

# Transformations and correlations among some clay parameters - the global database

## 一些黏土参数之间的转换和相关性 - 全球数据库

Jianye Ching\* and Kok-Kwang Phoon†

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### Abstract 摘要

This study compiles a large database of 10 clay parameters (labeled as CLAY/10/7490) from 251 studies, covering clay data from 30 regions or countries worldwide. Hence, the range of data covered by this “global” database is broader than that underlying the calibration of existing transformation models in the literature. These transformation models relate test measurements (e.g., cone tip resistance) to appropriate design parameters (e.g., undrained shear strength). The correlation behaviours exhibited by the database among the 10 clay parameters are consistent with those exhibited by existing transformation models in the literature. The biases and transformation uncertainties of these transformation models with respect to the global database are calibrated. It is found that more recent transformation models are less biased and that the transformation uncertainties are typically fairly large. Such large transformation uncertainties are further reduced by incorporating secondary input parameters, such as plasticity index or sensitivity. In a companion paper written by the same authors, a 10-dimensional multivariate probability distribution coupling these clay parameters is constructed from CLAY/10/7490 and a useful application involving updating the entire bivariate probability distribution of two design parameters from three separate measurements is presented.

**Key words:** clay properties, correlations, transformation models, database, statistics.

本研究汇编了来自 251 个研究的 10 个黏土参数（标记为 CLAY/10/7490）的大型数据库，涵盖了来自全球 30 个地区或国家的黏土数据。因此，该“全球”数据库所涵盖的数据范围比文献中现有转换模型的标定所依据的范围要广。这些转换模型将测试测量值（例如，锥头阻力）与适当的设计参数（例如，不排水的剪切强度）相关联。数据库显示的 10 个黏土参数之间的相关行为与文献中现有的转换模型所显示的相关行为一致。这些转换模型相对于全局数据库的偏差和转换不确定性已得到校准。结果发现，更新的转换模型偏差较小，并且转换不确定性通常相当大。通过合并次级输入参数（例如可塑性指数或灵敏度），可以进一步降低如此大的变换不确定性。在同一位作者撰写的伴随论文中，从 CLAY/10/7490 构建了耦合这些黏土参数的 10 维多元概率分布，并提出了一个有用的应用程序，其中涉及从三个独立的测量值更新两个设计参数的整个双变量概率分布。

**关键词：**黏土特性，相关性，转换模型，数据库，统计数据。

## 1 Introduction 简介

Geotechnical variability is a complex attribute that needs careful evaluation. Phoon and Kulhawy (1999a) demonstrated using fairly

岩土变异性是一个复杂的属性，需要仔细评估。Phoon and Kulhawy (1999a) 使用相

\*J. Ching. Department of Civil Engineering, National Taiwan University, Taiwan.

†K.-K. Phoon. Department of Civil and Environmental Engineering, National University of Singapore, Singapore.

‡Corresponding author: Jianye Ching (e-mail: jyching@gmail.com)

extensive soil statistics that geotechnical variability depends on the site condition, measurement error associated with a field test, and quality of the correlation model adopted to relate the field test to a design property. The first component refers to inherent soil variability, which is customarily categorized as aleatoric in nature because it cannot be reduced by performing more tests. The second and third components, namely measurement error inevitably introduced in a test procedure and data scatter about a mean correlation trend (typically in the form of a linear regression equation), are customarily categorized epistemic in nature. They can be reduced by gathering more data or building better models. While there are merits to categorizing uncertainties as aleatoric or epistemic, one should be mindful that this demarcation is in part a modeler's choice (Kiureghian and Ditlevsen, 2007). From a practical perspective, it is perhaps more important to align statistical characterization to the property evaluation procedure already embedded in our geotechnical engineering practice. In recognition of the need to respect sound geotechnical engineering practice, Phoon and Kulhawy (1999b) presented guidelines for coefficients of variation (COVs) of some soil properties as a function of the test method, correlation equation, and soil type. The key conclusion in this study is that it is not possible to assign a single coefficient of variation (COV) to a design property, such as the undrained shear strength. Geotechnical reliability-based design (RBD) equations that are calibrated using this single COV assumption are too simplistic, because diverse methodologies in estimating soil properties are ignored. This diversity is actually good practice, because there is a need to accommodate diverse site conditions. Phoon and Kulhawy (1999a,b) advocated that the calibration of geotechnical RBD equations should be carried out in explicit recognition of property variability and in full compliance with how soil properties are physically evaluated in practice. The framework recommended by Phoon and Kulhawy (1999a,b) and the ensuing three-tier classification scheme of soil property variability (Phoon and Kulhawy, 2008) should be viewed as the minimum requirements in variability characterization. The third edition of ISO 2394 (General principles on reliability for structures; to be published in 2015) includes a new Annex D on "Reliability of geotechnical structures" where the importance of respecting sound geotechnical engineering practices in variability characterization and reliability calibration is strongly emphasized.

The characterization of geotechnical variability is far from being a mature area in research. An astute practitioner would readily point out that multiple tests are commonly conducted in a site investigation and it is common practice to estimate a design property from these tests, either by straightforward averaging or picking a credible worst-case value from the range of values produced by different tests. The information collected in a site investigation programme is fundamentally

当广泛的土体统计数据证明, 岩土工程变异性取决于现场条件, 与现场测试相关的测量误差以及将现场测试与设计属性相关联的相关模型的质量。第一部分是土体固有的变异性, 由于无法通过执行更多的测试来减少, 因此习惯上被归类为无酸。第二和第三部分, 即不可避免地测试过程中引入的测量误差和关于平均相关趋势的数据散布 (通常以线性回归方程的形式), 本质上通常被归类为认识论。可以通过收集更多数据或建立更好的模型来减少它们。尽管将不确定性归类为偶然性或认知性是有好处的, 但应该记住, 这种划分在某种程度上是建模者的选择 (Kiureghian and Ditlevsen, 2007)。从实践的角度来看, 将地物特征与已经嵌入到我们的岩土工程实践中的属性评估程序对齐可能更为重要。考虑到需要尊重合理的岩土工程实践, Phoon and Kulhawy (1999b) 提出了一些土体特性的变异系数 (COV) 的准则, 这些准则是测试方法, 相关方程和土体类型的函数。这项研究的关键结论是, 不可能为设计特性 (例如不排水的剪切强度) 分配单个变异系数 (COV)。使用这种单一 COV 假设进行校准的基于岩土工程的基于可靠性的设计 (RBD) 方程过于简单, 因为忽略了估算土体性质的多种方法。实际上, 这种多样性是一种好习惯, 因为有必要适应各种现场条件。Phoon and Kulhawy (1999a,b) 提倡, 对岩土工程 RBD 方程的标定应在明确认识到物性变异性的前提下进行, 并完全符合实际中对土体物性的评估方法。Phoon and Kulhawy (1999a,b) 建议的框架和随后的三层土体性质变异性分类方案 (Phoon and Kulhawy, 2008) 应被视为变异性表征的最低要求。ISO 2394 第三版 (关于结构可靠性的一般原则; 将于 2015 年发布) 包括有关 "岩土结构可靠性" 的新附件 D, 在该附录 D 中, 强烈强调了在变异性表征和可靠性校准中尊重岩土工程实践的重要性。

岩土工程变异性的表征还远远不是研究的成熟领域。精明的从业人员会很容易地指出, 在现场调查中通常会进行多次测试, 并且通常的做法是根据这些测试来评估设计属性, 方法是直接取平均值, 或者从测试产生的值的范围内选择可信的最坏情况下的值。不同的测试。在现场调查程序中收集的信息本质上

multivariate in nature and this aspect has not been considered in the earlier studies mentioned above. The purpose of this paper is to develop unbiased transformation models and to quantify their associated uncertainties for 10 common clay parameters. A companion paper (Ching and Phoon, 2014) develops a multivariate probability model coupling these clay parameters. The supporting database contains information from multiple tests that are collected in close proximity. In other words, each data point records soil information at a specific location and depth, i.e., at a specific sampling point. Note that measurement error is present, but it is not possible to isolate measurement error from transformation uncertainty in conventional site investigation programs. Hence, the transformation uncertainties presented in this study include some measurement errors, but these errors are relatively minor for cone penetration testing with pore pressure measurement (CPTU) (Phoon and Kulhawy, 1999a). Inherent soil variability is clearly not considered in this study. In principle, inherent soil variability can be incorporated by extending the multivariate probability model (which applies to a sampling “point”) to a vector random field covering the three-dimensional (3D) spatial domain of the entire site. The outcomes of this study are thus incomplete in this sense, but they can be viewed as paving the way for characterization of geotechnical variability to advance beyond univariate data and to achieve closer alignment to how soil properties are estimated in actual practice from site investigation programs

As noted by Phoon and Kulhawy (1999a), the measurement from a geotechnical test is typically not directly applicable to design. Instead, a transformation model is needed to relate the test measurement to an appropriate design parameter. Most transformation models in geotechnical engineering are obtained by empirical or semi-empirical data-fitting using regression analyses. These transformation models are widely adopted in geotechnical engineering practice as a matter of practical expediency. Useful compilations of these models (mostly pairwise correlations) are available in the literature (e.g., Kulhawy and Mayne, 1990; Mayne et al., 2001). A cursory review of these compilations would reveal a rather bewildering variety and number of models. Most models were developed for a specific geomaterial type and (or) a specific locale.

It is not judicious to apply these models indiscriminately to other sites without a proper appreciation of geomaterial behaviour and geology. This “site-specific” limitation is a distinctive and fundamental feature of geotechnical engineering practice. Geotechnical design must take cognizance of this limitation to avoid gross oversimplification of “ground truths.” As opposed to site-specific models, Ching and Phoon (2012a) demonstrated the construction of “global” models. Global models are calibrated from global databases covering many

本质上是多元的, 并且在上述早期研究中并未考虑到这方面。本文的目的是为 10 个常见黏土参数建立无偏转换模型并量化其相关的不确定性。伴随论文 (Ching and Phoon, 2014) 开发了耦合这些粘土参数的多元概率模型。支持数据库包含来自紧密收集的多个测试的信息。换句话说, 每个数据点记录特定位置和深度, 即特定采样点的土体信息。请注意, 存在测量误差, 但是在传统的站点调查程序中无法将测量误差与变换不确定性区分开。因此, 本研究中提出的变换不确定性包括一些测量误差, 但是对于使用孔隙压力测量 (CPTU) 进行的圆锥渗透测试, 这些误差相对较小 (Phoon and Kulhawy, 1999a)。这项研究显然没有考虑土体固有的变异性。原则上, 可以通过将多元概率模型 (适用于采样“点”) 扩展到覆盖整个站点的三维 (3D) 空间域的向量随机字段来合并固有的土体可变性。因此, 从这个意义上说, 这项研究的结果是不完整的, 但可以认为它们为表征岩土工程变异性铺平了道路, 使岩土变异性超越了单变量数据, 并与现场调查程序在实际实践中对土体特性的估算更加接近。

正如 Phoon and Kulhawy (1999a) 指出的那样, 岩土试验的测量结果通常不适用于设计。取而代之的是, 需要一个转换模型来将测试度量与适当的设计参数相关联。岩土工程中的大多数转换模型都是通过使用回归分析的经验或半经验数据拟合获得的。出于实际考虑, 这些转换模型已在岩土工程实践中广泛采用。这些模型的有用汇编 (主要是成对相关) 可在文献中找到 (例如 Kulhawy and Mayne, 1990; Mayne et al., 2001)。粗略地回顾一下这些汇编, 将会发现令人困惑的各种模型。大多数模型是针对特定的土工材料类型和 (或) 特定的区域设置而开发的。

在没有适当了解地球物质行为和地质的情况下, 不加选择地将这些模型应用于其他地点并不明智。这种“特定于地点”的限制是岩土工程实践的独特和基本特征。岩土设计必须意识到这一局限性, 以避免对“地面真相”的过分简化。与特定地点的模型相反, Ching and Phoon (2012a) 演示了“全局”模型的构建。全局模型是根据覆盖许多站点和岩土材

sites and geomaterial types. Ching and Phoon (2012a) observed that site-specific models are generally more precise than global models, but they can be significantly biased when applied to another site. On the contrary, global models are less precise than site-specific models, but they are less biased. Their observations are already well appreciated by engineers. The key contribution from Ching and Phoon (2012a) was to demonstrate these observations with statistical rigor using a sizeable global database.

Because most transformation models were built based on their own databases, their ranges of application are, in principle, limited to the range of characteristics contained in the databases, e.g., certain soil types, certain range of soil properties (e.g., insensitive clays), and certain geographic locations. It is important to assess their biases and the uncertainties when these models are applied globally (i.e., applying these models outside their range of calibration). In the current paper, a global clay database is compiled and presented. This database consists of data points from 251 studies, covering clay data from 30 regions or countries worldwide. Hence, the range of data covered by this “global” database is broader than that underlying the calibration of existing transformation models in the literature. Ten parameters of clays are of main interest, including three index properties (i.e., Atterberg’s limits); four parameters for effective stresses, shear strength, and sensitivity; and three parameters from piezocone tests (CPTU). This global database is the largest database compiled by the authors thus far in terms of number of data points and number of parameters of interest. Table 1 shows the databases compiled by the authors, labeled as (soil type)/(number of parameters of interest)/(number of data points). The current global database is CLAY/10/7490. The first purpose of this paper is to present this large database and verify whether the correlation behaviours in the data points are consistent with those exhibited by existing transformation models in the literature. Most of these models are sitespecific models. The biases and uncertainties in these models will be estimated using the global database. The site-specific models can be applied to a wider range of conditions when their biases are corrected and their transformation uncertainties are suitably revised.

The uncertainties of the resulting global models are inevitably large because they are required to accommodate a broader range of clays, e.g., insensitive, sensitive, and quick clays. It is possible to reduce the transformation uncertainty by considering soil index properties (such as plasticity index and sensitivity) as secondary input (explanatory) parameters. Most of the existing transformation models do not include such secondary parameters. Nonetheless, with the global database compiled in this study, it is possible to augment the existing transformation models with secondary input parameters. The resulting

料类型的全局数据库进行校准的。Ching and Phoon (2012a) 观察到, 特定于站点的模型通常比全局模型更为精确, 但将其应用于其他站点时可能会出现明显偏差。相反, 全局模型不如特定于站点的模型精确, 但它们的偏向性较小。他们的观察已经得到工程师的赞赏。Ching and Phoon (2012a) 的主要贡献是通过使用

由于大多数转化模型都是基于其自身的数据库构建的, 因此, 其应用范围原则上仅限于数据库中包含的特征范围, 例如某些土体类型, 某些土体特性范围 (例如不敏感的粘土), 和某些地理位置。在全球范围内应用这些模型时 (即在校准范围之外应用这些模型), 评估它们的偏差和不确定性很重要。在当前的论文中, 一个全球粘土数据库被编译并呈现出来。该数据库包含来自 251 个研究的数据点, 涵盖了来自全球 30 个地区或国家的粘土数据。因此, 该“全球”数据库所涵盖的数据范围比文献中现有转换模型的标定所依据的范围要广。十个主要参数是黏土, 其中包括三个指数属性 (即, 阿特伯格极限); 有效应力, 剪切强度和灵敏度的四个参数; 以及压电锥测试 (CPTU) 的三个参数。就数据点的数量和感兴趣的参数的数量而言, 该全局数据库是迄今为止作者编写的最大的数据库。表1显示了作者编译的数据库, 标记为 (土体类型) / (感兴趣的参数数量) / (数据点数量)。当前的全局数据库是 CLAY/10/7490。本文的首要目的是介绍这个大型数据库, 并验证数据点中的相关行为是否与文献中现有转换模型所显示的行为一致。这些模型大多数是特定于站点的模型。这些模型中的偏差和不确定性将使用全球数据库进行估算。当特定位置的模型的偏差得到纠正并且适当地修改了转换不确定性时, 可以将其应用于更广泛的条件。

所产生的全局模型的不确定性不可避免地很大, 因为需要它们适应更大范围的粘土, 例如不敏感, 敏感和快速的粘土。通过将土体指数属性 (例如可塑性指数和敏感性) 视为辅助输入 (解释性) 参数, 可以减少变换不确定性。现有的大多数转换模型都不包含此类辅助参数。但是, 通过本研究中编译的全局数据库, 可以使用辅助输入参数来扩展现有的转换模型。所得模型仍将是全局模型, 但不



Table 1: Databases compiled by the authors.

表 1: 作者编译的数据库。

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)	$LL, s_u, s_u^{re}, \sigma'_p, \sigma'_v$	345	37 sites	1~4	-	Sensitive to quick clays
CLAY/6/535	Ching et al. (2014)	$s_u/\sigma'_v, OCR, (q_t - s_v)/\sigma'_v, (q_t - u_2)/\sigma'_v, (u_2 - u_0)/\sigma'_v, B_q$	535	40 sites	1~6	Low to very high plasticity	Insensitive to quick clays
CLAY/7/6310	Ching and Phoon (2013)	$s_u$ under seven different test types	6310	164 studies	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	This paper	$LL, PI, LI, \sigma'_v/P_a, \sigma'_p/P_a, s_u/\sigma'_v, S_t, (q_t - \sigma'_v)/\sigma'_v, (q_t - u_2)/\sigma'_v, B_q$	7490	251 studies	1~10	Low to very high plasticity	Insensitive to quick clays

models will still be global, but with less uncertainties. This is the second purpose of this paper. In a companion paper (Ching and Phoon, 2014), a 10-dimensional multivariate probability distribution coupling these clay parameters is constructed from CLAY/10/7490 and a useful application involving updating the entire bivariate probability distribution of two design parameters from three separate measurements is presented.

确定性较小。这是本文的第二个目的。在随附的论文中 (Ching and Phoon, 2014), 从 CLAY/10/7490 构建了耦合这些黏土参数的 10 维多元概率分布, 并呈现了一个有用的从三个独立的测量值中更新两个设计参数的整体二元概率分布的应用。

## 2 Database CLAY/10/7490 数据库 CLAY/10/7490

This study compiles a clay database (CLAY/10/7490) from the literature consisting of a large number of data points. This database consists of data points from 251 studies. The number of data points associated with each study varies from 1 to 419 with an average 30 data points per study. The geographical regions cover Australia, Austria, Brazil, Canada, China, England, Finland, France, Germany, Hong Kong, India, Iraq, Italy, Japan, Korea, Malaysia, Mexico, New Zealand, Northern Ireland, Norway, Poland, Singapore, South Africa, Spain, Sweden, Taiwan, Thailand, United Kingdom, United States, and Venezuela. The clay properties cover a wide range of overconsolidation ratio (OCR) values (but mostly 1~10), a wide range of sensitivity ( $S_t$ ) values (sites with  $S_t = 1$  tens or hundreds are fairly typical), and a wide range of plasticity index (PI) values (but mostly 8~100). Figure 1 shows the plasticity chart and Robertson's CPTU soil classification chart (Robertson, 1990) of all data points in the database —most data points are classified as clays (some are sensitive or organic clays). Some data points are classified as clayey silts or silt mixtures, and a few are classified as sand mixtures or sands. The details of this database are shown in Appendix A.

