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ARTICLE

Transformations and correlations among some clay parameters — the global database

Jianye Ching and Kok-Kwang Phoon

Abstract: 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.

Résumé : Cette étude compile une grande base de données de 10 paramètres d'argile (appelée CLAY/10/7490) provenant de 251 études, couvrant des données d'argile de 30 régions ou pays à travers le monde. Ainsi, la gamme de données couverte par cette base de données « globale » est plus vaste que celle utilisée pour calibrer les modèles de transformation existants dans la littérature. Ces modèles de transformation relient des mesures d'essais (par exemple la résistance à la pointe du cône) aux paramètres de conception appropriés (par exemple la résistance au cisaillement non drainé). Les comportements de corrélation démontrés par la base de données pour les 10 paramètres de l'argile sont consistants avec ceux démontrés par les modèles de transformation dans la littérature. Les biais et les incertitudes de transformation de ces modèles par rapport à la base de données globale sont calibrés. Il est démontré que les modèles de transformation plus récents sont moins biaisés et que les incertitudes de transformation sont généralement relativement grandes. De telles incertitudes de transformation sont encore plus réduites par l'ajout de paramètres d'entrée secondaires, comme l'indice de plasticité ou la sensibilité. Dans un article compagnon écrit par les mêmes auteurs, une distribution de probabilité multivariables à 10 dimensions couplée aux paramètres de l'argile est construite à partir de la base de données CLAY 10/7490. De plus, on présente une application intéressante impliquant la mise à jour de la distribution de probabilité bivariable pour deux paramètres de conception à partir de trois mesures séparées. [Traduit par la Rédaction]

Mots-clés : propriétés de l'argile, corrélations, modèles de transformation, base de données, statistiques.

Introduction

Geotechnical variability is a complex attribute that needs careful evaluation. Phoon and Kulhawy (1999*a*) demonstrated using fairly 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 (Der 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 (1999*b*) 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 (1999*a*, 1999*b*) advocated that the calibration of geotechnical RBD equations

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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 (1999*a*, 1999*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 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 1999*a*). 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 (1999*a*), 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 (2012*a*) demonstrated the construction of "global" models. Global models are calibrated from global databases covering many sites and geomaterial types. Ching and Phoon (2012*a*) observed that site-specific models are

Table 1. Databases compiled by the authors.

Database	Reference	Parameters of interest	No. of data points	No. of sites or studies	Range of properties		
					OCR	PI	S_t
CLAY/5/345	Ching and Phoon (2012*b*)	LI, s_u, s_u^{re}, σ'_p, σ'_v	345	37 sites	1~4	—	Sensitive to quick clays
CLAY/6/535	Ching et al. (2014)	s_u/σ'_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 s_u test types	6310	164 studies	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	This paper	LL, PI, LI, σ'_v/P_a, σ'_p/P_a, s_u/σ'_v, S_t, $(q_t - \sigma_v)/\sigma'_v$, $(q_t - u_2)/\sigma'_v$, B_q	7490	251 studies	1~10	Low to very high plasticity	Insensitive to quick clays

Fig. 1. (*a*) Plasticity chart; (*b*) Robertson's (1990) CPTU soil classification chart. B_q, pore pressure ratio; CH, high-plasticity clay; CL, low-plasticity 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; σ_v, total effective stress; σ'_v, vertical effective stress.

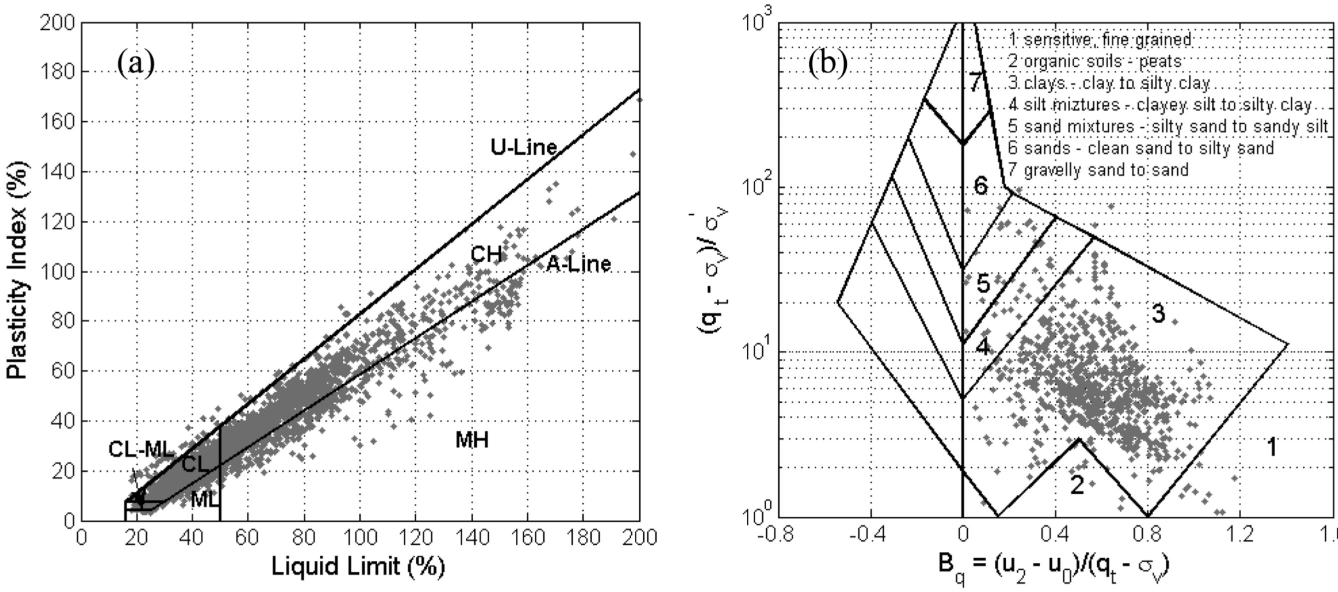


Table 2. Transformation models for s_u(mob).

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	$s_u(\text{mob})/\sigma'_v \approx s_u(\text{UC})/\sigma'_v \approx -0.073 + 1.018 s_u(\text{UU})/\sigma'_v$	Chen and Kulhawy (1993); Mesri and Huvaj (2007)
CIUC	$s_u(\text{mob})/\sigma'_v \approx s_u(\text{UC})/\sigma'_v \approx -0.278 + 1.172 s_u(\text{CIUC})/\sigma'_v$	Chen and Kulhawy (1993); Mesri and Huvaj (2007)
CK_0UC, DSS, CK_0UE	$s_u(\text{mob}) \approx \{[s_u(CK_0UC) + s_u(\text{DSS}) + [s_u(CK_0UE)]/3\}\mu_t$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
CK_0UC, CK_0UE	$s_u(\text{mob}) \approx \{[s_u(CK_0UC) + s_u(CK_0UE)]/2\}\mu_t$*	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
DSS	$s_u(\text{mob}) \approx [s_u(\text{DSS})]\mu_t$*	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
CK_0UC	$s_u(\text{mob}) \approx [s_u(\text{DSS})]\mu_t \approx [s_u(CK_0UC)][0.67\mu_t]$	Mesri and Huvaj (2007); Kulhawy and Mayne (1990)
CK_0UE	$s_u(\text{mob}) \approx [s_u(\text{DSS})]\mu_t \approx [s_u(CK_0UE)][1.53^{\dagger}(\mu_t)]$	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_0UC, K_0-consolidated undrained compression; DSS, direct simple shear; CK_0UE, K_0-consolidated undrained extension; μ, PI-dependent correction factor for s_u(FV) proposed in Bjerrum (1972); μ_t, PI-dependent strain rate correction factor proposed in Terzaghi et al. (1996).

