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Transformation models for effective friction angle and relative density calibrated based on generic database of coarse-grained soils

Jianye Ching, Guan-Hong Lin, Jie-Ru Chen, and Kok-Kwang Phoon

Abstract: This study compiles a generic database of seven parameters, including relative density and friction angle, for coarse-grained soils from 176 studies, covering a wide range of reconstituted and in situ coarse-grained soils. This database, labeled as "SAND/7/2794", is dominated by data from laboratory reconstituted soils such as Erksak, Hokksund, Monterey, Ottawa, Sacramento River, Ticino, and Tonegawa sands. About 15% of the data points in the database are in situ samples obtained from tube sampling, block sampling, or ground freezing techniques. The correlation behavior among some parameters in the database is consistent with existing transformation models in the literature. Mine tailings, volcanic soils, railroad ballast, gravelly soils with significant cobble or boulder content, and soils with high fines contents are removed from the database because they exhibit inconsistent behavior. Soils subjected to very high effective stresses are also removed from the database. The generic database is adopted to calibrate the bias and variability of existing transformation models. Transformation uncertainties are characterized based on their bias, variability, and the range of applicability.

Key words: SAND/7/2794, effective stress friction angle, relative density, coarse-grained soils, transformation model, transformation uncertainty.

Résumé : Cette étude compile une base de données générique de sept paramètres, dont la densité relative et l'angle de frottement, pour les sols pulvérulents à partir de 176 études, couvrant un large éventail de sols pulvérulents reconstitués et in situ. Cette base de données, appelée « SAND/7/2794 », est dominée par des données provenant de sols reconstitués de laboratoire comme les sables d'Erksak, Hokksund, Monterey, Ottawa, rivière Sacramento, Ticino et Tonegawa. Environ 15 % des points de données dans la base de données sont des échantillons in situ obtenus à partir d'échantillonnage de tube, d'échantillonnage de bloc de techniques de congélation de sol. Le comportement de la corrélation entre certains paramètres dans la base de données est compatible avec les modèles existants de transformation dans la littérature. Les résidus de mine, de sols volcaniques, de ballast de voies ferrées, des sols graveleux avec contenu significatif de galets ou rocher et de sols avec des contenus de fines élevées sont supprimés de la base de données, car ils présentent un comportement incohérent. Les sols soumis à de très fortes contraintes efficaces sont également supprimés de la base de données. La base de données générique est adoptée pour calibrer la partialité et la variabilité des modèles de transformation existantes. Les incertitudes de transformation sont caractérisées basé sur leur partialité, la variabilité et sur la gamme d'application. [Traduit par la Rédaction]

Mots-clés : SAND/7/2794, angle de frottement de contrainte effective, densité relative, sols pulvérulents, modèle de transformation, incertitude de transformation.

Introduction

Geotechnical design parameters are often estimated based on transformations from site investigation results (Phoon and Kulhawy 1999). Transformation models in geotechnical engineering are obtained by empirical or semi-empirical data fitting using regression analyses. They are widely adopted in geotechnical engineering practice as a matter of practical expediency. Useful compilations of these models are available in the literature (e.g., Djoenaidi 1985; Kulhawy and Mayne 1990, Mayne et al. 2001). Many transformation models are "bivariate" (pairwise) in nature. The relationship between the effective friction angle (ϕ') and standard penetration test (SPT) blow count (N) value proposed by Peck et al. (1974) is one classical example. This example and many earlier models are thought to be conservative. However, the degree of conservatism is difficult to judge because the data and (or) experience supporting these models are seldom described in detail. Hatanaka and Uchida (1996) presented an updated correlation between ϕ' and SPT N value that is unbiased for the sands considered in their study. For coarse-grained soils, the effective friction angle (ϕ') and relative density (D_r) are traditionally regarded as the key parameters in practice. Table 1 summarizes some transformation models for coarse-grained soils that are related to ϕ' and D_r. They are referred to as the D_r models and the ϕ' models. Been and Jefferies (1985) presented a critical-state soil mechanics framework to describe sand behavior. The authors defined a sand state parameter (Ψ) as the vertical difference between the in situ void ratio and the corresponding value on the critical-state or steady-state line. This alternate framework is not considered in this study because the state parameter is less frequently reported in the

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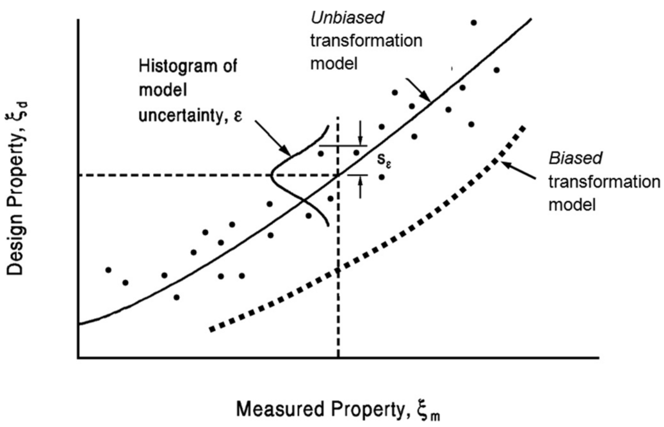
Table 1. Transformation models in literature for parameters of coarse-grained soils.

Type	Model	Literature	Transformation model	n (reconstituted + in situ)	Multiplicative lognormal			Additive normal			Data restriction
					b	δ (or σ)	p-value	b	σ	p-value	
D_r models	SPT–D_r	Holtz and Gibbs (1979)	Graphical curves on p. 441 (predict D_r based on N_{60} and σ'_v/P_a)	133 (81+52)	0.85	0.263	0.11	0.83	12.30	0.42	Data with $N_{60} < 70$ and $\sigma'_v/P_a < 3$
		Terzaghi and Peck (1967)	$D_r\ (\%) \approx 100\sqrt{(N_1)_{60}/60}$	198 (142+56)	1.05	0.231	0.72	1.03	13.63	0.34	Data with $(N_1)_{60} < 60$
		Marcuson and Bieganousky (1977)	$D_r\ (\%) \approx 100\left[12.2 + 0.75 \times \sqrt{222N_{60} + 2311 - 711\,\mathrm{OCR} - 779(\sigma'_v/P_a) - 50C_u^2}\right]$	132 (101+31)	1.00	0.211	0.11	1.00	11.24	0.47	Data with $N_{60} < 100$
		Kulhawy and Mayne (1990)**	$D_r\ (\%) \approx 100\sqrt{\dfrac{(N_1)_{60}}{[60 + 25\log_{10}(D_{50})]\,\mathrm{OCR}^{0.18}}}$	199 (155+44)	1.01	0.205	0.74	0.99	17.45	0.00 (reject)	All data with simultaneous information
	CPT–D_r	Jamiolkowski et al. (1985)	$D_r\ (\%) \approx 68[\log_{10}(q_{t1}) - 1]$	681 (666+15)	0.84	0.327	0.00 (reject)	0.85	14.50	0.66	Normally consolidated (NC) data with $q_{t1} < 300$
		Kulhawy and Mayne (1990)**	$D_r\ (\%) \approx 100\sqrt{\dfrac{q_{t1}}{305Q_C\,\mathrm{OCR}^{0.18}}}$	840 (840+0)	0.93	0.339	0.00 (reject)	0.93	13.29	0.19	All data with simultaneous information
ϕ' models	D_r–ϕ'	Bolton (1986)**	$\phi' \approx \phi'_{cv} + 3\{D_r[10 - \ln(p'_f)] - 1\}$	391 (391+0)	1.03	0.052	0.09	1.03	2.07	0.07	All data with simultaneous information
		Salgado et al. (2000)	$\phi' \approx \phi'_{cv} + 3\{D_r[8.3 - \ln(p'_f)] - 0.69\}$	127 (127+0)	1.08	0.054	0.76	1.08	2.18	0.79	Data with fines
	SPT–ϕ'	Peck et al. (1974)	Graphical curves in p. 310 (predict ϕ' based on N_{60})	43 (0+43)	1.15	0.132	0.66	1.14	5.39	0.62	Data with $N_{60} < 60$
		Schmertmann (1975)	Graphical curves in p. 63 (predict ϕ' based on N_{60} and σ'_v/P_a)	44 (0+44)	0.98	0.137	0.93	0.97	5.46	0.79	Data with $N_{60} < 60$ and $\sigma'_v/P_a < 3$
		Hatanaka and Uchida (1996)	$\phi' \approx \sqrt{15.4(N_1)_{60}} + 20$	28 (0+28)	1.04	0.095	0.84	1.04	3.61	0.89	Data with $(N_1)_{60} < 40$
		Hatanaka et al. (1998)	$\phi' \approx \begin{cases} \sqrt{15.4(N_1)_{60}}+20 & (N_1)_{60}\le 26 \\ 40 & (N_1)_{60}>26 \end{cases}$	58 (0+58)	1.07	0.090	0.56	1.07	3.71	0.43	Data with $(N_1)_{60} < 150$
		Chen (2004)**	$\phi' \approx 27.5 + 9.2\log_{10}[(N_1)_{60}]$	59 (0+59)	1.00	0.095	0.41	1.00	3.98	0.28	All data with simultaneous information
	CPT–ϕ'	Robertson and Campanella (1983)	$\phi' \approx \tan^{-1}[0.1 + 0.38\log_{10}(q_t/\sigma'_v)]$	99 (91+8)	0.93	0.056	0.77	0.92	2.16	0.87	All data with simultaneous information
		Kulhawy and Mayne (1990)**	$\phi' \approx 17.6 + 11\log_{10}(q_{t1})$	376 (368+8)	0.97	0.081	0.49	0.97	3.17	0.97	All data with simultaneous information

**OCR, overconsolidation ratio; $q_{t1} = (q_t/P_a)/(\sigma'_v/P_a)^{0.5}$; q_t, cone tip resistance; σ'_v, vertical effective stress; $(N_1)_{60} = N_{60}/(\sigma'_v/P_a)^{0.5}$; N_{60}, corrected N; P_a, atmospheric pressure; C_u, coefficient of uniformity; ϕ'_{cv}, critical-state friction angle; p'_f (mean effective stress at failure) = $(\sigma'_{1f} + \sigma'_{2f} + \sigma'_{3f})/3$; σ'_{1f}, maximum effective principal stress at failure; σ'_{2f}, intermediate effective principal stress at failure; σ'_{3f}, minimum effective principal stress at failure; Q_C = 1.09, 1.0, 0.91 for low, medium, high compressibility, respectively.

Fig. 1. Transformation uncertainty resulting from pairwise correlation between measured property and desired design property.



literature in comparison with the effective friction angle (ϕ') and relative density (D_r).

Some degree of transformation uncertainty will be introduced, as shown by the data scatter about the "unbiased" transformation model (Fig. 1). Moreover, some degree of bias may exist if the calibration database does not have sufficient coverage (or rules-of-thumb developed from a mixture of data, experience, and judgment). The dashed line in Fig. 1 shows an alternate transformation model that is biased on the conservative side. A transformation model is biased if the majority of the data points fall above or below the curve. It is clear that a general treatment of the transformation uncertainty will require the quantification of its bias (difference between model prediction and average of the data) and variability (data scatter about its average). On top of those first and second moment statistics, it is important to characterize the form of the transformation uncertainty (e.g., additive or multiplicative) and its probability distribution type (e.g., normal or lognormal). The form and the probability distribution type are related. The common probabilistic model for the additive form is a zero-mean normal random variable. The common probabilistic model for the multiplicative form is a unit-mean lognormal random variable. In the literature, transformation models are typically presented as regression equations without explicit characterization of the four aforementioned aspects: (*i*) bias; (*ii*) variability; (*iii*) form; and (*iv*) distribution type. Nonetheless, Honjo (2011) and Honjo and Otake (2014) showed that transformation uncertainty can be more influential than other sources of geotechnical uncertainties in realistic design problems. Therefore, transformation uncertainty deserves more explicit and more rigorous treatment, particularly with regards to the four aspects.