这项研究从文献中汇编了一个包含大量数据点的粘土数据库 (CLAY / 10/7490)。该数据库包含来自 251 个研究的数据点。与每个研究相关的数据点数量从 1 到 419 不等, 每个研究平均 30 个数据点。地理区域包括澳大利亚, 奥地利, 巴西, 加拿大, 中国, 英国, 芬兰, 法国, 德国, 香港, 印度, 伊拉克, 意大利, 日本, 韩国, 马来西亚, 墨西哥, 新西兰, 北爱尔兰, 挪威, 波兰, 新加坡, 南非, 西班牙, 瑞典, 台湾, 泰国, 英国, 美国和委内瑞拉。黏土的特性涵盖了大范围的超固结比 (OCR) 值 (但大多为 1~10), 大范围的敏感度 ( $S_t$ ) 值 ( $S_t = 1 \sim$  数十或数百的值是相当典型的) 和大范围的塑性指数 (PI) 值 (但多数为 8~100)。图1显示了数据库中所有数据点的可塑性图和 Robertson 的 CPTU 土体分类图 (Robertson, 1990)——大多数数据点被归类为黏土 (一些是敏感黏土或有机黏土)。一些数据点被分类为黏土粉砂或粉砂混合物, 而一些数据点被分类为砂混合物或砂。

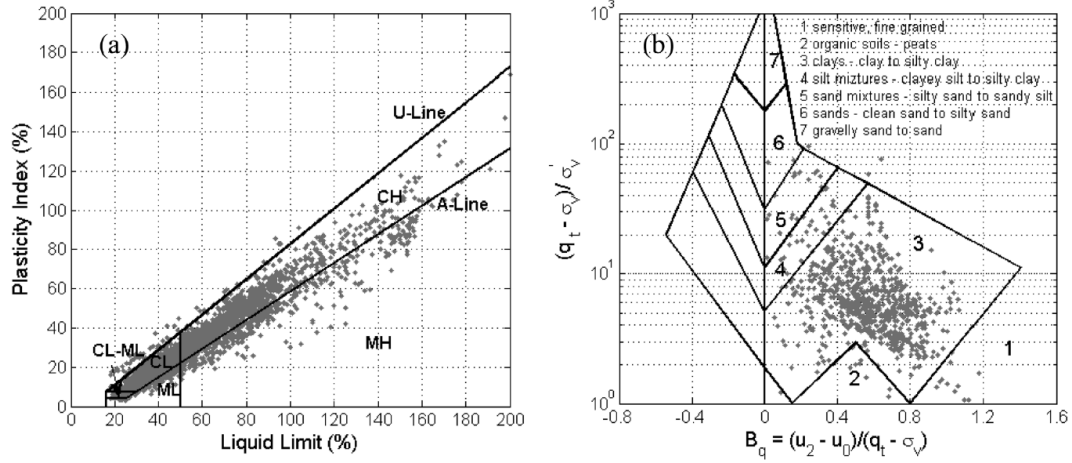


Figure 1: (a) Plasticity chart; (b) Robertson (1990) CPTU soil classification chart.  $B_q$ , pore pressure ratio; CH, high-plasticity clay; CL, lowplasticity clay; MH, high-plasticity silt; ML, low-plasticity silt;  $q_t$ , corrected cone tip resistance;  $u_0$ , hydrostatic pore pressure;  $u_2$ , pore pressure behind the cone;  $\sigma_v$ , total effective stress;  $\sigma'_v$ , vertical effective stress.

图 1: (a) 可塑性图; (b) Robertson (1990) 的 CPTU 土壤分类图。  $B_q$ , 孔隙压力比; CH, 高塑性粘土; CL, 低塑性粘土; MH, 高塑性淤泥; ML, 低塑性淤泥;  $q_t$ , 校正的锥头电阻;  $u_0$ , 静水孔隙压力;  $u_2$ , 锥体后面的孔隙压力;  $\sigma_v$ , 总有效应力;  $\sigma'_v$ , 垂直有效应力。

Ten dimensionless parameters of clays are of primary interest. They are categorized into three groups:

**1. Index properties**, including liquid limit (LL), plasticity index (PI), and liquidity index (LI).

**2. Stresses and strengths**, including normalized vertical effective stress ( $\sigma'_v/P_a$ , where  $P_a$  is one atmosphere pressure ( $=101.3\text{kN/m}^2$ )), normalized preconsolidation stress ( $\sigma'_p/P_a$ ), normalized undrained shear strength ( $s_u/\sigma'_v$ ), and sensitivity ( $S_t = s_u/s_u^{re}$ , where  $s_u^{re}$  is the remoulded undrained shear strength). The  $s_u$  values in the literature were obtained based on various types of tests, including isotropically consolidated undrained compression (CIUC),  $K_0$ -consolidated undrained compression ( $CK_0UC$ ),  $K_0$ -consolidated undrained extension ( $CK_0UE$ ), direct simple shear (DSS), unconsolidated undrained compression (UU), unconfined compression (UC), and field vane (FV). These values cannot be compared directly because  $s_u$  depends on stress state, strain rate, and sampling disturbance. By following the recommendations made by Bjerrum (1972), Kulhawy and Mayne (1990), and Mesri and Huvaj (2007), these  $s_u$  values are all converted to the “mobilized”  $s_u$  values, denoted by  $s_u(\text{mob})$ , which is defined as the in situ undrained shear strength mobilized in embankment and slope failures (Mesri and Huvaj, 2007). The transformation models used to convert undrained shear strengths derived from different test types to the reference  $s_u(\text{mob})$  are given in Table 2.

**3. Parameters from the piezocone test (CPTU)**, including

该数据库的详细信息显示在附录A中。

十个无量纲的黏土参数是最重要的。它们分为三类：

**1. 指数性质**，包括液体极限 (LL)，可塑性指数 (PI) 和流动性指数 (LI)。

**2. 应力和强度**，包括归一化垂直有效应力 ( $\sigma'_v/P_a$ ，其中  $P_a$  是一个大气压，归一化预固结应力 ( $\sigma'_p/P_a$ )，归一化不排水剪切强度 ( $s_u/\sigma'_v$ ) 和灵敏度 ( $S_t = s_u/s_u^{re}$ ，其中  $s_u^{re}$  是重新模制的不排水剪切强度)。文献中的  $s_u$  值是根据各种类型的测试获得的，包括各向同性固结不排水压缩 (CIUC)， $K_0$  固结不排水压缩 ( $CK_0UC$ )， $K_0$  固结不排水延伸 ( $CK_0UE$ )，直接简单剪切 (DSS)，未固结不排水压缩 (UU)，无限制压缩 (UC) 和现场叶片 (FV)。这些值不能直接比较，因为  $s_u$  取决于应力状态，应变率和采样扰动。通过遵循 Bjerrum (1972)，Kulhawy and Mayne (1990) 以及 Mesri and Huvaj (2007) 的建议，这些  $s_u$  值都被转换为“扰动” $s_u$  值，该值由  $s_u(\text{mob})$  定义，因为在路堤和边坡破坏中扰动了原地不排水的抗剪强度 (Mesri and Huvaj, 2007)。表2给出了用于将源自不同测试类型的不排水剪切强度转换为参考  $s_u(\text{mob})$  的转换模型。

pore pressure ratio  $B_q = (u_2 - u_0)/(q_t - \sigma_v)$ , where  $u_2$  is the pore pressure behind the cone,  $u_0$  is the hydrostatic pore pressure,  $q_t$  is the corrected cone tip resistance, and  $\sigma_v$  is the total effective stress; normalized cone tip resistance  $(q_t - \sigma_v)/\sigma'_v$ ; and normalized effective cone tip resistance  $q_t - u_2/\sigma'_v$ .

The CPTU data are nearly continuous with depth. However, only a few data points in a CPTU profile are adopted into the database at the depths where other clay parameters (such as  $s_u$  and PI) are also known. As a result, the vertical interval of the adopted CPTU data points at the same site is about 1 to 3 m. Note that the point data at the appropriate depths are adopted. A possible refinement involving averaging along the length of the undisturbed sample was not considered.

**3. 压电锥测试 (CPTU) 的参数**, 包括孔隙压力比  $B_q = (u_2 - u_0)/(q_t - \sigma_v)$ , 其中  $u_2$  是圆锥体后面的孔隙压力,  $u_0$  是静水孔隙压力,  $q_t$  是校正的锥头阻力,  $\sigma_v$  是总有效应力; 归一化锥头电阻  $(q_t - \sigma_v)/\sigma'_v$ ; 以及归一化的有效锥端电阻  $q_t - u_2/\sigma'_v$ 。

CPTU 数据在深度上几乎是连续的。但是, 在已知其他黏土参数 (例如  $s_u$  和 PI) 的深度处, CPTU 剖面中只有几个数据点被采用到数据库中。结果, 在同一站点上采用的 CPTU 数据点的垂直间隔约为 1 至 3 m。注意, 采用了适当深度的点数据。没有考虑可能的改进, 包括沿未扰动样本的长度取平均值。

Table 2: Transformation models for  $s_u(\text{mob})$ .表 2:  $s_u(\text{mob})$  的转换模型

Available $s_u$ information	Transformation model	Reference
FV	$s_u(\text{mob}) \approx s_u(\text{field}) \approx [s_u(\text{FV})]\mu$	Bjerrum (1972)
UC	$s_u(\text{mob}) \approx s_u(\text{UC})$	Mesri and Huvaj (2007)
UU	$s_u(\text{mob})/\sigma'_v \approx s_u(\text{UC})/\sigma'_v \approx -0.073 + 1.018s_u(\text{UU})/\sigma'_v$	Chen and Kulhawy (1993); Mesri and Huvaj (2007)
CIUC	$s_u(\text{mob})/\sigma'_v \approx s_u(\text{UC})/\sigma'_v \approx -0.278 + 1.172s_u(\text{CIUC})/\sigma'_v$	Chen and Kulhawy (1993); Mesri and Huvaj (2007)
CK <sub>0</sub> UC, DSS, CK <sub>0</sub> UE	$s_u(\text{mob}) \approx \{[s_u(\text{CK}_0\text{UC}) + s_u(\text{DSS}) + s_u(\text{CK}_0\text{UE})]/3\}\mu_t$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
CK <sub>0</sub> UC, CK <sub>0</sub> UE	$s_u(\text{mob}) \approx \{[s_u(\text{CK}_0\text{UC}) + s_u(\text{CK}_0\text{UE})]/2\}\mu_t^*$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
DSS	$s_u(\text{mob}) \approx [s_u(\text{DSS})]u_t^*$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
CK <sub>0</sub> UC	$s_u(\text{mob}) \approx [s_u(\text{DSS})]u_t \approx [s_u(\text{CK}_0\text{UC})][0.67\mu_t]$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
CK <sub>0</sub> UE	$s_u(\text{mob}) \approx [s_u(\text{DSS})]u_t \approx [s_u(\text{CK}_0\text{UE})][1.53^\dagger(\mu_t)]$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)

**Note:** FV, field vane; UC, unconfined compression; UU, unconsolidated undrained compression; CIUC, isotropically consolidated undrained compression; CK<sub>0</sub>UC, K<sub>0</sub>-consolidated undrained compression; DSS, direct simple shear; CK<sub>0</sub>UEE, K<sub>0</sub>-consolidated undrained extension;  $\mu$ , PI-dependent correction factor for  $s_u(\text{FV})$  proposed in Bjerrum (1972);  $\mu_t$ , PI-dependent strain rate correction factor proposed in Terzaghi et al. (1996).

\*These equations are based on the following two facts: (i)  $s_u(\text{mob}) \approx \{[s_u(\text{CK}_0\text{UC}) + s_u(\text{DSS}) + s_u(\text{CK}_0\text{UE})]/3\}\mu_t$  and (ii)  $s_u(\text{DSS})$  is roughly the average of  $s_u(\text{CK}_0\text{UC})$  and  $s_u(\text{CK}_0\text{UE})$  (Kulhawy and Mayne, 1990).

†This constant of 1.53 is based on the following two facts: (i)  $s_u(\text{DSS}) \approx 0.67s_u(\text{CK}_0\text{UC})$  (Kulhawy and Mayne, 1990) and (ii)  $s_u(\text{DSS})$  is roughly the average of  $s_u(\text{CK}_0\text{UC})$  and  $s_u(\text{CK}_0\text{UE})$ .

注意: FV, 现场试验; UC, 无限制压缩; UU, 不固结不排水压缩; CIUC, 各向同性固结不排水压缩; CK<sub>0</sub>UC, K<sub>0</sub> 固结不排水压缩; DSS, 直接剪切; CK<sub>0</sub>UE, K<sub>0</sub> 固结不排水拉伸;  $\mu$ , Bjerrum (1972) 提出的  $s_u(\text{FV})$  的 PI 依赖校正因子;  $\mu_t$ , Terzaghi et al. (1996) 提出的依赖 PI 的应变率校正因子。

\* 这些方程式基于以下两个事实: (i)  $s_u(\text{mob}) \approx \{[s_u(\text{CK}_0\text{UC}) + s_u(\text{DSS}) + s_u(\text{CK}_0\text{UE})]/3\}\mu_t$ , (ii)  $s_u(\text{DSS})$  大致为  $s_u(\text{CK}_0\text{UC})$  和  $s_u(\text{CK}_0\text{UE})$  的平均值 (Kulhawy and Mayne, 1990)。

†1.53 的常数基于以下两个事实: (i)  $s_u(\text{DSS}) \approx 0.67s_u(\text{CK}_0\text{UC})$  (Kulhawy and Mayne, 1990), (ii)  $s_u(\text{DSS})$  大约是  $s_u(\text{CK}_0\text{UC})$  和  $s_u(\text{CK}_0\text{UE})$  的平均值。

Some other dimensionless parameters of interest, such as  $s_u/\sigma'_p$ , OCR, and  $s_u^r/P_a$ , can be derived from the above 10 parameters. The basic statistics of all these parameters (10 basic parameters together with  $s_u/\sigma'_p$ , OCR, and  $s_u^r/P_a$ ) are listed in Table 3. The numbers of available data points ( $n$ ) are shown in the second column. The statistics are the mean value, coefficient of variation (COV), minimum value (min), and maximum value (max). Their percentiles are listed

可以从上述 10 个参数中得出其他一些无量纲的感兴趣参数, 例如  $s_u/\sigma'_p$ , OCR 和  $s_u^r/P_a$ 。表3列出了所有这些参数的基本统计信息 (连同  $s_u/\sigma'_p$ , OCR 和  $s_u^r/P_a$  一起的 10 个基本参数)。第二列显示了可用数据点的数量 ( $n$ )。统计信息是平均值, 变异系数 (COV), 最小值 (min) 和最大值 (max)。表4中列出

in Table 4, where the median values (50% percentiles) are shaded. It is worth mentioning that the statistical uncertainty is higher for the lower and higher percentiles.

了它们的百分位数，其中中值（50%百分数）用阴影表示。值得一提的是，上下百分位数的统计不确定性较高。

Table 3: Statistics of the data points in the database.

表 3: 数据库中数据点的统计信息。

Variable	$n$	Mean	COV	Min	Max
LL	3822	67.7	0.80	18.1	515
PI	4265	39.7	1.08	1.9	363
LI	3661	1.01	0.78	-0.75	6.45
$\sigma'_y/P_a$	3370	1.8	1.47	4.13E-3	38.74
$\sigma'_p/P_a$	2028	4.37	2.31	0.094	193.3
$s_u/\sigma'_v$	3532	0.51	1.25	3.68E-3	7.78
$S_t$	1589	35.0	2.88	1.0	1467
$B_q$	1016	0.58	0.35	0.01	1.17
$(q_t - \sigma_v)/\sigma'_v$	862	8.9	1.17	0.48	95.98
$(q_t - u_2)/\sigma'_v$	668	5.34	1.37	0.61	108.2
$s_u/\sigma'_p$	1467	0.23	0.55	3.68E-3	1.34
OCR	3531	3.85	1.56	1.0	60.23
$s_u^{re}/P_a$	1143	0.075	2.86	9.67E-5	2.47

Table 4: Statistics of the data points in the database.

表 4: 数据库中数据点的统计信息。

Variable	2.5%	5%	25%	50%	75%	95%	97.5%
LL	23.6	26.2	39.0	54.3	76	149.1	200.0
PI	5.8	8.0	18.5	29.3	46	91.4	135.0
LI	-8.6E-2	4.7E-3	0.54	0.87	1.32	2.51	3.0
$\sigma'_y/P_a$	0.11	0.14	0.43	0.94	2.03	6.27	8.37
$\sigma'_p/P_a$	0.26	0.33	0.8	1.71	3.69	19.57	29.19
$s_u/\sigma'_v$	0.08	0.11	0.21	0.31	0.56	1.46	2.25
$S_t$	1.7	2.3	5.0	8.0	23.0	140.8	217.6
$B_q$	0.15	0.23	0.45	0.57	0.72	0.91	0.99
$(q_t - \sigma_v)/\sigma'_v$	1.92	2.43	4.15	5.79	8.77	27.57	44.07
$(q_t - u_2)/\sigma'_v$	1.28	1.51	2.42	3.63	5.67	14.97	18.55
$s_u/\sigma'_p$	6.30E-2	8.38E-2	0.15	0.21	0.27	0.44	0.56
OCR	1.0	1.0	1.04	1.73	3.57	15.79	24.00
$s_u^{re}/P_a$	5.14E-4	8.05E-4	6.48E-3	0.021	0.062	0.26	0.54

### 3 Calibration of existing transformation models 校准现有的转换模型

In the database, there are data points where two or more clay parameters are simultaneously known. For instance, a disturbed clay sample is extracted to determine PI, and an undisturbed clay sample is extracted at a nearby borehole at the same depth to determine  $s_u$ . In this case, PI and  $s_u$  are simultaneously known. These data points can be compared with transformation models proposed in literature as a rough check for consistency. Twentyfour transformation models shown in Table 5 are considered. Most of these models were developed based on certain clay databases, but these databases may not be global in the sense that the data are limited to certain clay types or certain geographic locations. In other words, they are typically site-specific models. It is recommended that the basic statistics of the database supporting the development of transformation models should be explicitly reported in the form of Table 3 and (or) Table 4. The characteristics of the databases underlying numerous existing transformation models are not known and this complicates comparisons with other databases such as the one presented in this study. These characteristics are of interest, because engineers can make a more informed decision on the applicability of a particular transformation model to his or her design scenario at hand.