*These equations are based on the following two facts: (*i*) $s_u(\text{mob}) \approx \{[s_u(CK_0UC) + s_u(\text{DSS}) + s_u(CK_0UE)]/3\}\mu_t$ and (*ii*) s_u(DSS) is roughly the average of $s_u(CK_0UC)$ and $s_u(CK_0UE)$ (Kulhawy and Mayne 1990).

†This constant of 1.53 is based on the following two facts: (*i*) $s_u(\text{DSS}) \approx 0.67 s_u(CK_0UC)$ (Kulhawy and Mayne 1990) and (*ii*) s_u(DSS) is roughly the average of $s_u(CK_0UC)$ and $s_u(CK_0UE)$.

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

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
σ'_v/P_a	3370	1.80	1.47	4.13E−3	38.74
σ'_p/P_a	2028	4.37	2.31	0.094	193.30
s_u/σ'_v	3532	0.51	1.25	3.68E−3	7.78
S_t	1589	35.0	2.88	1	1467
B_q	1016	0.58	0.35	0.01	1.17
$(q_t - \sigma_v)/\sigma'_v$	862	8.90	1.17	0.48	95.98
$(q_t - u_2)/\sigma'_v$	668	5.34	1.37	0.61	108.20
s_u/σ'_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. Sample percentiles of the data points in the database.

Variable	2.5%	5%	25%	50% (median)	75%	95%	97.5%
LL	23.6	26.2	39.0	54.3	76.0	149.1	200.0
PI	5.8	8.0	18.5	29.3	46.0	91.4	135.0
LI	−8.6E−2	4.7E−3	0.54	0.87	1.32	2.51	3.00
σ'_v/P_a	0.11	0.14	0.43	0.94	2.03	6.27	8.37
σ'_p/P_a	0.26	0.33	0.80	1.71	3.69	19.57	29.19
s_u/σ'_v	0.080	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/σ'_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

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 (2012*a*) 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,

Table 5. The transformation models in literature and their calibration results.

Type	Relationship	Literature	n	Transformation model	Remarks	Comparison to the global database: Figure	Comparison to the global database: Fit to the trend?	Calibration results: Bias factor, b	Calibration results: COV of $\varepsilon = \delta$ (value in literature)
A	LI–s_u^{re}/P_a	Wroth and Wood (1978)	899	$s_u^{re}/P_a \approx 1.7\exp(-4.6\text{LI})$	Based on modified Cam Clay model	Figure 2	No	—	—
		Locat and Demers (1988)	899	$s_u^{re}/P_a \approx 0.0144\text{LI}^{-2.44}$	—	Figure 2	Yes	1.92	1.25 (n/a)
	LI–S_t	Bjerrum (1954)	1279	$S_t \approx 10^{0.8\text{LI}}$	Norwegian marine clays	Figure 3	Yes	2.06	1.09 (n/a)
		Ching and Phoon (2012*b*)	1279	$S_t \approx 20.726\text{LI}^{1.910}$	Structured clays with $S_t = 2\sim1000$ and OCR = $1\sim4$	Figure 3	Yes	0.88	1.28 (1.19)
B	LI–σ'_v/P_a–S_t	Mitchell (1993)	694	—	Graphical curves	Figure 4	No	—	—
	LI–σ'_p/P_a–S_t	NAVFAC (1982)	492	—	Graphical curves	Figure 5	No	—	—
		Stas and Kulhawy (1984)	249	$\sigma'_p/P_a \approx 10^{1.11-1.62\text{LI}}$ (for $S_t < 10$ only)	—	Figure 6	Yes	2.94	1.90 (0.34)
		Ching and Phoon (2012*b*)	489	$\sigma'_p/P_a \approx 0.235\text{LI}^{-1.319}S_t^{0.536}$	Structured clays with $S_t = 2\sim1000$ and OCR = $1\sim4$	Figure 7	Yes	1.32	0.78 (0.73)
C	LI–s_u/σ'_p	Bjerrum and Simons (1960)	1072	—	Graphical curves; Norwegian NC clays	Figure 8	No	—	—
	PI–s_u/σ'_p	Mesri (1975, 1989)	1155	$s_u(\text{mob})/\sigma'_p \approx 0.22$	—	Figure 9	Yes	1.04	0.55 (n/a)
	OCR–s_u/σ'_v	Jamiolkowski et al. (1985)	1402	$s_u(\text{mob})/\sigma'_v \approx 0.23(\text{OCR})^{0.8}$	—	Figure 10	Yes	1.11	0.53 (n/a)
	OCR–s_u/σ'_v–S_t	Ching and Phoon (2012*b*)	395	$s_u(\text{mob})/\sigma'_v \approx 0.229(\text{OCR})^{0.823}S_t^{0.121}$	Structured clays with $S_t = 2\sim1000$ and OCR = $1\sim4$	Figure 11	Yes	0.84	0.34 (0.34)
D	CPTU–s_u/σ'_v	Ching and Phoon (2012*a*)	423	$[(q_t - \sigma_v)/\sigma'_v]/[s_u(\text{mob})/\sigma'_v] \approx 29.1\exp(-0.513B_q)$	—	Figure 12	Yes	0.95	0.49 (0.31)
			428	$[(q_t - u_2)/\sigma'_v]/[s_u(\text{mob})/\sigma'_v] \approx 34.6\exp(-2.049B_q)$	—	Figure 12	Yes	1.11	0.57 (0.34)
			423	$[(u_2 - u_0)/\sigma'_v]/[s_u(\text{mob})/\sigma'_v] \approx 21.5B_q$	—	Figure 12	Yes	0.94	0.49 (0.32)
	CPTU–OCR	Chen and Mayne (1996)	690	$\text{OCR} \approx 0.259[(q_t - \sigma_v)/\sigma'_v]^{1.107}$	—	Figure 13	Yes	1.01	0.42 (n/a)
			542	$\text{OCR} \approx 0.545[(q_t - u_2)/\sigma'_v]^{0.969}$	—	Figure 13	Yes	1.06	0.57 (n/a)
			779	$\text{OCR} \approx 1.026B_q^{-1.077}$	—	Figure 13	Yes	1.28	0.86 (n/a)
		Kulhawy and Mayne (1990)	690	$\text{OCR} \approx 0.32(q_t - \sigma_v)/\sigma'_v$	—	Figure 13	Yes	1.00	0.39 (≈ 0.25)
	CPTU–σ'_p/P_a	Chen and Mayne (1996)	690	$\sigma'_p/P_a \approx 0.227[(q_t - \sigma_v)/P_a]^{1.200}$	—	Figure 14	Yes	0.99	0.42 (n/a)
			542	$\sigma'_p/P_a \approx 0.490[(q_t - u_2)/P_a]^{1.053}$	—	Figure 14	Yes	1.08	0.61 (n/a)
			690	$\sigma'_p/P_a \approx 1.274 + 0.761(u_2 - u_0)/P_a$	—	Figure 14	No	0.49	0.59 (n/a)
		Kulhawy and Mayne (1990)	690	$\sigma'_p/P_a \approx 0.33(q_t - \sigma_v)/P_a$	—	Figure 14	Yes	0.97	0.39 (≈ 0.2)
			690	$\sigma'_p/P_a \approx 0.54(u_2 - u_0)/P_a$	—	Figure 14	Yes	1.18	0.75 (≈ 0.25)

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 site-specific 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 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.

Database 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.

Fig. 2. LI–(s_u^{re}/P_a) models proposed by Wroth and Wood (1978) and Locat and Demers (1988).