It is challenging to calibrate the bias, variability, form, and distribution type of a transformation model because it requires a database that can effectively represent the target soil types and regions. In principle, the bias and variability calibrated by a database are only applicable to the soil types and regions represented in the database. If the goal is to calibrate "generic" bias and variability, a generic database not limited to a certain soil type or a certain region is required. The current paper compiles a generic multivariate database for coarse-grained soils of wide coverage. The purpose is twofold:

1. The bias and variability for existing transformation models will be calibrated by the generic multivariate database. The form (additive or multiplicative) and probability distribution type for the transformation uncertainty will also be addressed. This rigorous characterization of transformation uncertainty is valuable for reliability analysis and design.
2. The generic multivariate database is useful in the future for the development of a multivariate probability distribution for coarse-grained soil parameters.

In the literature, generic multivariate soil databases have been compiled for clays. Table 2 shows such databases, labelled as (soil type)/(number of parameters of interest)/(number of data points). Data points for coarse-grained soils in the literature are significantly less than those for clays, probably because it is very challenging to extract undisturbed samples. The data points in the generic multivariate database will be first compared with existing transformation models in Table 1. This serves as the basic consistency check for the database. Outlier data points will be detected based on this consistency check. The appropriately screened database is adopted to calibrate the bias and variability of existing transformation models, and recommendation on suitable transformation models will be made.

Database SAND/7/2794

This study compiles a generic database (SAND/7/2794) from the literature, consisting of a significant number of data points for seven parameters of coarse-grained soils. For notational simplicity, we use "SAND" to broadly denote coarse-grained soils, sands, and gravels. The SAND/7/2794 database consists of 2794 data points from 176 studies. The number of data points associated with each study varies from 1 to 295, with an average 9.3 data points per study. Unlike clay databases that are dominated by data from undisturbed in situ clay samples, the SAND/7/2794 database is dominated by data from laboratory reconstituted soils such as Erksak, Hokksund, Monterey, Ottawa, Sacramento River, Ticino, and Tonegawa sands. Many of these reconstituted soils are clean sands. The remaining (about 15%) data points in the database are in situ samples obtained from tube sampling, block sampling, or ground freezing techniques. The geographical regions for these in situ samples cover Canada, Chile, Germany, Greek, India, Italy, Japan, Kuwait, Pakistan, Puerto Rico, Russia, Slovakia, Taiwan, United Kingdom, and United States. The properties of the data in SAND/7/2794 cover a wide range of median grain size (D_{50}) (0.1 mm to more than 100 mm), uniformity coefficient (C_u) (1 to more than 1000), relative density (D_r) (−0.1% to 117%), and overconsolidation ratio (OCR) (1–15, but mostly 1). The details for this generic database are presented in Appendix A (Table A1). In this table, the third column "name of sand/region" shows the sand name if the soil sample is reconstituted and shows the region name if the soil sample is in situ. The fourth column "*n*" shows the number of data points. The fifth column "type" indicates whether the soil is primarily sand or gravel and also indicates whether the soil sample is reconstituted or in situ. The next four columns show the ranges of the index parameters (C_u, D_{50}, D_r) and OCR. The next column is for the critical-state friction angle ϕ'_{cv} if this information is provided in the references. The database only contains data from siliceous sands (sands composed primarily of silica). Bolton (1986), McDowell and Bolton (1998), and Safinus et al. (2013) suggested that the dilatancy behavior for calcareous sands (sands composed primarily of calcium carbonate) is different due to particle breakage. Therefore, the conclusions from this study are applicable to siliceous sands only. This is in line with development of conventional transformation models listed in Table 1.

Seven parameters are of primary interest, including D_{50}, C_u, D_r, σ'_v/P_a, ϕ', q_{t1}, and $(N_1)_{60}$. They are categorized into three groups:

1. Index properties: the median grain size (D_{50}), coefficient of uniformity (C_u), and relative density (D_r).
2. Effective stress and strength: the normalized vertical effective stress (σ'_v/P_a) (σ'_v is the vertical effective stress, and P_a is one atmosphere pressure (= 101.3 kN/m²)) and effective stress friction angle (ϕ'). The friction angle is the secant friction angle obtained in a triaxial compression test.

Table 2. Multivariate soil databases.

Database	Reference	Parameters of interest	No. of data points	No. of sites or studies	Range of properties: OCR	PI	S_t
CLAY/5/345	Ching and Phoon (2012*a*)	LI, s_u, s_u^{re}, σ'_p, σ'_v	345	37 sites	1~4	—	Sensitive to quick clays
CLAY/6/535	Ching et al. (2014)	s_u/σ'_v, OCR, $(q_t-\sigma_v)/\sigma'_v$, $(q_t-u_2)/\sigma'_v$, $(u_2-u_0)/\sigma'_v$, B_q	535	40 sites	1~6	Low to very high plasticity	Insensitive to quick clays
CLAY/7/6310	Ching and Phoon (2013, 2015)	s_u from seven different test procedures	6310	164 studies	1~10	Low to very high plasticity	Insensitive to quick clays
CLAY/10/7490	Ching and Phoon (2014*a*, 2014*b*)	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
F-CLAY/7/216	D'Ignazio et al. (2016)	s_u, σ'_p, σ'_v, LL, PL, w_n, S_t	216	24 sites	1~8	Low to very high plasticity	Insensitive to quick clays

Note: LL, liquid limit; PI, plasticity index; LI, liquidity index; PL, plastic limit; σ'_v, vertical effective stress; σ'_p, preconsolidation stress; s_u, undrained shear strength; s_u^{re}, remoulded s_u; S_t, sensitivity; OCR, overconsolidation ratio; $(q_t-\sigma_v)/\sigma'_v$, normalized cone tip resistance; σ_v, total vertical stress; $(q_t-u_2)/\sigma'_v$, effective cone tip resistance; u_0, hydrostatic pore pressure; u_2, pore pressure right behind cone; $(u_2-u_0)/\sigma'_v$, normalized excess pore pressure; B_q (pore-pressure ratio) = $(u_2-u_0)/(q_t-\sigma_v)$; P_a (atmospheric pressure) = 101.3 kPa; w_n, natural water content.

3. In situ tests: for cone penetration test (CPT), the normalized cone tip resistance $q_{t1} = (q_t/P_a)C_N$ is recorded, where q_t is the cone tip resistance, and C_N is the correction factor for overburden stress. For SPT, the normalized N value $(N_1)_{60} = N_{60}C_N$ is recorded, where N_{60} is the N value corrected for the energy ratio. The term "in situ tests" may be somewhat misleading because q_{t1} and $(N_1)_{60}$ data may be obtained from laboratory calibration chamber tests. Nonetheless, the term "in situ tests" is still adopted in this paper for all CPT and SPT test results.

   Liao and Whitman (1986) proposed that $C_N = (\sigma'_v/P_a)^{-0.5}$, and this formula is applicable for the range $\sigma'_v/P_a < 5$. Note that C_N is unbounded near ground surface where σ'_v approaches zero. Idriss and Boulanger (2008) suggested that an upper bound of 1.7 should be applied to C_N. For higher overburden stress, Boulanger (2003) proposed that $C_N = (\sigma'_v/P_a)^{-(0.7836-0.5208D_r)}$, and this formula is applicable for the range $\sigma'_v/P_a \le 10$. In this study, we adopt the following formula to evaluate C_N:

$$C_N = \begin{cases} \min[(\sigma'_v/P_a)^{-0.5},\ 1.7] & \text{for } \sigma'_v/P_a \le 5 \\ (\sigma'_v/P_a)^{-(0.7836-0.5208D_r)} & \text{for } 5 < \sigma'_v/P_a \le 10 \end{cases} \tag{1}$$

   where D_r is in decimal, not in percentage. The Liao–Whitman formula, namely $C_N = (\sigma'_v/P_a)^{-0.5}$, is adopted for the stress range $\sigma'_v/P_a \le 5$ because this formula does not require D_r information and does not significantly deviate from the Boulanger formula for this stress range. For scenarios with $5 < \sigma'_v/P_a \le 10$ and with unknown D_r, the Liao–Whitman formula can still be implemented as a first-order approximation because the Liao–Whitman formula is equivalent to the Boulanger formula with D_r = 54% (medium sand).

There are in total 2794 data points in the database. Each data "point" consists of a set of values stored in one row in the Excel worksheet. The resulting database is not a genuine multivariate database. The database is genuine multivariate if, for all data points, all seven parameters are simultaneously measured. However, such genuine multivariate data points are very rare in the literature. For the SAND/7/2794 database, the seven parameters are typically not fully measured. For instance, for some data points (Excel rows), (C_u, D_{50}, D_r, ϕ', $(N_1)_{60}$) are simultaneously measured, but for some other data points, (ϕ', D_r, q_{t1}) are simultaneously measured. There are 2794 such data points (or rows). The majority of the data points (or rows) in the database can be categorized into four types:

1. Laboratory "triaxial" compression test data "alone" (parallel CPT is not conducted). The majority of the data are measured from reconstituted soils. For these data points, D_r is recorded as the relative density prior to the consolidation stage (i.e., initial D_r), σ'_v is the effective consolidation stress during the consolidation stage, and ϕ' is the friction angle determined from the principle stresses at failure (σ'_{1f}, σ'_{3f}), namely $\phi' = 2\{\tan^{-1}[(\sigma'_{1f}/\sigma'_{3f})^{0.5}] - 45°\}$. The set of values ($D_r$, σ'_v, ϕ') is recorded in the same data row, i.e., we treat them as the properties from the same soil.
2. Laboratory "calibration" chamber CPT and SPT test data. The majority of the data are also measured from reconstituted soils. For these data points, D_r is recorded as the relative density before applying the chamber pressure (initial D_r), σ'_v is recorded as the overall vertical chamber pressure, and $q_{t1} = (q_t/P_a)C_N$ (or $(N_1)_{60} = N_{60}C_N$) is computed, where C_N is evaluated by eq. (1) with σ'_v equal to the overall vertical chamber pressure. The set of values (D_r, σ'_v, q_{t1}) (or (D_r, σ'_v, $(N_1)_{60}$)) is recorded in the same data row.
3. Laboratory calibration chamber CPT and SPT with parallel laboratory triaxial test data. The majority of the data are also measured from reconstituted soils. For these data points, the chamber test

values for D_r, σ'_v, q_{t1}, and $(N_1)_{60}$ are recorded. The ϕ' obtained from the triaxial tests is also recorded. The set of values (D_r, σ'_v, q_{t1}, ϕ') (or (D_r, σ'_v, $(N_1)_{60}$, ϕ')) is recorded in the same data row.

4. In situ SPT and CPT with parallel laboratory triaxial test data. The data are measured from in situ soils. Some are undisturbed samples obtained using the ground freezing technique and tested in laboratory. For the data points of this category, D_r is recorded as the in situ relative density, and $q_{t1} = (q_t/P_a)C_N$ or $(N_1)_{60} = N_{60}C_N$ is evaluated by eq. (1) with σ'_v equal to the in situ vertical effective stress. The value of ϕ' from the laboratory triaxial test is adjusted to the in situ σ'_v by first fitting a (curved) failure envelope to all failure Mohr circles and locating the secant friction angle at $\sigma' = \sigma'_v$. The set of values (D_r, σ'_v, q_{t1}, ϕ') (or (D_r, σ'_v, $(N_1)_{60}$, ϕ')) is recorded in the same data row.