In the section below, the global database is compared with existing transformation models to assess the quality of the compiled for this study. The global database is considered to be satisfactory if there

在数据库中,存在同时知道两个或多个黏土参数的数据点。例如,提取扰动的黏土样品以确定 PI,并在附近井眼的相同深度提取未扰动的黏土样品以确定  $s_u$ 。在这种情况下,PI 和  $s_u$  同时为已知。这些数据点可以与文献中提出的转换模型进行比较,作为对一致性的粗略检查。考虑了表5中所示的二十四个转换模型。这些模型中的大多数都是基于某些黏土数据库开发的,但是从数据仅限于某些黏土类型或某些地理位置的意义上讲,这些数据库可能不是全球性的。换句话说,它们通常是特定于站点的模型。建议以表3和(或)表4的形式明确报告支持转换模型开发的数据库的基本统计信息。尚不清楚许多现有转换模型所基于的数据库的特征,这会使比较变得复杂与其他数据库,例如本研究中介绍的数据库。这些特性很有趣,因为工程师可以根据特定转换模型对其手头设计方案的适用性做出更明智的决定。

在下面的部分中,我们将全球数据库与现有的转换模型进行比较,以评估本研究的编译质量。如果与文献中发布的转换模型达成广



Table 5: Transformation models for  $s_u(\text{mob})$ .表 5:  $s_u(\text{mob})$  的转换模型

Type	Relationship	Literature	$n$	Transformation model	Remarks	Comprasion Calibration		
						Figure	Fit to trend?	Bias COV of $\varepsilon = \delta$ factor, b (value in literature)
A	$\text{LI} - s_u^{\text{re}}/P_a$	Wroth and Wood (1978)	899	$s_u^{\text{re}}/P_a \approx 1.7 \exp(-4.6\text{LI})$	Based on modified Cam Clay model	Fig.2	No	—
		Locat and Demers (1988)	899	$s_u^{\text{re}}/P_a \approx 0.0144\text{LI}^{-2.44}$	—	Fig.2	YES	1.92 1.25(n/a)
	$\text{LI} - S_t$	Bjerrum (1954)	1279	$S_t \approx 10^{0.8\text{LI}}$	Norwegian marine clays	Fig.3	YES	2.06 1.09(n/a)
		Ching and Phoon (2012b)	1279	$S_t \approx 20.726\text{LI}^{1.910}$	Structured clays with $S_t = 2 \sim 1000$ and $\text{OCR} = 1 \sim 4$	Fig.3	YES	0.88 1.28(1.19)
B	$\text{LI} - \sigma'_v/P_a - S_t$	Mitchel (1993)	694	—	Graphical curves	Fig.4	NO	—
	$\text{LI} - \sigma'_p/P_a - S_t$	NAVFAC (1982)	492	—	Graphical curves	Fig.5	NO	—
		Stas and Kulhawy (1984)	249	$\sigma'_p/P_a \approx 10^{1.11-1.62\text{LI}}$ (for $S_t < 10$ only)	—	Fig.6	YES	2.94 1.90(0.34)
		Ching and Phoon (2012b)	489	$\sigma'_p/P_a \approx 0.235\text{LI}^{-1.319} S_t^{0.536}$	Structured clays with $S_t = 2 \sim 1000$ and $\text{OCR} = 1 \sim 4$	Fig.7	YES	1.32 0.78(0.73)
C	$\text{LI} - s_u/\sigma'_p$	Bjerrum and Simons (1960)	1072	—	Graphical curves; Norwegian NC clays	Fig.8	NO	—
	$\text{PI} - s_u/\sigma'_p$	Mesri (1975, 1989)	1155	$s_u(\text{mob})/\sigma'_p \approx 0.22$	—	Fig.9	YES	1.04 0.55(n/a)
	$\text{OCR} - s_u/\sigma'_p$	Jamiolkowski et al. (1985)	1402	$s_u(\text{mob})/\sigma'_p \approx 0.23(\text{OCR})^{0.8}$	—	Fig.10	YES	1.11 0.53(n/a)
	$\text{OCR} - s_u/\sigma'_p - S_t$	Ching and Phoon (2012b)	395	$s_u(\text{mob})/\sigma'_p \approx 0.229(\text{OCR})^{0.823} S_t^{0.121}$	Structured clays with $S_t = 2 \sim 1000$ and $\text{OCR} = 1 \sim 4$	Fig.11	YES	0.84 0.34(0.34)
D	$\text{CPTU} - s_u/\sigma'_p$	Ching and Phoon (2012a)	423	$[(q_t - \sigma_v)/\sigma'_v] / [s_u(\text{mob})/\sigma'_v] \approx 29.1 \exp(-0.513B_q)$	—	Fig.12	YES	0.96 0.49(0.31)
			428	$[(q_t - u_2)/\sigma'_v] / [s_u(\text{mob})/\sigma'_v] \approx 34.6 \exp(-2.049B_1)$	—	Fig.12	YES	1.11 0.57(0.34)
			423	$[(u_2 - u_0)/\sigma'_v] / [s_u(\text{mob})/\sigma'_v] \approx 21.5B_q$	—	Fig.12	YES	0.94 0.49(0.32)
	$\text{CPTU} - \text{OCR}$	Chen and Mayne (1996)	690	$\text{OCR} \approx 0.259 [(q_t - \sigma'_v)]^{1.107}$	—	Fig.13	YES	1.01 0.42(n/a)
			542	$\text{OCR} \approx 0.545 [(q_t - u_2)]^{0.969}$	—	Fig.13	YES	1.06 0.57(n/a)
			779	$\text{OCR} \approx 1.026B_q^{-1.077}$	—	Fig.13	YES	1.28 0.86(n/a)
	$\text{CPTU} - \sigma'_p/P_a$	Kulhawy and Mayne (1990)	690	$\text{OCR} \approx 0.32(q_t - \sigma_v)/\sigma'_v$	—	Fig.13	YES	1.00 0.39( $\approx 0.25$ )
		Chen and Mayne (1996)	690	$\sigma'_p/P_a \approx 0.227 [(q_t - \sigma_v)/P_a]^{1.200}$	—	Fig.14	YES	0.99 0.42(n/a)
			542	$\sigma'_p/P_a \approx 0.490 [(q_t - u_2)/P_a]^{1.053}$	—	Fig.14	YES	1.08 0.61(n/a)
			690	$\sigma'_p/P_a \approx 1.274 + 0.761(u_2 - u_0)/P_a$	—	Fig.14	NO	0.49 0.59(n/a)
		Kulhawy and Mayne (1990)	690	$\sigma'_p/P_a \approx 0.33(q_t - \sigma_v)/P_a$	—	Fig.14	YES	0.97 0.39( $\approx 0.2$ )
			690	$\sigma'_p/P_a \approx 0.54(u_2 - u_0)/P_a$	—	Fig.14	YES	1.18 0.75( $\approx 0.25$ )

is broad agreement with the transformation models published in the literature. Some differences are to be expected. In the absence of detailed information on the databases supporting published transformation models, it is assumed in this study that the differences arose because our global database covers a broader range of clays. As a result, correcting published transformation models will broaden the range of their applicability. The correction is undertaken by calibrating the bias factors and uncertainties for these models against the global database compiled in this study.

These 24 transformation models are labeled using the template: (primary input parameter) - (target parameter) - (secondary input parameter). They are categorized into four types (see Table 5):

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

**2. Type B - Models for effective stress**, including one LI - ( $\sigma'_v/P_a$ ) -  $S_t$  model and three LI - ( $\sigma'_p/P_a$ ) -  $S_t$  models.

**3. Type C - Models for shear strength**, including one LI - ( $s_u/\sigma'_p$ ) model, one PI - ( $s_u/\sigma'_p$ ) model, one OCR - ( $s_u/\sigma'_v$ ) model, and one OCR - ( $s_u/\sigma'_v$ ) -  $S_t$  model.

In the LI - ( $s_u/\sigma'_p$ ) model proposed by Bjerrum and Simons (1960) for normally consolidated (NC) clays, the  $s_u/\sigma'_p$  values are obtained from CIUC tests. For NC clays,  $s_u(\text{CIUC})/\sigma'_p$  is estimated to be 0.37, whereas  $s_u(\text{mob})/\sigma'_p$  is about 0.22 (Mesri, 1975). As a result, the  $s_u/\sigma'_p$  value in the original LI - ( $s_u/\sigma'_p$ ) model by Bjerrum and Simons (1960) is multiplied by  $0.22/0.37=0.59$ .

**4. Type D - Models relevant to CPTU**, including three CPTU - ( $s_u/\sigma'_v$ ) models, four CPTU - OCR models, and five CPTU - ( $\sigma'_p/P_a$ ) models.

Note that for the CPTU - ( $s_u/\sigma'_v$ ) models by Ching and Phoon (2012a), the target parameters are actually the cone factors (namely  $(q_t - \sigma_v)/s_u$ ,  $(q_t - u_2)/s_u$ , and  $(u_2 - u_0)/s_u$ ). In these models, the  $s_u$  values are obtained from CIUC tests. Therefore, the cone factors in these models are divided by the same factor of 0.59.

Most of these 24 transformation models are derived empirically using regression analyses. The only exception is the LI - ( $s_u^{\text{re}}/P_a$ ) model by Wroth and Wood (1978), which is derived theoretically from the modified Cam Clay model. Most models are not constructed for a specific type of clay. The exceptions are: (i) the LI - ( $\sigma'_p/P_a$ ) -  $S_t$  and OCR - ( $s_u/\sigma'_v$ ) -  $S_t$  models by Ching and Phoon (2012b), constructed primarily from sensitive (structured) clay data (database CLAY/5/535 in Table 1); (ii) the LI -  $S_t$  model by Bjerrum (1954), constructed from

泛共识, 则认为全球数据库令人满意。可能会有一些差异。在缺乏支持已发布的转换模型的数据库的详细信息的情况下, 本研究假设出现了差异, 因为我们的全球数据库涵盖了更广泛的粘土。结果, 更正已发布的转换模型将扩大其适用范围。通过根据本研究中编译的全球数据库对这些模型的偏倚因素和不确定性进行校准, 可以进行校正。

这 24 个转换模型使用以下模板标记: (主要输入参数) - (目标参数) - (辅助输入参数)。它们分为四种类型 (请参见表 ref table: 5):

**1. 类 A - 针对灵敏度  $S_t$  的模型**, 包括 2 个 LI - ( $s_u^{\text{re}}/P_a$ ) 模型和 2 个 LI -  $S_t$  模型

**2. 类 B - 针对有效应力的模型**, 包括 1 个 LI - ( $\sigma'_v/P_a$ ) -  $S_t$  模型和 3 个 LI - ( $\sigma'_p/P_a$ ) -  $S_t$  模型。

**3. 类 C - 针对抗剪强度的模型**, 包括 1 个 LI - ( $s_u/\sigma'_p$ ) 模型, 1 个 PI - ( $s_u/\sigma'_p$ ) 模型, 1 个 OCR - ( $s_u/\sigma'_v$ ) 模型, 和 1 个 OCR - ( $s_u/\sigma'_v$ ) -  $S_t$  模型。

在 Bjerrum and Simons (1960) 针对正常固结 (NC) 粘土提出的 LI - ( $s_u/\sigma'_p$ ) 模型中,  $s_u/\sigma'_p$  值是从 CIUC 试验获得的。对于 NC 粘土,  $s_u(\text{CIUC})/\sigma'_p$  估计为 0.37, 而  $s_u(\text{mob})/\sigma'_p$  约为 0.22 (Mesri, 1975)。结果, Bjerrum and Simons (1960) 在原始 LI - ( $s_u/\sigma'_p$ ) 模型中的  $s_u/\sigma'_p$  值乘以  $0.22/0.37=0.59$ 。

**4. 类 D - 与 CPTU 相关的模型**, 包括 3 个 CPTU - ( $s_u/\sigma'_v$ ) 模型, 4 个 CPTU-OCR 模型, 和 5 个 CPTU - ( $\sigma'_p/P_a$ ) 模型。

请注意, 对于 Ching and Phoon (2012a) 的 CPTU - ( $s_u/\sigma'_v$ ) 模型, 目标参数实际上是圆锥因子 (即  $(q_t - \sigma_v)/s_u$ ,  $(q_t - u_2)/s_u$  和  $(u_2 - u_0)/s_u$ )。在这些模型中,  $s_u$  值是从 CIUC 测试获得的。因此, 这些模型中的圆锥系数除以相同的系数 0.59。

这 24 个转换模型中的大多数都是根据经验使用回归分析得出的。唯一的例外是 Wroth and Wood (1978) 的 LI - ( $s_u^{\text{re}}/P_a$ ) 模型, 该模型理论上是从改进的 Cam Clay 模型推导出来的。大多数模型不是针对特定类型的粘土构造的。例外是: (i) Ching and Phoon (2012b) 的 LI - ( $\sigma'_p/P_a$ ) -  $S_t$  和 OCR - ( $s_u/\sigma'_v$ ) -  $S_t$  模型, 主要是根据敏感的 (结构化) 黏土数据构

Norwegian marine clay data only; and (iii) the  $LI - (s_u/\sigma'_p)$  model by Bjerrum and Simons (1960), constructed from Norwegian NC clay data. Some transformation models are presented as graphical curves only: (i) the  $LI - (\sigma'_v/P_a) - S_t$  model by Mitchel (1993), (ii) the  $LI - (\sigma'_p/P_a) - S_t$  by NAVFAC (1982), and (iii) the  $LI - (s_u/\sigma'_p)$  model by Bjerrum and Simons (1960). No equations were reported by the original authors.

The comparison results between the transformation models and the database are shown in Figs. 2-14. For the models with a secondary input parameter  $S_t$ , data points in our database are divided into four groups according to their  $S_t$  values, and four subplots are presented to compare with the transformation models. The four groups are obtained based on  $S_t < 4$ ,  $4 < S_t < 10$ ,  $10 < S_t < 20$ , and  $S_t > 20$ . Figures 2-14 show that the global data follow similar trends to most transformation models reported in the literature. The exceptions are the following six models:

1. The  $LI - (s_u^{re}/P_a)$  model proposed by Wroth and Wood (1978). This model was developed based on the modified Cam Clay model. It provides a reasonable average fit to the data for  $LI < 1$  as shown in Fig. 2. However, it deviates significantly from the data points in our global database for  $LI > 1.5$ .

2. The  $LI - (\sigma'_v/P_a) - S_t$  model proposed by Mitchel (1993). Despite the wide scatter as shown in Fig. 4, there is general agreement between this model and the global data for data points with  $4 < S_t < 20$ . However, for data with small  $S_t$  values ( $S_t < 4$ ) or with large  $S_t$  values ( $S_t > 20$ ), the agreement is poor. It is possible that this model was developed with most data points falling between  $4 < S_t < 20$ . In other words, the empirical support for small and large  $S_t$  values may be weak.

3. The  $LI - (\sigma'_p/P_a) - S_t$  model proposed by NAVFAC (1982). The observations here are similar to those for the Mitchell's model: there is a reasonably good agreement between the model and the global data for data points with  $4 < S_t < 20$  (see Fig. 5). The agreement is poor outside this range of  $S_t$ . One may venture to guess that the empirical support for small and large  $S_t$  values is also weak for this model.

4. The  $LI - (\sigma'_p/P_a) - S_t$  model proposed by Ching and Phoon (2012b). The agreement between this model and the global data are reasonable for data points with large  $S_t$  values ( $S_t > 20$ ) as shown in Fig. 7. However, this model does not fit data with small  $S_t$  values ( $S_t < 4$ ). This is because the database CLAY/5/345 used to develop this  $LI - (\sigma'_p/P_a) - S_t$  model contains only structured clays.

5.  $LI - (s_u/\sigma'_p)$  model proposed by Bjerrum and Simons (1960). In

造的 (表1中的数据库 CLAY/5/535); (ii) Bjerrum (1954) 的  $LI - S_t$  模型, 仅根据挪威海洋黏土数据建立; (iii) Bjerrum and Simons (1960) 的  $LI - (s_u/\sigma'_p)$  模型是根据挪威 NC 黏土数据构建的。一些转换模型仅以图形曲线形式显示: (i) Mitchel (1993) 的  $LI - (\sigma'_v/P_a) - S_t$  模型, (ii) NAVFAC (1982) 的  $LI - (\sigma'_p/P_a) - S_t$  模型, 以及 (iii) Bjerrum and Simons (1960) 的  $LI - (s_u/\sigma'_p)$  模型。原始作者未提出任何方程式。

转换模型与数据库之间的比较结果如图2-14所示。对于具有辅助输入参数  $S_t$  的模型, 我们数据库中的数据点根据其  $S_t$  值分为四组, 并提出了四个子图与转换模型进行比较。根据  $S_t < 4$ ,  $4 < S_t < 10$ ,  $10 < S_t < 20$  和  $S_t > 20$  获得这四个组。图2-14显示, 全球数据遵循与文献中报道的大多数转换模型相似的趋势。以下六个模型除外:

1. Wroth and Wood (1978) 提出的  $LI - (s_u^{re}/P_a)$  模型。该模型是基于修改后的 Cam Clay 模型开发的。如图2所示, 它为  $LI < 1$  的数据提供了合理的平均拟合。但是, 对于我们的  $LI > 1.5$ , 它与我们的全局数据库中的数据点有很大的出入。

2. Mitchel (1993) 提出的  $LI - (\sigma'_v/P_a) - S_t$  模型。尽管如图4所示分散范围很广, 但是对于  $4 < S_t < 20$  的数据点, 该模型与全局数据之间存在普遍共识。但是, 对于  $S_t$  值小的 ( $S_t < 4$ ) 或  $S_t$  值大的数据 ( $S_t > 20$ ), 匹配性很差。该模型可能是在大多数数据点落在  $4 < S_t < 20$  之间的情况下开发的。换句话说, 对小和大的  $S_t$  值的经验支持可能很弱。

3. NAVFAC (1982) 提出的  $LI - (\sigma'_p/P_a) - S_t$  模型。这里的观察结果与 Mitchell 模型的观察结果相似: 对于  $4 < S_t < 20$  的数据点, 模型与全局数据之间存在相当好的一致性 (见图5)。在  $S_t$  的这一范围之外, 该匹配的效果很差。有人可能会猜测, 对于该模型, 对于小和大的  $S_t$  值的经验支持也很弱。

4. Ching and Phoon (2012b) 提出的  $LI - (\sigma'_p/P_a) - S_t$  模型。如图7所示, 此模型与全局数据之间的一致性对于具有较大  $S_t$  值 ( $S_t > 20$ ) 的数据点是合理的。但是, 此模型不适用于具有较小  $S_t$  值 ( $S_t < 4$ ) 的数据。这是因为用于开发此  $LI - (\sigma'_p/P_a) - S_t$  模型的数

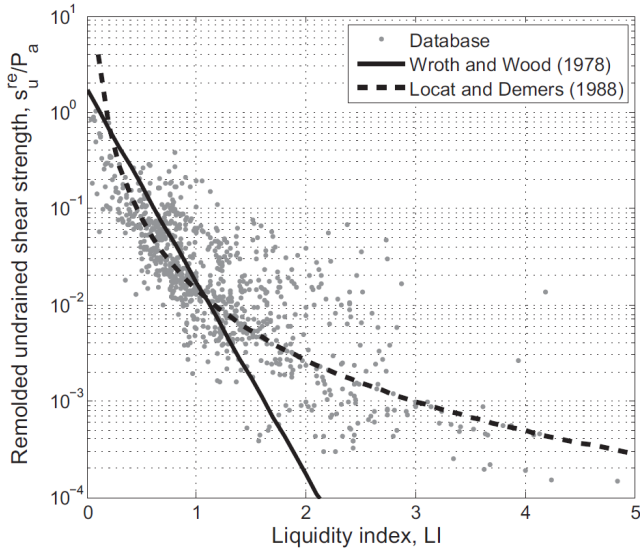


Figure 2: LI – ( $s_u^{\text{re}}/P_a$ ) models proposed by Wroth and Wood (1978) and Locat and Demers (1988).

