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A unified database of ring shear steel-interface tests on sandy-silty soils

Une base de données unifiée de résultats d'essais de cisaillement annulaire avec interface en acier sur des sols sablo-limoneux

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ABSTRACT: Characterisation of shearing behaviour at soil-structure interfaces is critical in the analysis and design of a wide range of geotechnical structures. Large-displacement ring shear interface testing employing pre-shearing stages has been recognised as a robust approach for characterising interface resistance, particularly when large relative displacements are developed between soil and interface during either installation or operation. Such tests are applied in practical design approaches, for example in the ICP method for driven piles (Jardine *et al*., 2005). This paper presents a database of interface shearing tests involving sandy-silty soils that contain low percentage (≤ 20%) of non-plastic fines, integrating outcomes from research and project studies conducted at Imperial College London and the Norwegian Geotechnical Institute using Bishop Ring Shear apparatuses. The outcomes enable a critical review of the potential effects of a wide range of factors, including: soil physical index properties (grading, fines content); interface characteristics (material type, surface roughness); and applied testing conditions (shear rate and normal effective stress). Trends identified from the datasets are integrated with previously reported studies to indicate the interface shear strength parameters that may be adopted for preliminary design with non-plastic sandy-silty soils on the basis of simple index tests.

RÉSUMÉ: La caractérisation du comportement en cisaillement aux interfaces sol-structure est essentielle pour l'analyse et la conception d'un large éventail de structures géotechniques. L'essai de cisaillement annulaire à grand déplacement utilisant des étapes de pré-cisaillement a été reconnu comme une approche robuste pour caractériser la résistance d'une interface, en particulier lorsque de grands déplacements relatifs se développent entre le sol et l'interface, que ce soit lors de l'installation ou de l'exploitation. Ces essais sont utilisés pour les approches de conception pratiques, par exemple dans la méthode ICP pour les pieux battus (Jardine et al., 2005). Cet article présente une base de données d'essais de cisaillement d'interface avec des matériaux sablo-limoneux, intégrant les résultats de recherches et d'études de projets conduites à l'Imperial College London (ICL) et à l'Institut géotechnique de Norvège (NGI) à l'aide d'appareils Bishop Ring Shear. Les résultats permettent un examen critique des effets potentiels d'un large éventail de facteurs. Les tendances identifiées à partir des jeux de données sont intégrées à des études précédentes, pour indiquer les paramètres de résistance au cisaillement d'interface qui peuvent être adoptés pour la conception préliminaire avec des sols sablo-limoneux sur la base d'essais d'indice.

Keywords: Bishop ring shear; interface friction angle; pile design

1 INTRODUCTION

Practical analysis and design of a wide range of offshore and onshore geotechnical structures, including piles, suction buckets, pipelines, oil risers, shallow foundations and retaining structures, require accurate characterisation of soil-structure interface shearing behaviour and rationalised selection of design parameters (Andersen *et al.*, 2013). Soil-pile shaft interface shear resistance is one of the major factors governing shaft capacity of axially loaded driven piles, and the interface shearing parameters need to be determined with high confidence (Jardine *et al.*, 2005). Interface shearing is also potentially important when analysing laterally loaded caissons and monopiles, whose behaviour can depend on their shaft and base shear resistances (Byrne *et al.*, 2017).

Soil-interface shearing angles (δ') and dilatancy properties have been characterised through direct shear, simple shear and torsional (ring) shear laboratory tests, as well as tilting table and other specialised apparatuses; see for example Liu (2018). The Bishop ring shear apparatus (Bishop *et al.*, 1971) provides a robust tool for interface shear testing as it can: (i) apply nominally unlimited shear displacements; (ii) impose uniform interface shear stresses and (iii) enable direct measurement of side friction. Pre-conditioning stages may also be applied that represent practical scenarios, for example pile installation or re-striking.