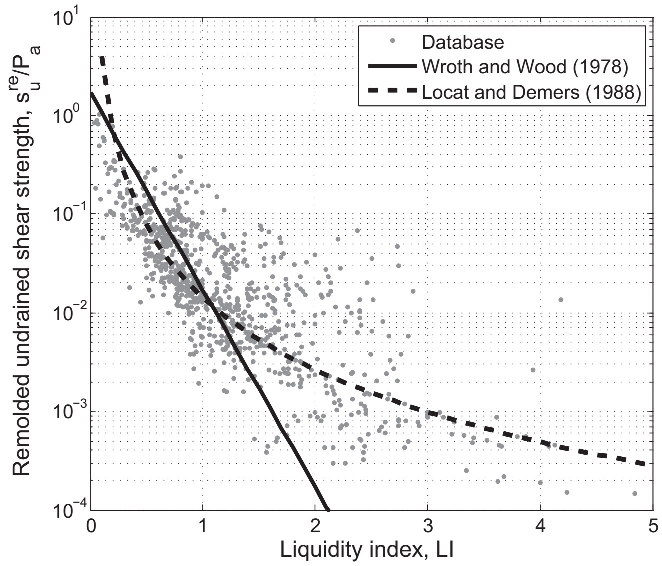
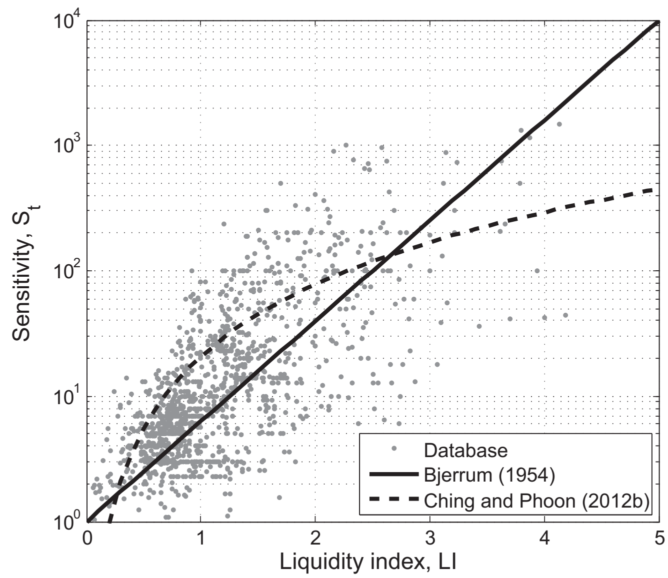


Fig. 3. LI–S_t models proposed by Bjerrum (1954) and Ching and Phoon (2012*b*).

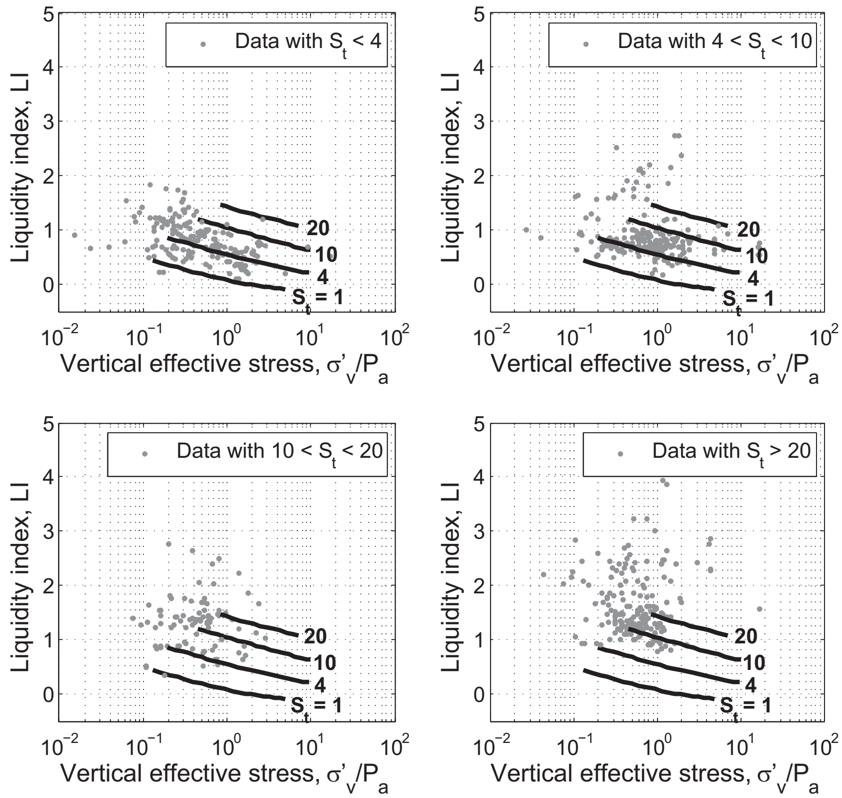


Ten dimensionless parameters of clays are of primary interest. They are categorized into three groups:

1. Index properties, including liquid limit (LL), plasticity index (PI), and liquidity index (LI).
2. Stresses and strengths, including normalized vertical effective stress (σ'_v/P_a, where P_a is one atmosphere pressure (= 101.3 kN/m²)), normalized preconsolidation stress (σ'_p/P_a), normalized undrained shear strength (s_u/σ'_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 distur-

Fig. 4. LI–(σ'_v/P_a)–S_t model proposed by Mitchell (1993).



bance. 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(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(mob) are given in Table 2.

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

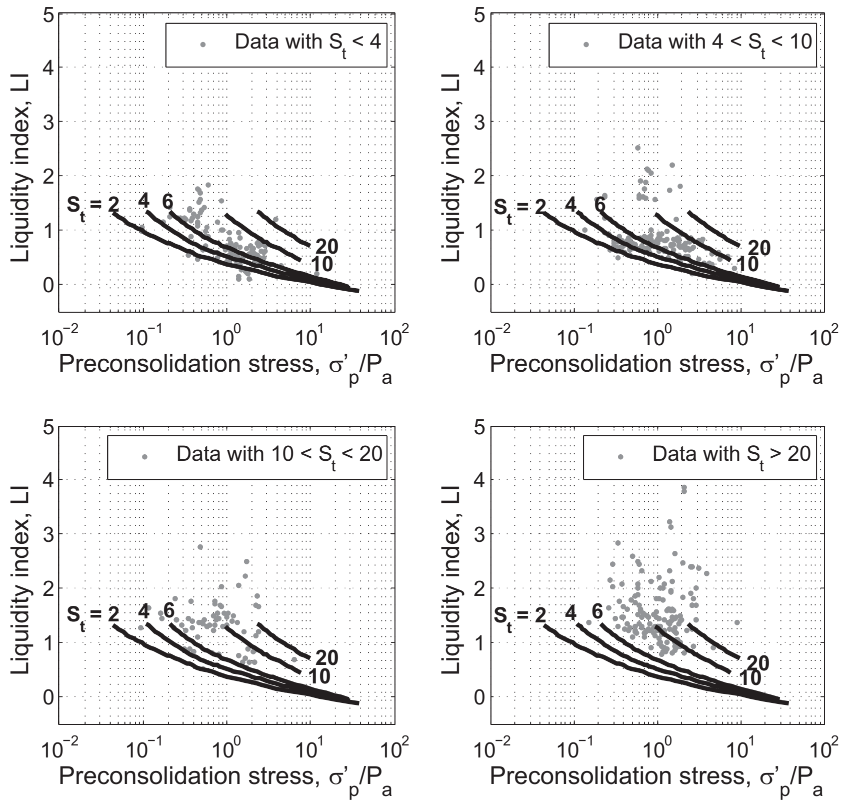
Some other dimensionless parameters of interest, such as s_u/σ'_p, OCR, and s_u^{re}/P_a, can be derived from the above 10 parameters. The basic statistics of all these parameters (10 basic parameters together with s_u/σ'_p, OCR, and s_u^{re}/P_a) are listed in Table 3. The numbers of available data 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 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.

