/P_a\right)-S_t$ lines for $S_t = 15$ and $S_t = 50$ (Figure 12(a)). In contrast, for the low to medium sensitive clays ($S_t < 15$) in S-CLAY/10/168, most of the data points are comprised between the $\mathrm{LI}-\left(\sigma'_p/\mathrm{P_a}\right)-S_t$ boundary lines for $S_t = 1$ and $S_t = 15$ (Figure 12(b)), while for the highly sensitive clays, the models cannot satisfactorily describe the observed values.

Ching and Phoon (2012b) 提出的 $\mathrm{LI}-\left(\sigma'_p/P_a\right)-S_t$ 模型似乎不适合 $S_t < 15$ 的 F-CLAY/10/216 中的数据点（图12(a)）。$\mathrm{LI}-\left(\sigma'_p/\mathrm{P_a}\right)-S_t$ 转换模型似乎可以更好地描述 F-CLAY/10/216 中的高敏感黏土（$S_t > 15$），因为大多数点都包含在 $S_t = 15$ 和 $S_t = 50$ 的 $\mathrm{LI}-\left(\sigma'_p/P_a\right)-S_t$ 线之间（图12(a)）。相比之下，对于 S-CLAY/10/168 中的中低敏感度黏土（$S_t < 15$），对于，大多数数据点包含在 $S_t = 1$ 和 $S_t = 15$ 的 $\mathrm{LI}-\left(\sigma'_p/\mathrm{P_a}\right)-S_t$ 边界线之间（图12(b)），而对于高度敏感的黏

土，模型不能令人满意地描述观测值。



(a) F-CLAY/10/216 (b) S-CLAY/10/168

Figure 12: $\mathrm{LI}-\left(\sigma_{\mathrm{p}}'/\mathrm{P_a}\right)-S_{\mathrm{t}}$ model by Ching and Phoon (2012b)
图 12: Ching and Phoon (2012b) 提出的 $\mathrm{LI}-\left(\sigma_{\mathrm{p}}'/\mathrm{P_a}\right)-S_{\mathrm{t}}$ 模型

Bias and uncertainties of the existing transformation models 现有转换模型的偏差和不确定性

Bias factor (denoted by b), and COV (denoted by δ) are evaluated and discussed for the transformation models described in the previous section, based on the F-CLAY/10/216 and S-CLAY/10/168 databases. The parameters b and δ represent the sample mean and the COV, respectively, of the ratio (actual target value)/(predicted If $b = 1$, the model prediction is unbiased. For instance, for the $\mathrm{OCR}-[\mathrm{s_u(mob)}/\sigma_{\mathrm{v}}']$ transformation model by Jamiolkowski et al. (1985), the actual target value is $s_{\mathrm{u}}(\mathrm{mob})/\sigma_{\mathrm{v}}'$ and the predicted target value is $0.23\mathrm{OCR}^{0.8}$. For the data points where $s_{\mathrm{u}}(\mathrm{mob})/\sigma_{\mathrm{v}}'$ and OCR are simultaneously known, (actual target value) (predicted target value) $= [s_{\mathrm{u}}(\mathrm{mob})/\sigma_{\mathrm{v}}'] / \left(0.23\mathrm{OCR}^{0.8}\right)$.

在 F-CLAY/10/216 和 S-CLAY/10/168 数据库的基础上，针对上一节中描述的转换模型评估并讨论了偏差因子（以 b 表示）和 COV（以 δ 表示）。参数 b 和 δ 分别代表比率（实际目标值）/（预测目标值）的样本平均值和 COV。如果 $b = 1$，则模型预测是无偏的。例如，对于Jamiolkowski et al. (1985) 的 $\mathrm{OCR}-[\mathrm{s_u(mob)}/\sigma_{\mathrm{v}}']$ 转换模型，实际目标值为 $s_{\mathrm{u}}(\mathrm{mob})/\sigma_{\mathrm{v}}'$，预测目标值为 $0.23\mathrm{OCR}^{0.8}$。对于同时知道 $s_{\mathrm{u}}(\mathrm{mob})/\sigma_{\mathrm{v}}'$ 和 OCR 的数据点，（实际目标值）/（预测的目标值）= $[s_{\mathrm{u}}(\mathrm{mob})/\sigma_{\mathrm{v}}'] / \left(0.23\mathrm{OCR}^{0.8}\right)$。

According to Ching and Phoon (2014a):

根据Ching and Phoon (2014a)：

$$\begin{aligned}\varepsilon &= (\text{actual target value})/(\text{b} \times \text{predicted target value}) \\ &= (\text{actual target value})/(\text{unbiased prediction})\end{aligned} \tag{10}$$

where ε is the variability term with mean = 1 and COV = δ. If $\delta = 0$ there is no data scatter about the transformation model, indicating

其中 ε 是 mean = 1 且 COV = δ 的变异项。如果 $\delta = 0$，则转换模型没有数据分散，表明

that the prediction is deterministic, rather than uncertain.

Bias factors and COVs for the different transformation models analyzed are reported in Table 6 for F-CLAY/10/216 and Table 7 for S-CLAY/10/168, respectively. Bias factor, COV of ε, and number of data points used for each calibration are denoted, respectively, by b, δ, and n.

预测是确定性的而不是不确定的。

表6和表7分别报告了 F-CLAY/10/216 和 S-CLAY/10/168 所分析的不同转换模型的偏差因子和 COV。偏差因子，ε 的 COV 和每次校准所使用的数据点数分别由 b，δ 和 n 表示。

Table 7: Transformation models for Finnish clays and their calibration results for S-CLAY/10/168
表 7: 芬兰黏土的转换模型及其对 S-CLAY/10/168 的校准结果

Type	Relationship	Literature	n	Transformation model	Compraison Figure	Calibration Fit to trend?	Bias factor,b	COV of $\varepsilon=\delta$
A	$\mathrm{LI}-\mathrm{s_u^{re}/P_a}$	Wroth and Wood (1978)	899	$s_u^{re}/P_a \approx 1.7^{-4.6\mathrm{LI}}$	Fig.9	NO	–	–
		Locat and Demers (1988)	899	$s_u^{re}/P_a \approx 0.0144\mathrm{LI}^{-2.44}$	Fig.9	YES	1.60	0.96
	$\mathrm{LI}-\mathrm{S_t}$	Bjerrum (1954)	1279	$S_t \approx 10^{0.8\mathrm{LI}}$	Fig.10	YES	1.48	0.65
		Ching and Phoon (2012b)	1279	$S_t \approx 20.726\mathrm{LI}^{1.910}$	Fig.10	NO	0.49	0.61
B	$\mathrm{LI}-(\sigma_p'/\mathrm{P_a})-\mathrm{S_t}(\text{for } \mathrm{S_t}<15)$	Ching and Phoon (2012b)	694	$\sigma_p'/P_a \approx 0.235\mathrm{LI}^{-1.139}\mathrm{S_t^{0.536}}$	Fig.12(b)	YES	1.23	0.51
	$\mathrm{LI}-(\sigma_p'/\mathrm{P_a})-\mathrm{S_t}(\text{for } \mathrm{S_t}>15)$	Ching and Phoon (2012b)	492	$\sigma_p'/P_a \approx 0.235\mathrm{LI}^{-1.139}\mathrm{S_t^{0.536}}$	Fig.12(b)	YES	0.84	0.54
C	$\mathrm{PI}-\mathrm{s_u(mob)}/\sigma_p'$	Mesri (1975, 1989)	1072	$s_u(\mathrm{mob})/\sigma_p' \approx 0.22$	Fig.5	YES	0.96	0.27
	$\mathrm{OCR}-\mathrm{s_u(mob)}/\sigma_v'$	Jamiolkowski et al. (1985)	1155	$s_u(\mathrm{mob})/\sigma_v' \approx 0.23\mathrm{OCR}^{0.8}$	Fig.6	YES	0.97	0.25
	$\mathrm{OCR}-\mathrm{s_u(mob)}/\sigma_v'-\mathrm{S_t}$	Ching and Phoon (2012b)	1402	$s_u(\mathrm{mob})/\sigma_p' \approx 0.229\mathrm{OCR}^{0.823}\mathrm{S_t^{0.121}}$	Fig.6(b)	YES	0.71	0.36
D	$\mathrm{LL}-(\mathrm{s_u^{FV}}/\sigma_p')$	Hansbo (1957)	423	$s_u^{\mathrm{FV}}/\sigma_p' \approx 0.45\mathrm{LI}$	Fig.7	YES	0.82	0.34
	$\mathrm{PI}-(\mathrm{s_u^{FV}}/\sigma_p')$	Larsson (1980)	428	$s_u^{\mathrm{FV}}/\sigma_p' \approx 0.08+0.0055\mathrm{PI}$	Fig.8	YES	0.85	0.37
		Chandler (1988)	423	$s_u^{\mathrm{FV}}/\sigma_p' \approx 0.11+0.0037\mathrm{PI}$	Fig.8	YES	0.96	0.31

The $\mathrm{LI}-(s_\mathrm{u}^\mathrm{re}/P_\mathrm{a})$ model by Locat and Demers (1988) seems quite conservative, as it underpredicts the actual value by a factor of 4.05 for Finnish clays (Table 6) and 1.60 for Scandinavian clays (Table 7). Bjerrum (1954) transformation model underestimates the actual S_t values for both Finnish and Scandinavian clays. Nevertheless, the uncertainty underlying these predictions still remains considerable, as the COV for type A models ranges between 61% and 302%. A similar analysis can be carried out for the $\mathrm{LI}-\left(\sigma_\mathrm{p}'/P_\mathrm{a}\right)-S_\mathrm{t}$ model by Ching and Phoon (2012b). The deviation of about 50%−60% from the mean trend lines of both F-CLAY/10/216 and S-CLAY/10/168, combined with a COV greater than 1 and equal to 0.61 for Finnish and Scandinavian clays, respectively, would result in predicted values characterized by a high degree of uncertainty. Therefore, models of type A and B are ”biased” models with respect to both databases.

Locat and Demers (1988) 提出的 $\mathrm{LI}-(s_\mathrm{u}^\mathrm{re}/P_\mathrm{a})$ 模型似乎很保守，因为它低估了芬兰黏土的实际价值（4.05）（表6）和斯堪的纳维亚黏土的 1.60（表7）。Bjerrum (1954) 的转换模型低估了芬兰和斯堪的纳维亚黏土的实际 S_t 值。但是，由于 A 型模型的 COV 在 61% 至 302% 之间，因此这些预测的不确定性仍然很大。Ching and Phoon (2012b) 对 $\mathrm{LI}-\left(\sigma_\mathrm{p}'/P_\mathrm{a}\right)-S_\mathrm{t}$ 进行类似的分析。与 F-CLAY/10/216 和 S-CLAY/10/168 的平均趋势线约为 50% – 60% 的偏差，芬兰和斯堪的纳维亚的 COV 分别大于 1 和等于 0.61，将导致以高度不确定性为特征的预测值。因此，相对于两个数据库，类型 A 和 B 的模型都是“有偏差的”模型。

In contrast, different outcomes are obtained for the transformation models of type C and D (models for shear strength). Models of type C ($s_\mathrm{u}(\mathrm{mob})/\sigma_\mathrm{v}'$ is the target parameter) show bias factors (b) close to 1 and COV (δ) lower than 0.30. Exception is found for the $\mathrm{OCR}-[s_\mathrm{u}(\mathrm{mob})/\sigma_\mathrm{v}']-S_\mathrm{t}$ model Ching and Phoon (2012b), which shows a bias factor of 0.71-0.77 with a COV of 0.32-0.36. These results would thus suggest that $s_\mathrm{u}(\mathrm{mob})$ of Scandinavian clays can be described by different well established transformation models with relatively low

相反，对于 C 型和 D 型转换模型（剪切强度模型）可获得不同的结果。C 型模型（$s_\mathrm{u}(\mathrm{mob})/\sigma_\mathrm{v}'$ 是目标参数）显示偏差因子（b）接近 1 而 COV（δ）低于 0.30。Ching and Phoon (2012b) 提出的 $\mathrm{OCR}-[s_\mathrm{u}(\mathrm{mob})/\sigma_\mathrm{v}']-S_\mathrm{t}$ 模型中发现了例外，其偏差因子为 0.71-0.77，COV 为 0.32-0.36。因此，这些结果表明，斯堪的纳维亚黏土的 $s_\mathrm{u}(\mathrm{mob})$ 可以用不确

uncertainty. For instance, the equation by Mesri (1975, 1989) can be adapted to Finnish soft clays by including the bias factor (b) calibrated from F-CLAY/10/216 database as $s_{\mathrm{u}}(\mathrm{mob})/\sigma'_{\mathrm{p}} = b(0.22) = 0.95(0.22) = 0.209$, with a COV$(\delta) = 0.28$(low variability).

定性相对较低的各种完善的转化模型来描述。例如，Mesri (1975, 1989) 的方程可以通过引入 F-CLAY/10/216 数据库中校准的偏差因子（b），$s_{\mathrm{u}}(\mathrm{mob})/\sigma'_{\mathrm{p}} = b(0.22) = 0.95(0.22) = 0.209$, with a COV$(\delta) = 0.28$（低变异性）。

Type D models ($s_u^{\mathrm{FV}}/\sigma'_{\mathrm{p}}$ is the target parameter, see Table 6-Table 7 show a bias factor b varying between 0.82 and 0.97 with COV between 0.31 and 0.43, suggesting reasonably low variability for these models. In particular, the PI $-$ $\left(s_{\mathrm{u}}^{\mathrm{FV}}/\sigma'_{\mathrm{p}}\right)$ model proposed by Chandler (1988) results almost "unbiased" with respect to both F-CLAY/10/216 and S-CLAY/10/168, suggesting b comprised between 0.96-0.97 and δ varying between 0.31 and 0.35.

D 型模型（$s_u^{\mathrm{FV}}/\sigma'_{\mathrm{p}}$ 是目标参数，请参见表 6-表7）显示偏置系数 b 在 0.82 和 0.97 之间变化，COV 在 0.31 和 0.43 之间，表明这些模型的变异性较低。特别是Chandler (1988) 提出的 PI $-$ $\left(s_{\mathrm{u}}^{\mathrm{FV}}/\sigma'_{\mathrm{p}}\right)$ 模型对于 F-CLAY/10/216 和 S-CLAY/10/168 几乎都是“无偏的”，表明 b 介于 0.96-0.97，δ 在 0.31 和 0.35 之间变化。

4 s_u/σ'_v transformation models for F-CLAY/10/173 F-CLAY/10/173 数据库的 s_u/σ'_v 转换模型

Removal of outliers in F-CLAY/10/216 移除 F-CLAY/10/216 数据库中的异常值

As the scope of this study is to derive transformation models for s_u of Finnish soft clays that are more refined than the existing models in the literature, the data points collected in F-CLAY/10/216 are analyzed with the purpose of improving the quality of the database by removing outliers. The quality of data points is assessed through criteria based on the physical nature of the soil, mechanical characteristics, and statistical considerations. The adopted criteria are listed below:

由于本研究的范围是获得比文献中现有模型更精细的芬兰软黏土 s_u 的转化模型，因此对 F-CLAY/10/216 中收集的数据点进行了分析，目的在于通过消除异常值来提高数据库的质量。通过基于土壤物理性质，机械特性和统计考虑因素的标准评估数据点的质量。通过的数据标准如下：

1. Points located near the ground surface that may belong to fissured upper layers (dry crust), as the study focuses on intact and saturated clays. Dry crust layers are generally unsaturated and contain cracks and fissures. s_u of such soils may be highly overestimated when measured with the FV test (La Rochelle et al., 1974; Lefebvre et al., 1987; D'Ignazio et al., 2015). Dry crust layers in Finland are normally 1 - 2 m thick. Therefore, points near the ground surface, at depths lower than 1.50 m, are left out.

2. Points with $s_{\mathrm{u}}(\mathrm{mob})/\sigma'_{\mathrm{p}}$ lower than an initial shear stress mobilization ($\tau_0/\sigma'_{\mathrm{p}}$ where τ_0 is the initially mobilized shear stress) in the soil $\tau_{\mathrm{o}}/\sigma'_{\mathrm{p}} = 0.5\,(1-K_0)$ equal to 0.15 for normally consolidated state. K_0 is the earth pressure coefficient at rest calculated from Jaky (1944) formula ($K_0 = 1-\sin\phi'$, where ϕ' is the effective friction angle of the soil). $\tau_0 = 0.15$ implies $\phi' = 18°$

1. 由于研究重点是完整的和饱和的黏土，因此位于地面附近的点可能属于裂隙的上层（干硬皮）。干燥的地壳层通常是不饱和的，并且包含裂纹和裂缝。用 FV 试验测量时，此类土壤中的 s_u 可能会被高估 (La Rochelle et al., 1974; Lefebvre et al., 1987; D'Ignazio et al., 2015)。芬兰的干硬皮层通常为 1-2m 厚。因此，在地面附近的深度小于 1.50m 的点被忽略了。

2. 在正常固结状态下，$s_{\mathrm{u}}(\mathrm{mob})/\sigma'_{\mathrm{p}}$ 低于初始剪应力激发点（$\tau_0/\sigma'_{\mathrm{p}}$，其中 τ_0 是初始动剪应力），$\tau_{\mathrm{o}}/\sigma'_{\mathrm{p}} = 0.5\,(1-K_0)$ 等于 0.15。K_0 是根据Jaky (1944) 公式计算得出的静止土压力系数（$K_0 = 1 - \sin\phi'$，其中 ϕ' 是土壤的有效摩擦角）。

which could represent, according to the authors' experience, the lowest boundary value for friction angle of Scandinavian clays.