图 2: Wroth and Wood (1978) 和 Locat and Demers (1988) 提出的 LI – ( $s_u^{\text{re}}/P_a$ ) 模型。

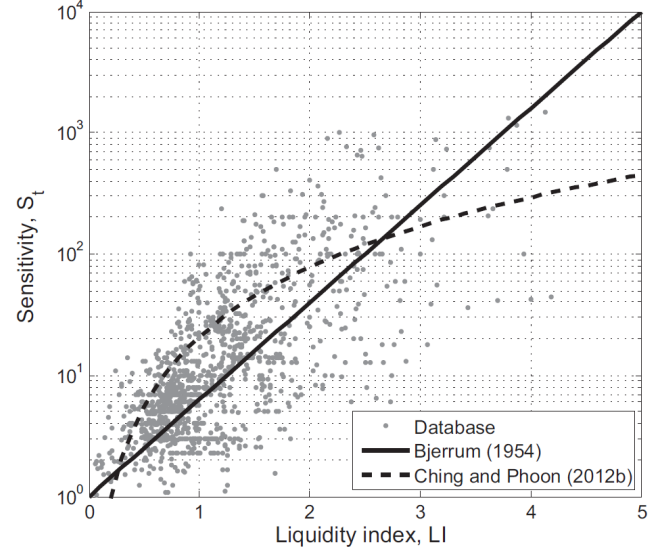


Figure 3: LI –  $S_t$  models proposed by Bjerrum (1954) and Ching and Phoon (2012b).

图 3: Bjerrum (1954) 和 Ching and Phoon (2012b) 提出的 LI –  $S_t$  模型。

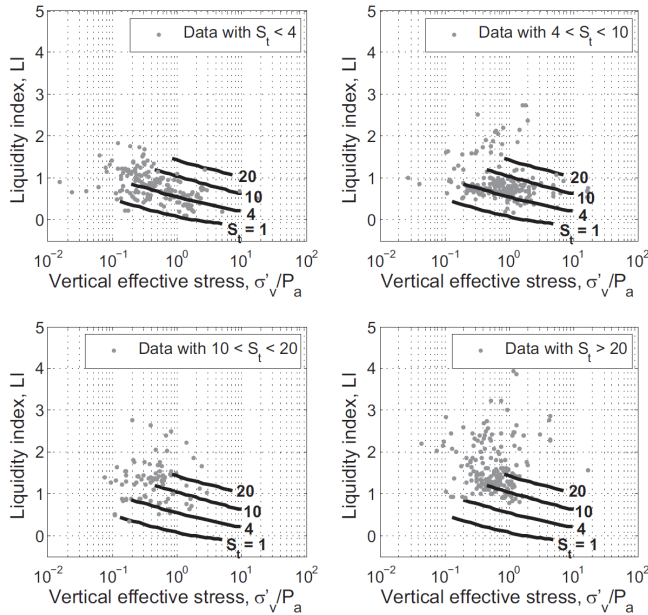


Figure 4: LI – ( $\sigma'_v/P_a$ ) –  $S_t$  model proposed by Mitchel (1993).

图 4: Mitchel (1993) 提出的 LI – ( $\sigma'_v/P_a$ ) –  $S_t$  模型。

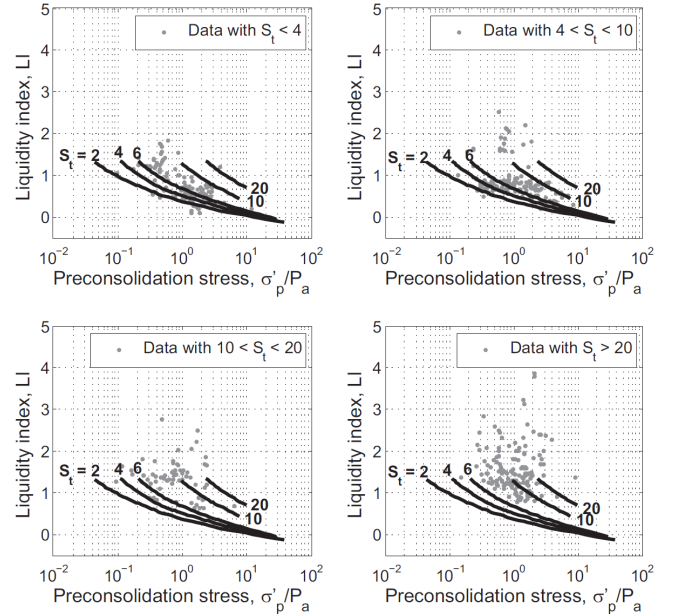


Figure 5: LI – ( $\sigma'_p/P_a$ ) –  $S_t$  models proposed by NAVFAC (1982).

图 5: NAVFAC (1982) 提出的 LI – ( $\sigma'_p/P_a$ ) –  $S_t$  模型。



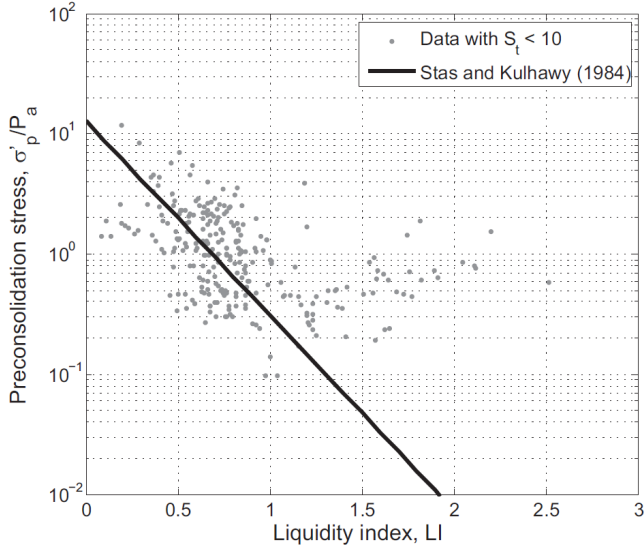


Figure 6: LI –  $(\sigma'_p/P_a)$  –  $S_t$  model proposed by Stas and Kulhawy (1984).

图 6: Stas and Kulhawy (1984) 提出的 LI –  $(\sigma'_p/P_a)$  –  $S_t$  模型。

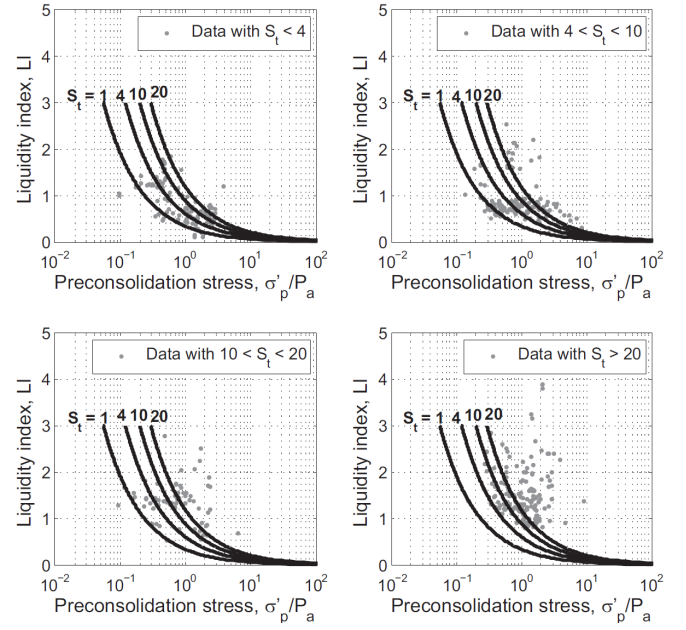


Figure 7: LI –  $(\sigma'_p/P_a)$  –  $S_t$  models proposed by Ching and Phoon (2012b).

图 7: Ching and Phoon (2012b) 提出的 LI –  $(\sigma'_p/P_a)$  –  $S_t$  模型。

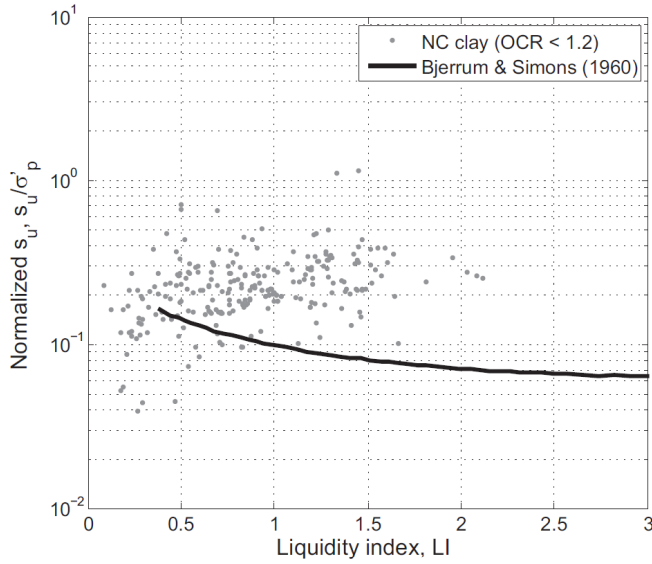


Figure 8: LI –  $(s_u/\sigma'_p)$  model proposed by Bjerrum and Simons (1960).

图 8: Bjerrum and Simons (1960) 提出的 LI –  $(s_u/\sigma'_p)$  模型。

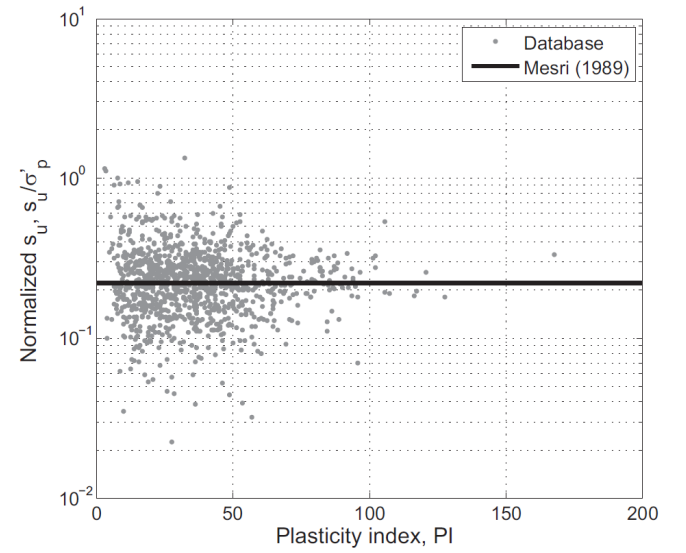


Figure 9: LI –  $(s_u/\sigma'_p)$  models proposed by Mesri (1975, 1989).

图 9: Mesri (1975, 1989) 提出的 LI –  $(s_u/\sigma'_p)$  模型。

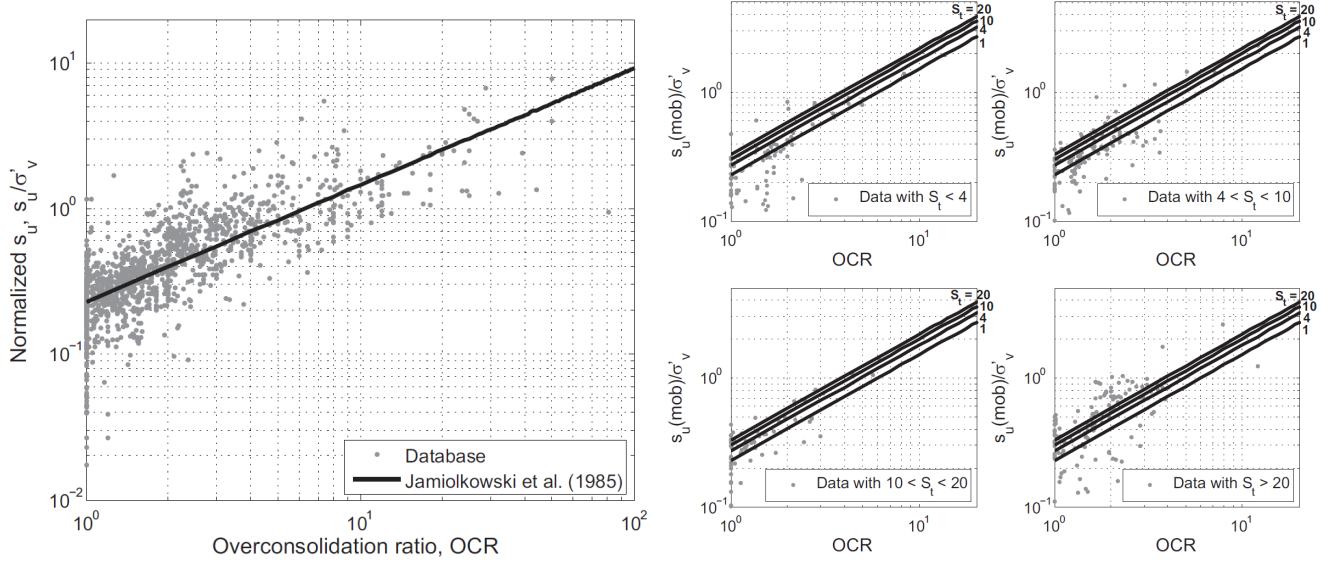


Figure 10: OCR –  $(s_u/\sigma'_p)$  model proposed by Jamiolkowski et al. (1985). Figure 11: OCR –  $(s_u/\sigma'_p)$  –  $S_t$  models proposed by Ching and Phoon (2012b).

图 10: Jamiolkowski et al. (1985) 提出的 OCR –  $(s_u/\sigma'_p)$  模型。图 11: Ching and Phoon (2012b) 提出的 OCR –  $(s_u/\sigma'_p)$  –  $S_t$  模型。

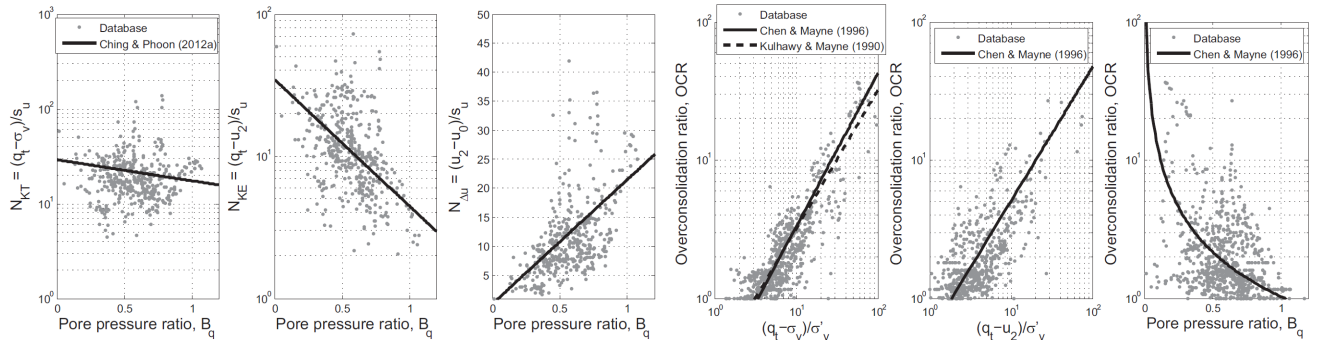


Figure 12: CPTU –  $s_u/\sigma'_v$  model proposed by Ching and Phoon (2012b). Figure 13: CPTU-OCR model proposed by Chen and Mayne (1996); Kulhawy and Mayne (1990).

图 12: Ching and Phoon (2012b) 提出的 CPTU –  $s_u/\sigma'_v$  模型。图 13: Chen and Mayne (1996); Kulhawy and Mayne (1990) 提出的 CPTU-OCR 模型。

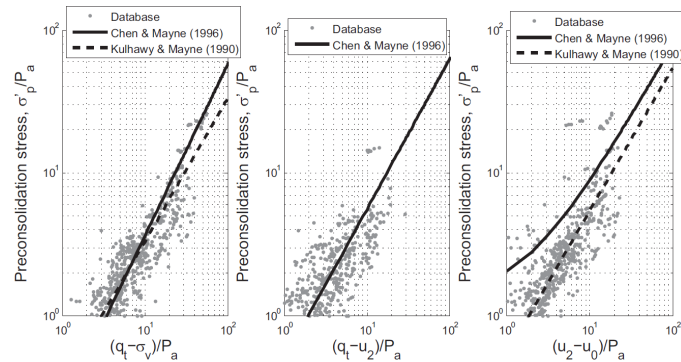


Figure 14: CPTU –  $\sigma'_p/P_a$  model proposed by Chen and Mayne (1996); Kulhawy and Mayne (1990).

图 14: Chen and Mayne (1996); Kulhawy and Mayne (1990) 提出的 CPTU –  $\sigma'_p/P_a$  模型。

Fig. 8, only data points with  $OCR < 1.2$  (nearly NC clays) in the global database are plotted. Nonetheless, the discrepancy between the model and the data is clear. Note that this model was developed based on Norwegian NC clays only. It is most likely that this site-specific model fits to the Norwegian data, but not to the global data from diverse geographic origins.

6. One of the  $CPTU - (\sigma'_p/P_a)$  models proposed by Chen and Mayne (1996) (the third model that relates  $\sigma'_p$  to  $(u_2 - u_0)/P_a$  in Table 5). The discrepancy between this model and our global data is apparent. However, the first two models developed by Chen and Mayne (1996) (the two models that relate  $\sigma'_p/P_a$  to  $(q_t - \sigma_v)/P_a$  and  $(q_t - u_2)/P_a$ ) provide reasonable fits to our global data. We are unable to explain this anomaly.