Calibration of existing transformation models

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. Twenty-four 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 data compiled for this study. The global database is considered to be satisfactory if there 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

Fig. 5. LI–(σ'_p/P_a)–S_t model proposed by NAVFAC (1982).



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^{re}/P_a) models and two LI–S_t models.
2. *Type B* — Models for effective stress, including one LI–(σ'_v/P_a)–S_t model and three LI–(σ'_p/P_a)–S_t models.
3. *Type C* — Models for shear strength, including one LI–(s_u/σ'_p) model, one PI–(s_u/σ'_p) model, one OCR–(s_u/σ'_v) model, and one OCR–(s_u/σ'_v)–S_t model.

   In the LI–(s_u/σ'_p) model proposed by Bjerrum and Simons (1960) for normally consolidated (NC) clays, the s_u/σ'_p values are obtained from CIUC tests. For NC clays, s_u(CIUC)/σ'_p is estimated to be 0.37, whereas s_u(mob)/σ'_p is about 0.22 (Mesri 1975, 1989). As a result, the s_u/σ'_p value in the original LI–(s_u/σ'_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/σ'_v) models, four CPTU–OCR models, and five CPTU–(σ'_p/P_a) models.

   Note that for the CPTU–(s_u/σ'_v) models by Ching and Phoon (2012*a*), 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^{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–(σ'_p/P_a)–S_t and OCR–(s_u/σ'_v)–S_t models by Ching and Phoon (2012*b*), 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 Norwegian marine clay data only; and (*iii*) the LI–(s_u/σ'_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–(σ'_v/P_a)–S_t model by Mitchell (1993), (*ii*) the LI–(σ'_p/P_a)–S_t by NAVFAC (1982), and (*iii*) the LI–(s_u/σ'_p) model by Bjerrum and Simons (1960). No equations were reported by the original authors.

Fig. 6. LI–(σ'_p/P_a)–S_t model proposed by Stas and Kulhawy (1984).

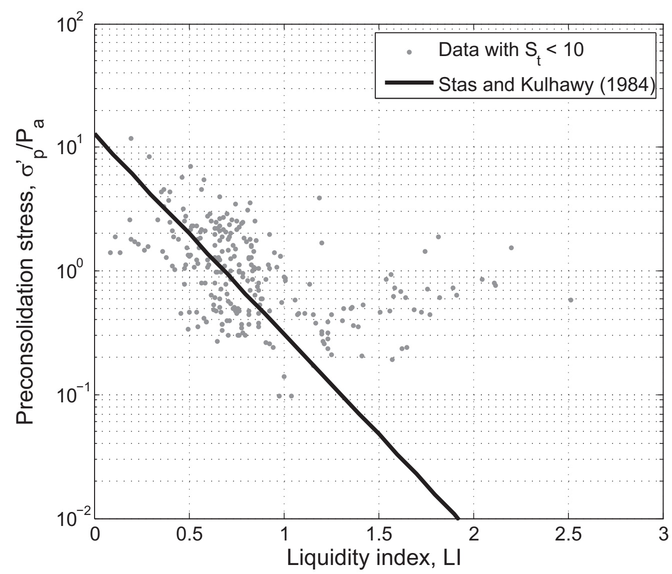
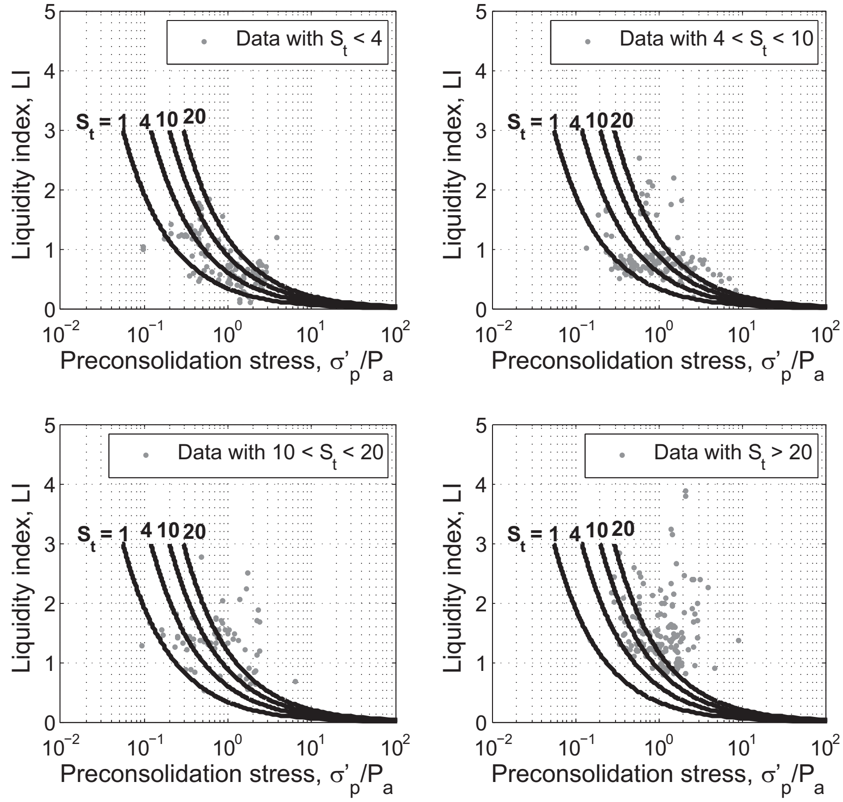


Fig. 7. LI–(σ'_p/P_a)–S_t model proposed by Ching and Phoon (2012*b*).



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–(σ'_v/P_a)–S_t model proposed by Mitchell (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–(σ'_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–(σ'_p/P_a)–S_t model proposed by Ching and Phoon (2012*b*). 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–(σ'_p/P_a)–S_t model contains only structured clays.
5. The LI–(s_u/σ'_p) model proposed by Bjerrum and Simons (1960). In 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–(σ'_p/P_a) models proposed by Chen and Mayne (1996) (the third model that relates σ'_p/P_a 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 σ'_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.

Biases and uncertainties of the existing transformation models

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 δ. Basically, *b* is the sample mean of (actual target value)/(predicted target value) for the global data points, and δ is the sample COV of (actual target value)/(predicted target value). For instance, for the LI–(s_u^{re}/P_a) model proposed by Locat and Demers (1988), the actual target value is the s_u^{re}/P_a value in the global database, and the predicted target value is $0.0144\text{LI}^{-2.44}$. For each data point with simultaneous knowledge of (LI, s_u^{re}), (actual target value)/(predicted target value) = $(s_u^{re}/P_a)/(0.0144\text{LI}^{-2.44})$ can be computed. The histogram of the ratio $(s_u^{re}/P_a)/(0.0144\text{LI}^{-2.44})$ is plotted in Fig. 15. The sample mean of this ratio is equal to 1.92, which is equal to *b*.

Fig. 8. LI–(s_u/σ'_p) model proposed by Bjerrum and Simons (1960).