3. Outliers identified through the "2σ" (95% confidence interval of $s_u(\text{mob})/\sigma'_v$) statistical criteria. "σ" is the standard deviation of the variable $s_u(\text{mob})/\sigma'_v$. Data points where, for a given "i" value $|[s_u(\text{mob})/\sigma'_v]_i - \text{mean}\,[s_u(\text{mob})/\sigma'_v]| > 2\sigma$, are removed. Normally, outliers for a given data set are identified using the 3σ (three sigma) rule, representing the 99% confidence interval of the data. The reason why in this study the 95% confidence interval criteria is used, has to do with the inherent soil variability. s_u profiles obtained from the FV test are likely to show clear fluctuations against a mean trend. Strength variability with depth may depend not only on the consolidation stresses (initial or mechanically induced), but also on the inherent variability of the soil layers (variation of grain size, index properties). Furthermore, sample disturbance can affect the preconsolidation pressure (σ'_p) trend with depth and consequently the ratio $s_u(\text{mob})/\sigma'_p$. To remove these points, a statistical criterion stronger than the " 3σ " was preferred to a "visual" one.

$\tau_0 = 0.15$ 表示 $\phi' = 18°$，根据作者的经验，这可能代表斯堪的纳维亚黏土的摩擦角最低边界值。

3. 通过“2σ”（$s_u(\text{mob})/\sigma'_v$ 的 95% 置信区间）统计标准识别异常值。“σ”是变量 $s_u(\text{mob})/\sigma'_v$ 的标准偏差。数据指向给定的“i”值，$|[s_u(\text{mob})/\sigma'_v]_i - \text{mean}\,[s_u(\text{mob})/\sigma'_v]| > 2\sigma$ 的点将被移除。通常，给定数据集的离群值使用 3σ 规则来标识，代表数据的 99% 置信区间。在本研究中使用 95% 置信区间标准的原因与土壤固有的变异性有关。从 FV 试验获得的 su 轮廓可能显示出相对于平均趋势的明显波动。强度随深度的变化可能不仅取决于固结应力（初始应力或机械应力），还取决于土层的固有变化性（晶粒尺寸，指数特性的变化）。此外，样品扰动会影响预固结压力（ p'）随深度变化的趋势，因此会影响 su（mob）/ p' 之比。为了消除这些问题，统计标准比“3.”强于“视觉”。

A Multivariate clay databases 多元黏土数据库

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Correlations for undrained shear strength of Finnish soft clays

Marco D'Ignazio, Kok-Kwang Phoon, Siew Ann Tan, and Tim Tapani Länsivaara

Abstract: The study focuses on the derivation of transformation models for undrained shear strength (s_u) of Finnish soft sensitive clays. Specific correlation equations for s_u of Finnish clays are presented in this work for the first time. Field and laboratory measurements from 24 test sites in Finland are exploited for this purpose and a multivariate database is constructed. The multivariate data consist of s_u from the field vane test, preconsolidation stress, vertical effective stress, liquid limit, plastic limit, natural water content, and sensitivity. The main objective is to evaluate the interdependence of s_u, consolidation stresses, and index parameters and provide a consistent framework for practical use. The new correlations are established through regression analyses. The constructed framework is further validated by another independent multivariate database of clays from Sweden and Norway as well as by empirical equations for Swedish and Norwegian clays. Existing correlations are evaluated for Finnish and Scandinavian clays. Finally, bias and uncertainties of the new correlations are presented.

Key words: global transformation models, soft clays, multivariate database, undrained shear strength.

Résumé : L'étude porte sur la dérivation de modèles de transformation pour la résistance non drainée au cisaillement (s_u) des argiles douces sensibles finlandaises. Des équations de corrélation spécifiques pour la s_u des argiles finlandaises sont présentées dans cette œuvre pour la première fois. Des mesures sur-le-champ et en laboratoire de 24 sites d'essai en Finlande sont exploitées à cette fin et une base de données multivariée est construite. Les données multivariées se composent de s_u à partir de l'essais d'un scissomètre, de la contrainte de préconsolidation, de la contrainte efficace verticale, de la limite de liquide, de la limite plastique, de la teneur naturelle en eau et de la sensibilité. L'objectif principal est d'évaluer l'interdépendance de la s_u, des contraintes de consolidation et les paramètres d'index et à fournir un cadre cohérent pour une utilisation pratique. Les nouvelles corrélations sont établies par analyse de régression. Le cadre construit est en outre validé par une autre base de données multivariée indépendante des argiles de Suède et de la Norvège, ainsi que par des équations empiriques pour les argiles suédoises et norvégiennes. Les corrélations existantes sont évaluées pour les argiles finlandaises et scandinaves. Enfin, les biais et les incertitudes des nouvelles corrélations sont présentés. [Traduit par la Rédaction]

Mots-clés : modèles de transformation globale, argiles molles, base de données multidimensionnelle, résistance au cisaillement.

Introduction

Soft sensitive clays are widespread in Scandinavia, especially on coastal areas. The high compressibility of these soils, along with their low undrained shear strength (s_u) (even lower than 10 kPa near the ground surface), makes geotechnical design often rather challenging. Therefore, s_u needs to be carefully evaluated for a reliable assessment of the safety level.

Scandinavian soft clays are typically slightly over consolidated. The overconsolidation is normally the result of the aging process (e.g., Bjerrum 1972). For quick clays, the remolded undrained shear strength (s_u^{re}) can be even less than 0.5 kPa and 50–100 times lower than the initially "intact" s_u (e.g., Rankka et al. 2004; Karlsrud and Hernandez-Martinez 2013).

s_u can be evaluated from in situ as well as laboratory tests. In Scandinavia, the field vane (FV) test and piezocone cone penetration (CPTU) test are the most commonly used in situ tests. Laboratory tests include undrained triaxial compression (TXC) and direct simple shear (DSS) tests. For some special cases where s_u anisotropy needs to be assessed, triaxial extension (TXE) tests are also performed.

In situations where s_u is not directly measured or measurements are considered to be unreliable, s_u is commonly evaluated from transformation models based on clay properties, such as vertical preconsolidation pressure (σ'_p) (e.g., Mesri 1975; Jamiolkowski et al. 1985) or plasticity (e.g., Hansbo 1957; Chandler 1988). Such transformation models are typically empirical or semi-empirical, obtained by data fitting through regression analyses (e.g., Kulhawy and Mayne 1990). However, such models must be carefully applied and their limitations be recognized, as soil properties, soil behavior, and site geology may differ from the data source from where the transformation models are calibrated. As a direct consequence, predictions from these models may result in biases with respect to the actual property (s_u) values.

According to Phoon and Kulhawy (1999), uncertainty coming from transformation models can be customarily categorized as epistemic, meaning that it can be reduced by collecting a greater number of data or improving the available models. Therefore, "global" models, calibrated from data sets covering several sites and soil types, are preferred to "site-specific" models, which are restricted to a specific soil type or a specific site. Ching and Phoon (2012*a*, 2012*b*, 2014*a*, 2014*b*) presented global models based on soil

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M. D'Ignazio* and T.T. Länsivaara. Department of Civil Engineering, Tampere University of Technology, Korkeakoulunkatu 5, 33720, Tampere, Finland.
K.-K. Phoon and S.A. Tan. Department of Civil and Environmental Engineering, National University of Singapore, No. 1 Engineering Drive 2, 117576, Singapore.
Corresponding author: Marco D'Ignazio (emails: marco.dignazio@tut.fi; marco.dignazio@ngi.no).
*Present address: Norwegian Geotechnical Institute (NGI), Sognsveien 72, N-0855 Oslo, Norway.

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Table 1. Summary of multivariate clay databases.

Database	Reference	Parameters of interest	No. of data points	No. of sites or studies	Range of properties: OCR	PI	S_t
CLAY/5/345	Ching and Phoon (2012*a*)	LI, s_u, s_u^{re}, σ'_p, σ'_v	345	37 sites	1~4	—	Sensitive to quick clays
CLAY/7/6310	Ching and Phoon (2013)	s_u^{CIUC}, $s_u^{CK_0UC}$, $s_u^{CK_0UE}$, s_u^{DSS}, s_u^{FV}, s_u^{UU}, s_u^{UC}	6310	164 studies	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/6/535	Ching et al. (2014)	s_u/σ'_p, OCR, $(q_t - \sigma_v)/\sigma'_v$, $(q_t - u_2)/\sigma'_v$, $(u_2 - u_0)/\sigma'_v$, B_q	535	40 sites	1~6	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	Ching and Phoon (2014*a*)	LL, PI, LI, σ'_v/P_a, σ'_p/P_a, s_u/σ'_v, S_t, $(q_t - \sigma_v)/\sigma'_v$, $(q_t - u_2)/\sigma'_v$, B_q	7490	251 studies	1~10	Low to very high plasticity	Insensitive to quick clays

data covering a large number of test sites from several countries. Ching and Phoon (2012*b*) pointed out how site-specific models are more accurate (or less uncertain) than global models, although bias can be significant when applied to another site. Instead, global models are less biased, although less precise (or more uncertain).

Global transformation models for s_u of Swedish and Norwegian clays are available in the literature (Larsson and Mulabdic 1991; Larsson et al. 2007; Karlsrud and Hernandez-Martinez 2013). However, a comparable model calibrated using a sufficiently large soil database containing Finnish soft clay data is still missing. Therefore, the main objectives of the present paper are (*i*) to test existing transformation models for s_u for Finnish soft clays and (*ii*) to derive, for the first time, transformation models for s_u specific to Finnish soft clays using a large multivariate database consisting of FV data points from Finland. Another independent multivariate database of FV data points from Sweden and Norway is compiled and used for comparison and validation.

The value of multivariate soil databases has been demonstrated by Ching and Phoon (2012*a*, 2012*b*, 2013, 2014*a*, 2014*b*) and Ching et al. (2014). Müller (2013), Müller et al. (2014, 2016), and Prästings et al. (2016) have demonstrated how uncertainties related to s_u can be reduced when multivariate soil data are available, showing the benefits of using multivariate analyses (e.g., Ching et al. 2010) in geotechnical engineering applications. Multivariate soil databases are, however, limited in the literature. A summary is given in Table 1. Ching and Phoon (2014*a*) proposed labeling a multivariate database as "soil type"/"number of parameters of interest"/ "number of data points". Based on this nomenclature, the two databases presented in this paper are (*i*) F-CLAY/7/216 for Finnish clays (where "F" stands for Finland) and (*ii*) S-CLAY/7/168 for Scandinavian clays (where "S" stands for Scandinavia). The seven parameters in these databases consisted of s_u from the FV test (s_u^{FV}), effective vertical stress (σ'_v), vertical preconsolidation pressure (σ'_p), natural water content (w), liquid limit (LL), plastic limit (PL), and sensitivity ($S_t = s_u/s_u^{re}$).

The paper is organized as follows. Firstly, after a brief overview on existing transformation models for s_u, the compilation of F-CLAY/7/216 and S-CLAY/7/168 databases is presented. Secondly, 10 dimensionless parameters are derived from the seven basic parameters, resulting in two dimensionless databases. These dimensionless databases (labelled as F-CLAY/10/216 and S-CLAY/10/168) are compared to existing correlations in the literature. To develop more refined correlations for Finnish clays, outliers are removed from F-CLAY/10/216 according to systematic criteria based on soil nature, mechanical characteristics, and statistical considerations. New transformation models for s_u specific to Finnish clays are derived through regression analyses from the resulting F-CLAY/10/173 database. These new transformation models are compared with existing correlations for Scandinavian clays from the literature. Finally, the performance of the new models derived from F-CLAY/10/173 is evaluated by calculating the biases and uncertainties associated with S-CLAY/10/168.

Overview on existing transformation models for undrained shear strength

The dependency of s_u on σ'_p and plasticity has been the object of research over the last decades, because of its practical usefulness. Skempton (1954) suggested a linear correlation between the normalized s_u determined from FV test (s_u^{FV}/σ'_v) and plasticity index (PI) for normally consolidated clays. Subsequently, Chandler (1988) indicated that the same correlation could be valid also for overconsolidated clays as shown in eq. (1), although attention must be paid when dealing with fissured, organic, sensitive or other special clays.

$$\frac{s_u^{FV}}{\sigma'_p} \approx 0.11 + 0.0037\text{PI} \tag{1}$$

Hansbo (1957) suggested, for Scandinavian clays, that s_u^{FV}/σ'_p is directly proportional to LL. Larsson (1980), collected strength data points from FV test in Scandinavian clays and proposed a transformation model similar to eq. (1), as described by eq. (2)

$$\frac{s_u^{FV}}{\sigma'_p} \approx 0.08 + 0.0055\text{PI} \tag{2}$$

According to Bjerrum (1972), s_u^{FV} needs to be converted into mobilized s_u(s_u(mob) ≈ $s_u^{FV}\lambda$). The parameter λ is a correction multiplier that accounts for rate effects as well as anisotropy, and it is thought to be dependent on the plasticity of the clay.

Mesri (1975, 1989) suggested a unique relationship for s_u(mob) of clays and silts, corresponding approximately to DSS condition (eq. (3)), regardless of the plasticity of the clay.

$$\frac{s_u(\text{mob})}{\sigma'_p} \approx 0.22 \tag{3}$$

However, according to Larsson (1980), eq. (3) tends to overestimate s_u in very low–plastic clays, while it underestimates s_u in high-plastic clays. For low overconsolidated clays with low to moderate PI, Jamiolkowski et al. (1985) recommended (eq. (4))

$$\frac{s_u(\text{mob})}{\sigma'_v} \approx (0.23 \pm 0.04)\text{OCR}^{0.8} \tag{4}$$

The transformation model suggested by Jamiolkowski et al. (1985) is based on the stress history and normalized soil engineering properties (SHANSEP) framework (eq. (5)) proposed by Ladd and Foott (1974). The SHANSEP framework is normally adopted to describe the variation of s_u with the overconsolidation ratio, OCR $(= \sigma'_p/\sigma'_v)$.

$$(5) \qquad \frac{s_u}{\sigma'_v} = S(\mathrm{OCR}^m)$$

where S and m are constants dependent on material and test type. S represents the normalized s_u for normally consolidated state. The exponent m varies between 0.75 and 0.95 (Jamiolkowski et al. 1985). A value of m equal to 0.8 is often assumed in practice. Note that $m = 1$ would reduce eq. (5) to eq. (3) with $S = 0.22$.

Larsson et al. (2007) studied the SHANSEP relation between s_u/σ'_v and OCR for inorganic Scandinavian clays. Data from undrained TXC, DSS, and TXE tests were collected to assess s_u anisotropy. By assuming an average m value equal to 0.8, it was shown how the normally consolidated undrained shear strength ratio (S) is material dependent for DSS (eq. (6)) and TXE, as it increases with increasing liquid limit; while it seems fairly constant for TXC.

Karlsrud and Hernandez-Martinez (2013) studied the (s_u/σ'_v)–OCR relation for Norwegian soft clays from laboratory tests on high-quality block samples. Outcomes from this study indicate that s_u strongly correlates with natural water content (w) combined with OCR (eq. (7) for DSS strength). More specifically, peak strengths from TXC, DSS, and TXE test were observed to increase with increasing w. Possible reasons to explain this might be e.g., (*i*) the open structure typical of Norwegian clays (Rosenqvist 1953, 1966), which allows the soil to retain a quantity of pore water, typically above the liquid limit of the soil or (*ii*) the increasing rate effects with plasticity.

$$(6) \qquad \frac{s_u^{DSS}}{\sigma'_v} \approx (0.125 + 0.205\mathrm{LL}/1.17)\mathrm{OCR}^{0.8}$$

$$(7) \qquad \frac{s_u^{DSS}}{\sigma'_v} \approx (0.14 + 0.18w)\mathrm{OCR}^{(0.35+0.77w)}$$

Ching and Phoon (2012*a*) proposed a global transformation model for s_u(mob) from FV and unconfined compression (UC) tests as a function of OCR and S_t. The model was built based on a large database of structured clays (CLAY/5/345) consisting of 345 clay data points from several locations all over the world (eq. (8)).

$$(8) \qquad \frac{s_u(\mathrm{mob})}{\sigma'_v} \approx 0.229\mathrm{OCR}^{0.823}S_t^{0.121}$$

Analysis of multivariate clay databases

F-CLAY/7/216 and S-CLAY/7/168

The first clay database compiled in this study consists of 216 FV data points from 24 different test sites from Finland. Each data "point" contains multivariate information, i.e., information from different tests conducted in close proximity is available. The collected data points contain information on seven basic parameters measured at comparable depths and sampling locations: s_u^{FV}, σ'_v, σ'_p, w, LL, PL, and S_t.

The standard FV test is normally carried out at high speed of rotation, inducing strain rates in the soil that are much higher than in conventional laboratory tests (e.g., triaxial tests, DSS tests). The main consequence is that s_u^{FV} is overestimated and, therefore, a correction is needed to convert s_u^{FV} into s_u(mob) (e.g., Bjerrum 1972). The parameter s_u(mob) is defined as the undrained shear strength that is mobilized in a full-scale failure of an embankment or slope in the field (Bjerrum 1972; Mesri and Huvaj 2007). s_u(mob) cannot be uniquely defined, as it is a function of failure mode, stress state, and strain rate, among others. In this study, the s_u^{FV} values are converted into s_u(mob) values through a correction factor λ, as reported in the Finnish Guidelines for stability analysis (Ratahallintokeskus 2005). In this way, rate effects and anisotropy are implicitly accounted for. The strength correction factor used is expressed by eq. (9)

$$(9) \qquad \lambda = \frac{1.5}{1 + \mathrm{LL}}$$

According to Jamiolkowski et al. (1985) and Chandler (1988), s_u obtained from FV is somewhat comparable to s_u from DSS test results. It is common practice in Sweden to consider s_u from DSS tests as a reference value (e.g., Westerberg et al. 2015). DSS tests may, however, be affected by some disturbance effects resulting from sampling as well as specimen preparation. In Finland, DSS tests are not in use and the FV test is normally assumed to provide reliable s_u values, despite some issues related to test equipment. As suggested by Mansikkamäki (2015), when casing is used to protect the vane during penetration into the ground, rod friction is minimized and, therefore, measured torque values are assumed to be less biased than when slip-coupling is used. FV data points from Finland collected in this study are mostly obtained using FV test equipment that includes casing. As a consequence, the results presented later will likely be representative of the best possible estimate of s_u^{FV} in Finnish current practice.