数据库 CLAY/5/345 仅包含结构化粘土。

5. Bjerrum and Simons (1960) 提出的  $LI - (s_u/\sigma'_p)$  模型。在图8中, 仅绘制了全局数据库中  $OCR < 1.2$  (接近 NC 黏土) 的数据点。尽管如此, 模型和数据之间的差异仍然很明显。请注意, 此模型仅基于挪威 NC 黏土开发。此特定于站点的模型很可能适合挪威的数据, 但不适合来自不同地理来源的全球数据。

6. Chen and Mayne (1996) 提出的  $CPTU - (\sigma'_p/P_a)$  模型之一 (表5中  $\sigma'_p$  与  $(u_2 - u_0)/P_a$  相关的第三种模型)。该模型与我们的全局数据之间的差异显而易见。然而, 由Chen and Mayne (1996) 开发的前两个模型 ( $\sigma'_p/P_a$  与  $(q_t - \sigma_v)/P_a$  相关的模型和  $(q_t - u_2)/P_a$  模型) 合理地拟合了我们的全球数据。我们无法解释这种异常。

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

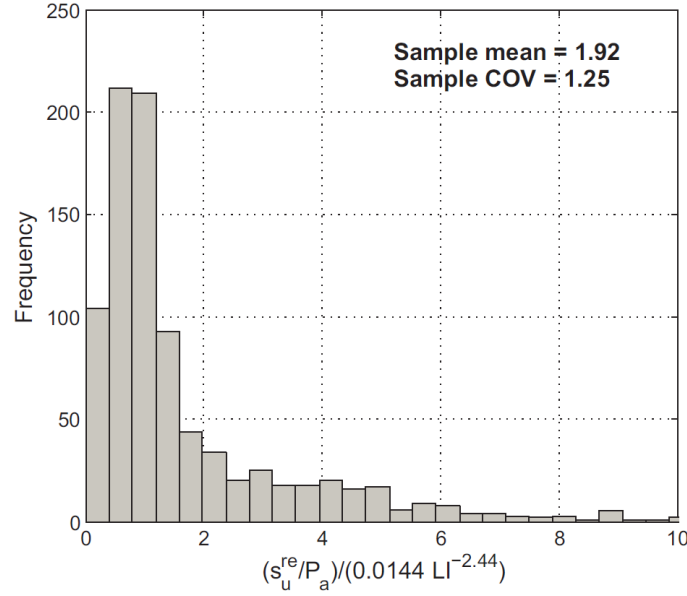
The bias factors and coefficients of variation (COVs) of all models with respect to the global database are calibrated, except the three models that are only presented as graphical curves in the literature. The bias factor is denoted by  $b$ , and the COV is denoted by  $\delta$ . Basically,  $b$  is the sample mean of (actual target value)/(predicted target value) for the global data points, and  $\delta$  is the sample COV of (actual target value)/(predicted target value). For instance, for the  $LI - (s_u^r/P_a)$  model proposed by Locat and Demers (1988), the actual target value is the  $s_u^r/P_a$  value in the global database, and the predicted target value is  $0.0144LI^{-2.44}$ . For each data point with simultaneous knowledge of  $(LI, s_u^r)$ , (actual target value)/(predicted target value) =  $(s_u^r/P_a)/(0.0144LI^{-2.44})$  can be computed. The histogram of the ratio  $(s_u^r/P_a)/(0.0144LI^{-2.44})$  is plotted in Fig. 15. The sample mean of this ratio is equation to 1.92, which is equation to  $b$ . The sample COV of this ratio is 1.25, which is equation to  $\delta$ . To be specific,

本文校正了所有模型相对于全局数据库的偏差因子和变异系数 (COV), 除了在文献中仅以图形曲线形式表示的三个模型外。偏置因子用  $b$  表示, COV 用  $\delta$  表示。基本上,  $b$  是全局数据点的 (实际目标值) / (预测目标值) 的样本均值, 并且  $\delta$  是 (实际目标值) / (预测目标值) 的样本 COV。例如, 对于Locat and Demers (1988) 提出的  $LI - (s_u^r/P_a)$  模型, 实际目标值为全球数据库中的  $s_u^r/P_a$  值, 而预测目标值为  $0.0144LI^{-2.44}$ 。对于同时了解  $(LI, s_u^r)$  的每个数据点, 可以计算 (实际目标值) / (预测目标值) =  $(s_u^r/P_a)/(0.0144LI^{-2.44})$ 。比值的直方图  $(s_u^r/P_a)/(0.0144LI^{-2.44})$  绘制在图15中。该比值的样本平均值等于 1.92, 等于  $b$ 。此比率的样本 COV 为 1.25, 等于  $\delta$ 。再具体一点,

$$\text{Actual target value} = \text{predicted target value} \times b \times \delta \quad (1)$$

where  $b$  is the bias factor ( $b = 1$  means unbiased) and  $\epsilon$  is the variability term with mean = 1 and COV =  $\delta$ . If  $\delta = 0$ , there is no data scatter about the transformation model, i.e., the prediction is single-valued or deterministic, rather than a distribution. The  $LI - (s_u^r/P_a)$

式中  $b$  是偏差因子 ( $b = 1$  表示无偏),  $\epsilon$  是均值 = 1 且 COV =  $\delta$  的可变项。如果  $\delta = 0$ , 则没有关于转换模型的数据分散, 即预测是单值或确定性的, 而不是某种分布。Locat and

Figure 15: Histogram of  $(s_u^{re}/P_a)/(0.0144LI^{-2.44})$ .图 15:  $(s_u^{re}/P_a)/(0.0144LI^{-2.44})$  的直方图。

model proposed by Locat and Demers (1988) is biased because the bias factor ( $b$ ) is around 1.92, and the COV of this model is around 1.25. This model basically underpredicts the actual value by a factor of about 2 (conservative model). The uncertainty underlying this prediction when it is made to cover the wide range of conditions in the global database is considerable given that the COV exceeds 100%. The calibrated bias factors and COVs for all models are shown in the last two columns of Table 5. The number of data points “ $n$ ” used for each calibration is listed in the table.

It is evident that models published in more recent studies, such as citetKulhawy1990, Chen and Mayne (1996), and Ching and Phoon (2012a,b) mostly have bias factors  $b \approx 1$  (less biased). These recent studies compiled fairly large databases as well. It is also evident that the COVs ( $\delta$ ) calibrated by the global database in this study are typically higher than those reported in the literature (see the numbers in the parentheses in the rightmost column in Table 5). The exceptions are the LI-S<sub>t</sub>, LI- $(\sigma'_p/P_a)$ -S<sub>t</sub> and OCR- $(s_u/\sigma'_v)$ -S<sub>t</sub> models developed in Ching and Phoon (2012b): COVs for these three models are close to those reported in Ching and Phoon (2012b). The statistics of the database used by Ching and Phoon (2012b) are given in the “Remarks” column in Table 5.

The bias factors in Table 5 still deviate somewhat from unity for two possible reasons:

1. The bias factors in Table 5 are calibrated using the global

Demers (1988) 提出的 LI- $(s_u^{re}/P_a)$  模型是有偏差的, 因为偏差因子 ( $b$ ) 约为 1.92, 而该模型的 COV 约为 1.25。该模型基本上将实际值低估了约 2 倍 (保守模型)。考虑到 COV 超过 100%, 当预测覆盖全球数据库中的广泛条件时, 这种不确定性是相当大的。表 5 的最后两列显示了所有模型的校准偏差因子和 COV。表中列出了每次校准使用的数据点 “ $n$ ” 的数量。

显然, 在最近的研究中发表的模型, 例如 Kulhawy and Mayne (1990), Chen and Mayne (1996) 以及 Ching and Phoon (2012a,b), 大多具有偏差因子  $b \approx 1$  (偏差较小)。这些最近的研究也汇编了相当大的数据库。同样明显的是, 这项研究中由全球数据库校准的 COV ( $\delta$ ) 通常高于文献报道的 COV (请参见表 5 最右栏中的括号中的数字)。Ching and Phoon (2012b) 开发的 LI-S<sub>t</sub>, LI- $(\sigma'_p/P_a)$ -S<sub>t</sub> 和 OCR- $(s_u/\sigma'_v)$ -S<sub>t</sub> 模型除外: 这三个模型的 COV 接近 Ching and Phoon (2012b) 中报道的那些。Ching and Phoon (2012b) 使用的数据库的统计信息在表 5 的“备注”列中给出。

表 5 中的偏差因子仍因某些可能的原因而偏离统一性:

1. 使用本研究中的全球数据库对表 5 中



database in this study that contains broader types of clays, typically broader than the databases used to develop the transformation models in the literature. For instance, [Ching and Phoon \(2012b\)](#) only considered structured clays.

2. All  $s_u$  data points in the global database are converted to  $s_u(\text{mob})$  (see Table 2). Such a conversion step may introduce an extra bias.

The COVs in Table 5 are typically larger than those reported in the literature for three possible reasons:

1. These COVs are calibrated using the global database that contains broader types of clays.

2. The conversion of the  $s_u$  data points to a reference strength,  $s_u(\text{mob})$ , would introduce transformation uncertainty. It is noteworthy that the COVs can be even larger without this conversion, because  $s_u$  varies significantly with the test type ([Ladd et al., 1977](#)).

3. The COVs summarized in [Ching and Phoon \(2012a\)](#) for the  $\text{CPTU} - (s_u/\sigma'_v)$  transformation models do not include measurement errors.

By definition, the models calibrated by the global database are unbiased with respect to the global database in this study. For instance, for the  $\text{LI} - s_u^{\text{re}}/P_a$  model by [Locat and Demers \(1988\)](#), the predicted value for  $s_u^{\text{re}}/P_a$  is  $0.0144\text{LI}^{-2.44}$ . This model has a bias factor  $b = 1.92$ , calibrated by the global database. As a result, the calibrated model  $s_u^{\text{re}}/P_a \approx b(0.0144)\text{LI}^{-2.44} = 1.92(0.0144)\text{LI}^{-2.44}$  is an “unbiased prediction” with respect to the global database. This means that this calibrated model can capture the mean trend of the global database, and the calibrated COV can adequately capture the data scatter around the mean trend. However, the COV is typically quite large to capture the data scatter. In the next section, the possibility of incorporating secondary input parameters to reduce the COV is addressed.

## 5 Secondary input parameters 辅助输入参数

A possible reason for the significant data scatter around the mean trend is that additional explanatory variables are not incorporated into the transformation model. As a result, the variation in these hidden explanatory variables, which is inevitable in a database, is added to the transformation uncertainty. A good example is the  $\text{OCR} - (s_u/\sigma'_v)$  model by [Jamiolkowski et al. \(1985\)](#). The COV with respect to the global database is 0.53 for this model (see Table 5). This means that the standard deviation of the data scatter is about 53% of the mean trend. A possible hidden explanatory variable is the sensitivity  $S_t$  — it is known that the “stress history and normalized soil engineering properties” SHANSEP parameters for sensitive (structured) clays are different from those for insensitive clays. In fact, by incorporating  $S_t$

的偏差因子进行校准, 该数据库包含更广泛的黏土类型, 通常比文献中用于开发转化模型的数据库更广泛。例如, [Ching and Phoon \(2012b\)](#) 仅考虑结构化黏土。

2. 全局数据库中的所有  $s_u$  数据点都将转换为  $s_u(\text{mob})$  (请参见表2)。这样的转换步骤可能会引入额外的偏差。

由于以下三种可能的原因, 表5中的 COV 通常大于文献报道的 COV:

1. 使用包含更广泛类型的黏土的全球数据库对这些 COV 进行校准。

2. 将  $s_u$  数据点转换为参考强度  $s_u(\text{mob})$ , 将引入转换不确定性。值得注意的是, 如果不进行这种转换, COV 可能会更大, 因为  $s_u$  随测试类型而变化很大 ([Ladd et al., 1977](#))。

3. [Ching and Phoon \(2012a\)](#) 中针对  $\text{CPTU} - (s_u/\sigma'_v)$  转换模型总结的 COV 不包括测量误差。

根据定义, 在本研究中, 由全局数据库校准的模型相对于全局数据库没有偏见。例如, 对于 [Locat and Demers \(1988\)](#) 的  $\text{LI} - s_u^{\text{re}}/P_a$  模型,  $s_u^{\text{re}}/P_a$  的预测值为  $0.0144\text{LI}^{-2.44}$ 。该模型的偏差因子  $b = 1.92$ , 已通过全局数据库进行了校准。结果, 校准后的模型  $s_u^{\text{re}}/P_a \approx b(0.0144)\text{LI}^{-2.44} = 1.92(0.0144)\text{LI}^{-2.44}$  对于全局数据库而言是“无偏预测”。这意味着该校准模型可以捕获全局数据库的平均趋势, 并且校准 COV 可以充分捕获平均趋势周围的数据散布。但是, COV 通常很大以捕获数据散布。在下一节中, 讨论了合并次级输入参数以降低 COV 的可能性。

围绕平均趋势出现大量数据分散的可能原因是, 其他解释变量未合并到转换模型中。结果, 这些隐藏的解释变量的变化 (这在数据库中是不可避免的) 被添加到变换不确定性中。一个很好的例子是 [Jamiolkowski et al. \(1985\)](#) 的  $\text{OCR} - (s_u/\sigma'_v)$  模型。对于此模型, 相对于全局数据库的 COV 为 0.53 (请参见表5)。这意味着数据散布的标准偏差约为平均趋势的 53%。可能的隐藏解释变量是敏感度  $S_t$  - 已知敏感 (结构化) 黏土的“应力历史和规范化的土工工程特性” SHANSEP 参数与不敏感黏土的参数不同。实际上, 通过

as a secondary input parameter, the OCR –  $(s_u/\sigma'_v) - S_t$  model by Ching and Phoon (2012b) carries a significantly smaller COV of 0.34 (see Table 5). It is widely known that parameters such as PI and  $S_t$  can be applied as secondary explanatory variables for some correlations. It is of interest to see whether the incorporation of these secondary input parameters can reduce COV significantly. If the COV reduction is significant, it is of interest to re-calibrate the transformation models to further update the bias factors and the COVs in Table 5. This is the main objective of this section.

### Correlation between $\epsilon$ and $(PI, S_t)$ $\epsilon$ 与 $(PI, S_t)$ 之间的相关性

Let us recall from eq. (1) that the variability term  $\epsilon$  for a transformation model can be expressed as

$$\epsilon = \frac{\text{actual target value}}{b \times \text{predicted target value}} = \frac{\text{actual target value}}{\text{unbiased prediction}} \quad (2)$$

where the unbiased prediction =  $b \times$  predicted target value. The variability term  $\epsilon$  quantifies the deviation between the actual value and the unbiased prediction. It has mean value of 1 and COV equation to the calibrated COV ( $\delta$ ). Equivalently

$$\ln(\epsilon) = \ln(\text{actual target value}) - \ln(\text{unbiased prediction}) \quad (3)$$

In essence,  $\ln(\epsilon)$  is the component that cannot be explained away by the primary input parameter. More precisely,  $\ln(\epsilon)$  should be uncorrelated to the primary input parameter. The reason why the natural logarithm is taken will be explained later. For instance,  $\ln(\epsilon)$  for the OCR –  $(s_u/\sigma'_v)$  model proposed by Jamiolkowski et al. (1985) is indeed nearly uncorrelated to the primary input parameter  $\ln(\text{OCR})$ , shown in Fig. 16a. Incidentally, the correlation between  $\ln(\epsilon)$  and  $\ln(\text{PI})$  is also nearly zero (Fig. 16b). However,  $\ln(\epsilon)$  and  $\ln(S_t)$  show some slight positive correlation (Fig. 16c). In this case, it may be possible to adopt  $S_t$  as the secondary input parameter for Jamiolkowski et al.'s model to reduce its COV.

In this section, the correlation between  $\ln(\epsilon)$  and the natural logarithm of the secondary input parameter (PI or  $S_t$ ) will be studied. The correlation with respect to  $\ln(\text{PI})$  will be studied for all models except the PI –  $(s_u/\sigma'_p)$  model proposed by Mesri (1975, 1989), because PI is already the primary input parameter. Similarly, the correlation with respect to  $\ln(S_t)$  will not be studied for models whose primary inputs already involve  $S_t$ . The correlation with respect to  $\ln(S_t)$  will not be studied for models whose target is  $s_u^{re}$ , because soil structure is supposed to be destroyed in the remoulded state and hence, it does not make much sense to infer  $s_u^{re}$  using  $S_t$ .

将  $S_t$  作为次要输入参数, Ching and Phoon (2012b) 的 OCR –  $(s_u/\sigma'_v) - S_t$  模型携带的 COV 值要小得多, 为 0.34 (参见表5)。众所周知, 诸如 PI 和  $S_t$  之类的参数可以用作某些相关性的次要解释变量。有趣的是, 这些辅助输入参数的合并是否可以显著降低 COV。如果 COV 降低很大, 则需要重新校准转换模型以进一步更新表5中的偏置因子和 COV。这是本节的主要目标。

让我们从等式 (1) 回忆, 转换模型的可变性项  $\epsilon$  可以表示为

其中无偏预测 =  $b \times$  预测目标值。可变性项  $\epsilon$  量化了实际值和无偏预测之间的偏差。它的平均值为 1, 且 COV 等于校准的 COV ( $\delta$ )。等效地,

本质上,  $\ln(\epsilon)$  是无法由主输入参数解释的成分。更准确地说,  $\ln(\epsilon)$  应该与主要输入参数不相关。取自然对数的原因将在后面说明。例如, Jamiolkowski et al. (1985) 提出的 OCR –  $(s_u/\sigma'_v)$  模型的  $\ln(\epsilon)$  的确与图16a所示的主要输入参数  $\ln(\text{OCR})$  几乎不相关。顺便提及,  $\ln(\epsilon)$  和  $\ln(\text{PI})$  之间的相关性也几乎为零 (图16b)。但是,  $\ln(\epsilon)$  和  $\ln(S_t)$  表现出一些轻微的正相关 (图16c)。在这种情况下, 有可能采用  $S_t$  作为 Jamiolkowski 等人模型的辅助输入参数, 以降低其 COV。

在本节中, 将研究  $\ln(\epsilon)$  与辅助输入参数 (PI 或  $S_t$ ) 的自然对数之间的相关性。因为 PI 已经是主要的输入参数, 所以将研究除 Mesri (1975, 1989) 提出的 PI –  $(s_u/\sigma'_p)$  模型以外的所有模型与  $\ln(\text{PI})$  的相关性。同样, 对于主要输入已经包含  $S_t$  的模型, 将不会研究与  $\ln(S_t)$  的相关性。对于目标为  $s_u^{re}$  的模型, 将不会研究与  $\ln(S_t)$  的相关性, 因为应该在重塑状态下破坏土体结构, 因此使用  $S_t$  推断  $s_u^{re}$  没有太大意义。

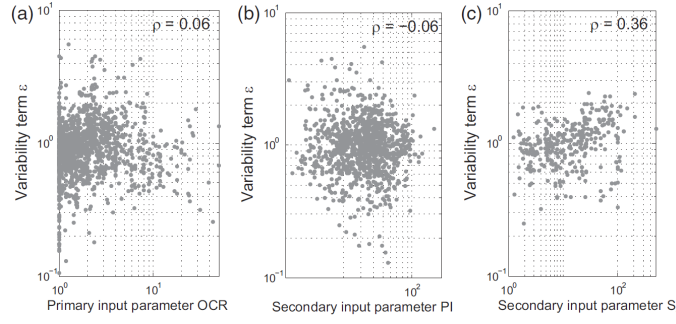


Figure 16: (a)  $\ln(\varepsilon)$ – $\ln(\text{OCR})$ , (b)  $\ln(\varepsilon)$ – $\ln(\text{PI})$ , and (c)  $\ln(\varepsilon)$ – $\ln(S_t)$  plots for the model proposed by Jamiolkowski et al. (1985).  $\rho$ , correlation coefficient.

图 16: (a)  $\ln(\varepsilon)$ – $\ln(\text{OCR})$ , (b)  $\ln(\varepsilon)$ – $\ln(\text{PI})$ , and (c)  $\ln(\varepsilon)$ – $\ln(S_t)$  Jamiolkowski et al. (1985) 提出的模型的图解。  $\rho$ , 相关系数。

The correlation between  $\ln(\varepsilon)$  and the natural logarithm of the secondary input parameter (PI or  $S_t$ ) is quantified by the Pearson product moment correlation coefficient ( $\rho$ ). The correlation coefficient for the  $\ln(\varepsilon)$ – $\ln(\text{PI})$  and  $\ln(\varepsilon)$ – $\ln(S_t)$  correlations are shown in Table 6. The parameter  $n$  shown in Table 6 is the number of data points used to estimate each correlation. It is clear that the  $\ln(\varepsilon)$ – $\ln(\text{PI})$  data points are abundant ( $n > 300$ ), whereas the  $\ln(\varepsilon)$ – $\ln(S_t)$  data points are less abundant. It is also evident that the  $\ln(\varepsilon)$ – $\ln(S_t)$  correlations seem stronger ( $\rho$  is farther away from zero) than the  $\ln(\varepsilon)$ – $\ln(\text{PI})$  correlations.