Comparison with existing transformation models

The data points in SAND/7/2794 can be compared with transformation models in Table 1 to verify whether they exhibit consistent correlation behavior. Some transformation models in Table 1 are selected to compare with the data points in SAND/7/2794. Many of these models were developed based on certain databases limited to certain types of sands and gravels. These databases may not be as generic as SAND/7/2794. Therefore, some differences in the correlation behavior between the transformation models and SAND/7/2794 are to be expected. It is possible that the differences arose because the SAND/7/2794 database covers a broader range of soils.

The transformation models in Table 1 are further labeled using the template: (primary input parameter)–(target parameter) (second column in Table 1). The (primary input parameter)–(target parameter) pairs are categorized into five types of models, SPT–D_r, CPT–D_r, D_r–ϕ', SPT–ϕ', and CPT–ϕ' models, for this comparison. The following observations can be made:

1. SPT–D_r models. Four models are presented in Table 1, and two models (Terzaghi and Peck 1967; Kulhawy and Mayne 1990) are compared with the data points in SAND/7/2794 in Fig. 2. In general, the majority of the data points follow the trends of the transformation models. There are two classes of data points that do not seem to follow the trends:
   (*a*) Volcanic soils (grey triangles). Their data show low $(N_1)_{60}$ (mostly less than 20) and yet high D_r (mostly higher than 60). It will be seen later that volcanic soils do not follow the trend for the SPT–ϕ' transformation models either. Chen (2004) also concluded that volcanic soils behave fairly differently from normal sands and gravels.
   (*b*) In situ gravels (grey diamonds). They show fairly large scattering (note that there is a data point in the upper-left corner of Fig. 2). However, it will be seen later that they follow the trend for the SPT–ϕ' models. It is likely that the D_r information of the data points is not reliable, given the fact that maximum and minimum void ratios (e_{max}, e_{min}) for in situ gravels may not be determined reliably owing to the lack of standardized procedures for gravels (Kudo et al. 1990; Cubrinovski and Ishihara 1999; Chen 2004; Chen and Kulhawy 2014).

   Other than the aforementioned two classes of data points, other data points show general consistency with the two transformation models (Terzaghi and Peck 1967; Kulhawy and Mayne 1990). In particular, the Terzaghi–Peck model fits the overall data trend well. It is known that the SPT–D_r relationship depends on the grain size. The Kulhawy–Mayne model incorporates this dependency. The two dashed lines in Fig. 2 show the model trends for D_{50} = 0.2 mm and 5 mm (OCR = 1 for both cases). The dashed line with D_{50} = 0.2 mm matches well with the data trend for reconstituted and in situ sands (reconstituted and in situ sand data exhibit similar trend). The dashed line with D_{50} = 5 mm matches well with the data trend for reconstituted gravels.

Fig. 2. SPT–D_r models and data points in SAND/7/2794. [Colour online.]

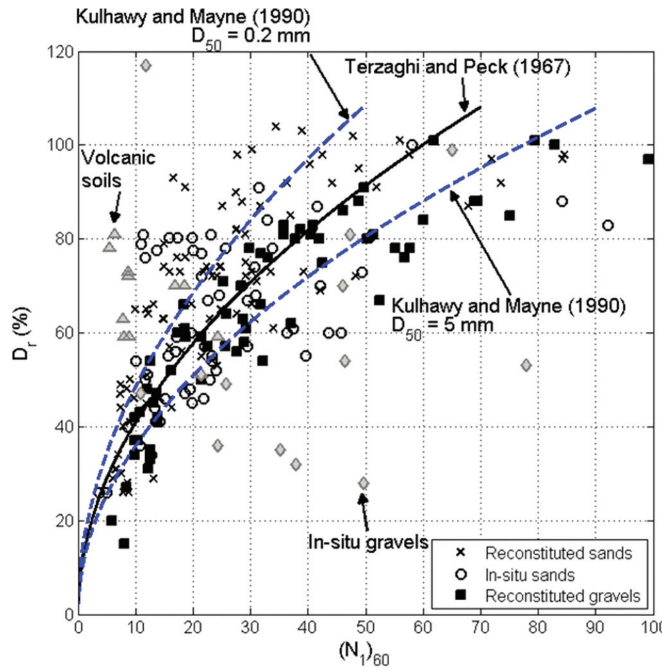
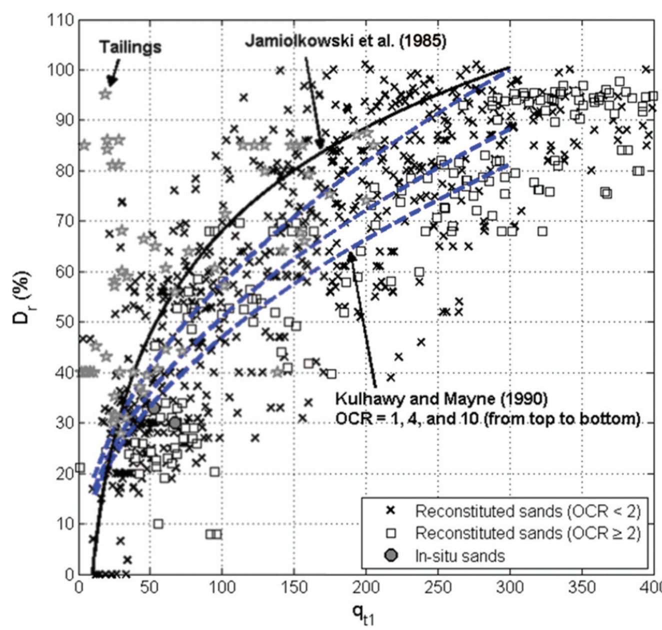
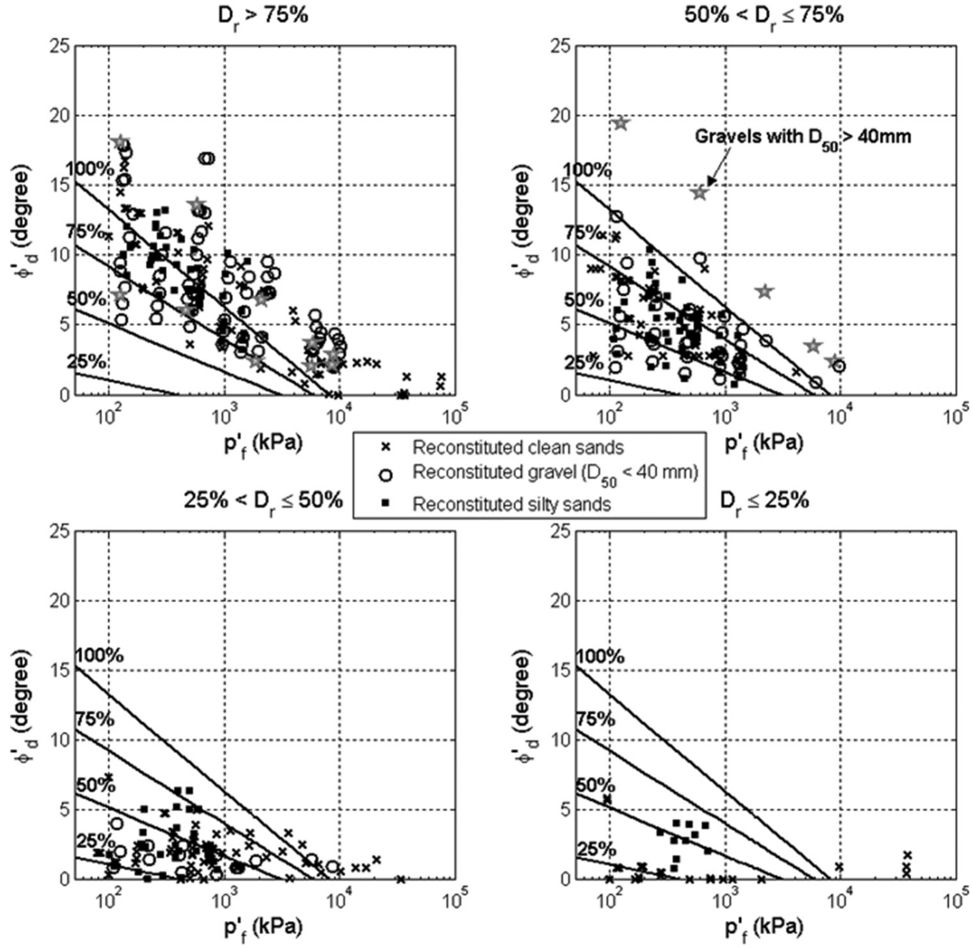


Fig. 3. CPT–D_r models and data points in SAND/7/2794. [Colour online.]



2. CPT–D_r models. Two models are presented in Table 1, and both models (Jamiolkowski et al. 1985; Kulhawy and Mayne 1990) are compared with the data points in SAND/7/2794 in Fig. 3 (the compressibility factor, Q_C = 1.0, is adopted for the Kulhawy–Mayne model). There are no data points for gravels because CPT is not applicable to gravelly soils. Data points with OCR < 2 and OCR ≥ 2 are plotted as different markers. The Jamiolkowski et al. (1985) model fits to data points with OCR < 2 but does not fit well to those with OCR ≥ 2. In general, the Kulhawy and Mayne (1990) model seems to provide a better fit. The mine tailings data do not follow the trends of the transformation models.
3. D_r–ϕ' models. Two models are presented in Table 1, and one model (Bolton 1986) is compared with the data points in SAND/

Fig. 4. D_r–ϕ' model and data points in SAND/7/2794.

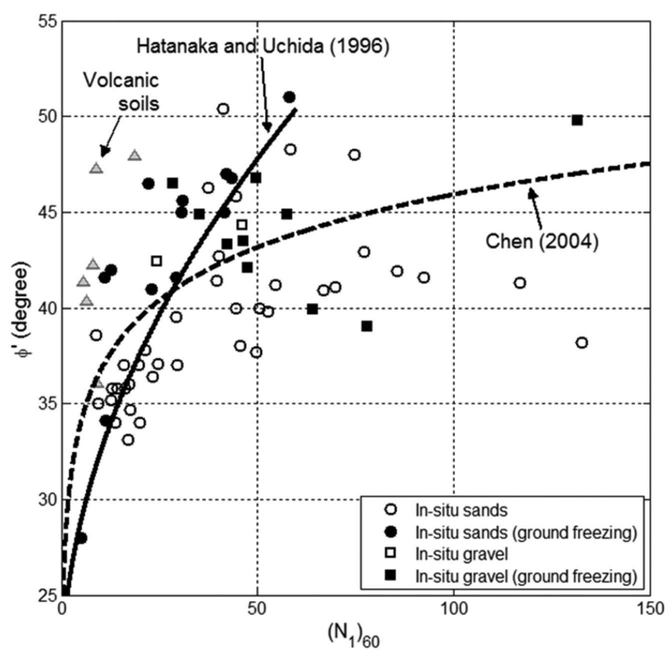


7/2794 in Fig. 4. Although Salgado et al. (2000) developed several D_r–ϕ' models for sands with different fines contents, only their model for 10% fines is shown in Table 1. Figure 4 shows the Bolton model and the data points in SAND/7/2794. The horizontal axis, p'_f, is the mean effective stress at failure equal to $(\sigma'_{1f} + \sigma'_{2f} + \sigma'_{3f})/3$. The four solid lines represent the dilation angle (ϕ'_d) predicted by the Bolton model for D_r (%) = 25, 50, 75, and 100. The dilation angles (ϕ'_d) of the data points are determined by subtracting the critical-state friction angle (ϕ'_{cv}) from ϕ'. The ϕ'_{cv} values are commonly reported in studies involving reconstituted soils (see the ϕ'_{cv} column in Table A1). Even for reconstituted sand data points with unknown ϕ'_{cv}, past experiences (e.g., table 1 in Bolton 1986; table 1 in Salgado et al. 2000; table 4 in Ching et al. 2012) can be adopted to estimate ϕ'_{cv} based on the sand type, mineralogy, angularity, grain size distribution, etc. In contrast, studies for in situ sand or gravel data points generally do not report the value of ϕ'_{cv}. This is why there are no in situ data points in Fig. 4.