The database is compiled from data given in Gardemeister (1973), Lehtonen et al. (2015), together with data from recent soil investigations performed by Tampere University of Technology, Finland (J. Selänpää, personal communication, 2015). Gardemeister (1973) collected FV and oedometer tests performed at different construction sites in Finland. For the purpose of the present study, sites characterized by organic (organic content higher than 2%) and (or) silty soils have been discarded, because the focus of this study is on the strength of inorganic clays. Some low organic clays may, however, be present in the database.

This database is labeled as F-CLAY/7/216 following the nomenclature proposed by Ching and Phoon (2014*a*). F-CLAY/7/216 is a new database that would contribute to the list of multivariate soil databases shown in Table 1. The basic statistics of the seven clay parameters in F-CLAY/7/216 are listed in Table 2. The parameters σ'_v and σ'_p are normalized to the atmospheric pressure, P_a (P_a = 101.3 kPa). The numbers of available data points (n) are reported in the second column. The statistics shown are the mean value, coefficient of variation (COV), minimum value (Min) and maximum value (Max). Clay properties cover a wide range of S_t values varying from 2 (insensitive clays) to 64 (quick clays), and a wide range of PI values (2∼95) and w values (25∼150).

A second independent database consisting of 168 FV data points from Sweden and Norway is extracted from the existing global CLAY/10/7490 database (Ching and Phoon 2014*a*). This database is labelled as S-CLAY/7/168 and it contains multivariate information on the same soil parameters as in F-CLAY/7/216. The purpose of S-CLAY/7/168 is to act as an independent set of data to be used for comparison with F-CLAY/7/216 in subsequent analyses. The geographical coverage of S-CLAY/7/168 is restricted to Sweden (12 sites) and Norway (seven sites). Full information on all seven parameters is available for only 59 data points. Fortunately, for the remaining 109 data points, information on all six parameters with the exception of S_t is known. The practical implication here is that the effect of S_t on s_u correlations is more difficult to discern in the case of S-CLAY/7/168. Basic statistics of the seven clay parameters in S-CLAY/7/168 are reported in Table 3. The multivariate clay data contained in F-CLAY/7/216 and S-CLAY/7/168 are listed in Appendix A.

Table 2. Basic statistics of the seven basic parameters in F-CLAY/7/216.

Variable	n	Mean	COV	Min	Max
s_u^{FV} (kPa)	216	21.443	0.501	5	75
σ'_v/P_a	216	0.464	0.485	0.074	1.609
σ'_p/P_a	216	0.948	0.515	0.251	2.884
LL	216	66.284	0.298	22.0	125.0
PL	216	27.740	0.204	10.0	50.0
w	216	76.340	0.268	25.0	150.0
S_t	216	17.447	0.789	2.0	64.0

Table 3. Basic statistics of the seven basic parameters in S-CLAY/7/168.

Variable	n	Mean	COV	Min	Max
s_u^{FV} (kPa)	168	16.346	0.505	5.62	48.75
σ'_v/P_a	168	0.503	0.632	0.068	2.101
σ'_p/P_a	168	0.786	0.726	0.150	3.116
LL	168	71.055	0.396	22.77	201.81
PL	168	29.448	0.344	2.73	73.92
w	168	76.631	0.347	17.27	180.11
S_t	59	12.068	0.779	3.0	42.5

Fig. 1. Plasticity chart.

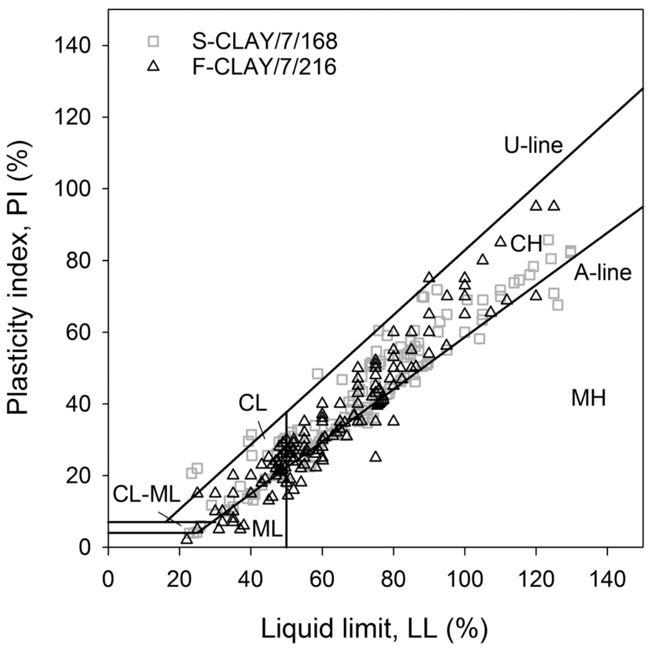


Figure 1 shows how the data points are positioned in the plasticity chart to provide a broad physical overview of the databases. Figure 2 suggests that w tends to increase for increasing LL, and that w is higher than LL for the majority of the data points.

Dimensionless databases: F-CLAY/10/216 and S-CLAY/10/168

Ten dimensionless soil parameters are of primary interest in this study. They are derived from the seven basic clay parameters appearing in F-CLAY/7/216 and S-CLAY/7/168 and they can be categorized into two groups:

1. Index properties, including natural water content (w), liquid limit (LL), plasticity index (PI), and liquidity index (LI).
2. Stresses and strengths, including OCR, normalized s_u(mob) against vertical effective stress [s_u(mob)/σ'_v] and preconsolidation pressure [s_u(mob)/σ'_p], normalized s_u^{FV} against vertical effective stress (s_u^{FV}/σ'_v) and preconsolidation pressure (s_u^{FV}/σ'_p), and sensitivity ($S_t = s_u/s_u^{re}$).

Fig. 2. Water content (w) versus liquid limit (LL) for F-CLAY/7/216 and S-CLAY/7/168.

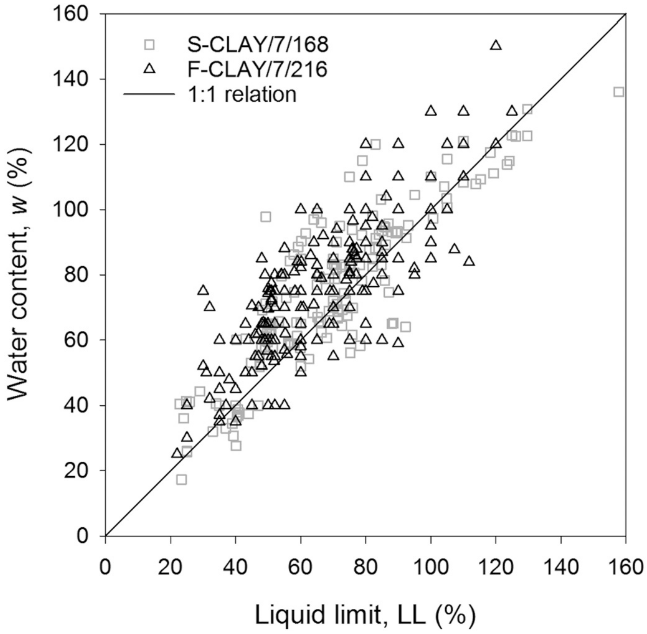
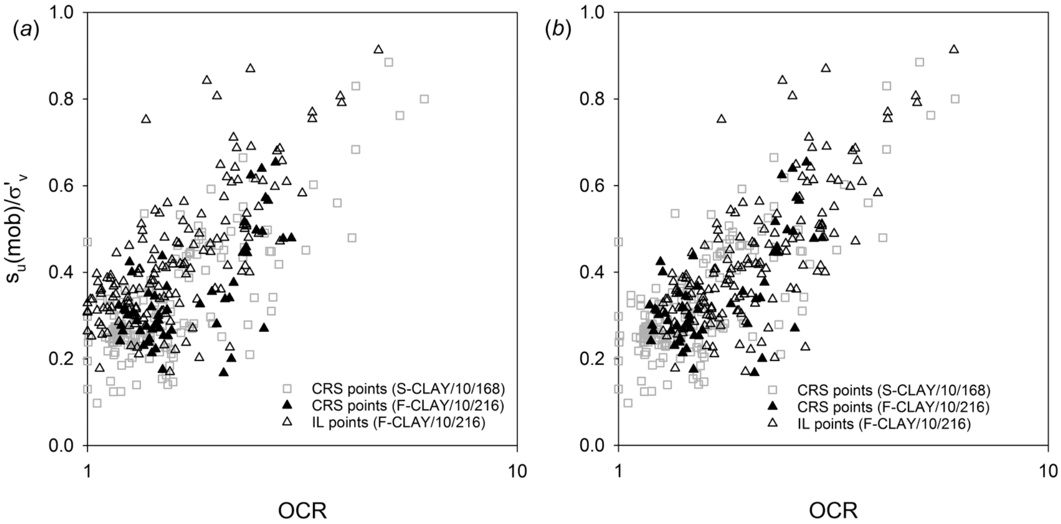


Figure 3*a* shows the s_u(mob)/σ'_v values plotted against OCR for F-CLAY/10/216 and S-CLAY/10/168. The trend described by the s_u(mob)/σ'_v points vs. OCR seem on average higher for Finnish clays than for Scandinavian clays. The reason for such a discrepancy could lie in the definition of σ'_p used to estimate OCR. Indeed, σ'_p is normally determined through an oedometer test and it is strongly affected by the strain rate used in the test (e.g., Leroueil et al. 1983, 1985). As suggested by Leroueil et al. (1985) and Leroueil (1988, 1996), constant rate of strain (CRS) oedometer tests provide stress–strain curves that normally differ from those provided by conventional 24 h incrementally loaded (IL) oedometer tests. The main reason for such differences can be found in the different rate of loading (or rate of straining) applied during the test. According to Leroueil and Soares Marques (1996), the strain rate in IL test after 24 h is between 1×10^{-7} s^{-1} for highly compressible clays and 5×10^{-8} s^{-1} for low compressible clays. The strain rate in CRS tests is normally between 1×10^{-6}–4×10^{-6} s^{-1}. As a consequence, σ'_p is larger in CRS than in the 24 h IL test (Leroueil 1996). More specifically, Leroueil (1996) suggests that σ'_p obtained from the CRS oedometer test is typically 25% larger than that deduced from the IL test. For Finnish clays, Kolisoja et al. (1989) reported, for one site in Finland, the ratio $\sigma'_{pCRS}/\sigma'_{pIL}$ to be equal to 1.16. Hoikkala (1991) observed the same ratio to be equal to 1.3 for three different sites in Finland. Länsivaara (1999), based on the data collected by Leroueil (1996) on several types of clays, suggested $\sigma'_{pCRS}/\sigma'_{pIL}$ = 1.27. Karlsrud and Hernandez-Martinez (2013) observed, for oedometer tests conducted on block samples of Norwegian clays, that σ'_p values derived from the IL tests were 10%–18% lower than for the CRS tests.

Upon examination of the original sources (listed in Table A1 of Ching and Phoon (2014*a*)) from where data contained in S-CLAY/7/168 have been collected, it seems that σ'_p points were mostly measured from CRS oedometer tests. F-CLAY/7/216 contains only 56 σ'_{pCRS} points, while the remaining 162 points are from 24 h IL tests (σ'_{pIL}) (Fig. 3*a*). Therefore, to make data suitable for comparison, σ'_{pIL} is increased by 27% for all data points as a first-order correction following the proposal by Länsivaara (1999) (Fig. 3*b*). By applying $\sigma'_{pCRS}/\sigma'_{pIL}$ = 1.27 to all 162 σ'_{pIL} values from Finland, the strength points from F-CLAY/10/216 seem to better adapt to the s_u(mob)/σ'_v – OCR trend shown by those contained in S-CLAY/10/168

Fig. 3. $s_u(\text{mob})/\sigma'_v$ against OCR for (*a*) raw data points and (*b*) data points corrected to σ'_p from CRS oedometer test using $\sigma'_{pCRS}/\sigma'_{pIL} = 1.27$.



(Fig. 3*b*). It is plausible that the difference between F-CLAY/10/216 and S-CLAY/10/168 in the $s_u(\text{mob})/\sigma'_v$ versus OCR plot is primarily caused by the difference between the CRS and IL test, rather than the difference between clay types, as also indicated by Fig. 1 and Fig. 2.

The basic statistics of the 10 dimensionless parameters are listed in Table 4 and Table 5 for the dimensionless databases, labeled as F-CLAY/10/216 and S-CLAY/10/168, respectively.

Comparison with existing transformation models

The 384 clay data points constituting F-CLAY/10/216 and S-CLAY/10/168 databases are compared with transformation models proposed in the literature to check their consistency. It is worth pointing out that transformation models are generally derived based on certain types of clays and geographical locations. The basis for these models is usually empirical. Very often, for such models we do not know the basic statistics (such as those reported in Table 4 and Table 5).

The 10 transformation models analyzed are labeled using the following template: "primary input parameter"–"target parameter"–"secondary input parameter". They are categorized into four types (see e.g., Table 6):

Type A — Models for S_t, including two LI–(s_u^{re}/P_a) models and two LI–(S_t) models.

Type B — Models for effective stress, including one LI–(σ'_p/P_a)–S_t model. Basic statistics of σ'_p/P_a are reported in Table 2 and Table 3 and not included in the dimensionless databases, as s_u^{FV} and $s_u(\text{mob})$ are the parameters of primary interest for this study.

Type C — Models for shear strength, including one PI–[$s_u(\text{mob})/\sigma'_p$] model, one OCR–[$s_u(\text{mob})/\sigma'_v$] model, and one OCR–[$s_u(\text{mob})/\sigma'_v$]–$S_t$ model.

Type D — Models for shear strength, including two PI–(s_u^{FV}/σ'_p), one LL–(s_u^{FV}/σ'_p). These three models are compared to uncorrected s_u^{FV} (λ correction factor is not applied), being originally derived from uncorrected measurements.

Many of the transformation models are derived empirically using regression analyses. Only the LI–(s_u^{re}/P_a) model by Wroth and Wood (1978) represents an exception. It is derived theoretically from the modified Cam clay model. The LI–(σ'_p/P_a)–S_t and OCR–[$s_u(\text{mob})/\sigma'_v$]–$S_t$ models proposed by Ching and Phoon (2012*a*) are derived from sensitive structured clay data. The LI–S_t model by Bjerrum (1954) is based on Norwegian marine clay data.

Table 4. Basic statistics of 10 dimensionless soil parameters in F-CLAY/10/216, derived from the seven basic parameters in F-CLAY/7/216.

Variable	*n*	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	216	0.458	0.715	0.167	2.754
$s_u(\text{mob})/\sigma'_p$	216	0.209	0.281	0.081	0.469
s_u^{FV}/σ'_v	216	0.513	0.712	0.176	2.938
s_u^{FV}/σ'_p	216	0.234	0.293	0.083	0.594
OCR	216	2.170	0.467	1.18	7.50
LL	216	66.284	0.298	22.0	125.0
PI	216	38.545	0.482	2.0	95.0
w	216	76.340	0.268	25.0	150.0
LI	216	1.443	0.459	0.425	4.800
S_t	216	17.447	0.789	2.0	64.0

Table 5. Basic statistics of 10 dimensionless soil parameters in S-CLAY/10/168, derived from the seven basic parameters in S-CLAY/7/168.

Variable	*n*	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	168	0.329	0.417	0.098	0.885
$s_u(\text{mob})/\sigma'_p$	168	0.210	0.269	0.088	0.470
s_u^{FV}/σ'_v	168	0.386	0.469	0.098	0.974
s_u^{FV}/σ'_p	168	0.244	0.311	0.088	0.490
OCR	168	1.664	0.476	1.00	6.07
LL	168	71.06	0.396	22.77	201.81
PI	168	41.61	0.496	3.91	127.89
w	168	76.63	0.347	17.27	180.11
LI	168	1.267	0.507	0.60	5.50
S_t	59	12.068	0.779	3.00	42.50

Figures 4–11 show the comparison between databases and transformation models. For the LI–(σ'_p/P_a)–S_t and OCR–[$s_u(\text{mob})/\sigma'_v$]–$S_t$ models by Ching and Phoon (2012*a*), data points are divided into two groups according to S_t values. The two groups are based on the distinction between "low to medium sensitive" (S_t < 15) and "highly sensitive" (S_t > 15) clays suggested by Karlsrud and Hernandez-Martinez (2013) for Norwegian clays.

The OCR–[$s_u(\text{mob})/\sigma'_v$] transformation model by Jamiolkowski et al. (1985) provides a reasonable average fit to the data. For OCR < 8, $s_u(\text{mob})/\sigma'_v$ seems to be strongly dependent on OCR (Fig. 4). A deviation from the trend line in Fig. 4 is visible at OCR values greater than 5. However, data points with OCR > 5 belong to layers located in proximity of the ground surface (above 1.50 m)

Table 6. Transformation models in literature and their calibration results for F-CLAY/10/216.