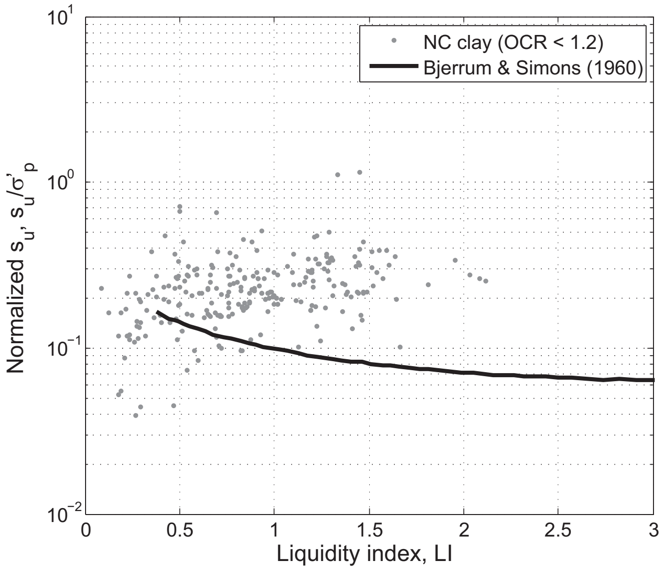
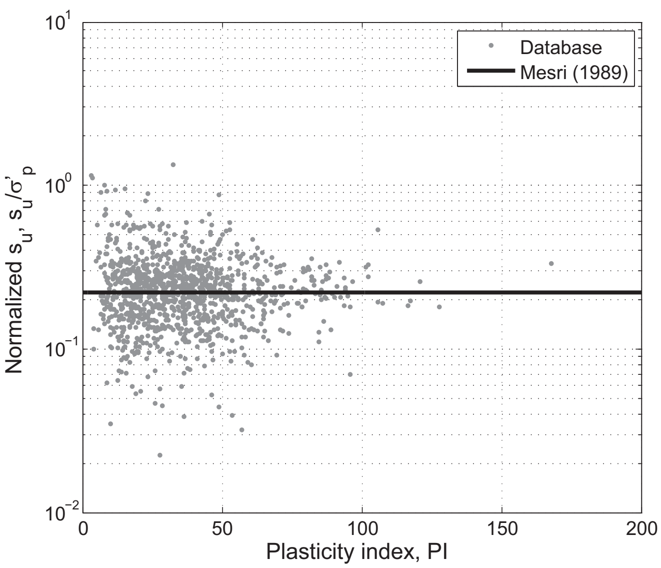


Fig. 9. PI–(s_u/σ'_p) model proposed by Mesri (1975, 1989).

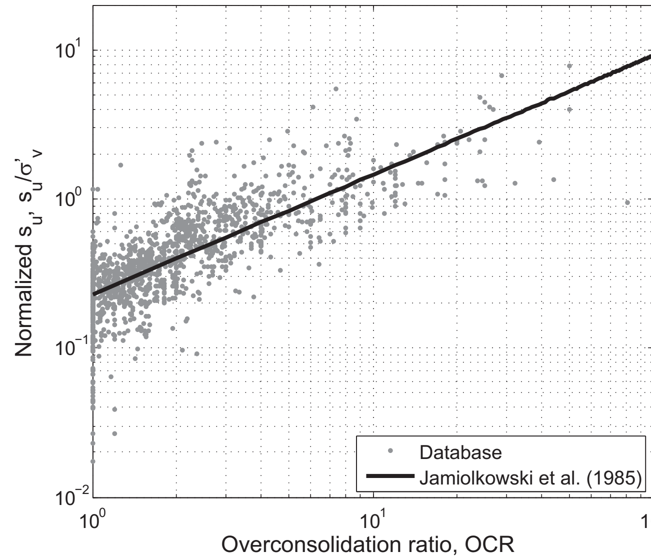


The sample COV of this ratio is 1.25, which is equal to δ. To be specific,

(1) $\quad$ Actual target value $=$ predicted target value $\times\, b \times \varepsilon$

where b is the bias factor (b = 1 means unbiased) and ε is the variability term with mean = 1 and COV = δ. If δ = 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^{re}/P_a) 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.

Fig. 10. OCR–(s_u/σ'_v) model proposed by Jamiolkowski et al. (1985).



It is evident that models published in more recent studies, such as Kulhawy and Mayne (1990), Chen and Mayne (1996), and Ching and Phoon (2012*a*, 2012*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 (δ) 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_t, LI–(σ'_p/P_a)–S_t, and OCR–(s_u/σ'_v)–S_t models developed in Ching and Phoon (2012*b*): COVs for these three models are close to those reported in Ching and Phoon (2012*b*). The statistics of the database used by Ching and Phoon (2012*b*) 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 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 (2012*b*) only considered structured clays.
2. All s_u data points in the global database are converted to s_u(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(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 (2012*a*) for the CPTU–(s_u/σ'_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 LI– s_u^{re}/P_a model by Locat and Demers (1988), the predicted value for s_u^{re}/P_a is $0.0144\mathrm{LI}^{-2.44}$. This model has a bias factor b = 1.92, calibrated by the global database. As a result, the calibrated model $s_u^{re}/P_a \approx b(0.0144)\mathrm{LI}^{-2.44} = 1.92(0.0144)\mathrm{LI}^{-2.44}$ is an

Fig. 11. OCR–(s_u/σ'_v)–S_t model proposed by Ching and Phoon (2012*b*).

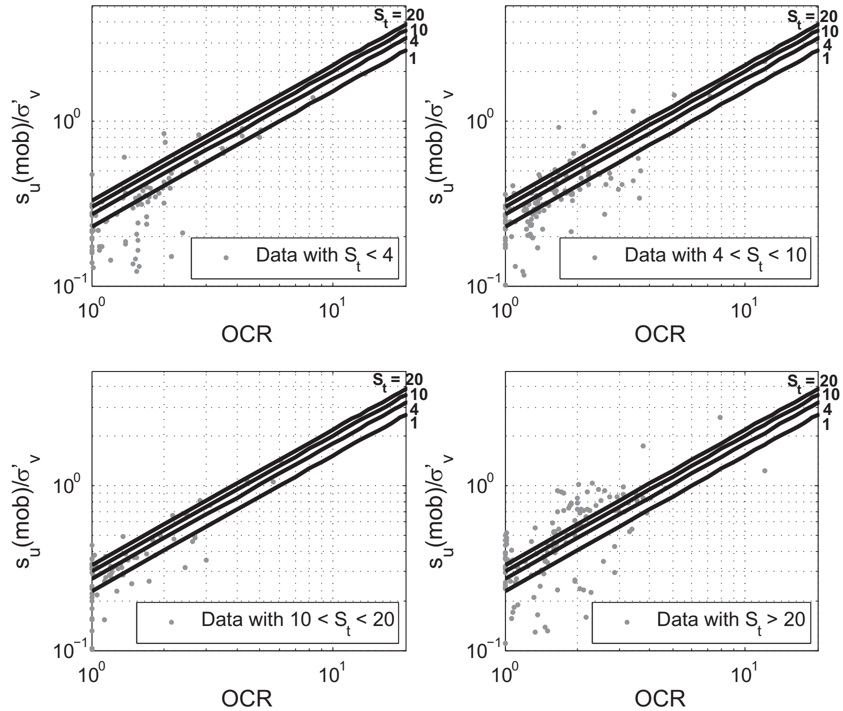
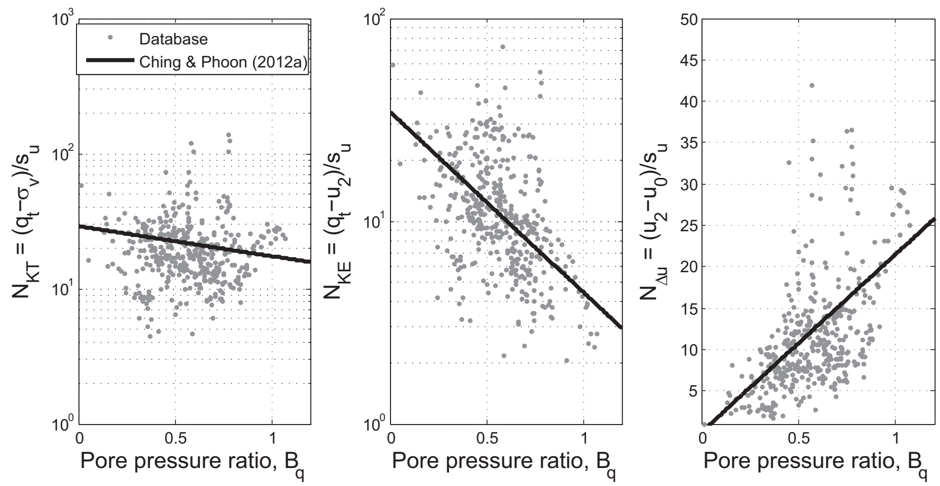


Fig. 12. CPTU–s_u/σ'_v models proposed by Ching and Phoon (2012*a*).