Among all the data points in Fig. 4, reconstituted gravelly soils with D_{50} > 40 mm (grey asterisks) do not seem to follow the trend for the Bolton model. These soils contain a significant portion of cobbles or even boulders. Other data points show general consistency with the Bolton model. Moreover, reconstituted gravels with D_{50} < 40 mm, reconstituted clean sands, and reconstituted silty sands (fines content 5%∼20%) seem to roughly follow the same trend.

4. SPT–ϕ' models. Five models are presented in Table 1, and two models (Hatanaka and Uchida 1996; Chen 2004) are compared with the data points in SAND/7/2794 in Fig. 5. They are all in

Fig. 5. SPT–ϕ' models and data points in SAND/7/2794.



situ soil data points because SPT is typically conducted in situ. Yoshida and Kokusho (1988) conducted calibration chamber SPT on reconstituted soils, but triaxial tests were not conducted. Volcanic soil data are associated with high ϕ' but low $(N_1)_{60}$ values, so this set of data is not consistent with the trends of the two transformation models and the rest of the data points. Other data points show a general consistent agreement, except that ground-freezing sand data seem to exhibit slightly higher ϕ'. In general, the Chen (2004) model provides a more satisfactory fit to the data because this model was calibrated by a broader database. Hatanaka and Uchida (1996) developed their model (solid curve in Fig. 5) based on limited ground-freezing data points with $(N_1)_{60} < 60$. Later in 1998, this model was updated by Hatanaka et al. (1998) by specifying an upper bound of $\phi' = 40°$. Among the five models in Table 1, only two models (Hatanaka and Uchida 1996; Chen 2004) are plotted in Fig. 5 for two reasons: (*i*) Peck et al. (1974)'s and Schmertmann (1975)'s models are not based on $(N_1)_{60}$, hence they cannot be shown in the same plot; (*ii*) Hatanaka et al. (1998)'s model is the same as Hatanaka and Uchida (1996)'s model with a 40° upper bound. Nonetheless, the biases and variabilities of all five models are calibrated using SAND/7/2794 in Table 1.

5. CPT–ϕ' models. Two models are presented in Table 1, and one model (Kulhawy and Mayne 1990) is compared with the data points in SAND/7/2794 in Fig. 6. There are no data points for gravels because CPT is not applicable to gravelly soils. Many data points in Fig. 6 overlap with the CPT–ϕ' database adopted by Kulhawy and Mayne (1990). These overlapping data points are shown as crosses in Fig. 6. Only one model (Kulhawy and Mayne 1990) is plotted in Fig. 6 because the other model (Robertson and Campanella 1983) is not based on q_{t1}, hence it cannot be shown in the same plot. Nonetheless, the biases and variabilities of both models are calibrated using SAND/7/2794 in Table 1.

Removal of outliers

Based on the preceding observations, it is determined that the following classes of data points should be excluded from the SAND/7/2794 database. The purpose is to exclude outliers with significantly different correlation behavior from the main population.

1. Volcanic soils (13 data points): they do not exhibit trends consistent with the existing SPT–D_r and SPT–ϕ' transformation models.
2. Mine tailings (59 data points): they do not exhibit a trend consistent with the existing CPT–D_r transformation models.
3. Gravelly soils with D_{50} > 40 mm (37 data points): they do not exhibit a trend consistent with the existing D_r–ϕ' transformation model.
4. The D_r information for all in situ gravel data are removed because it may be unreliable.
5. Cases with $\sigma'_v/P_a > 10$ (98 data points) are excluded because C_N in eq. (1) may not be applicable to data with $\sigma'_v/P_a > 10$ and also because this high stress level is of limited interest in routine projects.
6. Cases with more than 20% fines content (98 data points) (e.g., data from Brandon et al. 1990) are removed because the soil behavior may be dominated by the fines.
7. Railroad ballasts (16 data points) are removed because they have relatively high friction angles.

The revised database contains data points from reconstituted and in situ coarse-grained soils, excluding volcanic soils, mine tailings, railroad ballasts, soils with significant cobble or boulder contents, soils subjected to very high stress levels, and soils with fines content greater than 20%. The basic statistics of the seven parameters in the revised database are listed in Table 3. The statistics are the mean value, coefficient of variation (COV), minimum value (Min), and maximum value (Max). The numbers of available data points (n) are shown in the second column. The number of data points is further divided into the numbers of reconstituted and in situ data points. For instance, there are in total 1939 data points with C_u information. Among them, 1793 are reconstituted soils and 146 are in situ soils. About 85% of the data points in the revised SAND/7/2794 database are reconstituted soils.

Fig. 6. CPT–ϕ' model and data points in SAND/7/2794.

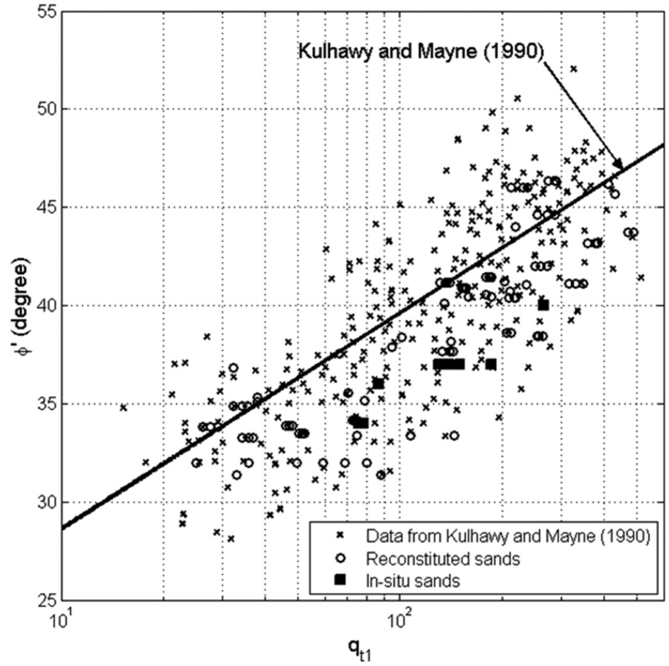


Table 3. Selected statistics of seven parameters in revised SAND/7/2794 database.

Parameter	n (reconstituted + in situ)	Mean	COV	Min	Max
C_u	1939 (1793+146)	9.62	3.787	1	504.0
D_{50} (mm)	2064 (1868+196)	1.52	2.303	0.11	35.0
D_r (%)	1686 (1587+99)	63.17	0.385	−0.071	113.0
σ'_v/P_a	1945 (1546+399)	1.87	0.917	0.049	9.9
ϕ'	1059 (928+131)	39.88	0.128	22.8	59.9
q_{t1}	1436 (1227+209)	163.39	0.697	0.75	536.8
$(N_1)_{60}$	589 (155+434)	34.66	0.757	2.11	243.5

Quantification of transformation uncertainty

Additive versus multiplicative forms

The data scatter about the transformation model can be quantified using probabilistic methods, as illustrated in Fig. 1. In this approach, the transformation model is typically evaluated using regression analyses. The spread of the data about the regression curve can be modeled in many instances as an additive form:

$$\varepsilon = \text{actual target value} - b(\text{predicted target value}) \tag{2}$$

where the actual target value equals the measured value of the design property, and the predicted target value equals the estimated value of the design property from a transformation model. The product of a constant b (bias factor) and the predicted target value produces an unbiased prediction on average. The bias of the prediction is captured by b, whereas ε only captures the variability of the prediction, not the bias. For ε to only capture the variability without the bias, ε must have a zero mean. Moreover, because ε can be negative, ε is usually modeled as a normal random variable (normal variable can be negative). As a result, the additive form is usually associated with a zero-mean normally distributed ε. The standard deviation of ε, denoted by σ, quantifies the variability of the transformation model. Ching and Phoon (2014*a*) used a common alternative multiplicative form for the data scatter:

$$\varepsilon = \frac{\text{actual target value}}{b(\text{predicted target value})} \tag{3}$$

where the random variable ε now quantifies the ratio between the actual target value and the unbiased prediction. For ε to only capture the variability without the bias, ε must have a unit mean. Moreover, because the ratio (actual parameter value)/(predicted parameter value) is usually positive, ε is also positive. Hence, ε is usually modeled as a lognormal random variable (lognormal variable can only be positive). As a result, the multiplicative form is usually associated with a unit-mean lognormally distributed ε. The standard deviation of ε, denoted by σ, quantifies the variability of the transformation model. Here, the standard deviation of ε is the same as its coefficient of variation (COV), denoted by δ. From a definition point of view, the multiplicative form is identical to the "model factor" in the reliability literature, which is typically defined as the ratio of a measured response (e.g., pile capacity) to the calculated response.

For the additive form (eq. (2)), ε has the same unit as for the actual target value. If the target value is D_r, ε has the unit of %, whereas if the target value is ϕ', ε has the unit of degrees. The standard deviation for ε has the same unit, either % or degree. For the multiplicative form (eq. (3)), ε is dimensionless. The standard deviation or COV of ε is also dimensionless.

Calibration of bias and variability

The bias and variability of all transformation models in Table 1 are calibrated by the revised SAND/7/2794 database. For the calibration of the CPT–D_r model proposed by Kulhawy and Mayne (1990), the secondary explanatory factor Q_C (compressibility index) is determined according to the fines content (FC): $Q_C = 1.09$ for clean sands (low compressibility), $Q_C = 1.0$ for 0% < FC ≤ 10% (medium compressibility), and $Q_C = 0.91$ for 10% < FC ≤ 20% (high compressibility). For the SPT–D_r model proposed by Kulhawy and Mayne (1990), there are two secondary explanatory factors: D_{50} and OCR. Between them, D_{50} is typically known, whereas OCR is unknown for many data points in SAND/7/2794. For those data points, OCR is assumed to be 1. In general, the uncertainty in a secondary explanatory factor would be lumped into the calibrated variability, i.e., the variability may be higher without the knowledge of the secondary explanatory factor.

For the multiplicative form (eq. (3)), the bias factor (b) for a transformation model is estimated as the sample mean of the ratio (actual target value)/(predicted target value). For instance, for the SPT–D_r model proposed by Terzaghi and Peck (1967) (the second model in Table 1), the actual target value is D_r (%), and the predicted target value is $100[(N_1)_{60}/60]^{0.5}$. The data points in the revised SAND/7/2794 database with simultaneous information of $[D_r, (N_1)_{60}]$ are extracted. However, not all these data points are accepted because the Terzaghi–Peck model is only applicable to soils with $(N_1)_{60} < 60$. 198 data points with simultaneous $[D_r, (N_1)_{60}]$ information and with $(N_1)_{60} < 60$ are finally adopted, and 198 ratios $D_r/\{100[(N_1)_{60}/60]^{0.5}\}$ are computed. The sample mean of these ratios is equal to 1.05 ($b \approx 1.05$). This means that b(predicted target value) = $105[(N_1)_{60}/60]^{0.5}$ is the unbiased prediction for D_r for the multiplicative form. The variability term $\varepsilon = D_r/\{105[(N_1)_{60}/60]^{0.5}\}$ is computed for all 198 data points. The sample COV (sample standard deviation divided by sample mean) of these ε values is 0.231 ($\delta \approx 0.231$).