					Comparison to F-CLAY/10/216 database		Calibration results	
Type	Relationship	Literature	n	Transformation model	Figure	Fit to the trend?	Bias factor, b	COV of $\varepsilon = \delta$
A	LI–(s_u^{re}/P_a)	Wroth and Wood (1978)	216	$s_u^{re}/P_a \approx 1.7^{-4.6LI}$	9	No	—	—
		Locat and Demers (1988)	216	$s_u^{re}/P_a \approx 0.0144LI^{-2.44}$	9	Yes	4.05	3.02
	LI–(S_t)	Bjerrum (1954)	216	$S_t \approx 10^{0.8LI}$	11	Yes	1.56	1.40
		Ching and Phoon (2012*a*)	216	$S_t \approx 20.726LI^{1.910}$	11	No	0.57	1.94
B	LI–(σ'_p/P_a)–S_t (for $S_t < 15$)	Ching and Phoon (2012*a*)	216	$\sigma'_p/P_a \approx 0.235LI^{-1.319}S_t^{0.536}$	12a	Yes	2.02	0.94
	LI–(σ'_p/P_a)–S_t (for $S_t > 15$)	Ching and Phoon (2012*a*)	216	$\sigma'_p/P_a \approx 0.235LI^{-1.319}S_t^{0.536}$	12a	Yes	0.95	0.47
C	PI–($s_u(mob)/\sigma'_p$)	Mesri (1975, 1989)	216	$s_u(mob)/\sigma'_p \approx 0.22$	5	Yes	0.95	0.28
	OCR–[$s_u(mob)/\sigma'_v$]	Jamiolkowski et al. (1985)	216	$s_u(mob)/\sigma'_v \approx 0.23OCR^{0.8}$	4	Yes	1.06	0.30
	OCR–[$s_u(mob)/\sigma'_v$]–S_t	Ching and Phoon (2012*a*)	216	$s_u(mob)/\sigma'_v \approx 0.229OCR^{0.823}S_t^{0.121}$	6a	Yes	0.77	0.32
D	LL–(s_u^{FV}/σ'_p)	Hansbo (1957)	216	$s_u^{FV}/\sigma'_p \approx 0.45LL$	7	Yes	0.84	0.38
	PI–(s_u^{FV}/σ'_p)	Larsson (1980)	216	$s_u^{FV}/\sigma'_p \approx 0.08 + 0.0055PI$	8	Yes	0.89	0.43
		Chandler (1988)	216	$s_u^{FV}/\sigma'_p \approx 0.11 + 0.0037PI$	8	Yes	0.97	0.35

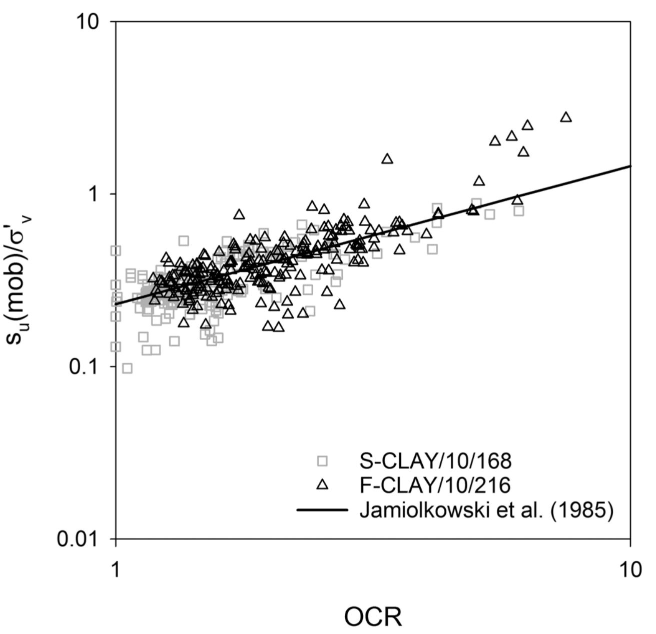


Fig. 4. OCR–[$s_u(mob)/\sigma'_v$] model proposed by Jamiolkowski et al. (1985).

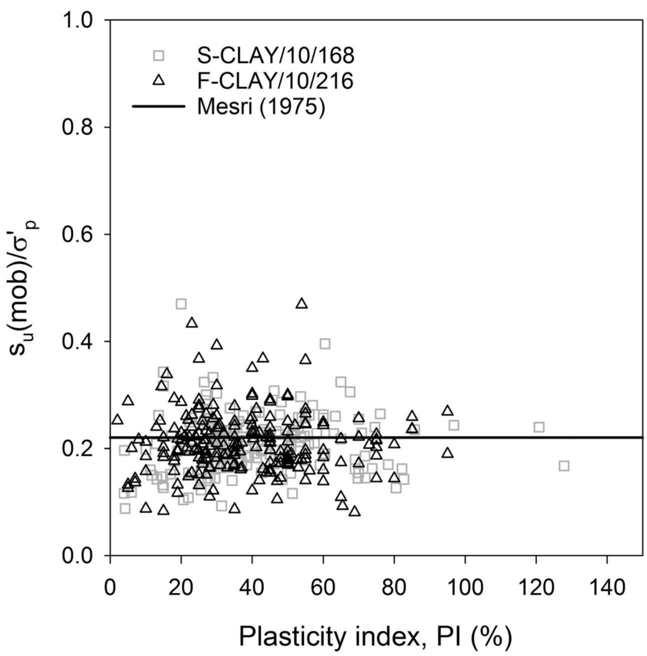


Fig. 5. PI–[$s_u(mob)/\sigma'_p$] model proposed by Mesri (1975, 1989).

where the clay might be fissured and (or) partially saturated. Therefore, the interest for those points is limited, because the focus of this study is on intact clays.

The PI–[$s_u(mob)/\sigma'_p$] model by Mesri (1975, 1989) takes out the dependency of $s_u(mob)$ on PI, stating that $s_u(mob)/\sigma'_p$ is constant and equal to 0.22. From Fig. 5, $s_u(mob)/\sigma'_p$ seems independent of PI, thus confirming the suggestion given by Mesri.

The dependency of s_u on S_t predicted by the OCR–[$s_u(mob)/\sigma'_v$]–S_t model by Ching and Phoon (2012*a*), is not visible from the collected data points (Fig. 6). However, the majority of the F-CLAY/10/216 data points for $S_t < 15$ are located between the $s_u(mob)/\sigma'_v$–OCR trend lines for $S_t = 1$ and $S_t = 15$ (Fig. 6*a*).

It is quite difficult to observe a well-defined trend for the data points to the LL–(s_u^{FV}/σ'_p) model by Hansbo (1957) (Fig. 7). Both databases seem to better adapt to the mean trend suggested by the PI–(s_u^{FV}/σ'_p) models (Fig. 8), although high scatter can be observed along the trend lines suggested by Larsson (1980) and Chandler (1988, after Skempton 1954).

Data points seem to depart from the LI–(s_u^{re}/P_a) model by Wroth and Wood (1978) for LI values greater than 1 (Fig. 9). However, the transformation model by Locat and Demers (1988) seems able to reproduce the trend observed for LI < 2 (Fig. 9). For LI > 2, the data points deviate from the existing transformation models. The authors believe that S_t was determined from the FV test for some of the Finnish data points (from Gardemeister 1973). The FV test is known to produce higher s_u^{re} values than the conventional fall cone (FC) test. Tanaka et al. (2012) demonstrated how s_u^{re} determined from the FV test and the laboratory vane test (LVT) is as much as tenfold larger than s_u^{re} determined using the FC test (Fig. 10*b*). This was attributed to the different remolding methods, as the turning of the vane is not equivalent to the remolded state for the FC test, which is obtained by kneading by hand. Hence, the actual s_u^{re} may be lower than that shown in Fig. 9, which consequently produces a higher S_t. However, there are only 29 points with LI > 2. The conclusions of this study will be largely unaffected, because 29 points only constitute 13.4% of the total num-

Fig. 6. OCR–[s_u(mob)/σ'_v]–S_t model by Ching and Phoon (2012*a*) for (*a*) F-CLAY/10/216 and (*b*) S-CLAY/10/168.

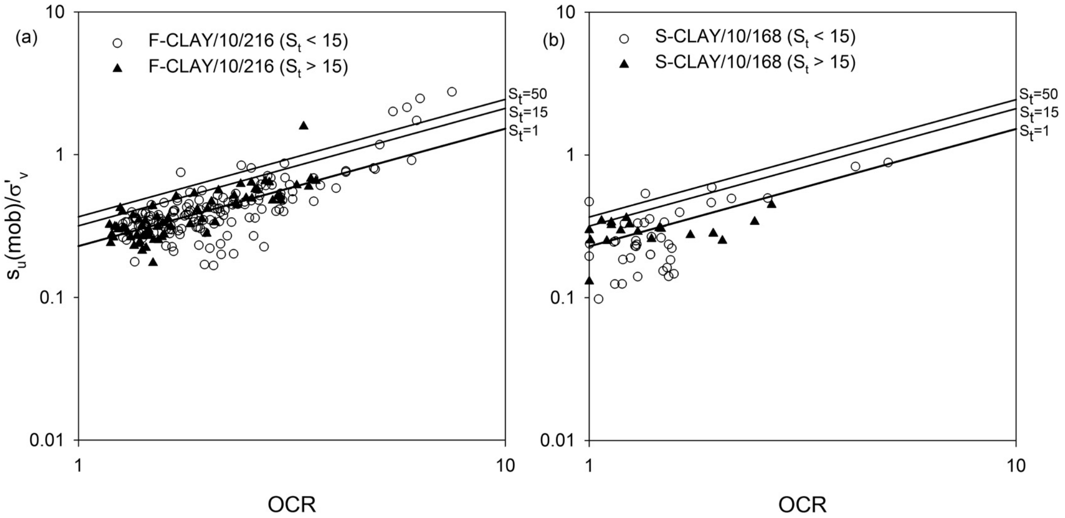


Fig. 7. LL–(s_u^{FV}/σ'_p) model proposed by Hansbo (1957).

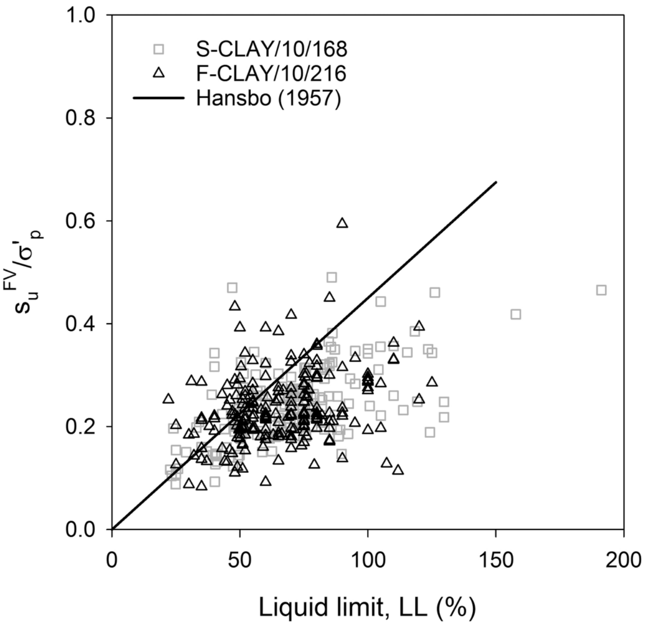
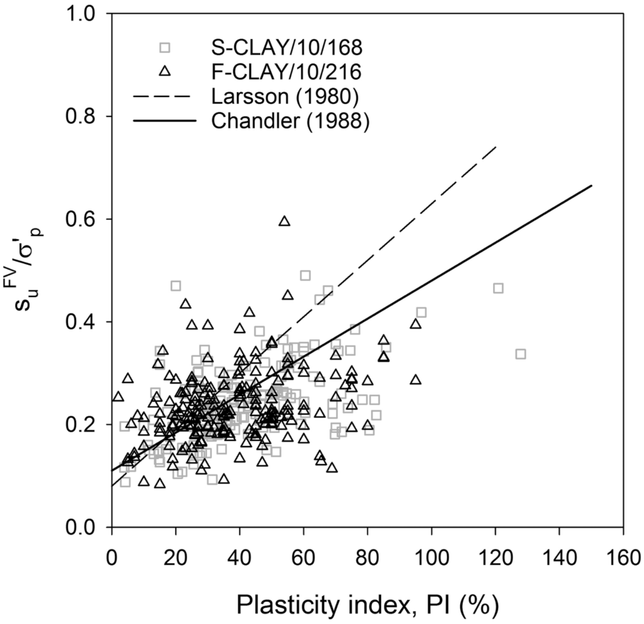


Fig. 8. PI–(s_u^{FV}/σ'_p) models proposed by Larsson (1980) and Chandler (1988).



ber of points. Based on the experimental results presented by Tanaka et al. (2012), the authors would like to further suggest that while undisturbed s_u values from FV and FC can be mixed (as shown in Fig. 10*a*), s_u^{re} or derived parameters (S_t) between FV and FC should be treated separately (as suggested by Fig. 10*b*).

The LI–(S_t) model by Bjerrum (1954) can reasonably describe the data points for LI < 2, despite the high scatter observed (Fig. 11). In contrast, the global model by Ching and Phoon (2012*a*) seems to provide an upper bound rather than an average fit to the databases (Fig. 11).

The LI–(σ'_p/P_a)–S_t model by Ching and Phoon (2012*a*) does not seem to fit the data points in F-CLAY/10/216 for $S_t < 15$ (Fig. 12*a*). The LI–(σ'_p/P_a)–S_t transformation model appears to provide a better description of the highly sensitive clays ($S_t > 15$) in F-CLAY/10/216, as the majority of the points are contained in the interval between the LI–(σ'_p/P_a)–S_t lines for $S_t = 15$ and $S_t = 50$ (Fig. 12*a*). In contrast, for the low to medium sensitive clays ($S_t < 15$) in S-CLAY/10/168, most of the data points are comprised between the LI–(σ'_p/P_a)–S_t boundary lines for $S_t = 1$ and $S_t = 15$ (Fig. 12*b*), while for the highly sensitive clays, the models cannot satisfactorily describe the observed values.

Bias and uncertainties of the existing transformation models

Bias factor (denoted by *b*), and COV (denoted by δ) are evaluated and discussed for the transformation models described in the previous section, based on the F-CLAY/10/216 and S-CLAY/10/168 databases. The parameters *b* and δ represent the sample mean and the COV, respectively, of the ratio (actual target value)/(predicted target value). If $b = 1$, the model prediction is unbiased. For instance, for the OCR–[s_u(mob)/σ'_v] transformation model by Jamiolkowski et al. (1985), the actual target value is s_u(mob)/σ'_v and the predicted target value is $0.23\mathrm{OCR}^{0.8}$. For the data points where s_u(mob)/σ'_v and OCR are simultaneously known, (actual target value)/(predicted target value) = [s_u(mob)/σ'_v]/($0.23\mathrm{OCR}^{0.8}$).

Fig. 9. LI–(s_u^{re}/P_a) models.

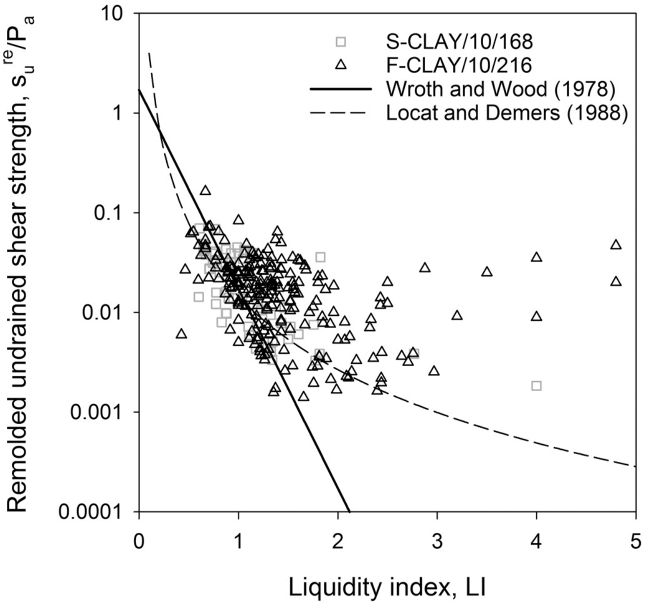


Fig. 10. Comparison of strengths measured by FC, FV, and LVT at (*a*) undisturbed and (*b*) remolded conditions (Tanaka et al. 2012).