$\ln(\varepsilon)$  和辅助输入参数 (PI 或  $S_t$ ) 的自然对数之间的相关性通过皮尔逊乘积矩相关系数 ( $\rho$ ) 进行量化。 $\ln(\varepsilon)$ – $\ln(\text{PI})$  和  $\ln(\varepsilon)$ – $\ln(S_t)$  相关性的相关系数如表6所示。表6中所示的参数  $n$  是用于估计每个相关性的数据点数。显然,  $\ln(\varepsilon)$ – $\ln(\text{PI})$  数据点数量丰富 ( $n > 300$ ), 而  $\ln(\varepsilon)$ – $\ln(S_t)$  数据点数量较少。同样明显的是,  $\ln(\varepsilon)$ – $\ln(S_t)$  相关性似乎比  $\ln(\varepsilon)$ – $\ln(\text{PI})$  相关性更强 ( $\rho$  离零更远)。

### Re-calibrate the existing transformation models - inference using PI and $S_t$ 重新校准现有的转换模型-使用 PI 和 $S_t$ 进行推断

For the inference using PI, it is possible to express  $\varepsilon$  as a function of PI

对于使用 PI 进行推理, 可以将  $\varepsilon$  表示为 PI 的函数

$$\varepsilon = [\alpha(\text{PI}/20)^\beta] \varepsilon' \quad (4)$$

where  $\varepsilon'$  is the (updated) variability term that cannot be explained away by PI, and  $\text{PI} = 20$  is a reference PI value (median plasticity). The mean value of  $\varepsilon'$  is still 1 and its (updated) COV is denoted by  $\delta'$ , which should be less than  $\delta$  if  $\ln(\varepsilon)$  and  $\ln(\text{PI})$  are correlated. The coefficients  $\alpha$  and  $\beta$  can be estimated using linear regression on the  $\ln(\varepsilon)$ – $\ln(\text{PI})$  data points. Namely, the following regression model is used:

其中  $\varepsilon'$  是无法由 PI 解释的 (更新的) 可变性项, 而  $\text{PI} = 20$  是一个参考 PI 值 (中位数可塑性)。  $\varepsilon'$  的平均值仍为 1, 并且其 (更新的) COV 用  $\delta'$  表示, 如果  $\ln(\varepsilon)$  和  $\ln(\text{PI})$  相关, 则其应小于  $\delta$ 。可以使用  $\ln(\varepsilon)$ – $\ln(\text{PI})$  数据点上的线性回归来估计系数  $\alpha$  和  $\beta$ 。即, 使用以下回归模型:

$$\ln(\varepsilon) \approx \ln(\alpha) + \beta \ln(\text{PI}/20) \quad (5)$$

where  $\ln(\varepsilon)$  is the known output and  $\ln(\text{PI}/20)$  is the known input,

其中  $\ln(\varepsilon)$  是已知输出, 而  $\ln(\text{PI}/20)$  是

Table 6: Analysis results for  $\ln(\varepsilon) - \ln(\text{PI})$  and  $\ln(\varepsilon) - \ln(S_t)$  correlations and inference results.表 6:  $\ln(\varepsilon) - \ln(\text{PI})$  和  $\ln(\varepsilon) - \ln(S_t)$  相关性和推断分析结果。

		Correlation coefficient				Inference results					
		$\varepsilon$ -PI		$\varepsilon - S_t$				Inference based PI only		Inference based on PI and $S_t$	
Relationship	Literature	$n$	$\rho$	$n$	$\rho$	Updated model	$b' = b \times [\text{BCF}]$	$\delta' = \delta \times [\text{CCF}\%]$	$b' = b \times [\text{BCF}]$	$\delta' = \delta \times [\text{CCF}\%]$	
LI - $s_u^{\text{re}}/P_a$	Locat and Demers (1988)	887	-0.24	—	—	$s_u^{\text{re}}/P_a \approx 0.0144\text{LI}^{-2.44}b'\varepsilon'$	$1.92 \times [1.11(\text{PI}/20)^{-0.258}]$	$1.25 \times (94\%)$	—	—	
LI - $S_t$	Bjerrum (1954)	1137	0.18	—	—	$S_t \approx 10^{0.8\text{LI}}b'\varepsilon'$	$2.05 \times [0.92(\text{PI}/20)^{0.251}]$	$1.09 \times (104\%)$	—	—	
	Ching and Phoon (2012b)	1137	-0.02	—	—	$S_t \approx 20.726\text{LI}^{1.910}b'\varepsilon'$	$0.88 \times [0.88(\text{PI}/20)^{-0.025}]$	$1.28 \times (99\%)$	—	—	
LI - $\sigma_p'/P_a - S_t$	Stas and Kulhawy (1984)	257	-0.37	—	—	$\sigma_p'/P_a \approx 10^{1.11-1.62\text{LI}}b'\varepsilon'$ (for $S_t < 10$ only)	$2.94 \times [2.94(\text{PI}/20)^{-0.478}]$	$1.90 \times (85\%)$	—	—	
	Ching and Phoon (2012b)	487	-0.35	—	—	$\sigma_p'/P_a \approx 0.235\text{LI}^{-1.319}S_t^{0.536}b'\varepsilon'$	$1.32 \times [1.32(\text{PI}/20)^{-0.444}]$	$0.78 \times (78\%)$	—	—	
PI - $s_u/\sigma_p'$	Mesri (1975, 1989)	—	—	433	0.43	$s_u(\text{mob})/\sigma_p' \approx 0.22b'\varepsilon'$	—	—	$1.04 \times [0.76S_t^{0.136}]$	$0.55 \times (63\%)$	
OCR - $s_u/\sigma_p'$	Jamiolkowski et al. (1985)	1091	-0.06	395	0.34	$s_u(\text{mob})/\sigma_p' \approx 0.23(\text{OCR})^{0.8}b'\varepsilon'$	$1.11 \times [1.11(\text{PI}/20)^{-0.050}]$	$0.53 \times (53\%)$	$1.11 \times [0.71(\text{PI}/20)^{0.133}S_t^{0.123}]$	$0.53 \times (67\%)$	
OCR - $s_u/\sigma_p' - S_t$	Ching and Phoon (2012b)	391	0.21	—	—	$s_u(\text{mob})/\sigma_p' \approx 0.229(\text{OCR})^{0.823}S_t^{0.121}b'\varepsilon'$	$0.84 \times [0.84(\text{PI}/20)^{0.131}]$	$0.34 \times (34\%)$	—	—	
CPTU - $s_u/\sigma_p'$	Ching and Phoon (2012a)	387	0.38	81	-0.24	$\frac{[(q_t - \sigma_v)/\sigma_v']}{[s_u(\text{mob})/\sigma_v']} \approx 29.1 \exp(-0.513B_q)b'\varepsilon'$	$0.95 \times [0.95(\text{PI}/20)^{0.348}]$	$0.49 \times (49\%)$	$0.95 \times [1.17(\text{PI}/20)^{0.133}S_t^{-0.198}]$	$0.49 \times (66\%)$	
		392	0.29	78	-0.39	$\frac{[(q_t - u_2)/\sigma_v']}{[s_u(\text{mob})/\sigma_v']} \approx 34.6 \exp(-2.049B_1)b'\varepsilon'$	$1.11 \times [1.11(\text{PI}/20)^{0.275}]$	$0.57 \times (57\%)$	$1.11 \times [1.40(\text{PI}/20)^{0.241}S_t^{-0.263}]$	$0.57 \times (72\%)$	
		387	0.38	81	-0.25	$\frac{[(u_2 - u_0)/\sigma_v']}{[s_u(\text{mob})/\sigma_v']} \approx 21.5B_qb'\varepsilon'$	$0.94 \times [0.94(\text{PI}/20)^{0.335}]$	$0.49 \times (49\%)$	$0.94 \times [1.22(\text{PI}/20)^{0.189}S_t^{-0.216}]$	$0.49 \times (78\%)$	
CPTU - OCR	Chen and Mayne (1996)	497	-0.09	163	0.12	$\text{OCR} \approx 0.259 [(q_t - \sigma_v')]^{1.107}b'\varepsilon'$	$1.01 \times [1.01(\text{PI}/20)^{-0.073}]$	$0.42 \times (42\%)$	$1.01 \times [1.09(\text{PI}/20)^{0.275}S_t^{0.002}]$	$0.42 \times (73\%)$	
		466	-0.11	123	0.27	$\text{OCR} \approx 0.545 [(q_t - u_2)]^{0.969}b'\varepsilon'$	$1.06 \times [1.06(\text{PI}/20)^{-0.105}]$	$0.57 \times (57\%)$	$1.06 \times [0.79(\text{PI}/20)^{-0.206}S_t^{0.102}]$	$0.57 \times (69\%)$	
		545	-0.17	173	0.12	$\text{OCR} \approx 1.026B_q^{-1.077}b'\varepsilon'$	$1.28 \times [1.28(\text{PI}/20)^{-0.196}]$	$0.86 \times (86\%)$	$1.28 \times [0.63(\text{PI}/20)^{-0.079}S_t^{-0.057}]$	$0.86 \times (52\%)$	
CPTU - $\sigma_p'/P_a$	Kulhawy and Mayne (1990)	497	-0.11	163	0.14	$\text{OCR} \approx 0.32 [(q_t - \sigma_v)/\sigma_v']b'\varepsilon'$	$1.00 \times [1.00(\text{PI}/20)^{-0.084}]$	$0.39 \times (39\%)$	$1.00 \times [1.04(\text{PI}/20)^{-0.188}S_t^{0.010}]$	$0.39 \times (71\%)$	
	Chen and Mayne (1996)	497	-0.04	163	0.15	$\sigma_p'/P_a \approx 0.227 [(q_t - \sigma_v)/P_a]^{1.200}b'\varepsilon'$	$0.99 \times [0.99(\text{PI}/20)^{-0.028}]$	$0.42 \times (42\%)$	$0.99 \times [1.07(\text{PI}/20)^{-0.124}S_t^{0.002}]$	$0.42 \times (70\%)$	
		466	-0.09	123	0.28	$\sigma_p'/P_a \approx 0.490 [(q_t - u_2)/P_a]^{1.053}b'\varepsilon'$	$1.08 \times [1.08(\text{PI}/20)^{-0.087}]$	$0.61 \times (61\%)$	$1.08 \times [0.78(\text{PI}/20)^{-0.268}S_t^{0.205}]$	$0.61 \times (68\%)$	
		498	-0.25	163	0.04	$\sigma_p'/P_a \approx [1.274 + 0.761(u_2 - u_0)/P_a]b'\varepsilon'$	$0.49 \times [0.49(\text{PI}/20)^{-0.235}]$	$0.59 \times (59\%)$	$1.49 \times [0.94(\text{PI}/20)^{-0.262}S_t^{0.026}]$	$0.59 \times (60\%)$	
	Kulhawy and Mayne (1990)	497	-0.11	163	0.14	$\sigma_p'/P_a \approx 0.33 [(q_t - \sigma_v)/P_a]b'\varepsilon'$	$0.97 \times [0.97(\text{PI}/20)^{-0.084}]$	$0.39 \times (39\%)$	$0.97 \times [1.04(\text{PI}/20)^{-0.188}S_t^{0.010}]$	$0.39 \times (71\%)$	
		497	-0.12	162	-0.01	$\sigma_p'/P_a \approx 0.54 [(u_2 - u_0)/P_a]b'\varepsilon'$	$1.18 \times [1.18(\text{PI}/20)^{-0.114}]$	$0.75 \times (75\%)$	$1.18 \times [1.04(\text{PI}/20)^{-0.114}S_t^{-0.069}]$	$0.75 \times (61\%)$	



whereas  $\ln(\alpha)$  and  $\beta$  are the intersect and gradient, respectively, to be estimated by the least squares method. The natural logarithm is taken for *varepsilon* and PI because traditional linear regression requires normality. Figure 17 shows the histograms of  $\varepsilon$  and  $\ln(\varepsilon)$  for the OCR -  $(s_u/\sigma'_v)$  model proposed by Jamiolkowski et al. (1985) -  $\ln(\varepsilon)$  is more normal than  $\varepsilon$ . In fact,  $\ln(\text{PI})$  is also more normal than PI (not shown). Hence, it is more appropriate to do regression on the  $\ln(\varepsilon) - \ln(\text{PI})$  data points. Once the least-squares estimates for  $\alpha$  and  $\beta$  are obtained, eq. (1) can be expressed as

已知输入, 而  $\ln(\alpha)$  和  $\beta$  是分别通过最小二乘法估计的相交和渐变。因为传统的线性回归需要正态性, 所以 PI 取自然对数。图17显示了 Jamiolkowski et al. (1985) 提出的 OCR -  $(s_u/\sigma'_v)$  模型的  $\varepsilon$  和  $\ln(\varepsilon)$  的直方图 -  $\ln(\varepsilon)$  比  $\varepsilon$  更为正常。实际上,  $\ln(\text{PI})$  也比 PI 更正常 (未显示)。因此, 对  $\ln(\varepsilon) - \ln(\text{PI})$  数据点进行回归更合适。使用最小二乘估计获得  $\alpha$  和  $\beta$ , 等式 (1) 可以表示为

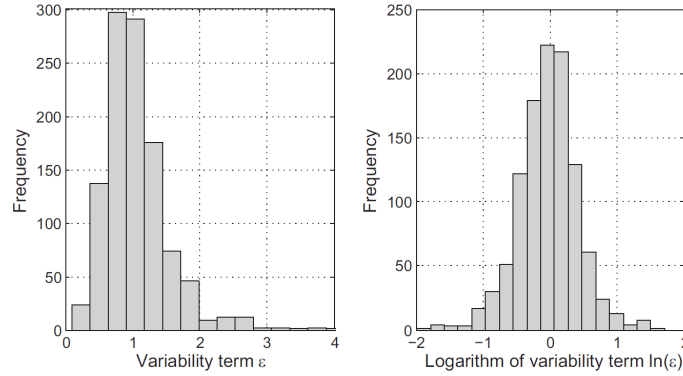


Figure 17: Histograms of  $\varepsilon$  and  $\ln(\varepsilon)$  for the OCR -  $(s_u/\sigma'_v)$  model proposed by Jamiolkowski et al. (1985).

图 17: Jamiolkowski et al. (1985) 提出的 OCR -  $(s_u/\sigma'_v)$  模型的  $\varepsilon$  和  $\ln(\varepsilon)$  直方图。

$$\begin{aligned} \text{Actual value} &= \text{predicted value} \times b \times [\alpha \times (\text{PI}/20)^\beta] \times \varepsilon' \\ &= \text{predicted value} \times b' \times \varepsilon' \end{aligned} \quad (6)$$

where  $b'$  is the updated bias factor and can be expressed as the product of the original bias  $b$  and a correction term  $\alpha \times (\text{PI}/20)^\beta$

其中  $b'$  是更新的偏差因子, 可以表示为原始偏差  $b$  与校正项  $\alpha \times (\text{PI}/20)^\beta$  的乘积

$$b' = b \times [\alpha \times (\text{PI}/20)^\beta] = b \times (\text{bias correction factor}) \quad (7)$$

The term  $\alpha \times (\text{PI}/20)^\beta$  is called the bias correction factor (BCF). In Table 6, the updated bias factors  $b'$  are shown in the format of  $b' = (\text{original } b) \times [\text{BCF}]$ . The sample COV of epsilon (the updated variability term) is denoted by delta. In Table 6,  $\delta'$  values are shown in the format of are shown in the format of  $\delta' = (\text{original } \delta) \times (\text{CCF}\%)$ , where CCF denotes the COV correction factor.

It is apparent that when the target parameter is  $\sigma'_p/P_a$  or OCR, the BCFs are always decreasing functions of PI ( $\beta < 0$ ). This implies that clays with larger PI values tend to have lower  $\sigma'_p/P_a$  and OCR values. For the CPTU -  $(s_u/\sigma'_v)$  model proposed by Ching and Phoon (2012a), the target parameter is the CPTU cone factors (namely  $(q_t - \sigma_v)/s_u$ ,  $(q_t - u_2)/s_u$  and  $(u_2 - u_0)/s_u$ ), the BCFs are increasing functions

项  $\alpha \times (\text{PI}/20)^\beta$  称为偏差校正因子 (BCF)。在表6中, 更新的偏差因子  $b'$  以  $b' = (\text{original } b) \times [\text{BCF}]$  的格式显示。 $\varepsilon'$  的样本 COV (更新的可变性项)  $\delta'$ 。在表6中,  $\delta'$  以  $\delta' = (\text{original } \delta) \times (\text{CCF}\%)$  的格式显示, 其中 CCF 表示 COV 校正因子。

显然, 当目标参数为  $\sigma'_p/P_a$  或 OCR 时, BCF 始终是 PI 的递减函数 ( $\beta < 0$ )。这意味着具有较大 PI 值的黏土往往具有较低的  $\sigma'_p/P_a$  和 OCR 值。对于 Ching and Phoon (2012a) 提出的 CPTU -  $(s_u/\sigma'_v)$  模型, 目标参数是 CPTU 锥因子 (即  $(q_t - \sigma_v)/s_u$ ,

of PI ( $\beta > 0$ ). This implies that clays with larger PI tend to have larger cone factors, hence smaller  $s_u$ . This observation is known (Aas et al. 1986; Marsland and Powell 1988; Powell and Quarterman 1988) although it has not been established with statistical rigor using such a large database. The CCFs are fairly close to 100%, indicating that the inference using PI does not significantly reduce the transformation uncertainties.