For the additive form (eq. (2)), the bias factor (b) is first estimated as (sample mean of actual target values)/(sample mean of predicted target values). For the SPT–D_r model proposed by Terzaghi and Peck (1967), b = (sample mean of 198 actual D_r values)/{sample mean of 198 $100[(N_1)_{60}/60]^{0.5}$ values}. The bias factor b is estimated to be 1.03. This means that b(predicted target value) = $103[(N_1)_{60}/60]^{0.5}$ is the unbiased prediction for D_r for the additive form. Then, ε = (actual target value) − b(predicted target value) = $D_r - \{103[(N_1)_{60}/60]^{0.5}\}$ is computed for all 198 data points. Recall that ε has mean = 0 and standard deviation of σ. The sample standard deviation of these ε values is 13.63(%) ($\sigma \approx 13.63\%$). Note that the standard deviation is not dimensionless. It has the unit of the design parameter: % for D_r and degrees for ϕ'.

The distribution type for ε is also examined by the K–S (Kolmogorov–Smirnov) test (Conover 1999). The common null hypothesis for the additive form is a normal random variable. The common null hypothesis for the multiplicative form is a lognormal random variable. If the p-value for the K–S test is larger than 0.05, the hypothesis is deemed acceptable (or more accurately, cannot be rejected at 5% significance). The null hypothesis of a normal distribution is also tested for the multiplicative form, but the p-value is always less than the lognormal hypothesis, indicating it is more reasonable to adopt the lognormal hypothesis for the multiplicative form. The p-values for all transformation models with variability assuming the additive normal and multiplicative lognormal forms are listed in Table 1.

Calibration results

Table 1 shows the calibrated bias and variability for various transformation models under the multiplicative lognormal and additive normal forms. The data restriction (e.g., $(N_1)_{60} < 60$) for each model is described in the rightmost column: only data in SAND/7/2794 fulfilling the restriction are adopted for the calibration. There are a few models that have broad application ranges. For these models, all data with the required simultaneous information are adopted for the calibration. The number of available calibration data points is shown in the fifth column. The number is further divided into the numbers of reconstituted and in situ soil data. It is clear that the SPT–D_r models are calibrated by the mixture of reconstituted and in situ soil data. The CPT–D_r, D_r–ϕ', and CPT–ϕ' models are mainly calibrated by reconstituted soil data, whereas SPT–ϕ' models are mainly calibrated by in situ soil data.

Within the same model type (e.g., SPT–D_r models), there seems to be a general trend that more recent transformation models are less biased (b closer to 1) than older models. The bias factor for the D_r–ϕ' model proposed by Salgado et al. (2000) is not very close to 1 probably because this model is calibrated in their study by silty sand data with fines contents not exactly 10% but ranging from 5% to 20%. Although there is also a general trend that more recent transformation models have less variability (smaller δ and σ) than older models, this trend for δ and σ is less clear than the trend for b, probably because δ and σ are more sensitive to statistical uncertainty.

Table 1 also shows the p-values for the multiplicative lognormal and additive normal forms. Most p-values are larger than 0.05, indicating that both variability forms may be adopted. For the D_r models (SPT–D_r and CPT–D_r models), the multiplicative lognormal form gets two rejections (p-value < 0.05), whereas the additive normal form gets only one. For the ϕ' models (D_r–ϕ', SPT–ϕ', and CPT–ϕ' models), both multiplicative lognormal and additive normal forms are applicable. The recommendation is to adopt the variability form with a larger p-value, but if the p-values are comparable, the multiplicative form has a practical edge because δ is dimensionless and an engineer can develop a "feel" for the significance of δ in reliability analysis from its numerical value (e.g., $\delta < 0.05$ is "small").

Models most consistent with SAND/7/2794 database

According to the calibration results, the following models are selected (one model is selected for each model type). The following factors are considered in this model selection: (*i*) it is preferable that b is close to 1 and δ (or σ) is small because this means that the model is consistent with the SAND/7/2794 database; (*ii*) it is preferable that the model has a broad range of applicability, e.g., applicable to both normally consolidated (NC) and overconsolidated (OC) soils or applicable to a wide range of $(N_1)_{60}$ or q_{t1}. The selected models are annotated with "**" in Table 1, discussed as follows:

1. For the SPT–D_r models, the two models that consider grain size distribution (Marcuson and Bieganousky (1977) consider C_u, whereas Kulhawy and Mayne (1990) consider D_{50}) are both nearly unbiased. The model proposed by Kulhawy and Mayne (1990) is selected because it has a broader application range. The multiplicative lognormal form is recommended for this model (substantially higher *p*-value).
2. For the CPT–D_r models, the model proposed by Kulhawy and Mayne (1990) is selected because it is less biased (b = 0.93) and can be broadly applicable to both NC and OC soils. Note that 92.5% (777 out of 840) of our data points overlap with the data points used by Kulhawy and Mayne in developing their model. The additive normal form is recommended for this model (substantially higher *p*-value). The model proposed by Jamiolkowski et al. (1985) is biased on the unconservative side (b = 0.84 < 1).
3. For the D_r–ϕ' models, the model proposed by Bolton (1986) is selected because it is nearly unbiased (b = 1.03) with small variability (δ = 0.052 and σ = 2.07°). Both multiplicative lognormal and additive normal forms are recommended for this model (comparable *p*-values). The variability of this model is relatively small compared with those for SPT–ϕ' and CPT–ϕ' models (see Table 1). However, this model requires an estimate of ϕ'_{cv}, which is not required for the SPT–ϕ' and CPT–ϕ' models. If the additional variability incurred by the estimation of ϕ'_{cv} is considered, the overall variability for the D_r–ϕ' model can be comparable to those for the SPT–ϕ' and CPT–ϕ' models.
4. For the SPT–ϕ' models, the model proposed by Chen (2004) is selected because it is unbiased (b = 1.00) and has a broad application range (a wide range of $(N_1)_{60}$). The multiplicative lognormal form is recommended for this model (higher *p*-values). All SPT–ϕ' models based on $(N_1)_{60}$ (Hatanaka and Uchida 1996; Hatanaka et al. 1998; Chen 2004) have δ and σ values that are smaller than those based on N_{60} or the combination of N_{60} and σ'_v/P_a (Peck et al. 1974; Schmertmann 1975). According to Table 3, the COV of ϕ' is 0.128. This is the "prior" COV when D_r, SPT, and CPT information is not available. The two SPT–ϕ' models based on N_{60} (Peck et al. 1974) or the combination of N_{60} and σ'_v/P_a (Schmertmann 1975) have δ = 0.132~0.137 that are close to the prior COV = 0.128. These two SPT–ϕ' models are not very effective because they do not reduce the COV.
5. For the CPT–ϕ' models, the model proposed by Kulhawy and Mayne (1990) is selected because it is nearly unbiased (b = 0.97) and with a broad application range (both NC and OC soils). Note that 97.6% (368 out of 376) of our data points overlap with the data points used by Kulhawy and Mayne in developing their model. The additive normal form is recommended for this model (substantially higher *p*-value).

Recall that SAND/7/2794 is a generic database. Its data points are not limited to a certain region or a certain soil type. The SPT–D_r, CPT–D_r, and CPT–ϕ' models from Kulhawy and Mayne (1990) are also developed from generic databases. It is possible that these models are the most consistent with the SAND/7/2794 database because of comparable breadth of coverage. A site-specific model calibrated for a specific soil type may not show the same degree of consistency. Ching and Phoon (2012*b*) discussed the establishment of generic transformations for geotechnical design parameters using such generic databases.

Probability distribution of actual target value

It is possible to characterize the probability distribution of the target value (D_r or ϕ') based on available input parameters (e.g., SPT or CPT information). For instance, for the SPT–ϕ' model proposed by Chen (2004), the target value is ϕ' and input parameter is $(N_1)_{60}$. For this model, the multiplicative lognormal form is acceptable. According to Table 1, the bias factor b = 1.00 and δ = 0.095 are calibrated by the SAND/7/2794 database. For the multiplicative lognormal form, the actual target value can be expressed as

$$\text{Actual target value} = (\text{predicted target value}) \times b \times \varepsilon \tag{4}$$

where b = 1.00, and ε is the lognormally distributed random variable with mean = 1 and COV = δ = 0.095. This means that

$$\text{Actual } \phi' = \{27.5 + 9.2 \log_{10}[(N_1)_{60}]\} \times 1.00 \times \varepsilon \tag{5}$$

As a result, the actual value of ϕ' is a lognormal random variable with mean = unbiased prediction = $\{27.5 + 9.2 \log_{10}[(N_1)_{60}]\}$ and COV = 0.095. It is also possible to represent the actual value of ϕ' using a standard normal random variable Z for the first-order reliability method (Hasofer and Lind 1974; Ditlevsen and Madsen 1996):

$$\text{Actual } \phi' = \exp\left\langle \ln\left\{\frac{27.5 + 9.2\log_{10}[(N_1)_{60}]}{\sqrt{1+\delta^2}}\right\} + \sqrt{\ln(1+\delta^2)} \times Z \right\rangle \tag{6}$$

Conclusions

In this paper, a generic database (SAND/7/2794) for coarse-grained soils is developed, and existing transformation models in the literature are investigated. This generic database contains reconstituted coarse-grained soils with wide range of characteristics (grain size distributions, sand types, OCR, etc.) as well as in situ coarse-grained soils from a wide range of geographical locales. Mine tailings, volcanic soils, railroad ballasts, gravelly soils with significant cobble or boulder content, and soils with fines contents more than 20% are excluded because they exhibit inconsistent correlation behavior. Soils subjected to very high stress levels (σ'_v/P_a > 10) are also excluded because they are out the scope of geotechnical engineering. Two types of transformation models are considered: models that predict the relative density (D_r models) and models that predict the friction angle (ϕ' models). It is found that the existing transformation models and the SAND/7/2794 database exhibit consistent correlation behavior. The SAND/7/2794 database is further used to calibrate the bias and variability for the existing transformation models (see Table 1 for the calibration results). It is found that more recent models tend to have smaller biases. Variability can be introduced in an additive or multiplicative form. Recommendations for the variability form (additive normal versus multiplicative lognormal) are also given. The SAND/7/2794 database can be further adopted to develop the multivariate probability distribution for the seven parameters of coarse-grained soils. This is a direction for future research.

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Appendix A

SAND/7/2794 database

This appendix presents a table (Table A1) that contains the basic information for the database as well as the reference list.

Table A1. Basic information for SAND/7/2794 database.