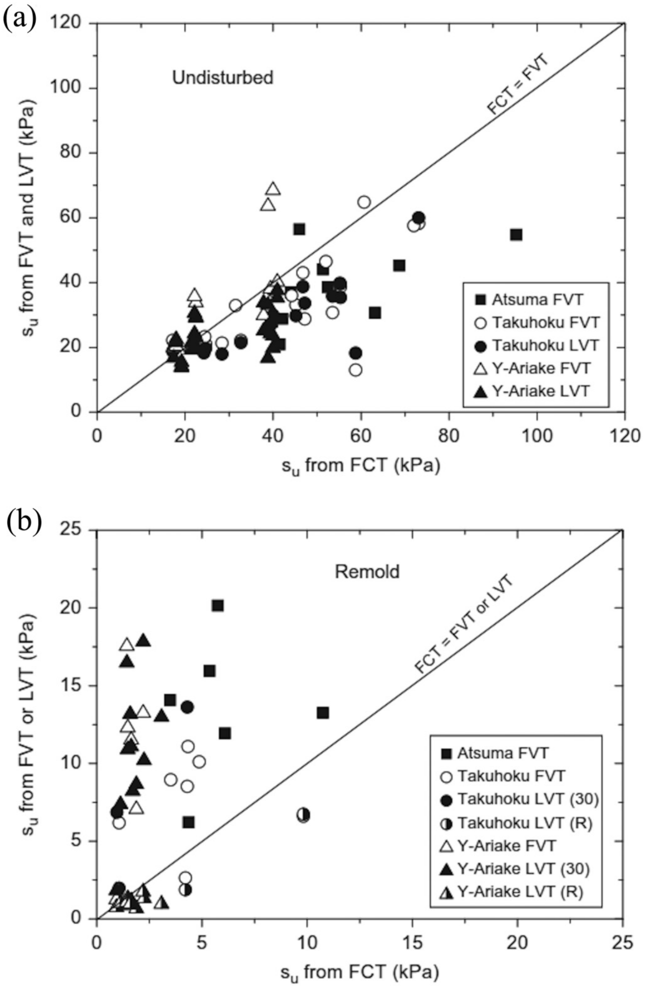
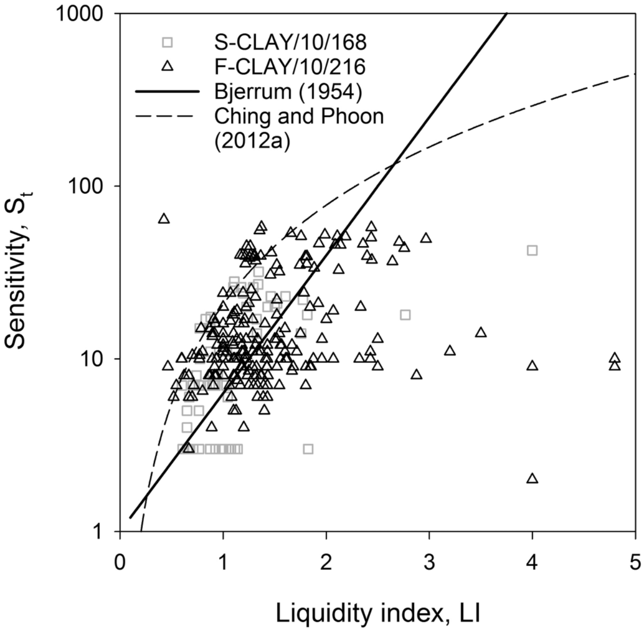


Fig. 11. LI–S_t models.



According to Ching and Phoon (2014*a*):

$$\varepsilon = \text{(actual target value)}/(b \times \text{predicted target value}) = \text{(actual target value)}/\text{(unbiased prediction)}$$

where ε is the variability term with mean = 1 and COV = δ. If $\delta = 0$, there is no data scatter about the transformation model, indicating that the prediction is deterministic, rather than uncertain.

Bias factors and COVs for the different transformation models analyzed are reported in Table 6 for F-CLAY/10/216 and Table 7 for S-CLAY/10/168, respectively. Bias factor, COV of ε, and number of data points used for each calibration are denoted, respectively, by b, δ, and n.

The LI–(s_u^{re}/P_a) model by Locat and Demers (1988) seems quite conservative, as it underpredicts the actual value by a factor of 4.05 for Finnish clays (Table 6) and 1.60 for Scandinavian clays (Table 7). Bjerrum's (1954) transformation model underestimates the actual S_t values for both Finnish and Scandinavian clays. Nevertheless, the uncertainty underlying these predictions still remains considerable, as the COV for type A models ranges between 61% and 302%. A similar analysis can be carried out for the LI–(σ'_p/P_a)–S_t model by Ching and Phoon (2012*a*). The deviation of about 50%–60% from the mean trend lines of both F-CLAY/10/216 and S-CLAY/10/168, combined with a COV greater than 1 and equal to 0.61 for Finnish and Scandinavian clays, respectively, would result in predicted values characterized by a high degree of uncertainty. Therefore, models of type A and B are "biased" models with respect to both databases.

In contrast, different outcomes are obtained for the transformation models of type C and D (models for shear strength). Models of type C (s_u(mob)/σ'_v is the target parameter) show bias factors (b) close to 1 and COV (δ) lower than 0.30. Exception is found for the OCR–[s_u(mob)/σ'_v]–S_t model (Ching and Phoon 2012*a*), which shows a bias factor of 0.71–0.77 with a COV of 0.32–0.36. These results would thus suggest that s_u(mob) of Scandinavian clays can be described by different well established transformation models with relatively low uncertainty. For instance, the equation by Mesri (1975, 1989) can be adapted to Finnish soft clays by including the bias factor (b) calibrated from F-CLAY/10/216 database as

Fig. 12. LI–(σ_p'/P_a)–S_t model by Ching and Phoon (2012*a*) for (*a*) F-CLAY/10/216 and (*b*) S-CLAY/10/168.

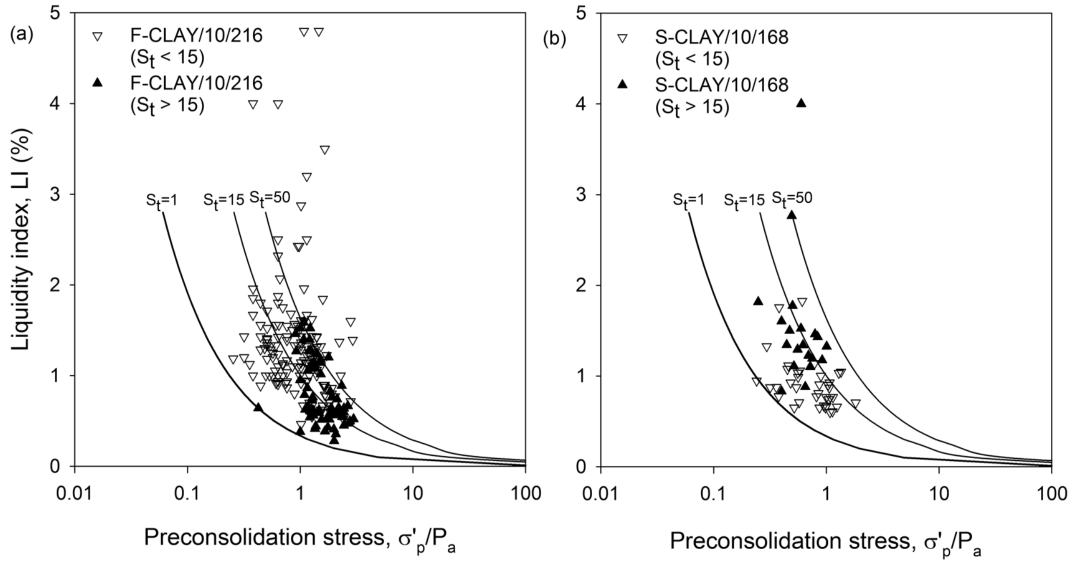


Table 7. Transformation models in literature and their calibration results for S-CLAY/10/168.

					Comparison to S-CLAY/10/168 database		Calibration results	
Type	Relationship	Literature	*n*	Transformation modelmodelmodel	Figure	Fit to the trend?	Bias factor, *b*	COV of $\varepsilon = \delta$
A	LI–(s_u^{re}/P_a)	Wroth and Wood (1978)	59	$s_u^{re}/P_a \approx 1.7^{-4.6LI}$	9	No	—	—
		Locat and Demers (1988)	59	$s_u^{re}/P_a \approx 0.0144LI^{-2.44}$	9	Yes	1.60	0.96
	LI–(S_t)	Bjerrum (1954)	59	$S_t \approx 10^{0.8LI}$	11	Yes	1.48	0.65
		Ching and Phoon (2012*a*)	59	$S_t \approx 20.726LI^{1.910}$	11	No	0.49	0.61
B	LI–(σ_p'/P_a)–S_t (for $S_t < 15$)	Ching and Phoon (2012*a*)	59	$\sigma_p'/P_a \approx 0.235LI^{-1.319}S_t^{0.536}$	12b	Yes	1.23	0.51
	LI–(σ_p'/P_a)–S_t (for $S_t > 15$)	Ching and Phoon (2012*a*)	59	$\sigma_p'/P_a \approx 0.235LI^{-1.319}S_t^{0.536}$	12b	Yes	0.84	0.54
C	PI–[s_u(mob)/σ_p']	Mesri (1975, 1989)	168	$s_u(mob)/\sigma_p' \approx 0.22$	5	Yes	0.96	0.27
	OCR–[s_u(mob)/σ_v']	Jamiolkowski et al. (1985)	168	$s_u(mob)/\sigma_v' \approx 0.23OCR^{0.8}$	4	Yes	0.97	0.25
	OCR–[s_u(mob)/σ_v']–S_t	Ching and Phoon (2012*a*)	168	$s_u(mob)/\sigma_v' \approx 0.229OCR^{0.823}S_t^{0.121}$	6b	Yes	0.71	0.36
D	LL–(s_u^{FV}/σ_p')	Hansbo (1957)	168	$s_u^{FV}/\sigma_p' \approx 0.45LL$	7	Yes	0.82	0.34
	PI–(s_u^{FV}/σ_p')	Larsson (1980)	168	$s_u^{FV}/\sigma_p' \approx 0.08 + 0.0055PI$	8	Yes	0.85	0.37
		Chandler (1988)	168	$s_u^{FV}/\sigma_p' \approx 0.11 + 0.0037PI$	8	Yes	0.96	0.31

$s_u(mob)/\sigma_p' = b(0.22) = 0.95(0.22) = 0.209$, with a COV ($\delta$) = 0.28 (low variability).

Type D models (s_u^{FV}/σ_p' is the target parameter, see Tables 6–7) show a bias factor *b* varying between 0.82 and 0.97 with COV between 0.31 and 0.43, suggesting reasonably low variability for these models. In particular, the PI–(s_u^{FV}/σ_p') model proposed by Chandler (1988) results almost "unbiased" with respect to both F-CLAY/10/216 and S-CLAY/10/168, suggesting *b* comprised between 0.96–0.97 and δ varying between 0.31 and 0.35.

s_u/σ_v' transformation models for F-CLAY/10/173

Removal of outliers in F-CLAY/10/216

As the scope of this study is to derive transformation models for s_u of Finnish soft clays that are more refined than the existing models in the literature, the data points collected in F-CLAY/10/216 are analyzed with the purpose of improving the quality of the database by removing outliers. The quality of data points is assessed through criteria based on the physical nature of the soil, mechanical characteristics, and statistical considerations. The adopted criteria are listed below:

1. Points located near the ground surface that may belong to fissured upper layers (dry crust), as the study focuses on intact and saturated clays. Dry crust layers are generally unsaturated and contain cracks and fissures. s_u of such soils may be highly overestimated when measured with the FV test (La Rochelle 1974; Lefebvre et al. 1987; D'Ignazio et al. 2015). Dry crust layers in Finland are normally 1–2 m thick. Therefore, points near the ground surface, at depths lower than 1.50 m, are left out.
2. Points with $s_u(mob)/\sigma_p'$ lower than an initial shear stress mobilization (τ_0/σ_p' where τ_0 is the initially mobilized shear stress) in the soil $\tau_0/\sigma_p' = 0.5(1 - K_0)$ equal to 0.15 for normally consolidated state. K_0 is the earth pressure coefficient at rest calculated from Jaky's (1944) formula ($K_0 = 1 - \sin\phi'$, where ϕ' is the effective friction angle of the soil). $\tau_0 = 0.15$ implies $\phi' = 18°$, which could represent, according to the authors' experience, the lowest boundary value for friction angle of Scandinavian clays.
3. Outliers identified through the "2σ" (95% confidence interval of $s_u(mob)/\sigma_v'$) statistical criteria. "σ" is the standard deviation of the variable $s_u(mob)/\sigma_v'$. Data points where, for a given "*i*"

value $|[s_u(\text{mob})/\sigma'_v]_i - \text{mean}[s_u(\text{mob})/\sigma'_v]| > 2\sigma$, are removed. Normally, outliers for a given data set are identified using the 3σ (three sigma) rule, representing the 99% confidence interval of the data. The reason why in this study the 95% confidence interval criteria is used, has to do with the inherent soil variability. s_u profiles obtained from the FV test are likely to show clear fluctuations against a mean trend. Strength variability with depth may depend not only on the consolidation stresses (initial or mechanically induced), but also on the inherent variability of the soil layers (variation of grain size, index properties). Furthermore, sample disturbance can affect the preconsolidation pressure (σ'_p) trend with depth and consequently the ratio $s_u(\text{mob})/\sigma'_p$. To remove these points, a statistical criterion stronger than the "3σ" was preferred to a "visual" one.

The number of data points left out is 43 out of 216, corresponding to 20% of the database. To be more specific, 10, 24, and 9 points are removed based on criteria 1, 2 and 3, respectively. The outcomes of this study will then be based on 173 higher quality multivariate clay data points. The updated dimensionless database is hereinafter called F-CLAY/10/173. Updated basic statistics of F-CLAY/10/173 database are listed in Table 8. One major outcome of this procedure is the reduction of the COV for all the analyzed dimensionless variables (see Table 8). Index parameters and sensitivity are not significantly affected by the removal of data points. However, OCR range drops considerably from 1~7.50 to 1~3.70. Such low OCR values are expected to be found in shallow clay deposits in Finland. Therefore, s_u of Finnish clays for OCR > 4 will not be discussed in this study. Moreover, the average $s_u(\text{mob})/\sigma'_p$ in Table 8 is slightly higher than in Table 4, resulting from the removal of the unreliable data points.

Derivation of new transformation models

Regression analyses are carried out to derive new transformation models for s_u of Finnish soft clays. The F-CLAY/10/173 database is used for this purpose. The SHANSEP framework (eq. (5)) proposed by Ladd and Foott (1974) is adopted to describe the variation of $s_u(\text{mob})$ and s_u^{FV} with OCR and index parameters.

Larsson et al. (2007) and Karlsrud and Hernandez-Martinez (2013) studied the anisotropic s_u of Scandinavian and Norwegian clays, respectively, from TXC, DSS, and TXE tests. Larsson et al. (2007) reported S and m (see eq. (5)) to be dependent on LL (eq. (6) for DSS), while Karlsrud and Hernandez-Martinez (2013) found w, combined with the OCR, to be the best index parameter for correlating their test results (eq. (7) for DSS). A direct comparison between s_u^{DSS} and s_u^{FV} would, however, be misleading, if rate effects are not accounted for. Nevertheless, eqs. (6) and (7) will be still used for qualitative comparison.

Linear regression analyses are performed using the "fminsearch" algorithm implemented in the mathematical software MATLAB (Mathworks 1995). The "fminsearch" function (see Mathworks 1995) finds the minimum of an unconstrained multivariable function through a derivative free method (unconstrained linear optimization). The multivariable function $F = f(s_{u,i}/\sigma'_v, \text{OCR}, Y_j)$ is defined by eq. (10)

$$F = \frac{s_{u,i}}{\sigma'_v} = \alpha \text{OCR}^{\beta} Y_j^{\gamma} \tag{10}$$

where $s_{u,i} = \{s_{u,1} = s_u(\text{mob}), s_{u,2} = s_u^{FV}\}$, $Y_j = \{Y_1 = \text{PI}, Y_2 = \text{LL}, Y_3 = w, Y_4 = \text{LI}, Y_5 = S_t\}$. The scalar coefficients α, β, and γ and the coefficient of determination (r^2) for the two newly constructed OCR–$(s_{u,i}/\sigma'_v)$–Y_j transformation models are given in Table 9. The r^2 of the new correlations ranges from 0.62 to 0.70.

The results of the regression analyses suggest that for the OCR–(s_u^{FV}/σ'_v)–Y_j transformation model, s_u^{FV}/σ'_v is directly proportional to PI, LL, w and inversely proportional to LI, while it is not markedly dependent on S_t. In contrast, a similar conclusion cannot be drawn for the OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ model, as $s_u(\text{mob})/\sigma'_v$ seems to be only lightly correlating with index parameters. This concept can be well understood by looking at the scalar coefficient γ for the OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ models from Table 9. For $\gamma > 0$, $s_u(\text{mob})/\sigma'_v$ increases with increasing Y_j; on the contrary, for $\gamma < 0$ it reduces by increasing Y_j. Although γ values indicate that $s_u(\text{mob})/\sigma'_v$ decreases with increasing PI or LL and, in contrast, increases with increasing w, LI or S_t, it should be emphasized how γ tends to zero for the OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ transformation model. As a result, $s_u(\text{mob})/\sigma'_v$ of Finnish soft clays results (*i*) slightly dependent or nearly independent of the secondary input variable Y_j, and (*ii*) strongly dependent on the consolidation stresses (increasing with increasing OCR). This result agrees with the findings of Mesri (1975, 1989) and Jamiolkowski et al. (1985). However, Mesri (1975, 1989) suggests $m = 1$, which is not consistent with the results presented in Table 9, as for Finnish clays m results lower than 1. To validate such observation, it is worth to mention that the modified Cam clay model (Schofield and Wroth 1968) predicts $m = 1 - C_s/C_c$, where C_c and C_s are the compression and swelling indices, respectively, of a clay. This result indicates that m is generally less than 1 for normally consolidated to lightly overconsolidated clays, which are typically known to be adequately modeled by the modified Cam clay model. Moreover, by averaging α and β from the five OCR–$[s_u(\text{mob})/\sigma'_v]$–$Y_j$ correlation equations of Table 9, and assuming $\gamma = 0$, for Finnish clays, eq. (11)

$$\frac{s_u(\text{mob})}{\sigma'_v} \approx 0.244\text{OCR}^{0.763} \tag{11}$$

which nearly corresponds to the unbiased transformation model presented by Jamiolkowski et al. (1985), as described earlier in this paper. The calibrated bias factor (b) from F-CLAY/10/216 database for the OCR–$[s_u(\text{mob})/\sigma'_v]$ model by Jamiolkowski et al. (1985) is equal to 1.06. This means $s_u(\text{mob})/\sigma'_v = b(0.23)\text{OCR}^{0.8} = 0.244\text{OCR}^{0.8}$ with a coefficient of variation (COV = δ) equal to 0.30.