For the inference using PI and  $S_t$ , it is possible to express  $\varepsilon$  as

$$\varepsilon = [\alpha \times (\text{PI}/20)^\beta \times S_t^\gamma] \times \varepsilon' \quad (8)$$

The coefficients  $\alpha, \beta$  and  $\gamma$  can be estimated using linear regression on the  $\ln(\varepsilon) - \ln(\text{PI}) - \ln(S_t)$  data points. Namely, the following regression model is used:

$$\ln(\varepsilon) \approx \ln(\alpha) + \beta \ln(\text{PI}/20) + \gamma \ln(S_t) \quad (9)$$

where  $\ln(\varepsilon)$  is the known output, and  $\ln(\text{PI}/20)$  and  $\ln(S_t)$  are the known inputs, whereas  $\ln(\alpha)$ ,  $\beta$  and  $\gamma$  are the intercept and gradients to be estimated by the least-squares method. Once the least-squares estimates for  $\ln(\alpha)$ ,  $\beta$  and  $\gamma$  are obtained, the term  $\alpha \times (\text{PI}/20)^\beta \times S_t^\gamma$  is now the BCF. Table 6 shows the updated bias factors  $b'$  in the format of  $b' = (\text{original } b) \times [\text{BCF}]$  and the updated  $\delta'$  in the format of  $\delta' = (\text{original } \delta) \times (\text{CCF}\%)$  for the inference using PI and  $S_t$ . It is apparent that when the target parameter is  $s_u/\sigma'_v$  or  $s_u/\sigma'_p$ , these BCFs are always increasing functions of  $S_t$  ( $\gamma > 0$ ), implying that clays with larger  $S_t$  values tend to have larger  $s_u/\sigma'_v$  and  $s_u/\sigma'_p$  values. When the target parameter is CPTU cone factors, these BCFs are decreasing functions of  $S_t$  ( $\gamma < 0$ ). This implies that clays with larger  $S_t$  values tend to have smaller cone factors, hence larger  $s_u$  values. The updated COV ( $\delta'$ ) is typically noticeably less than the original  $\delta$  value in Table 5. There are two possible explanations for such uncertainty reduction:

1. The uncertainty is indeed effectively reduced with the inclusion of  $S_t$  as a secondary explanatory variable.
2. The number of  $\ln(\varepsilon) - \ln(\text{PI}) - \ln(S_t)$  data points is substantially less than the number of  $\ln(\varepsilon) - \ln(\text{PI})$  data points (see the “ $n$ ” column in Table 5). The former  $n$  is typically around 100 to 200, except two models where  $n$  is around 400, while the latter  $n$  is about 2 to 5 times

$(q_t - u_2)/s_u$ , 以及  $(u_2 - u_0)/s_u$ , BCF 是 PI 的增函数 ( $\beta > 0$ )。这意味着具有较大 PI 的黏土往往具有较大的圆锥系数, 因此  $s_u$  较小。这种结论是可信的 (Aas et al. 1986; Marsland and Powell 1988; Powell and Quarterman 1988), 尽管还没有使用如此庞大的数据库以统计上的严格性来建立它。CCF 相当接近 100%, 这表明使用 PI 进行推理并不能显著减少变换的不确定性。

对于使用 PI 和  $S_t$  进行推理, 可以将  $\varepsilon$  表示为

可以使用  $\ln(\varepsilon) - \ln(\text{PI}) - \ln(S_t)$  数据点上的线性回归来估计系数  $\alpha$ ,  $\beta$  和  $\gamma$ 。即使用以下回归模型:

其中  $\ln(\varepsilon)$  是已知输出, 而  $\ln(\text{PI}/20)$  和  $\ln(S_t)$  是已知输入, 而  $\ln(\alpha)$ ,  $\beta$  和  $\gamma$  是通过最小二乘法估计的相交和渐变。一旦获得了  $\ln(\alpha)$ ,  $\beta$  和  $\gamma$  的最小二乘估计, 则  $\alpha \times (\text{PI}/20)^\beta \times S_t^\gamma$  项即为 BCF。表 6 显示了使用 PI 和  $S_t$  进行推导的  $b' = (\text{original } b) \times [\text{BCF}]$  格式的更新的偏差因子  $b'$  和  $\delta' = (\text{original } \delta) \times (\text{CCF}\%)$  格式的更新的  $\delta'$ 。很明显, 当目标参数为  $s_u/\sigma'_v$  或  $s_u/\sigma'_p$ , BCF 始终是  $S_t$  的增函数 ( $\gamma > 0$ ), 这意味着具有较大  $S_t$  值的黏土往往具有较大的  $s_u/\sigma'_v$  和  $s_u/\sigma'_p$ 。当目标参数是 CPTU 锥因子时, BCF 是  $S_t$  的递减函数 ( $\gamma < 0$ )。这意味着具有较大  $S_t$  值的黏土往往具有较小的圆锥系数, 因此具有较大的  $S_u$  值。通常, 更新后的 COV ( $\delta'$ ) 明显小于表 5 中的原始  $\delta$  值。对于这种降低不确定性有两种可能的解释:

1. 通过将  $S_t$  作为次要解释变量, 确实可以有效降低不确定性。
2.  $\ln(\varepsilon) - \ln(\text{PI}) - \ln(S_t)$  数据点的数量大大少于  $\ln(\varepsilon) - \ln(\text{PI})$  数据点的数量 (请参见表 5 中的 “ $n$ ” 列)。前者的  $n$  通常约为 100 到 200, 只有两个模型的  $n$  约为 400, 而后者

more. These relatively small numbers of the  $\ln(\varepsilon) - \ln(S_t)$  data points may not represent a “global” dataset. Hence, the resulting  $\delta'$  may look small.

的  $n$  大约是后者的 2 至 5 倍。这些相对较少的  $\ln(\varepsilon) - \ln(S_t)$  数据点可能无法表示“全局”数据集。因此，所得的  $\delta'$  看起来可能很小。

## 6 Implementation 实现

Tables 5 and 6 are useful for obtaining first-order estimates of the mean and COV of a clay parameter of interest (e.g.,  $s_u$  or  $\sigma'_p$ ) based on the test index at hand. These mean and COV estimates are essential for RBD. First of all, it is imperative to determine whether a transformation model is consistent with the CLAY/10/7490 database by checking the column “Comparison to the global database” and subcolumn “Fit to the trend?”. It is recommended to only adopt models that fit to the CLAY/10/7490 database. Using the well-known model developed by Jamiolkowski et al. (1985) as an example, suppose  $\text{OCR} = 2$  is known, and the goal is to determine the mean and COV of  $s_u(\text{mob})/\sigma'_v$ . According to Table 5, this model fits well to the CLAY/10/7490 database and this fit is shown in Fig. 10. The second step is to extract the bias factor  $b = 1.11$  and  $\text{COV} = 0.53$  from the column “Calibration results”. Then, the mean of  $s_u(\text{mob})/\sigma'_v$  is computed as  $b \times 0.23 \times \text{OCR}^{0.8} = 1.11 \times 0.23 \times 2^{0.8} = 0.44$  and the data scatter around the mean is quantified by  $\text{COV} = 0.53$ .

In the case where  $\text{PI} = 15$  and  $S_t = 10$  information is also available, one can extract the bias correction factor (BCF) and COV correction factor (CCF) from the column “Inference results” and subcolumn “Inference based on  $\text{PI}$  and  $S_t$ ” in Table 6. Thus,  $\text{BCF} = 0.71 \times (\text{PI}/20)^{0.133} \times S_t^{0.123} = 0.71 \times (15/20)^{0.133} \times 10^{0.123} = 0.907$  and  $\text{CCF} = 67\%$ . As a result, the mean for  $s_u(\text{mob})/\sigma'_v$  becomes  $0.44 \times 0.907 = 0.403$  and the COV becomes  $0.53 \times 67\% = 0.36$ . Updating the mean and COV of  $s_u(\text{mob})/\sigma'_v$  based on other measured pieces of information (for example,  $\text{PI}$ ,  $S_t$ ,  $(q_t - \sigma_v)/\sigma'_v$ , and  $B_q$  may have been simultaneously measured in close proximity at the same depth in a site investigation report) is possible once the multivariate probability distribution among these clay parameters is established. This is addressed in a companion paper (Ching and Phoon, 2014).

表5和表6用于基于手边的测试指数获得感兴趣的黏土参数（例如， $s_u$  或  $\sigma'_p$ ）的平均值和 COV 的一阶估计。这些均值和 COV 估计值对于 RBD 至关重要。首先，必须通过检查“与全局数据库比较”列和“适应趋势？”列来确定转换模型是否与 CLAY/10/7490 数据库一致。建议仅采用适合 CLAY/10/7490 数据库的模型。使用 Jamiolkowski et al. (1985) 开发的著名模型作为一个例子，假设  $\text{OCR} = 2$  是已知的，目标是确定  $s_u(\text{mob})/\sigma'_v$  的平均值和 COV。根据表5，此模型非常适合 CLAY/10/7490 数据库，并且该适合关系如图10所示。第二步是从“校准结果”列中提取偏差因子  $b = 1.11$  和  $\text{COV} = 0.53$ 。然后，将  $s_u(\text{mob})/\sigma'_v$  的平均值计算为  $b \times 0.23 \times \text{OCR}^{0.8} = 1.11 \times 0.23 \times 2^{0.8} = 0.44$ ，并用  $\text{COV} = 0.53$  量化围绕平均值的数据散布。

如果还提供  $\text{PI} = 15$  和  $S_t = 10$  的信息，则可以从“推断结果”列和子列“基于  $\text{PI}$  和  $S_t$  的推断”中提取偏差校正因子（BCF）和 COV 校正因子（CCF）。因此，表6中的  $\text{BCF} = 0.71 \times (\text{PI}/20)^{0.133} \times S_t^{0.123} = 0.71 \times (15/20)^{0.133} \times 10^{0.123} = 0.907$ ， $\text{CCF} = 67\%$ 。结果， $s_u(\text{mob})/\sigma'_v$  的平均值为  $0.44 \times 0.907 = 0.403$ ，COV 为  $0.53 \times 67\% = 0.36$ 。根据其他测得的信息（例如， $\text{PI}$ ， $S_t$ ， $(q_t - \sigma_v)/\sigma'_v$  和  $B_q$  可能同时在附近测量）更新  $s_u(\text{mob})/\sigma'_v$  的平均值和 COV。一旦在这些黏土参数之间建立了多元概率分布，就可能实现相同的深度。伴随文件对此进行了阐述 (Ching and Phoon, 2014)。

## 7 Conclusions 结论

In this paper, a global clay database is presented, and 24 transformation models among clay parameters in the literature are investigated. This database contains clays with a wide range of  $S_t$ ,  $\text{OCR}$ , and  $\text{PI}$  values and from a wide range of geographical locales. It is found that most of the 24 models fit to the data trends of the global database. There are few exceptions, and it is believed that the poor fit is due to

本文提出了一个全球黏土数据库，并研究了文献中 24 个黏土参数之间的转换模型。该数据库包含具有广泛的  $S_t$ ， $\text{OCR}$  和  $\text{PI}$  值且来自不同地理位置的粘土。发现这 24 个模型中的大多数都适合于全球数据库的数据趋势。几乎没有例外，并且认为拟合度较差是由于以

the fact that these models were developed by databases with a limited range of clay types (e.g., no quick clays are in the database or only clays of a single region were in the database).

The global database is further used to calibrate the biases and uncertainties for the models in literature. It is found that more recent models tend to have smaller biases. Also, the uncertainties calibrated by the global database are mostly larger than the uncertainties reported in the literature. The large uncertainties may be reduced by considering PI and  $S_t$  as secondary input parameters for the models. The biases are also updated after incorporating PI and  $S_t$ .

下事实:这些模型是由黏土类型范围有限的数据库开发的(例如,数据库中沒有快速黏土,或者只有单个区域的黏土在数据库中)。

全球数据库还用于校准文献中模型的偏差和不确定性。已经发现,较新的模型倾向于具有较小的偏差。此外,由全球数据库校准的不确定性大多大于文献中报道的不确定性。通过将 PI 和  $S_t$  作为模型的辅助输入参数,可以减少较大的不确定性。在合并 PI 和  $S_t$  之后,偏差也会更新。

## A Summary of database CLAY/10/7490 数据库 CLAY/10/7490 概览

Table 7: Basic information of the database CLAY/10/7490.

表 7: 数据库 CLAY/10/7490 的详细信息

Reference	Country	$n$	PI	LI	OCR	$S_t$	$s_u(\text{mob})/\sigma'_v$	CPTU
Aas et al. (1986)	Norway	12	—	—	1.5~10.0	—	—	—
Aas (1980)	Norway	2	—	—	—	—	0.30~0.33	—
Agarwal (1967)	UK	22	—	—	—	—	0.09~0.61	—
Akai and Adachi (1965)	Japan	6	27	0.54	—	—	—	—
Alberro and Santoyo (1973)	Mexico	85	284~363	0.71~1.19	—	—	0.03~0.68	—
Amerasinghe and Parry (1975)	UK	28	—	—	—	—	0.29~4.57	—
Andersen and Stenhamar (1982)	Brazil	16	47~102	1.09~1.63	1.6~7.4	2~5	0.31~5.44	—
Andersen et al. (1980)	Norway	11	—	—	1.0~50.0	—	0.04~7.78	—
Andresen and Bjerrum (1957)	Norway	18	12~32	0.48~0.95	—	2~5	—	—
Andersen and Stenhamar (1982)	Norway	3	—	—	1.6~40.0	—	—	—
Azzouz and Lutz (1986)	USA	33	29~69	0.18~0.47	1.0~1.4	—	0.04~0.20	Y
Azzouz et al. (1983)	Venezuela	10	42~57	0.45~0.78	1.1~3.3	—	0.14~0.20	Y
Balasubramaniam and Chaudhry (1976)	Thailand	10	82	—	—	—	0.07~0.87	—
Baligh et al. (1980)	USA	20	13~72	0.23~1.48	1.1~5.4	—	0.22~1.40	Y
Banerjee and Stipho (1978)	UK	2	26	0.36~0.38	1.0~1.2	—	0.15~0.22	—
Baracos et al. (1980)	Canada	9	36~64	-0.01~0.60	2.8~9.2	—	0.09~4.43	—
Battaglio et al. (1986)	Italy	15	—	—	21.0~36.4	—	—	Y
Berre and Bjerrum (1973)	Norway	14	10~88	0.61~1.04	1.0~1.8	5~11	0.19~0.41	—
Bishop (1971)	UK	14	39	0.06~0.21	2.1~16.0	1~2	0.39~4.89	—
Bishop et al. (1965)	UK	6	36~43	-0.14~-0.04	—	—	—	—
Bjerrum (1954)	Norway	246	3~33	-0.05~4.70	—	3~500	5.4	—
Bjerrum and Simons (1960)	—	35	7~92	0.28~3.43	—	2~100	—	—
Bjerrum and Lo (1963)	Norway	68	22~32	0.60~0.81	—	5	0.22~45.02	—
Bjerrum (1967)	Norway	89	4~41	0.61~3.22	—	2~300	0.05~0.25	—
Bjerrum (1969)	Norway	14	13~27	1.46~2.12	—	—	—	—
Bjerrum (1972)	—	6	11~85	0.3~1.1	—	—	—	—
Bjerrum (1973)	Norway	6	3~31	0.75~5.3	—	8~100	0.16~0.30	—
Bozozuk and Leonards (1972)	Canada	19	20~34	1.18~2.49	1.3~2.0	8~100	0.13~0.55	—
Broms and Ratnam (1963)	Norway	3	—	—	3.5~13.0	—	—	—
Burland et al. (1977)	UK	14	19~46	-0.19~-0.01	—	—	0.59~2.43	—

(Continued on next page)



(Continued to Table 7)

Reference	Country	$n$	PI	LI	OCR	$S_t$	$s_u(\text{mob})/\sigma'_v$	CPTU
Cadling and Odenstad (1950)	Sweden	136	22~88	0.77~1.24	—	2~167	0.06~0.29	—
Calabresi and Manfredini (1973)	Italy	1	33	0.24	—	—	—	—
Campanella et al. (1988)	Canada	20	—	—	1.0~4.5	12~25	—	Y
Cancelli (1981)	Italy	13	20~39	0.03~0.26	—	—	0.14~1.79	—
Cancelli and Cividini (1984)	Italy	5	31~39	0.04~0.44	1.0~26.7	—	0.23~4.00	Y
Carrier and Beckman (1984)	USA	14	110~165	0.5~1.43	—	—	—	—
Carter and Bentley (1991)	UK	24	—	-0.11~1.90	—	1~141	—	—
Chandler (1969)	UK	1	10	-0.75	—	—	—	—
Chandler (1988)	—	22	4~100	0.47~4	1~6.3	2~80	0.15~0.36	—
Chang (1991)	Singapore	13	18~87	0.33~0.95	0.8~1.9	3.1	0.10~0.62	Y
	Malaysia	11	33~79	0.51~1.77	1.3~3.5	3.6~5.0	0.26~0.63	Y
Chen and Hsieh (1996)	Taiwan	23	11~24	0.64~1.36	1.1~1.5	4~5	—	Y
Chen (2001)	Taiwan	12	—	—	—	—	—	—
Chen and Kulhawy (1993)	—	195	9~85	-0.44~2.40	1.0~39.0	3~128	0.03~2.48	—
Chin and Liu (1997)	Taiwan	12	—	—	1.0~4.1	—	0.18~0.90	—
Chin et al. (1989)	Taiwan	32	8~26	—	1.0~8.0	—	—	—
Clough and Denby (1980)	China	29	35~52	0.51~1.95	—	—	0.09~0.23	—
Cooling and Skempton (1942)	UK	113	36~67	-0.03~0.06	—	—	—	—
Coutinho (2007)	Brazil	12	27~168	0.50~2.23	0.9~2.2	5~14	0.24~0.91	Y
Cox et al. (1979)	USA	51	10~69	0.05~0.80	—	—	—	—
Crawford (1959)	Canada	3	14~27	0.53~1.21	—	3~6	—	—
Crawford (1964)	Canada	9	—	—	—	—	—	—
Crawford and Campanella (1991)	Canada	8	—	—	1.4~3.8	20~122	—	Y
Crawford and Eden (1965)	Canada	10	14~36	0.9~2.5	1.5~7.9	10~500	0.31~2.63	—
Croce et al. (1969)	Italy	14	23~47	-0.11~0.55	1.5~4.7	1~8	0.07~1.30	—
Crooks (1981)	Northern Ireland	15	—	—	1.4~2.8	—	0.31~0.71	—
Crooks and Graham (1976)	Canada	22	22~63	0.61~1.37	0.9~1.7	4~10	—	—
Cummings et al. (1950)	USA	10	4~18	0.20~0.97	—	—	—	—
D'Appolonia et al. (1971)	USA	1	17	0.7	9.3	—	0.77	—
D'Appolonia and Saad (1972)	Norway	104	—	—	1.0~37.5	—	—	—
Da Cruz (1963)	Brazil	15	—	—	0.6~3.4	—	—	—
Dascal and Tournier (1975)	Canada	11	9~12	1.11~3.89	1.4~35.8	—	0.28~0.85	—
DeGroot and Lutenegeger (2003)	USA	64	11~30	0.04~2.87	1.4~9.5	6~43	0.17~1.25	—
De Lory and Salvas (1967)	Canada	40	19~59	0.84~1.31	—	—	0.13~1.84	—
De Lory and Salvas (1969)	Canada	33	17~46	0.50~1.94	—	—	0.13~0.32	—
DiBiagio and Stenhamar (1976)	Norway	6	5~11	1.68~3.71	—	18~74	—	—
Donaghe and Townsend (1978)	USA	28	—	—	—	—	0.02~1.05	—
Duncan and Seed (1966)	USA	10	—	—	3.0~18.0	—	0.33~1.35	—
Eden and Bozozuk (1962)	Canada	9	15~40	1.32~2.12	1.2~1.9	8~18	0.31~0.38	—
Eden and Crawford (1957)	Canada	36	5~56	0.81~4.13	1.6~4.4	36~1467	0.49~1.46	—
Eden and Hamilton (1957)	Canada	49	5~56	0.63~4.4	1.0~3.5	4~1160	0.26~2.64	—
Eden and Kubota (1961)	Canada	113	—	0.66~3.10	—	1~307	—	—
Eden and Law (1980)	Canada	5	28~46	—	2.0~3.0	—	0.53~1.03	Y
Eden and Poorooshasb (1968)	Canada	12	18~26	0.57~2.90	—	—	—	—
Egashira and Ohtsubo (1982)	Japan	14	8~96	0.48~3.63	—	19~970	—	—