This paper presents a database of Bishop ring shear interface tests performed at Imperial College London (ICL) and at the Norwegian Geotechnical Institute (NGI) on sandy-silty soils containing relatively low percentage (≤ 20%) of non-plastic fines inclusions. Many of the tests were performed to derive interface friction angles for axial pile capacity assessment following the 'ICP' procedures of Jardine *et al.* (2005). The dataset is integrated with previously reported tests to allow assessments of how soil index properties, interface materials and surface characteristics affect interface shear resistance. Trends are identified that can help guide initial parameter selection for preliminary design involving similar soils. The value of project-specific testing is emphasised as the most secure means of deriving representative parameters for detailed design.

2 EQUIPMENT AND PROCEDURES

2.1 Equipment and modifications

Bishop ring shear apparatus, as shown in Figure 1, has been widely used for investigation of the residual states of soils undergoing very large shearing strains (Lupini *et al.*, 1981, Coop *et al.*, 2004), landslide analysis and design of piles driven in clays, sands and chalk (Ramsey *et al.*, 1998, Yang *et al.*, 2010, Barmpopoulos *et al.*, 2010, Ho *et al.*, 2011, Quinteros *et al.*, 2017, Liu, 2018, Chan *et al.*, 2019).

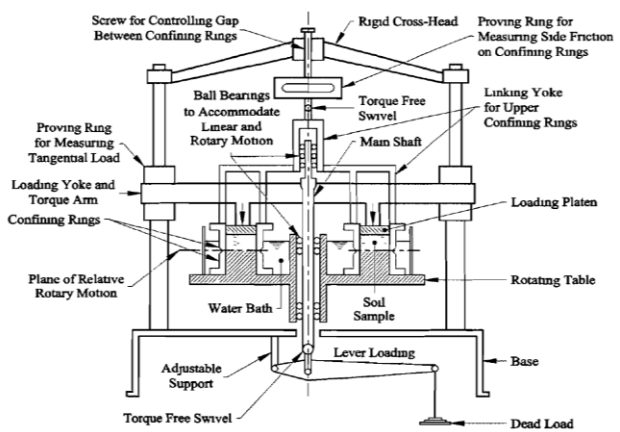

Figure 1. Soil interface configuration of Bishop ring shear apparatus (Bishop et al., 1971, Ramsey et al., 1998)

The apparatus can accommodate soil-soil or soil-interface testing of intact, reconstituted or remoulded soils. Soil-interface testing can be configured in lower interface and upper interface manners, as outlined by Ho *et al.* (2011). The apparatuses have been upgraded at ICL and NGI in the following aspects that include:

(1) Electrical transducers to measure displacements and loads;
(2) Torsional shearing at a wide range of shearing rates (from 10^{-3} to 10^{3} mm/min) with normal effective stresses up to 1.2 MPa;
(3) An automated electro-pneumatic system regulated by in-house software to enable continuous control of normal stresses;
(4) NGI's use of an aluminium loading yoke and loading arm (see Figure 1) to allow normal stresses as low as 10 kPa to be applied. For applying stresses < 10 kPa, a polyethylene yoke is also available.

2.2 Specimen reconstitution and testing procedures

Sandy-silty soil specimens are prepared by either dry pluviation or moist tamping to achieve targeted initial dry density. NGI employ Ladd's (1978) recommendations for moist tamping. In-situ conditions of water content and density are replicated wherever possible. The ICP procedures recommended by Jardine *et al*. (2005) are often adopted in the context of determining friction angles for the design of axially loaded driven piles. The procedures, which may be modified to represent specific conditions or shearing histories, consist of:

(1) Consolidation to a vertical effective stress equivalent to the initial in-situ free-field horizontal effective stress σ'_{r0}.
(2) Pre-shearing for 1 m up to five times at fast rates (100-500 mm/min) to represent pile driving.
(3) Consolidation follows to the radial effective stress σ'_{rc} expected at the pile shaft after all effects of pile installation have equalised.
(4) Slow shearing is then applied. This should be conducted at rates that ensure full drainage that may be assessed from the earlier consolidation stages. The default rate for clays and silts is 0.005 mm/min.