Table 8. Basic statistics of the data points after removal of outliers (database F-CLAY/10/173).

Variable	n	Mean	COV	Min	Max
$s_u(\text{mob})/\sigma'_v$	173	0.399	0.284	0.213	0.690
$s_u(\text{mob})/\sigma'_p$	173	0.213	0.183	0.148	0.338
s_u^{FV}/σ'_v	173	0.447	0.306	0.226	0.920
s_u^{FV}/σ'_p	173	0.239	0.203	0.148	0.394
OCR	173	1.91	0.31	1.18	3.69
LL	173	66.4	0.29	22	125.0
PI	173	38	0.47	2	95.0
w	173	78.3	0.25	25.00	150.0
LI	173	1.48	0.43	0.46	4.80
S_t	173	18.80	0.76	2.00	58.0

Table 9. Linear regression coefficients for multivariable function F.

Transformation model	Secondary input parameter, Y_j	α	β	γ	r^2
OCR–$s_u(\text{mob})/\sigma'_v$–$Y_j$	Y_1 (PI)	0.242	0.763	−0.013	0.67
	Y_2 (LL)	0.245	0.760	−0.005	0.67
	Y_3 (w)	0.246	0.760	0.027	0.67
	Y_4 (LI)	0.241	0.770	0.045	0.67
	Y_5 (S_t)	0.242	0.762	0.006	0.67
OCR–s_u^{FV}/σ'_v–Y_j	Y_1 (PI)	0.328	0.756	0.165	0.68
	Y_2 (LL)	0.319	0.757	0.333	0.70
	Y_3 (w)	0.296	0.788	0.337	0.69
	Y_4 (LI)	0.281	0.770	−0.088	0.63
	Y_5 (S_t)	0.280	0.786	−0.013	0.62

Fig. 13. Comparison between OCR–(s_u^{FV}/σ'_v)–LL for Finnish clays and OCR–(s_u^{DSS}/σ'_v)–LL model by Larsson et al. (2007) for Swedish clays.

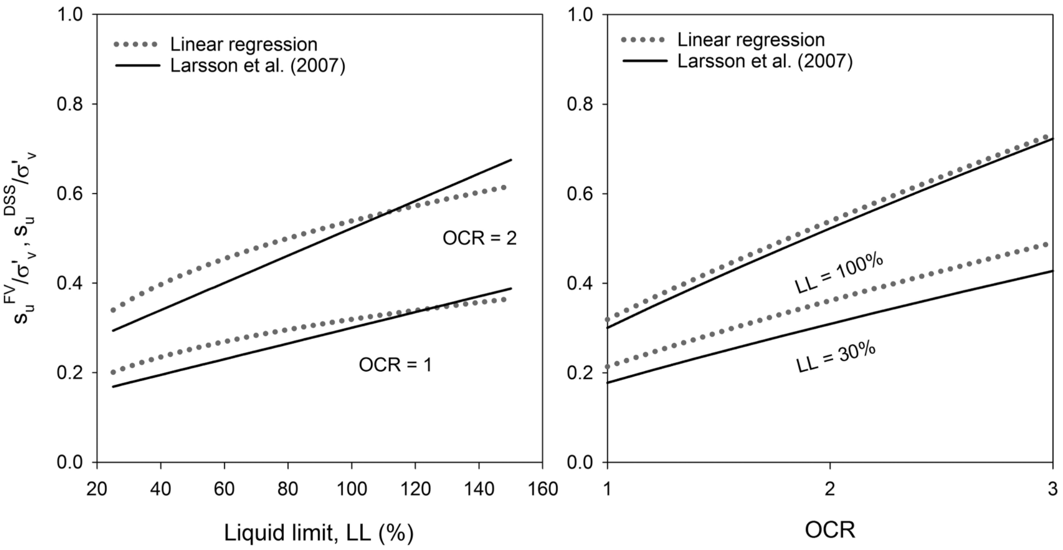
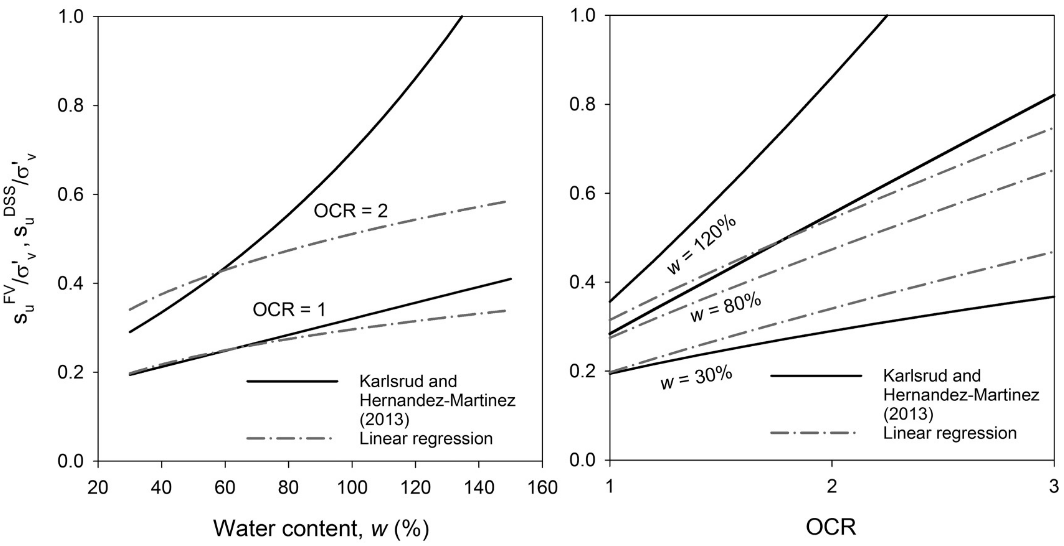


Fig. 14. Comparison between OCR–(s_u^{FV}/σ'_v)–w for Finnish clays and OCR–(s_u^{DSS}/σ'_v)–w model by Karlsrud and Hernandez-Martinez (2013) for Norwegian clays.



Validation of the new transformation models

It is apparent from Table 9 that the OCR–(s_u^{FV}/σ'_v)–Y_j transformation model is strongly dependent on index parameters. As earlier explained in this section, s_u^{DSS} of Scandinavian clays exhibits a marked dependency on LL (eq. (6)) and w (eq. (7)). These results may be explained by the fact that both tests at laboratory scale and FV test are performed at considerably high strain rate in relatively short time frames, if compared with the time scale needed for causing failure in situ. It is known that undrained failure of e.g., embankments may take several days (La Rochelle et al. 1974), while DSS and FV tests are performed on time scales in the order of hours or minutes, respectively. While TXC, TXE, DSS tests are normally performed at a strain rate of about 1%·h^{-1}, FV test is executed at strain rates typically 50–60 times larger (i.e., 60%·h^{-1}, Ching et al. 2013). This is well reflected in Fig. 13 and Fig. 14, where the OCR–(s_u^{FV}/σ'_v)–Y_j transformation model is compared to eq. (6) and eq. (7). From Fig. 13, it can be noticed how s_u^{FV}/σ'_v is generally greater than s_u^{DSS}/σ'_v, except for LL > 100% at OCR = 1. This is possibly due to the limited amount of LL > 100% data points used to derive the correlations.

However, more uncertainty comes when w is taken as secondary input parameter. The transformation model given by Karlsrud and Hernandez-Martinez (2013) for DSS strength tends to deviate from the mean trend suggested by F-CLAY/10/173 database (Fig. 14), intersecting the regression line and suggesting that for a certain number of combinations of OCR and w, s_u^{DSS} of Norwegian clays would result higher than s_u^{FV} of Finnish clays. One possible reason that could justify the differences between the two models could be that (*i*) eq. (6) is based only on a limited number of DSS tests (as reported by Karlsrud and Hernandez-Martinez 2013) and (*ii*) w of the tested specimens was about 25%~80%, while the new OCR–(s_u^{FV}/σ'_v)–w model is calibrated from a wider range of w (w = 25%–150%). Hence, attention must be paid when using eq. (7), as, based on this study, consistency was found only for w < 60%.

Figure 15 compares the variation of s_u^{FV}/σ'_v with OCR for various LL ranges. It is noticeable that for Finnish sensitive clays, the trend

Fig. 15. Comparison between measured (calibration and validation) data and OCR–(s_u^{FV}/σ'_v)–LL model for Finnish clays for various LL ranges: (*a*) LL ≤ 50%; (*b*) 50% < LL ≤ 75%; (*c*) 75% < LL ≤ 100%; (*d*) LL > 100%.

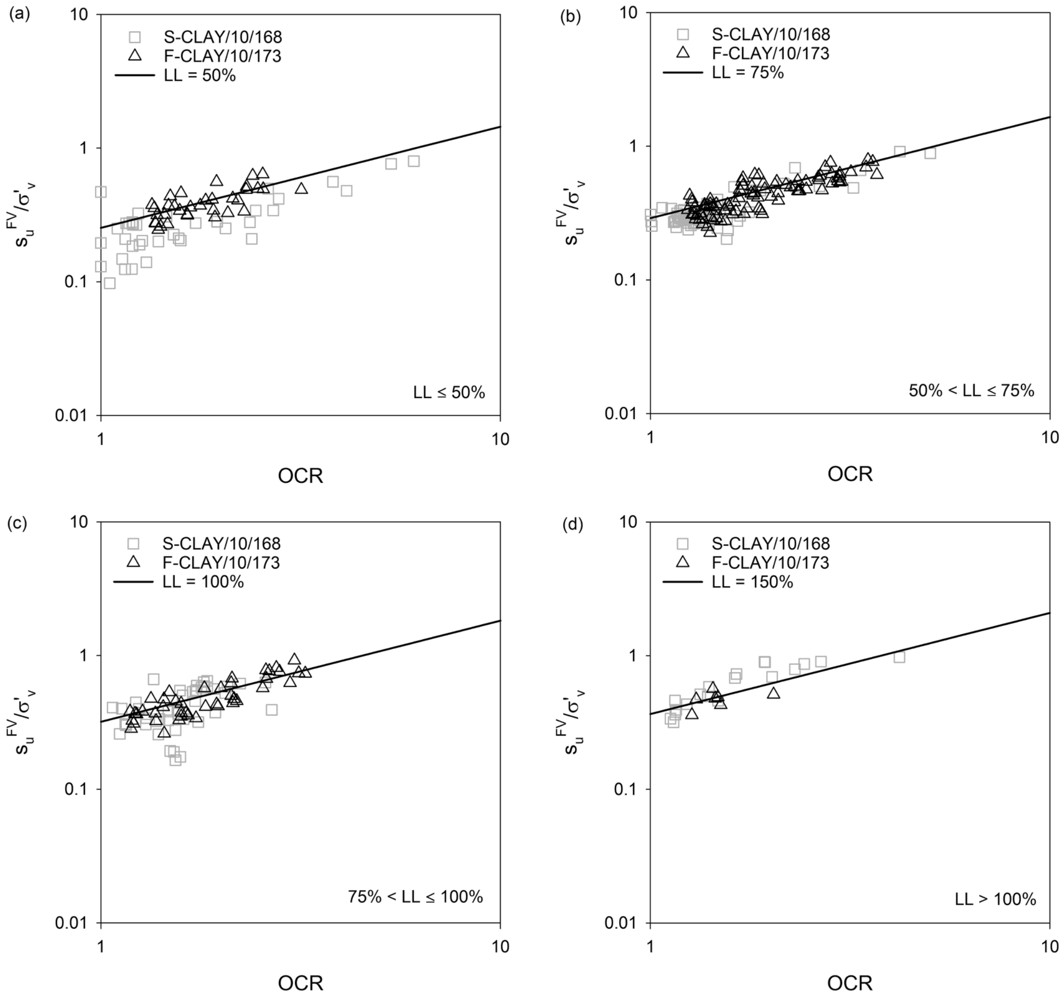


Table 10. Transformation models for Finnish clays and their calibration results for S-CLAY/10/168.

			Calibration results	
Relationship	*n*	Transformation model	Bias factor, *b*	COV of $\varepsilon = \delta$
OCR–[s_u(mob)/σ'_v]–PI	168	$s_u(\mathrm{mob})/\sigma'_v \approx 0.242\mathrm{OCR}^{0.763}\mathrm{PI}^{-0.013}$	0.94	0.26
OCR–[s_u(mob)/σ'_v]–LL	168	$s_u(\mathrm{mob})/\sigma'_v \approx 0.245\mathrm{OCR}^{0.760}\mathrm{LL}^{-0.005}$	0.94	0.25
OCR–[s_u(mob)/σ'_v]–*w*	168	$s_u(\mathrm{mob})/\sigma'_v \approx 0.246\mathrm{OCR}^{0.760}w^{0.027}$	0.94	0.25
OCR–[s_u(mob)/σ'_v]–LI	168	$s_u(\mathrm{mob})/\sigma'_v \approx 0.241\mathrm{OCR}^{0.770}\mathrm{LI}^{0.045}$	0.95	0.26
OCR–[s_u(mob)/σ'_v]–S_t	59	$s_u(\mathrm{mob})/\sigma'_v \approx 0.242\mathrm{OCR}^{0.762}S_t^{0.006}$	0.90	0.34
OCR–(s_u^{FV}/σ'_v)–PI	168	$s_u^{FV}/\sigma'_v \approx 0.328\mathrm{OCR}^{0.756}\mathrm{PI}^{0.165}$	0.95	0.29
OCR–(s_u^{FV}/σ'_v)–LL	168	$s_u^{FV}/\sigma'_v \approx 0.319\mathrm{OCR}^{0.757}\mathrm{LL}^{0.333}$	0.94	0.26
OCR–(s_u^{FV}/σ'_v)–*w*	168	$s_u^{FV}/\sigma'_v \approx 0.296\mathrm{OCR}^{0.788}w^{0.337}$	0.97	0.27
OCR–(s_u^{FV}/σ'_v)–LI	168	$s_u^{FV}/\sigma'_v \approx 0.281\mathrm{OCR}^{0.770}\mathrm{LI}^{-0.088}$	0.95	0.33
OCR–(s_u^{FV}/σ'_v)–S_t	59	$s_u^{FV}/\sigma'_v \approx 0.280\mathrm{OCR}^{0.786}S_t^{-0.013}S_t$	0.91	0.44

lines (solid lines) for given values of LL move gently upwards for increasing LL. The suggested trends appear to agree with the points from the S-CLAY/10/168 database, grouped following the LL ranges adopted.

Bias and uncertainties of the new transformation models

Bias factor (*b*) and coefficient of variation of ε (δ) are evaluated for the newly derived transformation models for s_u of Finnish soft clays, through the independent S-CLAY/10/168 database of Scandinavian clays. *b* and δ of the new correlations are summarized in Table 10. Calculated *b* values range between 0.94 and 0.97 when the effect of PI, LL, *w*, and LI is considered, with COV values lower than 0.30. Exception is only made for the OCR–(s_u^{FV}/σ'_v)–LI model which shows COV = 0.33. Therefore, the proposed correlations can be considered almost "unbiased" with respect to S-CLAY/10/168 database. The OCR–(s_u^{FV}/σ'_v)–S_t and OCR–[s_u(mob)/σ'_v]–S_t models are characterized by the lowest bias factors (0.91 and 0.90, respectively) and by the highest coefficients of variation δ (0.44 and 0.34, respectively). One possible reason could be that b and δ of the models where S_t is the secondary input parameter are calculated from a lower number of data points (n = 59) than for the other models (n = 168).

The new correlation equations appear to be less "biased" than the existing type C and type D transformation models presented in Table 6. In particular, s_u^{FV} evaluated using the new equations would result less "biased" ($b \sim 1$) than from type D models of Table 6, with δ values lower than 0.3 (Table 10) versus $\delta = 0.35–0.43$ (Table 6). In addition, equations for s_u(mob) from Table 10 provide an almost unbiased prediction with coefficient of variation (δ) as low as 0.25.

Discussion

Based on the results presented in Table 9, a correct evaluation of σ'_p would be of great importance for assessing s_u of Finnish soft clays when direct measurements are not available. The transformation models derived in this study can predict s_u with relatively low uncertainty, provided that OCR (primary input parameter) and a secondary input parameter (e.g., index parameter) are carefully chosen. The usability of the new models is straightforward, as only little information is required. For instance, simple tests such as oedometer and index tests would provide sufficient information for using the new models specific to Finnish clays. Moreover, the evaluation of a secondary input parameter may not be required, as s_u(mob) was observed to mainly depend on OCR (eq. (11)).

The transformation models presented in this study may also serve as a practical engineering tool for preliminary short-term analyses and (or) as a framework for validation of site-specific measurements that are suspected to be unreliable.

Conclusions

In this study, a calibration database of multivariate clay data points from Finland is compiled for the first time, for the scope of providing correlations for undrained shear strength (s_u) of Finnish clays and evaluating the dependency of s_u on the overconsolidation ratio (OCR), natural water content (w), liquid limit (LL), plasticity index (PI), liquidity index (LI), and sensitivity (S_t). The new transformation models are derived through linear regression analyses.