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
1	Agha and Masood (1997)	Barotha, Pakistan	1	In situ GW	111	34	—	—	—	—
2	Al-Hussaini and Townsend (1975*a*); Al-Hussaini and Townsend (1975*b*)	Reid-Bedford sand	3	Reconstituted clean sand	1.5	0.24	25~100	—	—	28.5~34
3	Al-Hussaini and Townsend (1975*b*)	Sangamon sand	2	Reconstituted clean sand	—	—	—	—	—	32.5~37.6
		Wabash sand	2	Reconstituted clean sand	—	—	—	—	—	34.6~38.6
		Chattahoochee sand	4	Reconstituted clean sand	—	—	—	—	—	32.3~40.5
		Brasted sand	2	Reconstituted clean sand	—	—	—	—	—	33.9~39
		—	4	Reconstituted clean sand	—	—	—	—	—	32.9~38.2
		Belgium sand	4	Reconstituted clean sand	—	—	—	—	—	34.2~43.3
		Minnesota sand	2	Reconstituted clean sand	—	—	—	—	—	28~37.5
		Pennsylvania sand	2	Reconstituted clean sand	—	—	—	—	—	31~35.8
4	Alsamman (1995); Rollberg (1977)	Dusseldorf, Germany	3	In situ sand–gravel mixture	—	—	55~56	—	—	39~40
5	Andrus and Youd (1987)	Whiskey Springs, US	11	In situ gravel	—	—	—	—	—	—
6	Aoyama et al. (1993); Hatanaka and Uchida (1996); Hatanaka et al. (1995)	Nagoya, Japan	1	In situ sand (ground-freezing sample)	3.4	0.48	78	—	—	—
7	Baker et al. (1991); Baker et al. (1993)	Cupertino, CA, US	1	In situ gravel	—	—	87	—	—	46
8	Baker et al. (1993)	Cupertino, CA, US	3	In situ gravel	—	—	—	—	—	—
9	Baldi et al. (1986); Jefferies and Been (2006)	Ticino sand	295	Reconstituted clean sand	1.58	0.5	16~98	1~15	31	32~48
		Hokksund sand	99	Reconstituted clean sand	2.05~2.2	0.39	17~100	1~15	29.5~31	33~48
10	Barton (1990); Barton et al. (1986)	Hampshire, UK	1	In situ SP	2.2	0.2	88	—	—	—
11	Barton and Palmer (1988); Barton and Palmer (1989)	Sussex, UK	1	In situ sand	2.2	0.17	108	—	—	—
12	Barton and Palmer (1990); Palmer and Barton (1987)	Cambridgeshire, UK	1	In situ sand	2.4	0.16	113	—	—	—
13	Becker et al. (1972); Becker et al. (1972)	Napa, CA, US	14	Reconstituted gravel	7~7.4	3.2~40.5	68~101	—	33.5~35	35~53
		Maxwell, CA, US	20	Reconstituted gravel	7~7.4	3.2~40.5	37~97	—	34~35	36~44
14	Beckwith and Bedenkop (1973)	Phoenix, AZ, US	7	In situ clay–gravel mixture	—	—	87~89	—	—	42
15	Been et al. (1987)	Erksak sand	28	Reconstituted SP	2.2	0.35	69~99	1	31	35~42
16	Bellotti (1976)	Medium sand	1	Reconstituted clean sand	—	—	16	—	—	—
17	Bishop (1958)	Brasted sand	1	Reconstituted clean sand	—	—	40	—	—	—
18	Bishop and Green (1965)	Ham River sand	40	Reconstituted clean sand	—	0.204	9~93	—	33.4	32~46
19	Brandon et al. (1990)	Yatesville sand	5	Reconstituted silty sand (with 40% fines)	32.5	0.1	—	1~2	—	—
20	Briaud (2000)	College Station, TX, US	2	In situ SP	1.6~2.2	0.16~0.19	55	—	—	—
21	Briaud and Gibbens (1997)	College Station, TX, US	1	In situ sand	—	0.19	55	—	—	36.4
22	Burton and Thomas (1987)	Palo Alto, CA, US	3	In situ sand	—	—	—	—	—	—
23	Canou et al. (1988)	Hostun sand	20	Reconstituted clean sand	2.22	0.35	15~95	1	—	—
24	Černák et al. (1988)	Bratislava, USSR	1	In situ gravel	—	—	—	—	—	—
		Sered, Czechoslovakia	1	In situ gravel	—	—	—	—	—	—
		Bratislava, USSR	1	In situ gravel	—	—	66	—	—	—
		Sered, Slovakia	1	In situ GM	—	—	—	—	—	—
25	Chapman and Donald (1981)	Frankston sand	36	Reconstituted clean sand	2.05	0.31	54~100	1~7.7	—	35~42
26	Charles and Watts (1980)	Sandstone rockfill	5	Reconstituted gravel	72.5	4.29	—	—	—	38.5~59.9
		Slate rockfill	2	Reconstituted gravel	48.33	4.91	—	—	—	43.3~56.1
		Basalt rockfill	1	Reconstituted gravel	5.71	13.06	—	—	—	58.7
27	Chen (2004)	Kaohsiung, Taiwan	3	In situ sand	—	—	—	—	—	35~38.6
		Pittsburgh, PA, US	2	In situ GW	46.7	11	36~70	—	—	42.4~44.3
		Pittsburgh, PA, US	2	In situ sand	3.7	0.4	41~68	—	—	35.8~37.1
		Pittsburgh, PA, US	2	In situ sand	31.5	2.4	38~67	—	—	38.4~39.5
28	Chen and Hsieh (2001)	Taichung, Taiwan	6	In situ SW	240	—	75~88	—	—	47

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Table A1 (*continued*).

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
29	Chin et al. (1988)	Hsinta Power Plant, Kaohsiung, Taiwan	35	In situ sand	—	—	—	—	—	—
30	Chong (1988)	Leighton Buzzard sand	30	Reconstituted clean sand	1.5	0.37	35~83	1	33	31~50
31	Chu et al. (1989)	Linkou, Taiwan	2	In situ gravel	304~1913	26~60	—	—	—	—
		Sanyi, Taiwan	1	In situ gravel	543	70	—	—	—	—
		Changhua, Taiwan	4	In situ gravel	63~167	2.7~32	—	—	—	—
		Taoyuan, Taiwan	2	In situ gravel	130	6~12	—	—	—	—
32	Chu et al. (1996)	Taichung, Taiwan	8	In situ GW	163~732	64~120	—	—	—	—
33	Meyers (1992)	Albuquerque, NM	1	In situ sand–gravel mixture	—	—	50	—	—	39
34	Clayton and Rollins (1994); Rollins et al. (1994); Rollins et al. (1997*a*)	Spanish Fork, UT, US	3	In situ GW	30~90	—	72~78	—	—	45~47
		American Fork, UT, US	4	In situ GW	53~107	—	66~73	—	—	44~45
		Kennecott, UT, US	4	In situ gravel	19~500	—	59~73	—	—	43~46
35	Cornforth (1964); Cornforth (1973)	Brasted sand	21	Reconstituted clean sand	—	0.26	8~84	—	33.4	33~42
36	Crova et al. (1993)	Sicily, Italy	2	In situ gravel	69~92	2.1~3.3	—	—	—	—
37	Daramola (1980)	Ham River sand	2	Reconstituted clean sand	—	0.35	—	—	—	—
38	Dayal et al. (1970)	Falgu sandy gravel	3	Reconstituted gravel	1.4~1.5	1.9~6	4~88	—	—	33~41
39	Deb et al. (1964); Mohan et al. (1971); Narahari et al. (1968)	Rishikish, India	1	In situ GW	900	60	—	—	—	—
40	DiMillio et al. (1987)	California, US	5	In situ clean sand	—	—	40~52	—	—	—
41	Douglas (1982)	California, US	16	In situ silt–sand mixture	—	—	—	—	—	—
		California, US	15	In situ clay–sand–gravel mixture	—	—	—	—	—	—
		California, US	7	In situ clay–silt–sand mixture	—	—	—	—	—	—
42	East Japan Railway Co. et al. (1996)	Tabata Station, Japan	2	In situ GW	—	—	—	—	—	—
		Toyama Station, Japan	1	In situ SW	—	—	—	—	—	—
		Japan	5	In situ SW	—	—	—	—	—	—
		Tabata Station, Japan	1	In situ SM	—	—	—	—	—	—
		Tokyo, Japan	4	In situ sand	—	—	—	—	—	—
43	Edil and Dhowian (1981)	Ottawa sand	3	Reconstituted clean sand	1.2	0.75	—	—	—	30.4~34.6
44	Farr and Aurora (1981)	Ponce, Puerto Rico	1	In situ sand–gravel mixture	—	—	70	—	—	42
45	Finno (1989)	Evanston, IL, US	1	In situ SP	1.2	0.25	48	—	—	—
		Northwestern University site, IL, US	2	In situ SP	—	—	—	—	—	37
46	Finno et al. (2000); Fujioka and Yamada (1994)	Evanston, IL, US	1	In situ SP	1.8	0.25	—	—	—	37
		Takasaki, Japan	3	In situ sand–gravel mixture	—	—	59~60	—	—	41
47	Fioravante et al. (1991)	Toyoura sand	28	Reconstituted sand	1.5	0.16	41~91	1~7.3	—	—
48	Fjodorov and Malychev (1959)	Russian sand	1	Reconstituted clean sand	—	—	—	—	—	—
49	Fragaszy et al. (1992)	Lake Valley Dam, CA, US	9	Reconstituted SW–SM	33	2.2	15~61	—	—	42.9~48.1
		Lake Valley Dam, CA, US	9	Reconstituted GW	40	5	13~64	—	—	42.7~47.8
50	Frank et al. (1991)	Chalkis, Greek	2	In situ SC–SM	—	—	—	—	—	—
51	Fujioka and Yamada (1994)	Takasaki, Japan	4	In situ GP	—	—	—	—	—	—
		Takasaki, Japan	4	In situ sand	—	—	—	—	—	—
52	Fujioka et al. (1992)	Japan	1	In situ sand	—	—	—	—	—	—
53	Fujioka et al. (1998)	Toyama, Japan	3	In situ GW	—	—	—	—	—	—
		Tabata Station, Japan	2	In situ sand	—	—	—	—	—	—
54	Fukuoka (1988)	Bannosu, Japan	2	In situ GC	—	—	—	—	—	—
55	Ghionna and Jamiolkowski (1991)	Messina, Italy	25	In situ gravel	—	2.18~3.67	—	—	—	—
		Messina, Italy	25	In situ gravel	—	1.45~10.27	—	—	—	—
56	Gibbens and Briaud (1994)	Texas, US	4	In situ sand	—	—	55~57	—	—	—

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Table A1 (*continued*).