"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.

Secondary input parameters

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 OCR–(s_u/σ'_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 as a secondary input parameter, the OCR–(s_u/σ'_v)–S_t model by Ching and Phoon (2012*b*) 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 ε and (PI, S_t)

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

Fig. 13. CPTU–OCR models proposed by Chen and Mayne (1996) and Kulhawy and Mayne (1990).

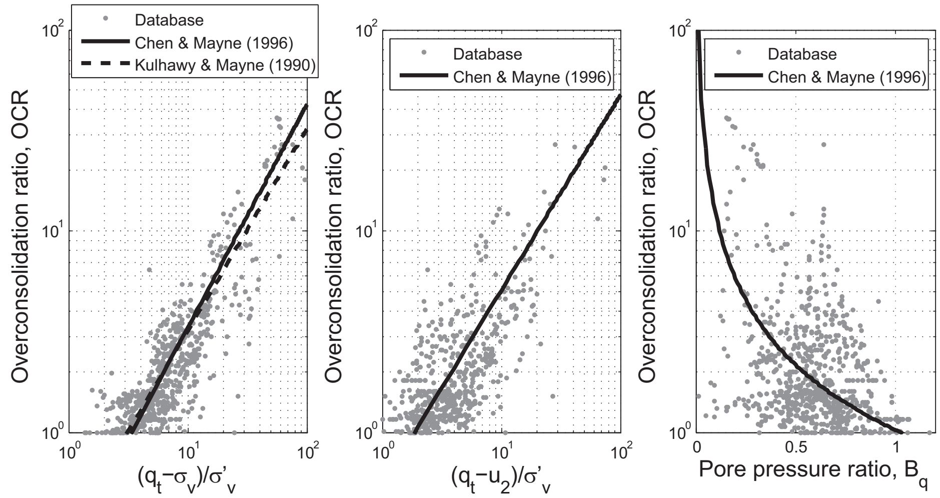


Fig. 14. CPTU–σ'_p/P_a models proposed by Chen and Mayne (1996) and Kulhawy and Mayne (1990).

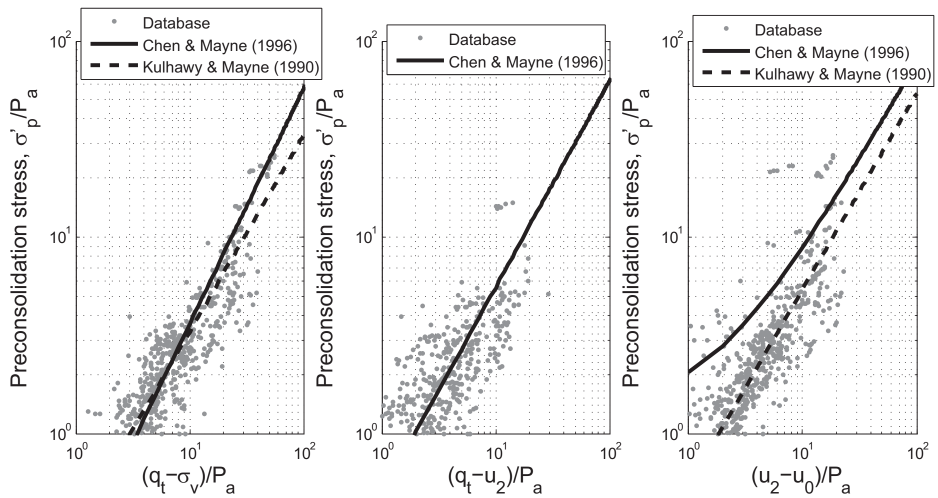
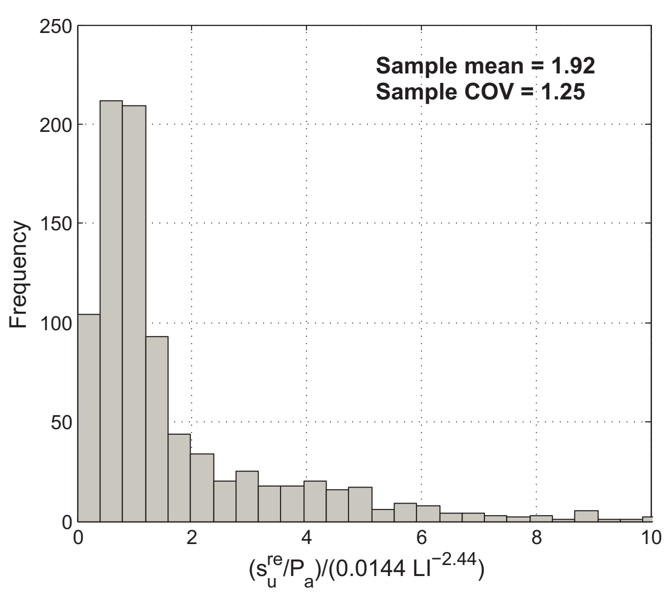


Fig. 15. Histogram of $(s_u^{re}/P_a)/(0.0144\mathrm{LI}^{-2.44})$.



$$\varepsilon = \frac{\text{actual target value}}{b \times \text{predicted target value}} = \frac{\text{actual target value}}{\text{unbiased prediction}} \tag{2}$$

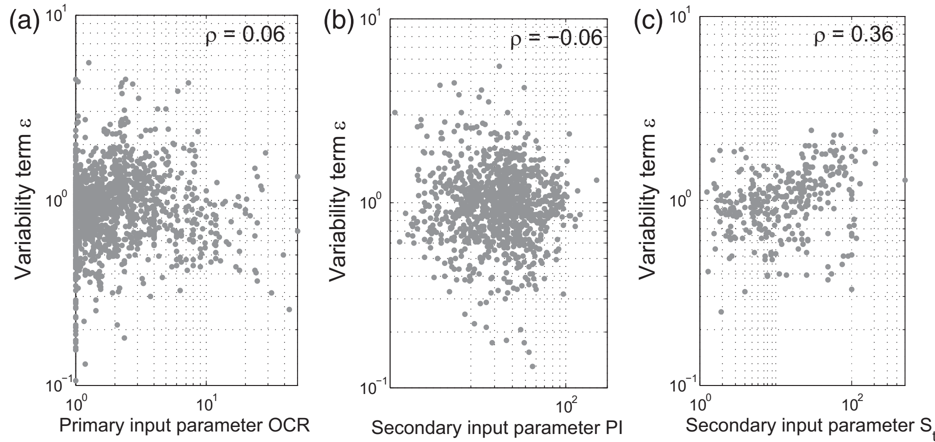
where the unbiased prediction = b × predicted target value. The variability term ε quantifies the deviation between the actual value and the unbiased prediction. It has mean value of 1 and COV equal to the calibrated COV (δ). Equivalently,

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

In essence, ln(ε) is the component that cannot be explained away by the primary input parameter. More precisely, ln(ε) should be uncorrelated to the primary input parameter. The reason why the natural logarithm is taken will be explained later. For instance, ln(ε) for the OCR–(s_u/σ'_v) model proposed by Jamiolkowski et al. (1985) is indeed nearly uncorrelated to the primary input parameter ln(OCR), shown in Fig. 16*a*. Incidentally, the correlation between ln(ε) and ln(PI) is also nearly zero (Fig. 16*b*). However, ln(ε) and ln(S_t) show some slight positive correlation (Fig. 16*c*). 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(ε) and the natural logarithm of the secondary input parameter (PI or S_t) will be studied. The correlation with respect to ln(PI) will be studied for all

Fig. 16. (*a*) ln(ε)–ln(OCR), (*b*) ln(ε)–ln(PI), and (*c*) ln(ε)–ln(S_t) plots for the model proposed by Jamiolkowski et al. (1985). ρ, correlation coefficient.



models except the PI–(s_u/σ'_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.