According to the results presented in this paper, a mutual dependence between the uncorrected s_u from FV test (s_u^{FV}), OCR, and index parameters (PI, LL, w, and LI) exists. The only exception is observed for S_t, which seems to have a negligible influence on s_u^{FV}. On the contrary, the mobilized undrained shear strength s_u(mob) seems to be mainly dependent on OCR and not significantly affected by index parameters.

Another independent clay database of Scandinavian clays is compiled to validate the new equations. Consistency of the new transformation models is checked by (*i*) evaluating bias factors and coefficients of variation associated with the validation database and (*ii*) comparison with existing transformation models for undrained shear strength of Swedish and Norwegian clays. Consistency is clearly revealed by the validation process. In particular, the new transformation models result in overall less biased than the existing ones, showing coefficients of variation lower than 0.30.

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List of symbols

B_q pore pressure ratio [= $(u_2 - u_0)/(q_t - \sigma_v)$]
b bias factor
C_c compression index of clay
C_s swelling index of clay
COV coefficient of variation
F multivariable function
K_0 earth pressure coefficient at rest from Jaky's formula
LI liquidity index [= (w – PL)/(LL – PL)]
LL liquid limit
m SHANSEP exponent
OCR overconsolidation ratio (= σ'_p/σ'_v)
P_a atmospheric pressure (= 101.3 kPa)
PI plasticity index (= LL – PL)
PL plastic limit
q_t cone tip resistance
$(q_t - \sigma_v)/\sigma'_v$ normalized cone tip resistance
$(q_t - u_2)/\sigma'_v$ effective cone tip resistance
S normalized s_u for normally consolidated state
S_t sensitivity (= s_u/s_u^{re})
s_u undrained shear strength
s_u(mob) mobilized undrained shear strength (= λs_u^{FV})
s_u^{CIUC} s_u from isotropically consolidated undrained compression test
$s_u^{CK_0UC}$ s_u from K_0-consolidated undrained compression test
$s_u^{CK_0UE}$ s_u from K_0-consolidated undrained extension test
s_u^{DSS} undrained shear strength from direct simple shear test
s_u^{FV} undrained shear strength measured from field vane test
s_u^{re} remolded undrained shear strength
s_u^{UC} s_u from unconfined compression test
s_u^{UU} s_u from unconsolidated undrained compression test
u_0 hydrostatic pore pressure
u_2 pore pressure acting behind the cone
Y_j secondary input parameter
w natural water content
α scalar coefficient in the multivariable function F
β scalar coefficient in the multivariable function F
γ scalar coefficient in the multivariable function F
δ coefficient of variation of ε
ε variability term
λ correction factor for s_u^{FV} based on plasticity
σ standard deviation of $s_u(\mathrm{mob})/\sigma'_v$
σ_v vertical stress
σ'_v effective vertical stress
σ'_p vertical preconsolidation pressure
σ'_{pCRS} vertical preconsolidation pressure from CRS test
σ'_{pIL} vertical preconsolidation pressure from IL test
τ_0 initially mobilized shear stress
ϕ' effective friction angle of soil

Appendix A. Multivariate clay databases

Appendix Tables A1–A2 appear on the following pages.

Table A1. Basic information of the F-CLAY/7/216 database: σ'_p data points from IL oedometer test.

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Espoo, Kaukalahti	3.2	13.0	30.2	43.0	70.0	25.0	85.0	11.0
	4.6	7.0	38.6	60.0	60.0	25.0	75.0	11.0
	5.2	7.5	42.2	45.0	45.0	20.0	50.0	10.0
Espoo, Martinkylä	5.5	7.0	24.5	25.0	70.0	20.0	80.0	4.0
	6.0	7.0	27.0	30.0	30.0	15.0	75.0	2.0
	7.0	12.0	32.0	40.0	80.0	20.0	100.0	6.0
	8.0	12.0	37.0	40.0	90.0	15.0	120.0	5.0
Helsinki, Malmi	3.0	9.0	18.0	30.0	80.0	35.0	110.0	12.0
	4.0	11.0	23.0	35.0	75.0	30.0	100.0	10.0
	5.0	10.0	28.0	30.0	43.0	20.0	65.0	10.0
	6.0	11.0	33.0	40.0	55.0	20.0	80.0	11.0
	7.0	8.0	38.0	50.0	25.0	20.0	40.0	9.0
	8.0	16.0	43.0	50.0	22.0	20.0	25.0	13.0
Kouvola	1.5	42.0	24.2	150.0	45.0	20.0	40.0	6.5
	3.0	15.0	33.0	40.0	80.0	25.0	100.0	11.0
	5.0	21.0	43.0	50.0	110.0	25.0	130.0	8.0
	6.0	23.0	48.0	55.0	110.0	25.0	120.0	8.0
	7.0	25.0	53.0	60.0	80.0	25.0	110.0	7.0
Kurkela*	2.2	19.1	35.4	105.4	69.0	32.3	75.0	40.0
	2.7	20.0	37.8	107.8	66.3	31.6	79.0	39.5
	3.2	28.2	40.3	110.3	60.8	30.2	70.0	39.0
	3.7	25.0	42.7	112.4	55.2	28.8	62.0	38.5
	4.2	22.3	45.2	115.2	49.7	27.4	56.7	37.0
	4.7	23.7	47.6	117.6	48.8	27.2	60.0	35.0
	5.2	31.3	50.1	120.1	48.5	27.1	65.3	24.1
	6.2	28.4	55.0	127.3	48.0	27.0	52.1	24.2
	7.2	27.8	59.9	140.0	51.8	28.0	53.5	24.0
	8.2	29.9	64.8	152.3	55.8	28.9	55.7	24.0
	9.2	34.9	69.7	160.0	68.8	32.2	65.0	13.5
	10.2	34.1	74.6	163.0	82.4	35.6	77.4	10.0
	11.2	35.1	79.5	170.0	94.9	38.7	82.0	10.5
	12.2	23.3	84.4	182.3	107.3	41.8	87.7	10.5
	13.2	21.1	89.3	185.0	111.8	42.9	83.9	10.0
Loimaa	3.0	20.0	24.0	48.0	55.0	25.0	65.0	11.0
	4.0	19.0	31.0	90.0	51.0	23.0	60.0	9.0
	5.0	18.0	38.0	50.0	75.0	23.0	70.0	7.0
	7.0	24.0	52.0	65.0	48.0	23.0	65.0	9.0
	8.0	24.0	59.0	85.0	47.0	23.0	70.0	13.0
	9.0	23.0	66.0	67.0	55.0	25.0	70.0	13.0
	10.0	25.0	73.0	110.0	49.0	23.0	60.0	9.0
	11.0	25.0	80.0	120.0	51.0	23.0	60.0	8.0
	12.0	27.0	87.0	110.0	55.0	23.0	57.0	7.0
	13.0	27.0	94.0	100.0	52.0	22.0	65.0	8.0
Lokalahti	5.0	9.0	16.5	22.0	60.0	20.0	100.0	17.0
	7.0	10.0	26.5	28.0	49.0	20.0	80.0	19.0
Nurmijarvi	2.4	8.0	15.6	25.0	120.0	50.0	150.0	10.0
	3.6	7.0	20.4	30.0	52.0	25.0	75.0	9.0
	6.0	16.0	30.0	35.0	80.0	30.0	120.0	7.0
	7.0	17.0	34.0	48.0	75.0	30.0	100.0	10.0
	8.0	22.0	38.0	51.0	75.0	30.0	100.0	12.0
	9.0	24.0	42.0	60.0	90.0	30.0	100.0	13.0
	10.0	25.0	46.0	75.0	75.0	30.0	90.0	13.0
	11.0	28.0	53.0	80.0	65.0	30.0	75.0	14.0
	13.0	34.0	67.0	90.0	60.0	25.0	58.0	12.0
	14.0	22.0	74.0	130.0	65.0	25.0	60.0	8.0
	16.0	28.0	88.0	100.0	40.0	25.0	35.0	6.0
	17.0	30.0	95.0	100.0	52.0	25.0	60.0	7.0
	18.0	35.0	102.0	140.0	70.0	25.0	55.0	8.0
Otaniemi	2.7	5.0	10.1	20.0	105.0	25.0	120.0	9.0
	5.5	12.0	19.5	28.0	70.0	30.0	75.0	5.0
	6.5	11.0	24.5	35.0	70.0	25.0	65.0	4.0
	7.5	14.0	29.5	50.0	80.0	30.0	85.0	5.0
	8.5	19.0	34.5	80.0	65.0	30.0	80.0	7.0
	9.5	12.0	39.5	60.0	43.0	25.0	50.0	6.0
	10.5	15.0	44.5	80.0	47.0	25.0	55.0	8.0

Table A1 (*continued*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Perniö (location 1)*	2.2	9.30	28.9	74.3	79.0	32.0	75.0	14.0
	2.7	10.20	31.4	62.6	74.0	32.0	78.5	18.6
	2.6	12.20	31.0	64.7	75.0	32.0	80.8	19.1
	2.7	13.60	31.6	61.5	82.0	32.0	97.6	22.9
	2.1	19.10	28.5	73.8	76.0	32.0	88.0	25.2
	5.1	12.80	43.5	61.5	65.0	32.0	80.1	30.7
	3.1	9.30	33.5	51.5	65.0	32.0	83.0	32.0
	2.2	18.60	29.1	73.9	46.0	32.0	61.7	32.7
	5.7	11.60	46.4	64.4	58.0	32.0	80.9	33.7
	3.6	9.90	36.0	54.0	63.0	32.0	86.0	35.0
	4.2	12.80	39.1	57.1	64.0	32.0	90.0	35.5
	5.2	15.40	44.1	62.1	64.0	32.0	70.9	35.6
	6.1	13.30	48.5	66.5	38.0	32.0	47.9	36.7
	4.7	14.80	41.6	59.6	55.0	32.0	88.2	37.4
	3.2	11.30	33.9	51.9	60.0	32.0	82.3	39.1
	3.7	6.40	36.4	54.4	51.0	32.0	77.5	39.4
	4.6	10.70	41.0	59.0	76.0	32.0	96.6	41.3
	4.7	11.60	41.4	59.4	51.0	32.0	72.6	45.7
	4.1	10.40	38.5	56.5	50.0	32.0	69.6	45.7
	3.7	16.00	36.6	54.6	50.0	32.0	74.4	46.3
	5.2	9.90	43.9	61.9	59.0	32.0	84.1	46.5
	3.2	12.50	34.1	52.1	45.0	32.0	70.6	49.4
	5.7	16.80	46.6	64.6	54.0	32.0	80.1	51.1
	4.2	11.30	38.9	56.9	51.0	32.0	72.0	51.3
	5.6	11.30	46.0	64.0	50.0	32.0	75.9	57.7
Perniö (location 2)*	1.5	38.0	19.0	64.0	89.9	36.0	58.9	64.0
	2.5	10.0	24.2	44.2	89.9	36.0	110.0	58.0
	3.0	8.7	26.4	41.4	86.3	36.0	104.0	55.5
	3.5	7.5	28.6	38.6	71.1	36.0	94.0	53.5
	4.0	8.7	30.8	40.8	60.2	36.0	84.0	52.3
	4.5	10.0	33.0	43.0	58.2	36.0	75.0	51.4
	5.0	11.0	35.2	45.2	54.1	36.0	80.0	50.4
	5.5	15.0	37.4	47.4	50.4	36.0	75.0	47.5
	6.0	17.0	39.6	49.6	52.0	36.0	80.0	43.8
	6.5	14.0	41.8	51.8	66.9	36.0	92.0	39.2
	7.0	16.0	44.0	54.0	75.5	36.0	84.0	39.5
	7.5	17.0	46.2	56.2	75.9	36.0	88.0	40.0
	8.0	15.0	48.4	58.4	76.3	36.0	87.0	40.0
	8.5	16.5	50.6	60.6	76.7	36.0	86.0	45.0
	9.0	15.0	52.8	62.8	77.2	36.0	88.0	45.0
	9.5	21.0	55.0	65.0	77.2	36.0	85.0	40.0
	2.0	13.0	21.5	45.0	75.0	25.0	75.0	11.0
	3.0	10.0	27.0	30.0	75.0	30.0	75.0	20.0
	5.0	16.0	38.0	60.0	51.0	25.0	75.0	21.0
	6.0	18.0	43.5	65.0	49.0	30.0	65.0	20.0
Raisio, Autolava	0.8	49.0	19.8	125.0	50.0	20.0	40.0	3.0
	1.5	13.0	18.5	39.0	70.0	20.0	70.0	10.0
	2.5	10.0	24.5	50.0	70.0	23.0	90.0	9.0
	3.0	12.0	27.0	38.0	75.0	25.0	90.0	8.0
	4.0	14.0	32.0	40.0	100.0	27.0	130.0	10.0
Raisio, Krookila	2.5	13.0	26.3	60.0	85.0	25.0	87.0	11.0
	3.5	11.0	30.8	40.0	80.0	25.0	90.0	12.0
	4.5	12.0	35.3	48.0	85.0	25.0	80.0	9.0
	5.5	17.0	39.8	47.0	125.0	30.0	130.0	10.0
	6.5	25.0	44.3	50.0	120.0	25.0	120.0	10.0
	7.5	23.0	48.8	50.0	110.0	25.0	110.0	9.0
	8.5	22.0	53.3	60.0	100.0	25.0	95.0	10.0
	9.5	22.0	57.8	90.0	100.0	25.0	95.0	8.0
	10.5	23.0	62.3	80.0	85.0	25.0	80.0	8.0
Raisio, Ristimaki	0.5	10.0	7.5	30.0	70.0	30.0	70.0	12.0
	1.5	10.0	12.5	35.0	75.0	40.0	85.0	9.0
	2.5	10.0	17.5	35.0	80.0	45.0	95.0	12.0
	3.5	17.0	22.5	50.0	65.0	25.0	100.0	10.0
	5.5	15.0	32.5	43.0	70.0	35.0	80.0	11.0
	8.0	18.0	45.0	50.0	55.0	30.0	75.0	9.0

Table A1 (*continued*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Raisio, Siirinpelto	3.5	7.0	29.5	50.0	48.0	20.0	85.0	10.0
	4.5	8.0	34.5	52.0	49.0	20.0	80.0	10.0
	6.0	9.5	42.0	90.0	35.0	20.0	37.0	10.0
	7.5	10.0	49.5	90.0	30.0	20.0	52.0	11.0
Saimaan kanava	3.0	30.0	31.0	120.0	80.0	27.0	60.0	8.0
	4.0	30.0	37.0	80.0	100.0	30.0	110.0	7.5
	5.0	20.0	43.0	80.0	55.0	25.0	65.0	7.0
	6.0	20.0	49.0	85.0	32.0	22.0	70.0	10.0
	7.0	18.0	55.0	90.0	35.0	25.0	50.0	9.0
	8.0	25.0	61.0	80.0	55.0	25.0	65.0	7.0
	9.0	30.0	67.0	110.0	60.0	25.0	75.0	6.0
Salo, Salonkyla	10.0	18.0	50.0	50.0	105.0	25.0	100.0	10.0
	16.0	28.0	80.0	100.0	90.0	25.0	85.0	16.0
	20.0	28.0	100.0	160.0	90.0	25.0	75.0	10.0
Sipoo	1.0	47.0	16.0	120.0	60.0	35.0	50.0	10.0
	1.5	20.0	20.5	80.0	85.0	25.0	80.0	9.0
	3.5	24.0	32.5	80.0	80.0	25.0	85.0	12.5
	4.5	21.0	37.5	78.0	75.0	25.0	75.0	11.5
	5.5	20.0	42.5	90.0	70.0	25.0	80.0	10.5
	6.5	20.0	47.5	80.0	49.9	25.0	65.0	10.0
	7.5	21.0	52.5	125.0	44.0	25.0	60.0	9.0
	10.0	16.0	42.0	42.0	85.0	25.0	85.0	8.0
	12.0	17.0	52.0	67.0	75.0	25.0	80.0	10.0
	14.6	24.0	65.0	70.0	100.0	25.0	85.0	11.0
Somero, Joenssu	1.0	45.0	17.0	100.0	85.0	30.0	60.0	7.0
	2.0	23.0	25.0	60.0	100.0	25.0	90.0	15.0
	4.0	20.0	35.0	55.0	100.0	25.0	110.0	13.0
	6.0	28.0	45.0	75.0	80.0	25.0	110.0	14.0
	8.0	23.0	55.0	85.0	80.0	30.0	110.0	15.0
	10.0	27.0	65.0	95.0	70.0	25.0	80.0	13.0
	12.0	28.0	79.0	98.0	60.0	23.0	75.0	16.0
	14.0	33.0	93.0	100.0	52.0	23.0	70.0	10.0
	18.0	40.0	121.0	180.0	60.0	23.0	60.0	13.0
	20.0	43.0	135.0	175.0	50.0	23.0	60.0	8.0
	24.0	51.0	163.0	220.0	60.0	25.0	50.0	7.0
Somero, Kirkonkyla	4.0	35.0	39.0	130.0	75.0	27.0	70.0	14.0
	5.0	33.0	45.0	115.0	80.0	25.0	75.0	17.0
	6.0	31.0	51.0	75.0	70.0	25.0	70.0	16.0
	7.0	31.0	57.0	110.0	75.0	24.0	75.0	13.0
	8.0	33.0	64.0	110.0	55.0	23.0	65.0	12.0
	11.0	42.0	85.0	150.0	60.0	24.0	55.0	8.0
	12.0	45.0	92.0	230.0	46.0	23.0	55.0	7.0
Somero, Pajulanjoki	4.0	19.0	21.0	70.0	80.0	27.0	110.0	12.0
	5.0	17.0	25.0	79.0	75.0	27.0	100.0	13.0
	6.0	23.0	29.0	80.0	75.0	27.0	100.0	22.0
	7.0	23.0	33.0	90.0	75.0	27.0	100.0	18.0
	8.0	25.0	37.0	62.0	80.0	25.0	85.0	18.0
	9.0	27.0	42.0	105.0	75.0	25.0	80.0	12.0
	10.0	28.0	47.0	110.0	75.0	27.0	85.0	17.0
	11.0	30.0	52.0	120.0	70.0	25.0	80.0	20.0
	12.0	31.0	57.0	135.0	70.0	25.0	80.0	10.0
	13.0	32.0	62.0	100.0	65.0	25.0	75.0	21.0
Tampere	1.5	75.0	33.0	180.0	70.0	27.0	70.0	9.0
	2.5	37.0	40.0	190.0	52.0	27.0	40.0	6.0
	3.0	24.0	43.5	80.0	55.0	27.0	40.0	9.0
	3.5	18.0	47.0	60.0	60.0	25.0	70.0	17.0
	4.0	16.0	50.5	55.0	47.0	27.0	62.0	14.0
	4.5	17.0	54.0	70.0	40.0	25.0	60.0	20.0
	5.0	13.0	57.5	75.0	35.0	28.0	45.0	11.0
	5.5	14.0	61.0	77.0	32.0	25.0	42.0	10.0
	6.0	22.0	64.5	80.0	35.0	27.0	50.0	8.0
	6.5	21.0	68.0	68.0	51.0	25.0	55.0	16.0
	7.0	35.0	71.5	130.0	35.0	25.0	60.0	14.0
	7.5	42.0	75.0	115.0	31.0	26.0	50.0	9.0
	8.0	37.0	78.5	220.0	37.0	32.0	40.0	11.0