Jardine *et al*. (2005) proposed equations for the radial effective stresses (σ'_{r0} and σ'_{rc}) applying to tubular steel or concrete piles driven in silica sands:

$$\sigma'_{\mathrm{r0}} = K_0 \cdot \sigma'_{\mathrm{v0}} \tag{1}$$

$$\sigma'_{\mathrm{rc}} = 0.029 \cdot q_{\mathrm{c}} \cdot (\sigma'_{\mathrm{v0}}/P_{\mathrm{a}})^{0.13}(h/R^{*})^{-0.38} \tag{2}$$

$$\tau_{\mathrm{rzf}} = \sigma'_{\mathrm{rf}} \cdot \tan\delta'_{\mathrm{ult}} \tag{3}$$

where σ'_{v0} and σ'_{r0} are the local free-field vertical and radial effective stress and K_0 is the earth pressure coefficient at rest; σ'_{rc} denotes radial effective stress after installation and equalisation, which depends on σ'_{v0}, local CPT resistance q_c, relative depth to pile tip h, and equivalent pile radius $R^* = (R^2_{outer}\text{-}R^2_{inner})^{0.5}$ for open- or closed-ended tubular piles. P_a equals to atmospheric pressure (=101.3 kPa). τ_{rzf} and σ'_{rf} represent shear stress and effective radial stress at pile shafts at failure, which are correlated through ultimate interface friction angle δ'_{ult}. Different expressions apply to other pile cross-sections.

3 DATABASE OF INTERFACE RING SHEAR TESTS

The soils included in the database span a wide range of particle sizes from coarse sand to fine silt, with the majority being medium to fine sands, as shown in Figure 2. The D_{50} values range from 0.07 mm to 0.25 mm, C_U from 1.4-27, and fines contents (FC, defined as the percentage passing 0.063 mm standard sieve aperture) of up to 20 %. Further details are given in Table 1. Atterberg limit tests were attempted on the soils with fines content (FC) greater than 10% to examine the plasticity of the fines inclusions, and no measurable plastic limit was attained. The fines inclusions can therefore be generally considered as non-plastic, which is in agreement with the geological history of the soils tested.

Most tests were performed with mild steel interfaces that had been air-abraded or rusted to reach average centre-line roughness (R_{CAL}) of 10-15 μm to represent industrial steel piles. However, other interface materials and surface roughness conditions were considered including: (i) polished stainless steel interfaces with R_{CAL} < 2 μm that may represent CPT or model pile shafts with smooth surfaces; (ii) stainless steel interfaces with R_{CAL} in the range of 3-5 μm to represent the conditions of the 'mini-ICP', see Yang *et al*. (2010); (iii) smooth painted steel, PVC or plastic interfaces with R_{CAL} < 5 μm representing pipelines, see Quinteros *et al*. (2017); (iv) concrete interfaces manufactured to form R_{CAL} around 14 μm, as used by Barmpopoulos *et al*. (2010).

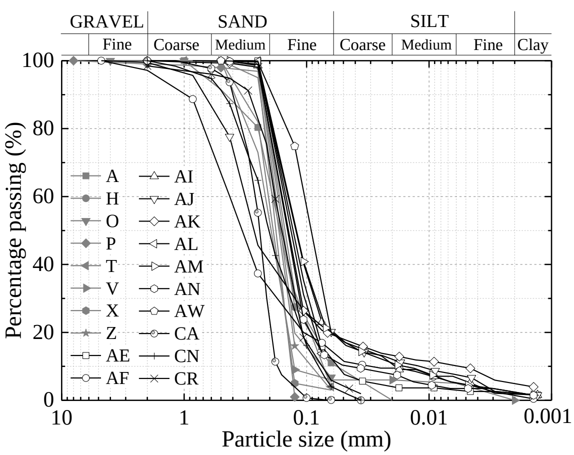

Figure 2. Ranges of grain size distribution of the soils

4 DISCUSSION OF RESULTS

This paper focuses on the outcomes of tests employing rough mild steel (R_{CLA} within 8~14 μm) interfaces that represent industrial piles and revisits the questions of how fines content (FC), normal effective stress level (σ_n') and shear rates affect the ultimate interface friction angles (δ'_{ult}) attained at shear displacement of around 50 mm. The latter are independent of initial relative density and control ultimate pile capacity (Jardine *et al.*, 2005). Peak (δ'_{peak}) and intermediate angles depend on soils' initial states.