The correlation between ln(ε) and the natural logarithm of the secondary input parameter (PI or S_t) is quantified by the Pearson product moment correlation coefficient (ρ). The correlation coefficient for the ln(ε)–ln(PI) and ln(ε)–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(ε)–ln(PI) data points are abundant (n > 300), whereas the ln(ε)–ln(S_t) data points are less abundant. It is also evident that the ln(ε)–ln(S_t) correlations seem stronger (ρ is farther away from zero) than the ln(ε)–ln(PI) correlations.

Re-calibrate the existing transformation models – inference using PI and S_t

For the inference using PI, it is possible to express ε as a function of PI

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

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

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

where ln(ε) is the known output and ln(PI/20) is the known input, whereas ln(α) and β are the intersect and gradient, respectively, to be estimated by the least squares method. The natural logarithm is taken for ε and PI because traditional linear regression requires normality. Figure 17 shows the histograms of ε and ln(ε) for the OCR–(s_u/σ'_v) model proposed by Jamiolkowski et al. (1985) — ln(ε) is more normal than ε. In fact, ln(PI) is also more normal than PI (not shown). Hence, it is more appropriate to do regression on the ln(ε)–ln(PI) data points. Once the least-squares estimates for α and β are obtained, eq. (1) can be expressed as

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

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

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

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

It is apparent that when the target parameter is σ'_p/P_a or OCR, the BCFs are always decreasing functions of PI (β < 0). This implies that clays with larger PI values tend to have lower σ'_p/P_a and OCR values. For the CPTU–(s_u/σ'_v) model proposed by Ching and Phoon (2012*a*), 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 of PI (β > 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 ε as

$$\varepsilon = \left[\alpha \times (\mathrm{PI}/20)^{\beta} \times S_t^{\gamma}\right] \times \varepsilon' \tag{8}$$

The coefficients α, β, and γ can be estimated using linear regression on the ln(ε)–ln(PI)–ln(S_t) data points. Namely, the following regression model is used:

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

where ln(ε) is the known output, and ln(PI/20) and ln(S_t) are the known inputs, whereas ln(α), β, and γ are the intersect and gradients to be estimated by the least-squares method. Once the least-squares estimates for α, β, and γ are obtained, the term $\alpha \times (\mathrm{PI}/20)^{\beta} \times S_t^{\gamma}$ is now the BCF. Table 6 shows the updated bias factors b' in the format of b' = (original b) × [BCF] and the updated δ' in the format of δ' = (original δ) × (CCF%) for the inference using PI and S_t. It is apparent

Table 6. Analysis results for ln(ε)–ln(PI) and ln(ε)–ln(S_t) correlations and inference results.

		Correlation coefficient					Inference results			
		ε–PI		ε–S_t			Inference based PI only		Inference based on PI and S_t	
Relationship	Literature	n	ρ	n	ρ	Updated model	$b' = b$×[BCF]	$\delta' = \delta$×(CCF%)	$b' = b$×[BCF]	$\delta' = \delta$×(CCF%)
LI–(s_u^{re}/P_a)	Locat and Demers (1988)	887	−0.24	—	—	$s_u^{re}/P_a = 0.0144\mathrm{LI}^{-2.44}b'\varepsilon'$	1.92×[1.11(PI/20)$^{-0.258}$]	1.25×(94%)	—	—
LI–S_t	Bjerrum (1954)	1137	0.18	—	—	$S_t = 10^{0.8\mathrm{LI}}b'\varepsilon'$	2.05×[0.92(PI/20)$^{0.251}$]	1.09×(104%)	—	—
	Ching and Phoon (2012*b*)	1137	−0.02	—	—	$S_t = 20.726\mathrm{LI}^{1.910}b'\varepsilon'$	0.88×[1.01(PI/20)$^{-0.025}$]	1.28×(99%)	—	—
LI–σ'_p/P_a–S_t	Stas and Kulhawy (1984) (for S_t < 10 only)	257	−0.37	—	—	$\frac{\sigma'_p}{P_a} = 10^{1.11-1.62\mathrm{LI}}b'\varepsilon'$	2.94×[1.25(PI/20)$^{-0.478}$]	1.90×(85%)	—	—
	Ching and Phoon (2012*b*)	487	−0.35	—	—	$\frac{\sigma'_p}{P_a} = 0.235\mathrm{LI}^{-1.319}S_t^{0.536}b'\varepsilon'$	1.32×[1.24(PI/20)$^{-0.444}$]	0.78×(93%)	—	—
PI–s_u/σ'_p	Mesri (1975, 1989)	—	—	433	0.43	$s_u(\mathrm{mob})/\sigma'_p = 0.22b'\varepsilon'$	—	—	1.04×[0.76$S_t^{0.136}$]	0.55×(63%)
OCR–s_u/σ'_v	Jamiolkowski et al. (1985)	1091	−0.06	395	0.34	$s_u(\mathrm{mob})/\sigma'_v = 0.23\mathrm{OCR}^{0.8}b'\varepsilon'$	1.11×[1.10(PI/20)$^{-0.050}$]	0.53×(94%)	1.11×[0.71(PI/20)$^{0.133}S_t^{0.123}$]	0.53×(67%)
OCR–$s_u\sigma'_v$–S_t	Ching and Phoon (2012*b*)	391	0.21	—	—	$\frac{s_u(\mathrm{mob})}{\sigma'_v} = 0.229\mathrm{OCR}^{0.823}S_t^{0.121}b'\varepsilon'$	0.84×[0.93(PI/20)$^{0.131}$]	0.34×(102%)	—	—
CPTU–s_u/σ'_v	Ching and Phoon (2012*a*)	387	0.38	81	−0.24	$\frac{(q_t-\sigma_v)/\sigma'_v}{s_u(\mathrm{mob})/\sigma'_v} = 29.1[\exp(-0.513B_q)]b'\varepsilon'$	0.95×[0.80(PI/20)$^{0.348}$]	0.49×(100%)	0.95×[1.17(PI/20)$^{0.241}S_t^{-0.198}$]	0.49×(77%)
		392	0.29	78	−0.39	$\frac{(q_t-u_2)/\sigma'_v}{s_u(\mathrm{mob})/\sigma'_v} = 34.6[\exp(-2.049B_q)]b'\varepsilon'$	1.11×[0.78(PI/20)$^{0.275}$]	0.57×(90%)	1.11×[1.40(PI/20)$^{0.189}S_t^{-0.263}$]	0.57×(72%)
		387	0.38	81	−0.25	$\frac{(u_2-u_0)/\sigma'_v}{s_u(\mathrm{mob})/\sigma'_v} = 21.5B_q b'\varepsilon'$	0.94×[0.80(PI/20)$^{0.335}$]	0.49×(101%)	0.94×[1.22(PI/20)$^{0.275}S_t^{-0.216}$]	0.49×(78%)
CPTU–OCR	Chen and Mayne (1996)	497	−0.09	163	0.12	$\mathrm{OCR} = 0.259[(q_t-\sigma_v)/\sigma'_v]^{1.107}b'\varepsilon'$	1.01×[1.01(PI/20)$^{-0.073}$]	0.42×(110%)	1.01×[1.09(PI/20)$^{-0.206}S_t^{0.002}$]	0.42×(73%)
		466	−0.11	123	0.27	$\mathrm{OCR} = 0.545[(q_t-u_2)/\sigma'_v]^{0.969}b'\varepsilon'$	1.06×[1.10(PI/20)$^{-0.105}$]	0.57×(99%)	1.06×[0.79(PI/20)$^{-0.273}S_t^{0.102}$]	0.57×(69%)
		545	−0.17	173	0.12	$\mathrm{OCR} = 1.026B_q^{-1.077}b'\varepsilon'$	1.28×[1.05(PI/20)$^{-0.196}$]	0.86×(91%)	1.28×[0.63(PI/20)$^{-0.079}S_t^{-0.057}$]	0.86×(52%)
	Kulhawy and Mayne (1990)	497	−0.11	163	0.14	$\mathrm{OCR} = 0.32[(q_t-\sigma_v)/\sigma'_v]b'\varepsilon'$	1.00×[1.01(PI/20)$^{-0.084}$]	0.39×(108%)	1.00×[1.04(PI/20)$^{-0.188}S_t^{0.010}$]	0.39×(71%)
CPTU-σ'_p/P_a	Chen and Mayne (1996)	497	−0.04	163	0.15	$\sigma'_p/P_a = 0.227[(q_t-\sigma_v)/P_a]^{1.200}b'\varepsilon'$	0.99×[1.02(PI/20)$^{-0.028}$]	0.42×(105%)	0.99×[1.07(PI/20)$^{-0.124}S_t^{0.002}$]	0.42×(70%)
		466	−0.09	123	0.28	$\sigma'_p/P_a = 0.490[(q_t-u_2)/P_a]^{1.053}b'\varepsilon'$	1.08×[1.09(PI/20)$^{-0.087}$]	0.61×(99%)	1.08×[0.78(PI/20)$^{-0.268}S_t^{0.105}$]	0.61×(68%)
		498	−0.25	163	0.04	$\sigma'_p/P_a = \left[1.274 + 0.761\frac{(u_2-u_0)}{P_a}\right]b'\varepsilon'$	0.49×[0.99(PI/20)$^{-0.235}$]	0.59×(89%)	0.49×[0.94(PI/20)$^{-0.262}S_t^{0.026}$]	0.59×(60%)
	Kulhawy and Mayne (1990)	497	−0.11	163	0.14	$\sigma'_p/P_a = 0.33[(q_t-\sigma_v)/P_a]b'\varepsilon'$	0.97×[1.01(PI/20)$^{-0.084}$]	0.39×(108%)	0.97×[1.04(PI/20)$^{-0.188}S_t^{0.010}$]	0.39×(71%)
		497	−0.12	162	−0.01	$\sigma'_p/P_a = 0.54[(u_2-u_0)/P_a]b'\varepsilon'$	1.18×[0.96(PI/20)$^{-0.114}$]	0.75×(93%)	1.18×[1.04(PI/20)$^{-0.114}S_t^{-0.069}$]	0.75×(61%)