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
57	Golder Associates Project Files	Syncrude oil sands tailings	8	Reconstituted clean sand (tailings)	1.85	0.21	55~94	1~3	—	—
	(Jefferies and Been 2006)	Ticino sand	10	Reconstituted clean sand	1.57	0.54	2~89	1~6	31	—
58	Goto et al. (1992); Goto et al. (1994); Suzuki et al. (1993)	Saitama, Japan	1	In situ GW (ground-freezing sample)	39.9	10.77	49	—	—	—
59	Greeuw et al. (1988)	Oosterschelde sand	20	Reconstituted clean sand	1.8	0.17	30~87	1	33.2	35~44
60	Haldar et al. (2000)	Newfoundland, Canada	1	In situ SW	12.4	4.5	60	—	—	—
		Newfoundland, Canada	1	In situ SW	12.4	4.5	60	—	—	38
61	Harman (1976)	Hilton mine tailings	20	Reconstituted clean sand (tailings)	2.3	0.2	27~88	1	35	—
		Ottawa sand	30	Reconstituted clean sand	1.46	0.48	20~82	1	29.25	—
62	Hatanaka and Uchida (1996);	Japan	3	In situ SP (volcanic, ground-freezing sample)	2.8~6.5	0.4~0.42	59~72	—	—	36~47.2
	Hatanaka et al. (1990); Hatanaka	Kyushu, Japan	1	In situ sand (volcanic, ground-freezing sample)	2.7	0.21	70	—	—	47.9
	et al. (1995)	Kyushu, Japan	1	In situ sand (volcanic, ground-freezing sample)	2.7	0.21	70	—	—	—
		Kyushu, Japan	1	In situ SP (volcanic, ground-freezing sample)	4.1	0.41	63	—	—	—
		Japan	2	In situ SP (ground-freezing sample)	1.6~2.3	0.29~0.39	34~57	—	—	42~46.5
		Japan	2	In situ sand (ground-freezing sample)	1.7~2.1	0.29~0.33	50~67	—	—	—
		Narita, Japan	1	In situ SP (ground-freezing sample)	2.2	0.18	81	—	—	34.1
		Narita, Japan	1	In situ sand (ground-freezing sample)	1.9	0.16	76	—	—	—
		Nagoya, Japan	3	In situ sand (ground-freezing sample)	4~4.5	0.39~0.47	74~81	—	—	41~45
		Japan	2	In situ sand (volcanic, ground-freezing sample)	9.5~18	0.3~0.6	78~81	—	—	40.3~41.3
		Kagoshima, Japan	1	In situ sand (volcanic, ground-freezing sample)	8.2	0.45	73	—	—	—
63	Hatanaka et al. (1985)	Kagoshima, Japan	1	In situ sand (volcanic, ground-freezing sample)	13.3	0.41	59	—	—	—
64	Hatanaka et al. (1988)	Tokyo, Japan	1	In situ gravel (volcanic, ground-freezing sample)	66.1	10.75	58	—	—	—
65	Hatanaka et al. (1997)	Port Island Hanshin, Japan	1	In situ gravel (ground-freezing sample)	22.3	2.43	117	—	—	—
66	Hatanaka et al. (1998)	Japan	2	In situ sand	—	0.19~0.36	—	—	—	40~41.2
		Japan	2	In situ sand	—	0.15~0.17	—	—	—	39.8~41.4
		Japan	3	In situ sand	—	0.2~0.21	—	—	—	41.1~42.7
		Japan	4	In situ sand	—	0.34~0.49	—	—	—	37.7~45.8
		Japan	3	In situ sand	—	0.18~0.24	—	—	—	40.9~41.6
67	Hatanaka et al. (1999)	Japan	1	In situ sand (ground-freezing sample)	—	—	60	—	—	46.8
		Japan	1	In situ sand (ground-freezing sample)	—	—	68	—	—	45.6
		Japan	1	In situ sand (ground-freezing sample)	—	—	70	—	—	47
		Japan	1	In situ sand (ground-freezing sample)	—	—	57	—	—	41.6
		Japan	1	In situ sand (ground-freezing sample)	—	—	100	—	—	51
		Japan	1	In situ sand (ground-freezing sample)	—	—	—	—	—	—
68	Hendron (1963)	Minnesota sand	1	Reconstituted clean sand	—	—	34	—	—	36.9
69	Hirayama (1990)	Bannosu, Japan	1	In situ clay–gravel mixture	—	—	45	—	—	38
70	Hirschfield and Poulos (1964)	Glacial outwash sand	6	Reconstituted clean sand	—	0.673	68~87	—	36.9	36~46
71	Holden (1971)	Sangamon sand	1	Reconstituted clean sand	—	—	—	—	—	—
		Wabash sand	1	Reconstituted clean sand	—	—	—	—	—	—
		Pennsylvania sand	1	Reconstituted clean sand	—	—	—	—	—	—
		Ottawa sand	1	Reconstituted clean sand	—	—	—	—	—	—
		Edgar sand	1	Reconstituted clean sand	—	—	—	—	—	—
72	Houlsby and Hitchman (1988)	Leighton Buzzard sand	76	Reconstituted clean sand	1.3	0.85	20~90	1	33	33~47
73	Hu (1993); Hu (1995)	Taoyuan, Taiwan	2	In situ sand–gravel mixture	—	—	82	—	—	47
74	Huang et al. (1999)	Mia-Liao, Taiwan	60	Reconstituted silty sand (with 15.1% fines)	2.6	0.11	50~85	—	31.6	31.9~39.5
75	Huntsman et al. (1986)	Monterey sand	41	Reconstituted clean sand	1.6	0.37	27~73	1	31	36~41
76	Iai and Kurata (1991)	Higashi-Ogishima Island, Tokyo, Japan	1	In situ SP (ground-freezing sample)	1.7	0.28	26	—	—	—
		Tokyo, Japan	1	In situ SP (ground-freezing sample)	1.7	0.28	26	—	—	28
77	Inamura et al. (1995)	Ohito Bridge, Japan	3	In situ gravel	—	—	—	—	—	—

Table A1 (*continued*).

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
78	Indraratna et al. (1993)	Thailand	12	Reconstituted gravel	6	4.9	—	—	—	38.2~44.5
79	Indraratna et al. (1998)	Railway Ballast, New South Wales, Australia	16	Reconstituted gravel	1.5~1.6	30.3~38.9	—	—	—	47.7~79.8
80	Ishihara et al. (1978); Ishihara et al. (1979); Ishihara and Koga (1981); Skempton (1986); Yoshimi et al. (1984); Yoshimi et al. (1989)	Kawagish-cho, Niigata, Japan	1	In situ SP	2.4	0.35	51	—	—	—
		Niigata, Japan	1	In situ SP (ground-freezing sample)	1.9	0.46	46	—	—	—
		Niigata, Japan	1	In situ SP	1.7	0.27	70	—	—	—
81	Ishihara and Koga (1981)	Niigata, Japan	20	In situ sand	—	—	—	—	—	—
		Niigata, Japan	8	In situ sand	—	—	—	—	—	—
82	Iwasaki et al. (1988)	Toyoura sand	29	Reconstituted clean sand	1.46	0.16	33~86	1	31	34~45
83	Kasim et al. (1986)	Alameda, CA, US	65	In situ SM, SP–SM	—	0.14~0.28	—	—	—	—
84	Kjellman (1936)	German standard sand	1	Reconstituted clean sand	1	1	—	—	—	35
85	Kokusho and Tanaka (1994); Kudo et al. (1991); Tanaka et al. (1988); Tanaka et al. (1989)	Japan	1	In situ GW (ground-freezing sample)	44.9	21.33	62	—	—	—
86	Kokusho et al. (1995)	Hokkaido, Japan	1	In situ gravel (volcanic, ground-freezing sample)	222.3	7.84	51	—	—	—
87	Konno et al. (1993); Konno et al. (1994); Suzuki et al. (1992)	Tadotsu, Japan	1	In situ gravel (ground-freezing sample)	27.1	9.98	99	—	—	—
88	Konstantinidis et al. (1987)	Baker, CA, US	2	In situ sand	—	—	80~82	—	—	43~44
		Baker, CA, US	3	In situ SP–SM	—	—	—	—	—	—
		Caliente, NV, US	3	In situ SP–SM	—	—	—	—	—	—
89	Kou (1995)	Linkou, Taiwan	2	In situ GW	133~236	20~28	—	—	—	—
90	Kudo et al. (1990)	Tonegawa sand	74	Reconstituted SP	2~5.7	0.34~1.13	40~100	—	36~39	36~50
		Tonegawa sand	69	Reconstituted GW	11.3~31.1	2.28~7.3	40~100	—	37.5~39	38~51
91	Kudo et al. (1991)	Japan	1	In situ gravel (ground-freezing sample)	85.5	7.8	32	—	—	—
		Japan	1	In situ SW (ground-freezing sample)	11.8	1.81	61	—	—	—
		Japan	1	In situ SP (ground-freezing sample)	5	1.71	73	—	—	—
		Japan	2	In situ GW (ground-freezing sample)	28.5~78.3	7.3~8.3	28~35	—	—	44.9~46.8
92	Lambrechts and Leonards (1978)	Ottawa sand	10	Reconstituted clean sand	1.1	0.28	57	—	29.25	32
93	Lee and Seed (1967)	Sacramento River sand	39	Reconstituted clean sand	—	0.297	38~100	—	31.2	30~41
94	Lhuer (1976)	Reid Bedford sand	17	Reconstituted clean sand	1.69	0.24	24~83	1	—	—
95	Lin et al. (1998); Lin et al. (2000)	Taichung, Taiwan	1	In situ GW	857	160	—	—	—	—
96	Little and Carder (1990)	St. Albans, UK	1	In situ sand	8.3	0.43	56	—	—	—
		St. Albans, UK	1	In situ SP	2.6	0.33	60	—	—	—
		Vale of St. Albans, UK	1	In situ gravel	32.3	9.17	47	—	—	—
97	Little et al. (1994); Pillai and Stewart (1994); Plewes et al. (1994); Sego et al. (1994)	British Columbia, Canada	1	In situ SP (ground-freezing sample)	2.5	0.2	44	—	—	—
98	Loadtest, Inc. (1994)	Truth or Consequences, NM, US	1	In situ GP–GM	—	—	—	—	—	—
99	Loadtest, Inc. (1999)	Puerto Rico	7	In situ gravel	—	—	—	—	—	—
100	Loadtest, Inc. (2000)	DeSoto, MS, US	2	In situ SW	—	—	—	—	—	—
		Pt of Mtn. West, UT, US	2	In situ SP	3.08	0.65	—	—	—	—
101	Lunne and Christoffersen (1983)	Hokksund sand	9	Reconstituted clean sand	2.2	0.44	22~93	—	29.5	35~47
102	Mach (1970)	German sand	1	Reconstituted clean sand	—	—	—	—	—	—
103	Manassero (1991)	Ticino sand	17	Reconstituted sand	1.62	0.5	46~92	1~7.7	—	—
		Po River sand	15	In situ sand	2.25	0.3	—	1	—	—
		Ticino river sand	4	In situ sand	9.17	0.25	—	1	—	—
104	Marachi et al. (1969)	Pyramid Dam, US	19	Reconstituted gravel	7~7.4	3.2~40.5	10~83	—	33~34	35~52
		Oroville Dam, US	20	Reconstituted gravel	38.3~39	2.4~28.9	69~100	—	36~38	38~56

Table A1 (*continued*).

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
105	Matsui (1993)	Osaka, Japan	1	In situ clay–gravel mixture	—	—	57	—	—	37
		Osaka Bay, Japan	6	In situ GM	—	—	—	—	—	—
106	Mayne (2001)	Atlanta, GA, US	2	In situ sand	—	0.08	—	—	—	35.2~35.8
107	Meigh and Nixon (1961); Skempton (1986)	Suffolk, UK	1	In situ sand	2.4	0.2	46	—	—	—
108	Menzies et al. (1977)	Ripley sand	1	Reconstituted clean sand	—	—	—	—	—	—
109	Moh and Associates (1997)	Taipei, Taiwan	2	In situ clay–sand–gravel mixture	—	—	46~47	—	—	35~36
		Taipei, Taiwan	2	In situ clay–sand–gravel mixture	—	—	45~46	—	—	35
110	Mohan et al. (1971)	Ram Nagar, India	1	In situ GW	68	15	-	—	—	—
111	Nishio and Tamaoki (1988); Suzuki et al. (1993)	Chiba, Japan	1	In situ SP (ground-freezing sample)	8.2	1.93	83	—	—	—
112	Ochiai et al. (1993)	Fukuoka, Japan	2	In situ sand–clay mixture (volcanic)	—	—	91	—	—	—
113	Osterberg (1995)	Truth or Consequences, NM, US	1	In situ silt–gravel mixture	—	—	—	—	—	—
		Truth or Consequences, NM, US	1	In situ sand–gravel mixture	—	—	59	—	—	—
114	Pacal and Shively (1983); Briaud et al. (1984);	Caliente, NV, US	1	In situ sand	—	—	—	—	—	48
		Baker, CA, US	3	In situ sand	—	—	—	—	—	46.3~50.4
		Caliente, NV, US	2	In situ sand	—	—	75~77	—	—	45
115	Pacific Geotechnical Engineers (1994)	Halawa Valley, HI, US	4	In situ GM	—	—	—	—	—	—
116	Parkin et al. (1980)	Hokksund sand	127	Reconstituted clean sand	2.2	0.44	8~101	1~8	29.5	29~50
117	Parsons-Brinkerhof-Hirota Associates (1991)	H-3, HI, US	7	In situ GM	—	—	—	—	—	—
118	Pells (1973)	Decomposed granite	1	Reconstituted gravel	—	—	—	—	—	—
119	Plelm (1965)	Czechoslovakian sand	1	Reconstituted clean sand	—	—	—	—	—	—
120	Price (1993); Price et al. (1992)	Scipio, Utah, US	1	In situ silt–sand–gravel mixture	—	—	72	—	—	43
		Sigurd–Salina, Utah, US	2	In situ sand–gravel mixture	—	—	58~61	—	—	41~42
		Belknap, Utah, US	2	In situ sand–gravel mixture	—	—	56~62	—	—	40~42
		Belknap, Utah, US	2	In situ sand–gravel mixture	—	—	48~52	—	—	39~40
		Black Rock, Utah, US	2	In situ clay–silt–sand–gravel mixture	—	—	50~51	—	—	40
121	Price et al. (1992)	Scipio, UT, US	2	In situ GM	—	—	—	—	—	—
		Sigurd–Salina, US	3	In situ GM	—	—	—	—	—	—
122	Rao et al. (1981)	Roorkee, India	1	In situ GW	23	20	—	—	—	—
123	Rix and Stokoe (1991)	Washed mortar sand	42	Reconstituted sand	1.65	0.35	9~106	—	—	—
124	Rodriguez-Roa (2000)	Santiago, Chile	1	In situ GW	77	35	—	—	—	—
125	Rollins and Mikesell (1993); Rollins et al. (1994); Rollins et al. (1997*a*); Rollins et al. (1997*b*)	Big cottonwood, UT, US	4	In situ sand	10~30	—	64~77	—	—	42~43
		Mountain East, UT, US	4	In situ sand	18.75~30	—	67~87	—	—	43~47
		Mountain West, UT, US	2	In situ SP	3.25	—	64	—	—	43
		Mapleton, UT, US	3	In situ GW	50~116	—	74~87	—	—	46~48
		Provo, UT, US	4	In situ gravel	—	—	78~83	—	—	44~45
126	Rollins et al. (2005)	American Fork, UT, US	4	In situ gravel	108.5	11.32	—	—	—	—
		Kennecott, UT, US	4	In situ GC	504	8.96	—	—	—	—
		Mapleton, UT, US	2	In situ GW	62.69	14.51	—	—	—	—
		Provo, UT, US	1	In situ GM	—	—	—	—	—	—
		Spanish Fork, UT, US	3	In situ GW-GM	86.47	11.5	—	—	—	—
		Cottonwood, AZ, US	4	In situ sand	8.25	0.24	—	—	—	—
		Pt of Mtn. East, UT, US	4	In situ sand	23.44	1.41	—	—	—	—
		Provo, UT, US	2	In situ SM	—	—	—	—	—	—
127	Saglamer (1975)	Kilyos sand	1	Reconstituted clean sand	1.25	0.15	47	—	—	28
		Ayvalik sand	3	Reconstituted clean sand	1.3	0.59	33~86	-	-	29.5~36.5
128	Saglamer et al. (2001)	Izmir, Turkey	1	In situ GC	—	—	—	—	—	—