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(Continued to Table 7)

Reference	Country	$n$	PI	LI	OCR	$S_t$	$s_u(\text{mob})/\sigma'_v$	CPTU
Eide and Holmberg (1972)	Thailand	9	83~108	0.76~0.93	1.6~2.2	6~10	0.33~0.47	—
Endley et al. (1979)	USA	24	13~56	-0.10~0.69	—	—	—	—
Esu and Calabresi (1969)	Italy	3	44~51	0.1~0.16	—	—	—	—
Feyling-Hanssen (1957)	Norway	10	8~26	-0.20~0.88	—	—	—	—
Finno (1989)	USA	17	15~21	0.20~2.59	0.8~4.2	2~3	—	Y
Flaate and Preber (1974)	Norway	18	6~33	0.09~0.48	—	—	0.06~0.91	—
Focht and Drash Jr. (1991)	Mexico	108	8~41	-0.52~3.95	—	—	0.07~27.75	—
Gregersen (1979)	Norway	19	6~13	0.56~2.67	—	13	—	—
Gregersen and Løken (1979)	Norway	37		0.14~2.46	—	2~185	—	—
Hansen and Clough (1980)	—	8	10~105	0.65~1.04	—	5~11	—	—
Hanzawa (1977a)	Iraq	11	34~36	0.62~0.73	—	—	0.83~2.35	—
Hanzawa (1977b)	Iraq	31	11~31	0.65~1.10	1	—	0.09~0.37	—
Hanzawa (1979)	Japan	60	—	—	—	—	—	—
Hanzawa et al. (1979)	Iraq	12	35~38	0.63~0.66	1.3~5.7	—	0.32~0.92	—
Hanzawa (1981)	Japan	3	—	—	—	—	0.20~0.23	—
Hara et al. (1974)	Japan	182	10~92	—	1.0~3.0	—	—	—
Harris et al. (1995)	France	67	—	0.33~1.66	—	—	—	—
Helenelund (1977)	Sweden	36	22~94	—	—	—	0.15~0.31	—
Henkel and Sowa (1963)	England	59	—	—	—	—	—	—
Henry and Henry (1957)	Hong Kong	22	—	—	—	—	—	—
Hight et al. (1992)	UK	9	24~44	—	1.3~1.6	—	0.38~0.64	Y
Holmberg (1977)	Thailand	52	57~105	0.63~1.16	1.4~2.5	5~15	0.20~4.72	—
Holtz and Baker (1972)	USA	22	10~16	-0.45~0.45	—	—	—	—
Holtz and Holm (1979)	Sweden	13	74~114	0.66~0.99	1.3~3.0	—	—	—
Hong et al. (2010)	Korea	17	—	—	—	—	0.17~0.27	Y
Horn and Lambe (1964)	USA	12	14~31	0.37~0.81	0.8~4.0	4~10	0.07~0.50	—
Hutchinson (1969)	UK	2	31~51	-0.16~0.02	—	—	—	—
Jamiolkowski et al. (1988)	Italy	17	—	—	7.9~20.7	—	—	—
Janbu et al. (1977)	Norway	7	3~11	-0.25~0.71	—	3~14	—	—
Jardine et al. (2003)	UK	13	41~95	0.44~0.98	—	1~11	—	—
Karlsrud and Myrvoll (1976)	Norway	25	20~27	0.60~3.60	—	—	0.17~0.64	—
Karlsson and Pusch (1967)	Sweden	11	24~42	0.34~2.75	—	14~307	0.23~1.37	—
Kenney (1966)	Norway	40	10~36	0.52~2.86	—	3~60	0.02~2.71	—
Kinner and Ladd (1970)	USA	62	—	—	1.0~24	—	0.05~2.07	—
Kitago et al. (1976)	Japan	4	—	—	—	—	—	—
Kjekstad and Lunne (1981)	Norway	29	19~34	-0.15~0.28	—	—	0.26~1.64	—
Konrad and Law (1987b)	Canada	29	3~37	0.50~4.51	1.0~4.9	7~35	0.34~1.66	Y
Konrad and Law (1987a)	Canada	17	—	—	1.0~2.6	—	—	Y
Koumoto (1990)	Japan	58	43~298	0.16~1.24	—	—	—	—
Koumoto and Houlsby (2001)	Japan	74	14~293	0.00~1.45	—	—	—	—
Koutsoftas and Fischer (1976)	USA	95	13~50	0.28~1.14	1.0~29.5	108~414	0.19~2.55	—
Koutsoftas (1978)	USA	21	13~41	0.66~1.17	1.0~4.0	—	—	—
Koutsoftas (1981)	USA	19	—	—	1.0~11.7	—	0.20~1.72	—
Koutsoftas and Ladd (1985)	USA	20	—	—	1.0~7.7	—	0.23~1.16	—
Koutsoftas et al. (1987)	Hong Kong	13	12~66	0.19~1.82	1.9~3.8	5.5	0.33~1.13	Y

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Reference	Country	$n$	PI	LI	OCR	$S_t$	$s_u(\text{mob})/\sigma'_v$	CPTU
Kulhawy and Mayne (1990)	—	159	9~80	-0.44~2.4	1	—	0.14~0.27	—
Kulkarani et al. (1967)	India	5	39~65	0.57~1.00	0.7~1.0	3~4	0.12~0.23	—
Lacasse et al. (1977)	Canada	20	—	—	1.0~2.9	—	—	—
	USA	7	—	—	1.0~4.8	—	—	—
Lacasse et al. (1981)	Norway	11	—	—	1.1~2.7	—	0.19~0.45	—
Lacasse et al. (1985)	Norway	17	4~43	0.94~5.50	1.4~7.1	—	0.24~0.65	—
Ladd (1964)	USA	22	—	—	5.7~6.2	—	0.09~2.07	—
Ladd (1965)	USA	8	—	—	—	—	0.21~0.67	—
Ladd (1967)	USA	16	—	—	—	—	—	—
Ladd (1972)	USA	43	8~29	0.60~2.52	1.3~7.8	—	0.23~1.84	—
Ladd (1973)	USA	12	—	—	—	—	—	—
Ladd (1981)	USA	7	20~55	—	—	—	0.11~0.22	—
Ladd (1991)	USA	100	5~85	1.08~2.32	1.0~16.4	4~8	0.07~0.81	—
Ladd et al. (1971)	USA	6	45	1.04	1.0~8.1	8	0.20~0.94	—
Ladd et al. (1972)	USA	14	7~23	0.78~2.52	1.3~2.8	7~10	0.20~1.50	—
Ladd et al. (1977)	—	10	—	—	3.0~18.2	—	—	—
Ladd and Azzouz (1983)	Venezuela	75	12~57	-0.67~0.67	1.0~2.7	—	0.16~0.57	—
Ladd et al. (1971)	USA	108	7~88	—	1.0~12.1	5~100	0~1.60	—
Ladd and Foott (1974)	USA	22	10~39	0.57~2.68	1.0~4.9	—	0.17~4.37	—
Ladd and Lambe (1963)	—	39	8~80	—	1.0~3.0	5~10	0.07~0.61	—
Lafleur et al. (1988)	Canada	10	33~47	1.21~1.72	1.1~6.1	14	0.26~1.42	Y
Lacasse and Lunne (1982)	Norway	109	16~72	0.28~1.87	1.0~13.5	3~7	0.05~1.95	Y
Lambe (1964)	Venezuela	10	—	—	—	—	0.06~0.24	—
La Rochelle et al. (1974)	Canada	23	8~35	1.14~3.25	2.0~5.2	—	0.52~0.98	—
La Rochelle et al. (1988)	Canada	3	15~44	1.39~1.69	1.1~3.5	—	0.24~0.53	Y
Larsson (1980)	Norway	4	7~53	—	—	—	0.19~0.25	—
Larsson and Mulabdic (1991)	Sweden	50	29~86	0.84~1.49	1.1~4.2	—	0.20~0.67	Y
Landva et al. (1988)	Canada	26	6~21	0.74~2.63	2.2~4.0	—	—	—
Leathers and Ladd (1978)	USA	7	32~46	0.66~1.00	1.1~9.9	—	0.28~0.94	—
Lefebvre and LeBoeuf (1987)	Canada	26	—	—	—	—	0.19~0.25	—
Lembo Fazio et al. (1984)	Italy	1	28	-0.25	—	—	—	—
Leon and Alberro (1977)	Mexico	7	—	—	—	—	—	—
Leroueil et al. (1983)	Canada	10	20~43	1.11~2.87	1.4~2.6	—	0.37~0.76	—
Lew (1981)	Canada	6	—	—	—	—	0.04~0.15	—
Liu (1999)	Taiwan	53	6~26	—	—	—	0.18~0.37	—
Lo and Stermac (1963)	Canada	13	49~55	—	—	—	—	—
Locat and Demers (1988)	Canada	49	11~37	0.59~2.44	—	8~82	—	—
Long and Menkiti (2007)	UK	2	—	—	—	—	—	—
Lowe and Karafiath (1960)	Venezuela	11	—	—	—	—	0.42~2.22	—
Lumb and Holt (1968)	Hong Kong	25	57~117	0.70~1.11	—	—	0.15~1.81	—
Lunne et al. (1981)	UK	91	10~40	-0.71~1.08	1.7~55.6	—	—	—
Lunne et al. (1985)	Norway	39	15~29	0.08~0.37	—	—	0.13~1.87	Y
	Norway	188	10~36	-0.12~1.42	1.3~6.8	—	0.06~2.02	—
Lunne et al. (1986)	Norway	9	13~39	0.66~0.86	1.2~15.5	—	0.34~1.75	Y
Mahar and O'Neill (1983)	USA	4	6~29	0.19~0.72	3.7~5.0	—	0.65~2.85	Y

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Reference	Country	$n$	PI	LI	OCR	$S_t$	$s_u(\text{mob})/\sigma'_v$	CPTU
Massarsch et al. (1975)	Sweden	41	22~128	0.50~2.77	0.9~2.7	8~36	0.14~0.74	—
Massarsch and Broms (1976)	Sweden	17	35~62	0.51~1.53	1.1~2.7	11~36	0.25~0.73	—
Mayne (1980)	USA	7	—	—	1.0~21.1	—	—	—
Mayne (1985b)	USA	64	—	—	1.0~75.0	—	0.24~0.33	—
Mayne (1985a)	—	87	2~105	—	1	—	0.12~0.54	—
Mayne (1988)	—	419	—	—	0.9~60.2	—	0.12~7.20	—
Mayne (1989)	USA	13	—	—	2.3~9.3	—	—	Y
Mayne (1991)	USA	19	—	—	1.7~3.5	—	—	Y
Mayne (2008)	—	43	—	—	1.3~4.3	—	—	Y
Mayne and Holtz (1985)	USA	66	—	—	—	—	0.16~0.54	—
Mitchell et al. (1972)	Canada	12	6~61	0.63~6.45	—	6~310	—	—
Mitachi and Kitago (1976)	Japan	21	—	—	—	—	—	—
Mitchell (1956)	USA	4	—	—	1.0~7.7	—	—	—
Mishtak (1964)	Canada	1	74	0.44	—	—	—	—
Moh et al. (1969)	Thailand	9	37~59	0.08~0.84	1.2~24.0	2~5	0.74~4.78	—
Morin et al. (1983)	Canada	57	10~43	0.67~2.22	1.1~54.2	—	0.28~6.75	—
Moum and Rosenqvist (1961)	USA	12	27~261	0.18~0.97	—	3~9	0.13~0.46	—
Nakase and Kamei (1983)	Japan	40	11~29	—	—	—	0.24~0.67	—
Nakase and Kamei (1986)	Japan	18	—	—	—	—	0.22~0.45	—
Nakase and Kamei (1988)	Japan	12	11~56	—	—	—	0.26~0.30	—
Newland and Allely (1957)	New Zealand	16	—	0.04~1.21	—	—	—	—
Ng and Lo (1985)	Canada	30	19~51	—	1.2~2.0	4~9	0.17~0.44	—
Niazi et al. (2010)	UK	9	—	—	2.9~11.5	—	0.62~1.95	Y
Ohtsubo et al. (1982)	Japan	19	—	0.39~3.41	—	13~759	0.52~4.15	—
Ohtsubo et al. (1995)	Japan	18	41~102	1.06~2.62	0.8~2.5	11~34	—	—
Ohtsubo et al. (2007)	Japan	9	16~96	0.89~1.55	0.8~5.1	4~1000	0.27~0.67	—
Olsen et al. (1986)	USA	73	11~33	0.65~2.70	1	—	0.15~1.44	—
O'Riordan et al. (1982)	UK	14	9~96	—	—	—	—	—
Ou and Hsiao (1994)	Taiwan	37	—	0.73~2.22	1.0~5.9	—	0.22~0.45	—
Parry (1960)	England	14	—	—	1.0~24.5	—	0.31~1.22	—
Parry (1968)	Australia	68	93~106	—	—	2	0.02~1.33	—
Parry and Nadarajah (1974)	UK	17	—	0.74~1.21	—	—	0.35~0.46	—
Parry and Wroth (1981)	Canada	8	14~23	—	1.1~3.9	10~115	0.05~0.74	—
Phoon (2013)	Singapore	12	13~52	0.86~2.83	1.2~26.2	—	0.16~4.39	Y
Powell and Quarterman (1988)	UK	42	24~57	0.10~1.17	1.4~3	—	0.21~4.14	Y
Prevost and Hoeg (1977)	Norway	11	29~85	0.57~1.02	1~4	—	0.42~0.99	—
Prevost (1979)	—	3	18~85	—	—	—	0.26~0.63	—
Quiros and Young (1988)	USA	8	—	—	1.0~6.2	—	0.19~0.65	—
Rad and Lunne (1988)	—	79	4~87	—	1.2~12	—	0.04~1.37	Y
Ramalho-Ortigao et al. (1983)	Brazil	35	48~92	0.17~5.75	—	1~6	—	—
Raymond (1973)	Canada	11	8~49	1.22~1.64	1.0~2.5	2~11	—	—
Raymond et al. (1971)	Canada	31	20~57	0.10~0.98	—	5~22	0.20~0.35	—
Rocha Filho and Alencar (1985)	Brazil	8	44~63	0.66~2.60	1.6~2.1	2~8	—	Y
Roy et al. (1982)	Canada	19	10~37	0.03~2.08	2.3~6.1	—	0.28~1.12	—
Sanchez et al. (1979)	UK	10	—	—	1.0~2.0	—	0.13~0.38	—

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Reference	Country	$n$	PI	LI	OCR	$S_t$	$s_u(\text{mob})/\sigma'_v$	CPTU
Schofield and Wroth (1968)	UK	36	11~145	—	—	—	0.08~0.99	—
Schwab and Broms (1976)	Sweden	34	86~103	0.68~1.03	—	—	—	—
Seed and Reese (1957)	USA	26	—	—	—	—	—	—
Senneset and Janbu (1985)	Norway	13	4~10	0.40~2.69	—	—	0.08~0.63	Y
Senneset et al. (1988)	Norway	18	—	—	1.0~2.4	—	—	Y
Sherif et al. (1972)	USA	46	—	—	1.0~32.0	—	—	—
Silvestri and Aubertin (1988)	Canada	9	39~48	0.64~1.41	2.9~7.2	6~24	0.71~1.41	—
Simons (1960)	Norway	12	12~20	—	—	3~20	0.05~0.13	—
Simons (1976)	UK	7	11~85	—	—	—	0.18~0.47	—
Skempton (1948b)	UK	17	39~77	0.26~1.04	0.8~1.4	1~4	—	—
Skempton (1948a)	UK	17	18~34	0.42~0.90	—	2~3	0.46~55.61	—
Skempton (1950)	South Africa	8	61~83	0.31~0.44	2.1~2.3	4~5	—	—
Skempton (1957)	Hong Kong	28	9~59	-0.11~0.77	—	—	0.29~2.53	—
Skempton (1961)	UK	23	57~70	-0.11~0.06	1.4~44.0	—	0.43~1.34	—
Skempton and Bishop (1954)	—	14	13~75	-0.16~0.76	1	1~8	0.10~0.21	—
Skempton and Henkel (1953)	UK	26	15~118	0.13~0.87	0.9~2.8	2~7	0.20~2.30	—
Skempton and Northey (1953)	—	23	13~61	0.48~1.3	—	1~19	—	—
Skempton and Sowa (1963)	UK	51	—	—	—	—	0.09~0.97	—
Strachan (1960)	New Zealand	4	8~14	-0.08~0.33	1.2~1.4	—	—	—
Stille and Fredriksson (1979)	Sweden	15	15~33	1.02~1.54	—	4~22	0.15~0.26	—
Tan et al. (2003)	Singapore	43	20~73	0.27~0.68	—	—	0.08~0.16	—
Tanaka and Sakagami (1989)	Japan	7	66~79	0.25~0.53	0.5~0.8	—	—	Y
Tanaka et al. (2003)	Japan	14	36~45	0.63~1.52	—	—	0.52~2.57	—
Tani and Craig (1995)	Japan	5	—	—	—	—	—	—
Tavenas et al. (1975)	Canada	15	10~37	1.43~4.14	1.8~2.2	—	0.62~1.10	—
Tavenas et al. (1978)	Canada	20	25~52	0.62~1.30	—	—	—	—
Tavenas and Leroueil (1978)	Canada	7	—	—	—	—	0.16~3.17	—
Tschuschke and Waliński (2005)	Poland	8	19~29	0.66~1.67	—	—	—	Y
Tschuschke (2010)	Poland	16	—	—	—	—	—	Y
Tsuchida et al. (1999)	Japan	44	22	0.49~4.08	—	—	—	—
Tumay and Acar (1985)	USA	7	32~80	0.24~0.74	1.1~1.8	—	—	—
Vaid et al. (1979)	Canada	1	16	1.38	—	100	—	—
Ward et al. (1959)	UK	7	40~52	-0.03~-0.19	—	—	—	—
Wei et al. (2010)	USA	14	31~68	0.27~0.61	—	—	0.05~7.22	Y
Windle and Wroth (1977)	UK	8	—	—	—	—	—	—
Wroth and Houlsby (1985)	USA	15	12~41	0.59~1.31	1.0~5.6	—	0.19~0.90	—
Wu (1958)	USA	70	7~32	0.13~1.25	0.8~3.0	2~50	0.10~0.84	—
Wu et al. (1962)	USA	16	—	—	—	2~8	0.13~0.16	—
Wu et al. (1963)	USA	23	—	—	—	—	0.20~0.38	—
Wu et al. (1975)	USA	17	—	—	1.3~15.4	—	0.26~1.06	—
Wu et al. (1978)	USA	12	—	—	1.0~3.3	—	0.18~0.55	—
YASUHARA et al. (1982)	Japan	9	—	—	—	—	0.13~0.44	—
Zreik et al. (1995)	USA	12	20	0.48~5.63	—	—	—	—

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