Liquefaction Evaluation of Aveiro Sands from SCPTU and SDMT Tests

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ABSTRACT: The paper analyses the results of the liquefaction potential evaluation at the harbour of Aveiro (Portugal) from distinct in situ testing approaches. The study was based on the results of CPTu/SCPTu tests and DMT/SDMT tests, including the measurement of shear wave velocity (V_S), taking into account the grain size distribution curves. The analysis was performed to estimate the cyclic resistance ratio (*CRR*) from in situ tests, and to compare the *CRR* with the cyclic stress ratio (*CSR*), with the seismic action evaluated according to Portuguese National Annex of the Eurocode 8. These two parameters were used to assess the liquefaction safety factor (*FS*) and the liquefaction potential index (*LPI*). In addition, the liquefaction severity number (*LSN*) was also used to quantify the effects of liquefaction and consequent land damage by estimating the volumetric strains. The estimate of the cyclic resistance ratio *CRR* from DMT appears to be interesting since the horizontal stress index K_D is sensitive to a factors which are known to increase liquefaction resistance.

1 INTRODUCTION

The study focuses on the liquefiability assessment of the harbour of Aveiro, located in the North-West Portugal. Even though the seismic hazard of the region is low, the presence of industrial facilities with sensitive structures and pipelines required ground characterization analyses according to the Eurocode 8, as shown by preliminary liquefaction analyses developed by Rodrigues et al. (2014).

A significant number of in situ tests, such as piezocone (CPTu) and seismic piezocone (SCPTu) tests, flat dilatometer (DMT) and seismic dilatometer (SDMT) tests, including the measurement of shear wave velocity (V_S), in combination with laboratory grain size distribution curves to check the fine content (*FC*), were carried out between 2006 and 2012. The liquefaction analysis was performed to estimate the cyclic resistance ratio (*CRR*) from in situ geotechnical investigations, and to compare the *CRR* with the cyclic stress ratio (*CSR*). These two parameters were used to enable the determination of the safety factor (*FS*) against liquefaction and the liquefaction potential index (*LPI*). In addition, the potential liquefaction-induced ground settlements index (*S*) and the lateral displacement index (*LDI*) were estimated together with the liquefaction severity number (*LSN*) in order to quantify the effects of liquefaction and consequent land damage.

2 GEOLOGICAL CONTEXT

The Aveiro region corresponds to the northern sector of the Portuguese Occidental Meso-Cenozoic sedimentary basin. The Ria de Aveiro is a very recent barrier-lagoon system, located along the North-West Portuguese coast (Fig. 1).

Onshore geology reveals dune, beach and lagoon sediments of Quaternary age, composed essentially of normally consolidated sands and clays, overlying a sedimentary succession of Mesozoic clays and limestone of the Lusitanian. The main Quaternary formations in the Aveiro region consist of deposits attributed to old beaches and fluvial terraces of Plio-Pleistocene age, as well as of alluvial and lagoon

Holocene deposits. These deposits are partially covered by recent dune deposits and recent sediments of the Aveiro lagoon. In particular, the sedimentary sequence detects Pliocene river terraces and ancient beaches terraces at the base, followed by soils of grain size decreasing with depth, with a gravelly layer at the bottom, often covered by one or more organic mud layers, dune sands and modern alluvium, namely the Quaternary formation. At Aveiro test site this Plio-Quaternary Unit reaches about 35 m of thickness and lies on the Sandstone and Mudstone Aveiro Unit (Upper Cretaceous).