4.1 Effects of soils' index properties

Considering first the effects of soils' D_{50} and FC on the ultimate friction angles, Figure 3(a) plots the δ'_{ult}-D_{50} data against the trends proposed from direct shear tests by Jardine *et al.* (1992) and later updated by Ho *et al.* (2011) from Bishop ring shear interface tests. Also indicated in the plot are the conditions under which the interface tests were performed, noting the variations in soils' D_{50} and normal effective stress levels (σ_n') as well as the steel interfaces' material and roughness.

The Authors' δ'_{ult} values deviate from the δ'_{ult} = 29° value prescribed by CRU (2001) and scatter around the trends proposed by Ho *et al.* (2011), from ICP style Bishop ring shear tests on clean silica sands and non-plastic silts against stainless steel interfaces, which exhibited a modest dependency on normal effective stress σ_n' and indicated less distinct variations of δ'_{ult} against D_{50} than were seen in direct shear tests that involved smaller displacements and no pre-conditioning stages. The greater scatter seen with the current database reflect wider ranges of normal effective stresses, soil uniformity, fines content, particle shape and mineralogical composition. Soils with higher proportions of non-plastic fines tended to develop higher δ'_{ult} values, as shown in Figure 3(b).

4.2 Effects of normal effective stress

Figure 4 demonstrates the correlation between δ'_{ult} and σ_n' observed in the dataset of tests that imposed fast conditioning shearing before slow shearing which indicated δ'_{ult} increasing with σ_n'. Tests performed under low stresses (σ_n' < 30 kPa) inevitably manifest greater variations in δ'_{ult} and are not plotted here to aid clarity.

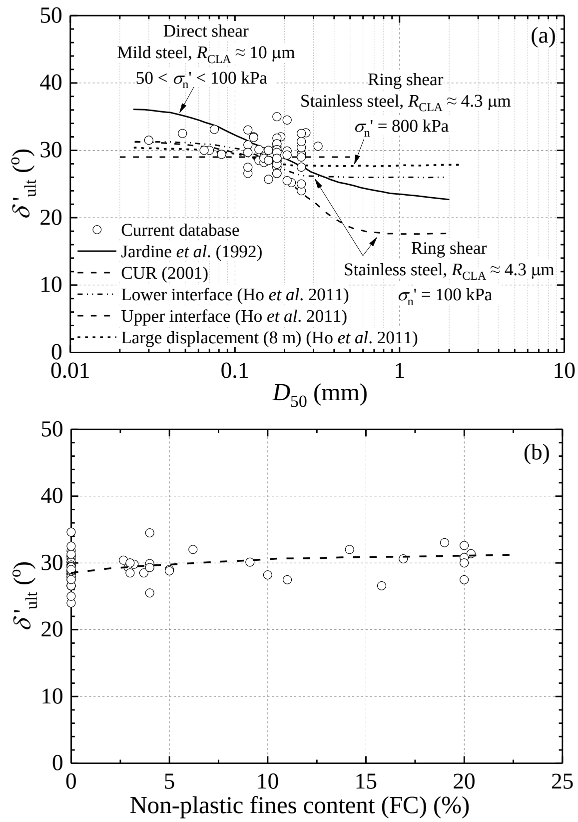

Figure 3. (a) Comparison of δ'_{ult} against D_{50} with published trends; (b) Correlation between δ'_{ult} and fines content (FC)

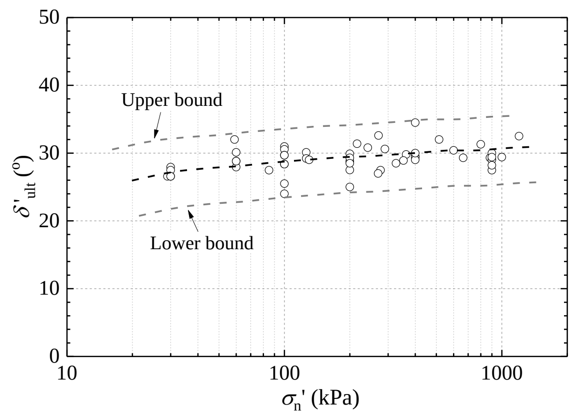

Figure 4. Correlation between δ'_{ult} and σ_n'