Table A1 (*concluded*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Vihti	3.0	20.0	23.0	55.0	35.0	15.0	35.0	10.0
	4.0	23.0	30.0	85.0	75.0	50.0	80.0	16.0
	6.0	21.0	44.0	85.0	60.0	30.0	65.0	7.0
	9.0	18.0	65.0	70.0	25.0	10.0	30.0	11.0
	10.0	26.0	72.0	95.0	40.0	20.0	45.0	7.0
	11.0	29.0	79.0	97.0	55.0	30.0	57.0	6.0
	12.0	32.0	86.0	120.0	48.0	25.0	52.0	9.0
	13.0	34.0	93.0	100.0	52.0	25.0	55.0	10.0
	14.0	37.0	100.0	115.0	51.0	25.0	55.0	10.0
Viiala	3.0	22.0	23.8	45.0	65.0	25.0	75.0	8.5
	4.0	22.0	29.3	40.0	48.0	25.0	60.0	9.0
	4.5	20.0	32.0	75.0	75.0	25.0	80.0	8.0
	6.0	25.0	40.3	90.0	52.0	25.0	70.0	8.5
	6.5	22.0	43.0	100.0	85.0	30.0	95.0	11.0
	7.0	35.0	45.8	95.0	100.0	35.0	100.0	14.0
	8.0	32.0	51.3	120.0	85.0	35.0	90.0	14.0
	8.5	42.0	54.0	110.0	80.0	30.0	90.0	11.0
	9.0	43.0	56.8	125.0	77.0	35.0	80.0	16.6
	9.5	55.0	59.5	130.0	95.0	25.0	80.0	15.0
	15.0	43.0	90.5	95.0	80.0	30.0	65.0	6.0
	14.0	32.0	83.5	83.5	75.0	30.0	60.0	6.0

*σ'_p data points from CRS oedometer test.

Table A2. Basic information of the S-CLAY/7/168 database. σ'_p data points from CRS oedometer test.

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Drammen (Norway)	4.0	8.3	41.2	57.4	39.3	9.7	30.7	3.0
	5.2	11.8	50.4	78.7	58.7	10.3	65.5	3.0
	6.2	11.7	57.8	89.6	65.6	18.8	65.6	3.0
	7.1	12.3	64.7	98.5	75.2	20.6	56.2	3.0
	7.5	13.0	67.1	100.0	88.5	18.7	65.3	3.0
	7.5	22.8	68.0	95.2	88.0	18.0	65.0	6.0
	7.8	25.2	70.0	105.0	60.0	29.0	52.0	8.0
	8.5	20.6	74.5	114.4	75.8	15.4	61.7	3.0
	8.5	12.3	74.5	114.4	75.8	15.4	61.7	3.0
	9.0	13.7	78.7	124.3	78.2	19.1	58.2	3.0
	9.3	11.2	80.0	104.0	33.0	23.0	32.0	8.0
	9.4	20.9	81.5	113.4	92.2	20.4	64.1	3.0
	11.9	10.0	102.6	108.0	40.2	8.8	27.6	7.0
	13.0	20.8	112.5	135.0	25.0	3.0	26.0	6.0
	13.0	14.0	112.5	129.3	25.0	3.0	25.7	7.0
	17.4	19.0	152.6	182.3	23.3	2.7	17.3	7.0
Ellingsrud (Norway)	10.5	7.8	60.0	60.0	24.0	20.0	36.0	42.5
Fredrikstad (Norway)	6.5	10.8	43.0	47.3	34.0	21.0	40.5	20.0
Haga (Norway)	2.8	41.6	52.0	315.6	41.1	26.3	37.9	—
	2.8	40.4	53.0	282.5	40.6	27.5	38.8	—
	3.9	40.3	72.0	274.3	40.8	26.1	36.9	—
	4.9	45.0	92.0	296.2	62.5	28.2	54.2	—
	5.2	48.7	97.0	257.1	68.0	29.6	60.7	—
	6.2	39.3	115.0	310.5	40.4	25.4	36.5	—
	6.5	39.3	121.0	150.0	39.0	25.4	34.4	—
Onsøy (Norway)	1.9	10.8	12.2	61.1	50.2	32.1	65.1	3.0
	2.1	12.7	13.9	58.4	65.2	32.1	67.1	3.0
	3.5	11.8	22.4	48.2	59.9	29.4	57.6	3.0
	5.2	12.1	32.6	45.1	56.8	33.9	58.5	3.0
	5.5	12.0	34.3	46.1	56.4	34.0	58.9	3.0
	7.6	12.9	47.5	54.3	66.3	34.8	62.3	3.0
	7.9	13.5	48.9	56.3	66.2	34.9	65.8	3.0
	10.8	17.6	66.2	85.2	74.4	38.3	67.5	7.0
	11.0	19.5	67.5	86.9	72.9	36.8	69.4	7.0
	13.4	22.2	82.2	106.3	71.4	35.6	66.7	7.0
	13.6	22.0	83.5	107.0	71.5	35.6	68.9	7.0
	16.3	27.4	99.8	100.2	72.7	37.9	64.5	7.0
Studenterlunden (Norway)	15.0	16.5	87.0	108.8	37.0	20.0	33.0	5.0
	15.0	17.0	87.0	87.0	44.0	25.0	37.4	4.0
Sundland (Norway)	6.5	15.1	43.0	55.9	58.0	30.0	59.0	11.0
Unknown location 1 (Norway)	3.1	14.8	21.4	49.1	56.1	29.2	59.2	—
	5.0	14.6	31.3	56.2	58.8	30.2	61.2	—
	7.0	13.1	43.4	64.8	63.6	31.6	68.3	—
	9.2	17.6	54.8	96.8	71.3	27.9	68.7	—
	10.0	17.9	61.2	83.3	68.6	27.9	68.9	—
Unknown location 2 (Norway)	4.5	16.6	34.6	142.5	22.8	18.9	40.3	—
	6.0	17.9	42.7	119.0	29.0	17.2	44.3	—
	7.5	14.6	52.3	123.5	25.8	19.8	41.1	—
	8.0	11.4	54.6	130.1	24.8	20.7	41.3	—
Vaterland (Norway)	7.5	24.4	52.0	52.0	47.0	27.0	40.0	5.0
Bäckebol (Sweden)	9.1	18.2	55.4	81.8	87.1	32.1	74.7	15.0
	11.1	26.6	66.6	75.1	85.6	37.3	94.9	24.0
	13.1	32.1	78.7	84.1	86.1	39.9	89.2	—
	14.1	33.2	84.7	226.6	89.7	38.4	93.3	—
	15.1	34.3	91.6	177.0	89.2	38.4	92.8	—
	4.0	17.7	26.7	36.1	85.8	25.3	78.4	11.0
	6.0	16.3	36.4	44.5	84.7	31.1	103.1	32.0
	7.0	16.5	41.5	51.6	83.0	35.1	88.1	28.0

Table A2 (*continued*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Göta Älv (Sweden)	2.6	12.7	20.5	45.6	76.5	33.2	85.3	—
	3.0	13.4	23.1	42.7	75.8	33.9	84.4	—
	3.5	13.1	26.1	41.8	75.2	34.2	83.4	—
	3.9	13.1	28.2	53.0	72.7	34.6	82.4	—
	4.5	12.8	32.0	47.1	70.3	35.2	83.0	—
	5.0	12.7	34.4	53.6	78.8	35.9	92.2	—
	5.5	12.5	37.3	60.1	82.1	35.9	98.1	—
	5.9	12.5	39.4	69.0	75.8	33.2	93.8	—
	6.9	12.6	46.2	63.4	69.6	32.6	83.4	—
	7.9	13.3	51.8	65.4	65.7	31.3	79.4	—
	8.9	14.7	56.9	63.4	78.1	35.5	83.0	—
Järva Krog (Sweden)	5.0	18.6	48.8	72.0	88.1	37.7	93.2	26.0
	7.0	21.1	61.7	69.5	51.4	24.4	57.5	20.0
	9.0	25.8	74.4	79.5	50.4	23.9	62.6	23.0
Kalix (Sweden)	2.0	13.5	15.0	40.1	201.8	73.9	180.1	17.0
	3.0	14.8	16.5	31.8	191.3	70.4	176.0	15.0
	5.0	15.8	23.2	37.8	157.8	61.0	136.1	10.0
Lilla Mellösa (Sweden)	2.1	8.7	14.9	20.9	129.7	47.5	130.8	—
	2.8	8.4	18.4	21.1	129.7	47.0	122.6	—
	3.6	8.6	21.8	25.3	124.2	43.7	114.9	—
	4.2	9.4	24.7	28.5	119.3	41.0	111.1	—
	5.0	10.3	28.3	32.6	110.0	38.2	108.3	—
	5.7	10.8	31.9	35.9	105.1	36.0	100.7	—
	6.4	11.2	35.2	40.2	100.7	31.7	97.4	—
	7.1	12.1	39.2	45.1	93.0	30.0	95.2	—
	7.9	13.2	43.4	49.9	84.8	27.3	83.1	—
	8.5	14.2	47.0	54.3	82.1	26.2	82.6	—
	9.0	17.0	50.0	65.0	76.0	25.0	69.9	17.5
	9.1	15.3	50.5	58.4	78.8	25.1	78.2	—
	9.9	17.4	55.3	64.4	73.8	22.3	72.2	—
	10.7	18.4	61.2	71.5	71.1	23.4	71.1	—
	11.5	18.6	67.5	79.1	73.3	22.3	74.4	—
	12.4	18.6	74.8	86.7	73.3	22.9	83.1	—
Munkedal (Sweden)	3.2	25.0	37.7	126.6	65.1	31.3	98.9	—
	4.1	22.7	45.4	105.0	64.0	31.0	97.0	—
	6.1	31.6	63.5	102.9	61.6	30.4	92.7	—
	7.2	22.1	73.3	122.8	60.3	30.1	90.4	—
	8.1	22.7	82.2	135.5	59.2	29.8	88.5	—
	9.2	29.2	91.9	132.9	57.9	29.5	86.3	—
	10.1	30.9	100.3	143.5	56.7	29.2	84.2	—
	12.2	28.7	120.7	149.8	54.1	28.5	79.7	—
	16.2	33.5	160.4	184.5	49.3	27.3	71.2	—
	17.1	34.4	169.7	215.4	48.1	27.0	69.2	—
	21.2	31.5	212.9	240.8	43.1	25.8	60.4	—
Nörrkaping (Sweden)	2.1	10.9	27.5	42.8	82.0	35.5	85.0	—
	2.9	10.0	31.2	42.8	83.0	35.8	120.0	—
	3.4	10.3	33.9	43.8	79.0	34.8	115.0	—
	4.1	10.6	37.5	45.8	75.0	33.8	110.0	—
	4.7	11.2	40.2	48.5	60.0	30.0	85.0	—
	5.3	12.0	43.1	50.8	65.0	31.3	77.0	—
	5.9	13.1	45.8	54.4	70.0	32.5	70.0	—
	6.6	14.3	49.5	59.1	71.0	32.8	82.0	—
	7.3	15.6	52.4	64.7	72.0	33.0	95.0	—
	7.8	16.1	55.1	69.4	71.0	32.8	90.0	—
	8.6	16.5	59.1	78.3	70.0	32.5	85.0	—
	9.4	16.7	64.1	89.6	60.0	30.0	65.0	—
	10.3	16.9	69.0	101.6	70.0	32.5	72.0	—
	11.1	16.9	74.7	113.5	35.0	23.8	40.0	—
	12.0	17.0	80.3	125.8	40.0	25.0	40.0	—
	12.9	17.5	86.0	136.1	40.0	25.0	40.0	—

Table A2 (*concluded*).

Location	Depth (m)	s_u^{FV} (kPa)	σ'_v (kPa)	σ'_p (kPa)	LL (%)	PL (%)	w (%)	S_t
Skå-Edeby (Sweden)	10.0	15.6	60.0	84.0	51.0	23.0	63.0	20.0
	2.0	11.1	12.5	24.1	126.1	58.5	122.5	8.0
	4.0	6.9	21.0	24.9	66.4	30.2	95.9	18.0
	6.0	10.5	31.5	38.1	51.3	24.1	71.8	14.0
	8.0	13.8	44.7	40.1	55.5	26.6	73.0	23.0
	9.9	15.0	59.1	59.5	50.7	24.1	64.6	21.0
Stora an (Sweden)	1.5	10.2	10.4	43.8	113.8	40.0	107.8	—
	2.0	8.9	11.3	26.0	115.3	40.7	109.3	—
	2.3	8.2	11.9	24.0	125.0	54.2	122.8	—
	3.1	7.2	14.0	18.7	118.3	42.2	117.5	—
	3.8	7.1	16.4	20.2	123.5	37.7	113.8	—
	4.6	9.0	19.6	28.9	104.1	46.0	107.1	—
	5.3	11.3	22.8	31.7	104.9	41.5	103.4	—
Svartiolandet (Sweden)	2.0	8.8	14.0	36.0	92.5	32.4	91.3	—
	2.5	8.5	16.2	33.1	81.2	27.6	87.7	—
	3.0	8.4	18.4	31.6	76.4	24.6	80.6	—
	3.7	8.3	22.1	31.6	70.5	26.4	78.8	—
	4.3	8.2	25.0	32.4	68.7	26.4	78.8	—
	4.9	8.5	28.3	34.9	67.5	27.0	78.8	—
	5.5	9.3	32.0	37.9	58.0	24.0	74.6	—
	6.0	9.7	36.0	41.2	53.2	20.5	65.7	—
	6.4	10.3	37.9	43.4	51.4	20.5	65.1	—
	6.8	11.0	40.1	46.3	49.6	19.3	63.9	—
	7.3	11.9	43.4	51.1	49.6	19.3	63.9	—
	7.9	13.0	46.3	55.5	49.6	21.0	62.1	—
	8.5	13.7	50.4	60.7	49.6	21.0	60.9	—
	9.0	14.6	54.4	65.4	49.0	19.3	59.7	—
	9.6	15.5	58.1	71.3	49.0	19.9	58.0	—
	10.3	16.8	62.5	76.8	51.4	19.3	57.4	—
Tuve (Sweden)	2.1	5.9	6.9	16.7	110.0	40.0	121.0	—
	3.1	6.7	9.2	15.2	105.0	40.0	115.5	—
	4.0	7.7	12.0	22.1	100.0	40.0	110.0	—
	5.0	8.7	14.7	25.5	100.0	40.0	110.0	—
	6.0	9.5	17.4	27.5	95.0	40.0	104.5	—
	7.0	10.4	20.5	47.1	75.0	30.0	82.5	—
	7.9	13.2	23.5	45.1	83.0	30.0	91.3	—
	8.9	15.8	26.9	55.9	95.0	30.0	104.5	—
	10.0	19.2	30.4	54.9	87.0	30.0	95.7	—
	11.0	19.9	33.8	61.3	86.0	30.0	94.6	—
	11.5	20.4	35.5	63.2	85.0	30.0	93.5	—
	12.1	21.0	38.2	66.2	85.0	30.0	93.5	—
	12.6	21.4	39.5	68.1	84.0	30.0	92.4	—
	13.2	22.2	41.6	70.6	83.0	30.0	91.3	—
Ursvik (Sweden)	2.0	5.6	11.3	29.6	47.9	18.5	57.5	14.0
	4.0	6.9	20.2	49.4	49.2	21.7	97.8	18.0
	5.0	7.2	25.7	50.2	40.3	14.7	60.1	22.0
	6.0	9.0	31.9	62.3	49.9	21.7	59.5	27.0
	6.9	11.7	38.1	55.6	47.3	21.1	55.0	26.0
	8.0	11.2	44.7	91.8	47.3	21.7	51.8	26.0
	10.0	16.1	58.4	100.8	44.7	19.2	53.1	17.0