3 SITE INVESTIGATIONS

In the area of study the site investigation campaign was developed in three different locations between 2006 and 2012 (Fig. 1b). During June-July 2006 (phase 1A) three seismic piezocone tests (SCPTu1-1A, SCPTu2-1A, SCPTu3-1A), 20 m depth, and four boreholes (BH1-1A, BH2-1A, BH3-1A, BH4-1A), 27-31 m depth, with Standard Penetration Tests (SPT), were performed. Then, between October and November 2009 (phase 1B), additional investigations were carried out for the construction of the industrial area. They consisted of four flat dilatometer tests (DMT1-1B, DMT2-1B, DMT3-1B, DMT4-1B), 20-24 m depth, three piezocone/seismic piezocone tests (CPTu1-1B, SCPTu2-1B, SCPTu3-1B), 20-22 m depth, and nine boreholes (BH1-1B, BH2-1B, BH3-1B, BH4-1B, BH5-1B, BH6-1B, BH7-1B, BH8-1B, BH9-1B), 27 m depth, with SPTs and sampling for laboratory tests. Finally, in November 2012 (phase 2C) the site investigation campaign was completed with two seismic dilatometer tests (SDMT1-2C, SDMT2-2C), 20-22 m depth, two piezocone tests (CPTu1-2C, CPTu2-2C), 22-23 m depth, and a borehole (BH1-2C) with sampling for additional analyses.

Fig. 2 shows the profiles with depth of two DMT parameters, i.e. the material index I_D (indicating soil type) and the horizontal stress index K_D (related to stress history/OCR) obtained from common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001), and the CPTu measured parameters, i.e. the cone resistance q_c, the sleeve friction f_s, and the pore pressure u_2, as well as the profile of the shear wave velocity V_S measured by SDMT and SCPTu, for phase 1B and phase 2C. Additional test results are available in Rodrigues et al. (2014).

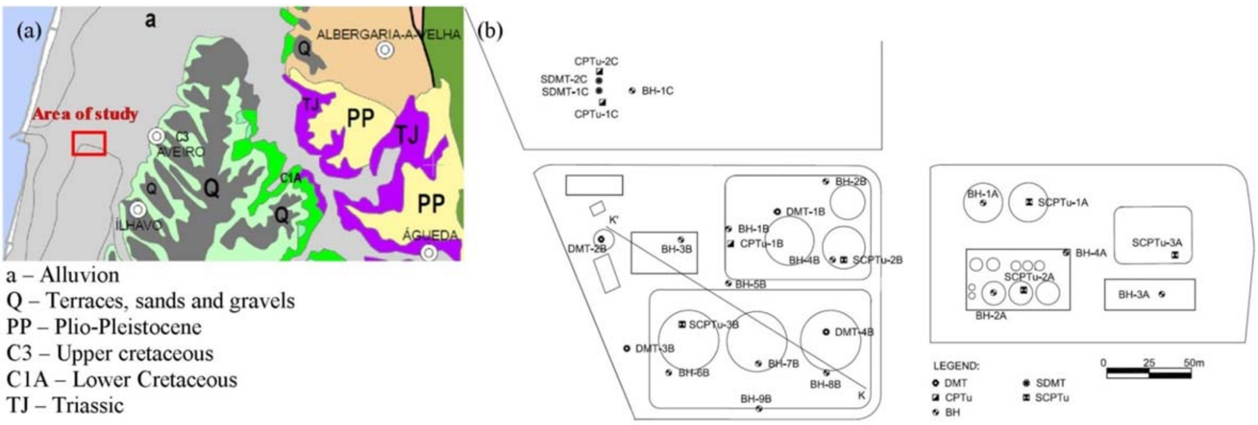

Fig. 1. Geological map of Aveiro area (a). Site investigation map of area of study (b).