4.3 Effects of interface characteristics

The ultimate shear angles are plotted as $\tan(\delta'_{ult})$ and correlated in Figure 5 with the normalised pre-test interface surface roughness (R_{CLA}/D_{50}) trend reported from direct shear tests by Jardine *et al.* (1992). The ring-shear interface tests performed with relatively high R_{CLA}/D_{50} ratios (> 0.05) scatter around the direct shear trend, which shows a linear $\tan(\delta'_{ult})$ - R_{CLA}/D_{50} trend until a plateau is approached that represents soils' critical state shearing resistance angle.

However, at lower R_{CLA}/D_{50} ratios the ring shear $\tan(\delta'_{ult})$-R_{CLA}/D_{50} data invariably plot above the direct shear trend. Liu (2018) argued that higher δ'_{ult} values develop in the 'ICP-style' ring shear tests because: (i) the fast conditioning shearing stages lead to grain crushing and interface smoothening; (ii) the confining conditions of direct shear tests are less representative than those applying in the Bishop ring shear interface apparatus.

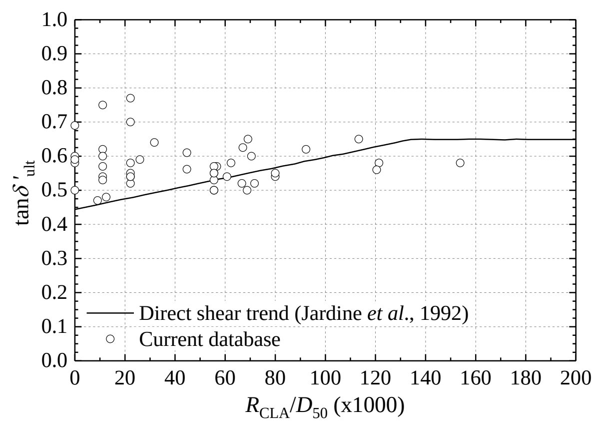

Figure 5. Correlation between $\tan(\delta'_{ult})$ and pre-test normalised roughness R_{CLA}/D_{50}

4.4 Relation between δ'_{20mm} and δ'_{ult}

Interface friction angles at 20 mm shear displacement (δ'_{20mm}) are often required in pile design practice. Figure 6 shows the correlation between the ratio $\delta'_{20mm}/\delta'_{ult}$ against σ_n', suggesting that δ'_{20mm} is marginally higher than δ'_{ult} by about 2 %.

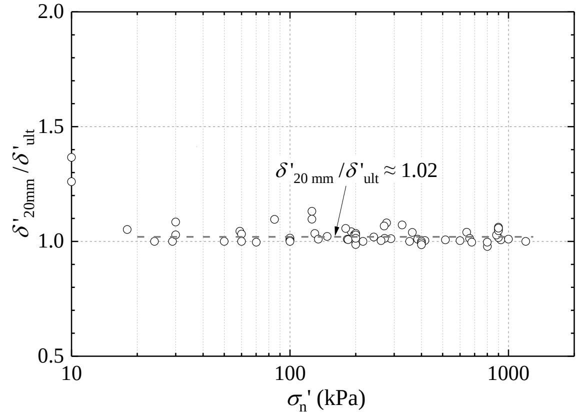

Figure 6. Correlation between $\delta'_{20mm}/\delta'_{ult}$ against σ_n'

4.5 Shearing rate effects

Shear rates effects were investigated through parallel tests on two silty sands (Sand A and AW). Shearing rates from 0.007 mm/min to 500 mm/min were applied and the corresponding ultimate friction angles are summarised in Figure 7. A moderate trend for δ'_{ult} to reduce by around 1˚ over five orders of displacement rate can be observed in test A series over the rate ranges considered. No reduction of δ'_{ult} is observed for sand AW.