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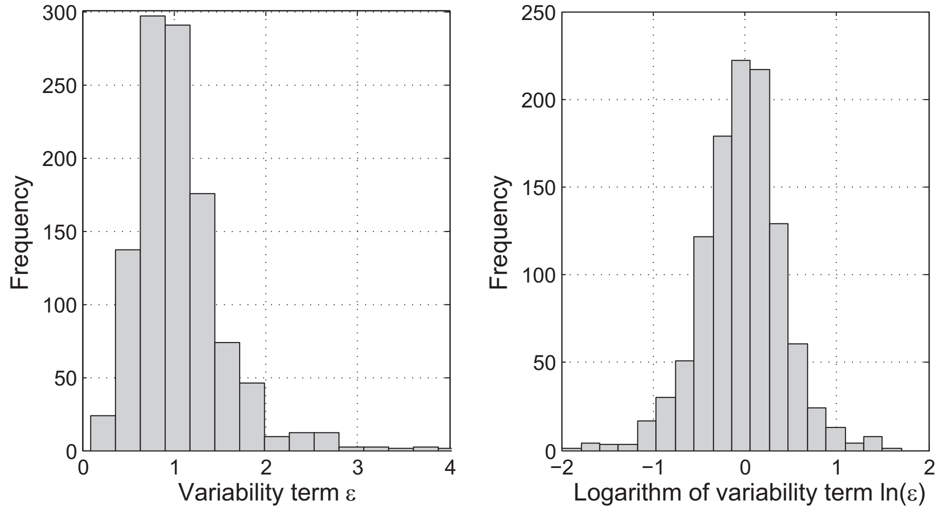
Fig. 17. Histograms of ε and $\ln(\varepsilon)$ for the OCR–(s_u/σ'_v) model proposed by Jamiolkowski et al. (1985).



that when the target parameter is s_u/σ'_v or s_u/σ'_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/σ'_v and s_u/σ'_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 (δ') is typically noticeably less than the original δ 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 more. These relatively small numbers of the $\ln(\varepsilon)$–$\ln(S_t)$ data points may not represent a "global" dataset. Hence, the resulting δ' may look small.

Implementation

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 σ'_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 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 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 COV = 0.53.

In the case where 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 PI and S_t" in Table 6. Thus, 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 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, 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).

Conclusions

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, OCR, and 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 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.

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Appendix A. Summary of database CLAY/10/7490

Table A1. Basic information of the database CLAY/10/7490.

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	—
Anderson et al. (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
Balasubramanian 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	5.40	—
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	—
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	—	—	—	—

Table A1 (*continued*).

Reference	Country	*n*	PI	LI	OCR	S_t	$s_u(mob)/\sigma'_v$	CPTU
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	—
Colling 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 Saada (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 Lutenegger (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	—	—
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 (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 (1977*a*)	Iraq	11	34~36	0.62~0.73	—	—	0.83~2.35	—
Hanzawa (1977*b*)	Iraq	31	11~31	0.65~1.10	1.0	—	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	—	—	—	—

Table A1 (*continued*).

Reference	Country	n	PI	LI	OCR	S_t	$s_u(\text{mob})/\sigma'_v$	CPTU
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 (1987*a*)	Canada	29	3~37	0.50~4.51	1.0~4.9	7~35	0.34~1.66	Y
Konrad and Law (1987*b*)	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
Kulhawy and Mayne (1990)	—	159	9~80	−0.44~2.4	1.0	—	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 and Edgers (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
Massarch et al. (1975)	Sweden	41	22~128	0.50~2.77	0.9~2.7	8~36	0.14~0.74	—
Massarch 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	—	—	—

Table A1 (*continued*).

Reference	Country	*n*	PI	LI	OCR	S_t	$s_u(\text{mob})/\sigma'_v$	CPTU
Mayne (1985*a*)	USA	64	—	—	1.0~75.0	—	0.24~0.33	—
Mayne (1985*b*)	—	87	2~105	—	1.0	—	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	—	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	—
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 (1948*a*)	UK	17	39~77	0.26~1.04	0.8~1.4	1~4	—	—
Skempton (1948*b*)	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	1.0	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	—	—	—	—	—	—

Table A1 (*concluded*).

Reference	Country	*n*	PI	LI	OCR	S_t	$s_u(\text{mob})/\sigma'_v$	CPTU
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 (1977)	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 and Pant (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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