Table A1 (*continued*).

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
129	Salgado et al. (2000)	Ottawa sand	17	Reconstituted SP	1.48	0.39	27~81	—	29	30~37
		Ottawa sand	13	Reconstituted silty sand (with 5% fines)	—	—	14~81	—	30.5	32~41
		Ottawa sand	12	Reconstituted silty sand (with 10% fines)	—	—	23~80	—	32	33~42
		Ottawa sand	17	Reconstituted silty sand (with 15% fines)	—	—	7~100	—	32.5	32~46
		Ottawa sand	11	Reconstituted silty sand (with 20% fines)	—	—	27~72	—	33	34~39
130	Saito (1977); Skempton (1986)	Ogishima Island, Tokyo, Japan	1	In situ sand	4	0.3	54	—	—	—
131	Schmertmann (1978)	Hilton mine sand	25	Reconstituted SP	2	0.2	20~80	1	35	33~46
		Ottawa sand	25	Reconstituted SP	1.85	0.22	20~80	1	29.25	28~43
		Reid Bedford sand	10	Reconstituted SP	1.7	0.24	30~81	1	32	35~47
		Jacksonville, FL, US	31	In situ SP (tailings)	1.2	0.154	40~95	1	—	—
132	Shen and Lee (1995)	Chek Lap Kok sand	10	Reconstituted clean sand	4.5	1.05	25~82	1	—	—
		West Kowloon sand	18	Reconstituted clean sand	1.88	0.28	32~80	1	—	—
133	Sherif et al. (1974)	Ottawa sand	3	Reconstituted clean sand	2.1	0.42	4~73	—	—	25~42.7
		Del Monte sand	3	Reconstituted clean sand	2.1	0.18	13~60	—	—	26.2~40.9
		Mixture sand	4	Reconstituted clean sand	3.9	0.43	7~83	—	—	25.7~40.6
		Highway sand	3	Reconstituted clean sand	1.9	0.32	7~86	—	—	30~45.4
		Golden Gardens sand	3	Reconstituted clean sand	1.8	0.5	27~77	—	—	33.8~43.5
		Seward Park sand	3	Reconstituted clean sand	1.9	0.86	25~92	—	—	34.9~47.8
		Sayers Pit sand	3	Reconstituted clean sand	2.3	0.69	18~71	—	—	30.7~38.8
		Mathews Beach sand	3	Reconstituted clean sand	3.9	0.9	6~61	—	—	27.3~44.7
		Alki Beach sand	3	Reconstituted clean sand	1.4	0.32	21~83	—	—	22.8~42.6
		Pier sand	3	Reconstituted clean sand	2.4	0.44	3~93	—	—	30~37.1
134	Skempton (1986)	Niigata, Japan	1	In situ SP	2.8	0.63	36	—	—	—
135	Soroush and Jannatiaghdam (2012)	Masjed-Soleyman, Iran	24	Reconstituted gravel	7.2~8.95	4.74~29.54	—	—	—	32.4~51
		San Francisco Basalt, US	3	Reconstituted gravel	22.46	10	—	—	—	38.3~46.2
		Motorway Embankment Gneiss, Italy	3	Reconstituted gravel	—	—	—	—	—	42
		Limestone Lorestan Roodbar Dam, Iran	3	Reconstituted gravel	19.74	4.78	—	—	—	39
		Sandstone Vanyar Dam, Iran	3	Reconstituted gravel	19.74	—	—	—	—	36
		Andesibasalt and Andesite Sabalan Dam, Azerbaijan	3	Reconstituted gravel	19.74	—	—	—	—	41
		Dolomite Railroad Ballast, Coteau, Quebec, Canada	3	Reconstituted gravel	2.85	—	—	—	—	40
		Blasting Lime stone Roodbar Dam, Iran	3	Reconstituted gravel	23	7.2	—	—	—	30.6
		Blasting Andesibasalt Sabalan Dam, Azerbaijan	3	Reconstituted gravel	22.1	6.48	—	—	—	40~42
		Blasting Andesite Aydoghmosh Sabalan Dam, Iran	3	Reconstituted gravel	22.9	7.37	—	—	—	38
		Blasting sandstone Vanyar Dam, Iran	2	Reconstituted gravel	22.9	7.25	—	—	—	38
		Mica granitic–gneiss	3	Reconstituted gravel	20.67	48.57	—	—	—	43~44.5
		Andesite Yamchi Dam, Iran	3	Reconstituted gravel	65.4	2.26	—	—	—	38.7
		Andesibasalt Ghale chai Dam, Iran	2	Reconstituted gravel	138.9	3.54	—	—	—	36.5
136	Suzuki et al. (1993)	Chiba, Japan	1	In situ GW (ground-freezing sample)	10.3	2.8	—	—	—	49.8
		Kagawa, Japan	2	In situ GW (ground-freezing sample)	19~46.6	7.2~10.7	—	—	—	39.9~44.9
		Saitama, Japan	2	In situ GW (ground-freezing sample)	23.8~59	5.6~16.9	—	—	—	43.3~46.5

Table A1 (*concluded*).

No.	Reference	Name or site	n	Type	C_u	D_{50} (mm)	D_r (%)	OCR	ϕ'_{cv} (°)	ϕ' (°)
137	Sweeney (1987)	Monterey sand	6	Reconstituted clean sand	1.37	0.45	24~64	1	—	33~39
138	Tanaka et al. (1988)	Japan	3	In situ GW (ground-freezing sample)	5.3~11.9	1.9~3	53~81	—	—	39~43.5
		Japan	1	In situ GW (ground-freezing sample)	44.9	21.3	62	—	—	54.9
139	Tand et al. (1994)	Alvin, TX, US	1	In situ sand	—	0.11	—	—	—	34.7
		Alvin, TX, US	1	In situ sand	2.1	0.15	77	—	—	37.8
		Alvin, TX, US	6	In situ sand	2.125	0.11~0.15	77~80	—	—	34~40
140	Thomas (1968)	Lanchester sand	21	Reconstituted clean sand	1.4	0.4	0~100	1	—	—
141	Tokimatsu et al. (1990) Yoshimi et al. (1984)	Higashi–Ogishima Island, Tokyo	1	In situ SP (ground-freezing sample)	2.1	0.22	91	—	—	—
142	Tringale (1983)	Monterey sand	9	Reconstituted clean sand	1.5	0.36	27~74	1	—	—
143	Tsai et al. (1995)	Taichung, Taiwan	1	In situ GW	166	67	—	—	—	—
		Chiayi, Taiwan	3	In situ GW	103~268	47~50	—	—	—	—
		Tiehchenshan, Taiwan	2	In situ gravel	1067~1880	55~74	—	—	—	—
		Changhua, Taiwan	1	In situ GW	119	57	—	—	—	—
144	Tucker (1987)	California, US	2	In situ GW–SW	—	—	—	—	—	—
		California, US	6	In situ sand	—	—	—	—	—	—
		California, US	8	In situ sand	—	—	—	—	—	—
145	Uchida et al. (1990)	Niigata, Japan	1	In situ sand (ground-freezing sample)	—	—	87	—	—	45
		Niigata, Japan	4	In situ sand (ground-freezing sample)	—	—	50~84	—	—	—
		Niigata, Japan	1	In situ sand (ground-freezing sample)	—	—	72	—	—	—
146	Varadarajan et al. (2003)	Ranjit Sagar Dam, India	6	Reconstituted gravel	145~148.5	3.8~12	87	—	—	39~50.1
		Purulia Dam, India	9	Reconstituted gravel	18.33~18.95	5~15.8	87	—	—	36.3~42.5
147	Veismanis (1974)	Earlston sand	5	Reconstituted clean sand	2.6	0.33	20~73	1	—	33~41
		Edgar sand	15	Reconstituted clean sand	1.7	0.45	56~95	1	—	35~46
		Ottawa sand	7	Reconstituted clean sand	1.2	0.54	75~104	1~4	—	31~41
		South Oakleigh sand	35	Reconstituted clean sand	1.6	0.17	28~86	1	—	29~34
		South Oakleigh sand	27	Reconstituted clean sand	2.2	0.32	44~89	1~8	—	30~35
148	Vesic and Clough (1968)	Chattahoochee River sand	40	Reconstituted clean sand	2.5	0.37	8~94	—	32.5	29~44
149	Villet and Mitchell (1981)	Lone Star sand	13	Reconstituted clean sand	2	1	22~68	1	—	—
		Lone Star sand	30	Reconstituted clean sand	1.86	0.39	21~89	1	31	—
		Lone Star sand	28	Reconstituted clean sand	1.48	0.3	21~84	—	—	35~46
150	Weiler and Kulhawy (1978)	Filter sand	3	Reconstituted clean sand	1.8	0.82	—	—	—	35.8~49.2
151	Wright (1969)	Monterey sand	2	Reconstituted clean sand	—	—	32~93	—	—	40
		Eastern Silica sand	2	Reconstituted clean sand	—	—	33~93	—	—	36.5
152	Xiao et al. (2014)	Tacheng rockfill material	12	Reconstituted gravel	5.54	23.1	51~84	—	—	41.9~48.9
153	Yoshida and Kokusho (1988); Yoshida et al. (1988); Kokusho (1997); Kokusho and Yoshida (1997)	Tonegawa sand	91	Reconstituted SP	1.95~5.65	0.34~1.13	26~104	—	—	—
		Tonegawa sand	64	Reconstituted GW	11.3~31.1	2.28~7.3	15~101	—	—	—

Note: GC, clayey gravel; GM, silty gravel; GP, poorly graded gravel; GW, well-graded gravel; SC, clayey sand; SM, silty sand; SP, poorly graded sand; SW, well-graded sand.

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