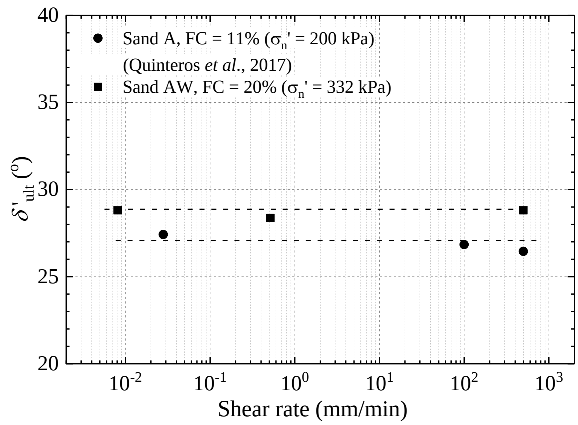

Figure 7. Shear rate effects: δ'_{ult} against shear rates

5 SUMMARY AND CONCLUSIONS

This paper presents a summary of about 50 Bishop ring shear interface tests performed at ICL and NGI on sandy-silty soils that contain low proportion (≤ 20%) of non-plastic fines. Most of the tests followed the 'ICP' procedures proposed by Jardine *et al.*, (2005) for use in the design of driven piles, which are used widely in offshore oil, gas and wind-energy projects. The following conclusions can be drawn from the results obtained:

(1) The δ'_{ult} angles varied with D_{50} data in a similar way to that described by Ho *et al*. (2011), although factors such as fines content, interface roughness and normal stress level play important roles that can lead to significant variations;

(2) Neither the simplifying assumption of δ'_{ult} = 29º or the use of direct shear interface tests are as satisfactory as conducting site-specific ring shear tests;

(3) The ring shear δ'_{ult} values generally increased with the fraction of non-plastic fines;

(4) Ring shear δ'_{ult} values manifested clear stress (σ_n') dependency and increase with σ_n' over relatively high stress range (σ_n' > 30 kPa);

(5) The friction angles at 20 mm shear displacement (δ'_{20mm}) were about 2 % higher than those at ultimate states (δ'_{ult});

(6) Ultimate friction angles were moderately affected by shearing rates. Approximately 1˚ decrease in δ'_{ult} was noted for one sand over five orders of shear rate magnitude.

While the established database and correlations facilitate the preliminary section of interface friction angles as design parameters, soil/project-specific interface testing is highly recommended to derive detailed design inputs that can represent in-situ soil conditions, interface characteristics, effective stress level and history, as well as consolidation (ageing) time.

Table 1. Soils and testing conditions for the database

Soil ID.	Soil[1]			Interface[2]		Pre-shearing[3]		Slow shearing		δ'$_{peak}$ (°)	δ'$_{20mm}$ (°)	δ'$_{ult}$ (°)	Tested at
	D_{50}	C_U	FC	Type	R_{CLA}	Shear rate mm/min	σ'$_v$ kPa	Shear rate mm/min	σ'$_v$ kPa				
A	0.18	2.8	11	RRS	13	99.8	207	0.028	277	32.8	29.7	27.5	NGI
B	-	-	-	RRS	13	98.2	249	0.031	270	32.9	28.8	27.0	NGI
C	-	-	-	RRS	13	99.7	281	0.031	353	32.1	28.9	28.9	NGI
D	-	-	-	RRS	13	99.7	371	0.030	1000	31.8	29.7	29.4	NGI
E	-	-	-	RRS	13	99.0	249	0.032	126	40.7	33.0	29.2	NGI
F	-	-	-	RRS	13	99.9	258	0.030	882	33.2	30.1	29.3	NGI
G	-	-	-	RRS	13	99.2	308	0.029	900	31.5	30.5	29.0	NGI
H	0.15	-	10	RRS	13	99.2	371	0.033	900	31.5	29.9	28.2	NGI
O	0.15	2.4	5	RRS	13	NA	NA	0.651	130	35.0	30.1	29.0	NGI
O	0.15	2.4	5	RRS	13	NA	NA	0.653	200	33.3	29.8	28.8	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	10	62.2	39.4	28.8	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	30	32.8	27.3	26.6	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	60	32.0	28.8	27.9	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	100	31.9	29.9	29.7	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	100	32.8	30.1	29.7	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	60	33.7	28.8	28.8	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	30	36.9	28.8	26.6	NGI
P	0.18	1.4	0	RRS	13	NA	NA	4.200	10	42.0	27.5	21.8	NGI
T	0.14	2.3	3.7	RMS	8.5	500.9	169	0.005	326	32.8	31.0	28.5	NGI
V	0.19	1.7	6	RMS	8.5	500.5	253	0.006	515	33.8	32.2	32.0	NGI
X	0.19	1.6	2.9	RMS	8.5	503.6	321	0.006	664	31.9	30.0	29.3	NGI
Z	0.15	2.0	3.2	RMS	8.5	502.3	158	0.005	363	35.3	31.0	29.8	NGI
AE	0.12	2.4	13	RMS	8.7	500.1	29	0.515	29	40.4	26.6	26.6	NGI
AF	0.32	17.1	15	RMS	8.3	500.0	290	0.006	290	31.3	31.0	30.6	NGI
AG	-	-	20	RMS	8.4	500.0	216	0.007	216	32.5	31.4	31.4	NGI
AI	0.12	6.8	20	RMS	8.5	500.0	242	0.006	242	32.1	31.4	30.8	NGI
AJ	0.12	24.8	20	RMS	8.5	500.0	271	0.006	271	34.0	33.0	32.6	NGI
AK	0.12	23.3	19	RMS	8.3	499.1	24	0.005	24	42.6	33.0	33.0	NGI
AL	0.13	26.7	14	RMS	8.3	498.3	59	0.006	59	40.0	33.4	32.0	NGI
AM	0.12	7.2	20	RMS	8.6	499.6	85	0.007	85	35.0	30.1	27.5	NGI
AN	0.14	2.9	9	RMS	8.7	500.5	126	0.004	126	34.2	33.0	30.1	NGI
AW	0.09	-	20	RRS	8.2	500.0	332	0.008	332	29.8	28.8	28.8	NGI
CA	0.25	1.7	0	RSS	12.5	500.0	100	0.016	100	25.0	24.1	24.0	ICL
CB	0.25	1.7	0	RSS	12.5	500.0	100	0.016	100	25.0	24.1	24.0	ICL
CC	0.25	1.7	0	RSS	12.5	500.0	200	0.016	200	26.5	25.7	25.0	ICL
CD	0.25	1.7	0	RSS	12.5	500.0	400	0.016	400	31.0	29.5	29.5	ICL
CE	0.25	1.7	0	RSS	12.5	500.0	400	0.016	400	29.5	29.4	29.4	ICL
CF	0.25	1.7	0	RMS	15.1	500.0	200	0.016	200	29.0	27.5	27.5	ICL
CG	0.25	1.7	0	RMS	13.5	500.0	400	0.016	400	29.5	28.8	29.0	ICL
CH	0.25	1.7	0	RMS	12.9	500.0	600	0.016	600	31.0	30.5	30.4	ICL
CI	0.25	1.7	0	RMS	12.9	500.0	800	0.016	800	31.5	31.2	31.3	ICL
CJ	0.25	1.7	0	RMS	12.9	500.0	1200	0.016	1200	35.1	32.5	32.5	ICL
CN	0.21	2.9	4	RMS	8.0	500.0	100	0.016	100	26.5	25.5	25.5	ICL
CO	0.21	2.9	4	RMS	8.0	500.0	200	0.016	200	30.3	29.5	29.9	ICL
CP	0.21	2.9	4	RMS	13.0	500.0	200	0.016	200	30.0	29.7	29.3	ICL
CQ	0.21	2.9	4	RMS	13.0	500.0	400	0.016	400	37.0	34.0	34.5	ICL
CR	0.16	2.4	3	RMS	13.0	500.0	200	0.016	200	31.0	27.8	28.5	ICL
CS	0.16	2.4	3	RMS	13.0	500.0	400	0.016	400	32.1	30.1	30.0	ICL

[1] Grading curves and fines contents of sands B to G were similar to specimens A and H which were from identical boreholes and close-by depths; [2] RRS = Rusted rough steel, RMS = Rough mild steel, RSS = Rough stainless steel; [3] NA = Non applicable

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