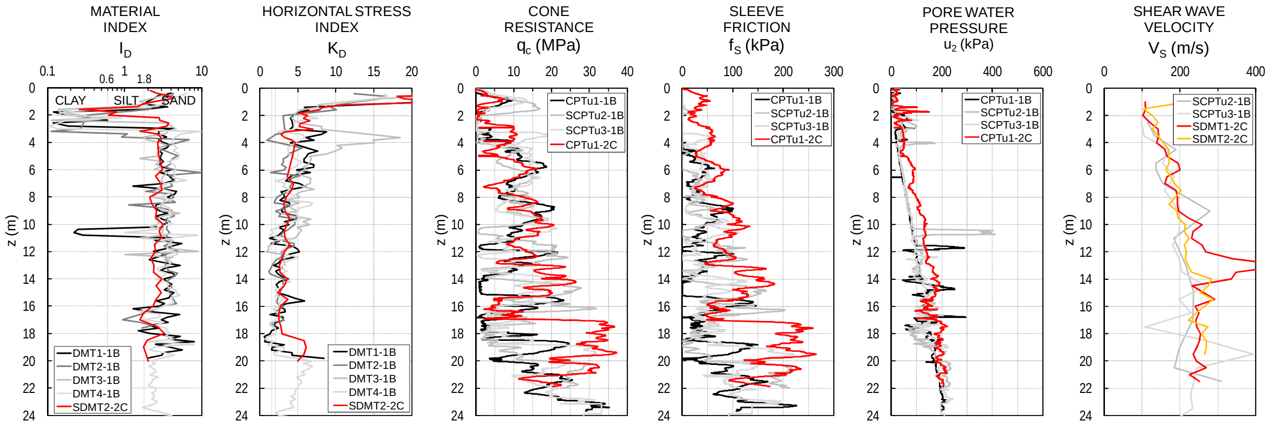

Fig. 2. DMT/SDMT and CPTu/SCPTu results for two site investigation campaigns (phase 1B, phase 2C).

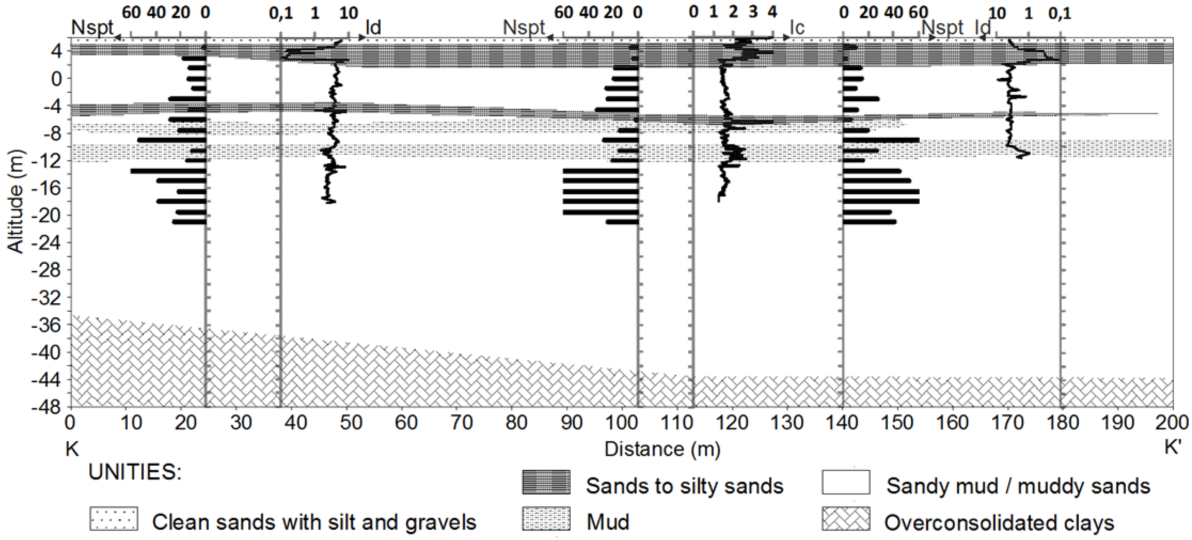

Fig. 3. Litostratigraphic cross section K-K' at Aveiro site.

These data, in terms of the material index I_D, soil behavior type index I_C, together with borehole logs and SPT results, namely the SPT blow count N_{SPT}, were used to reconstruct the litostratigraphic cross section K-K', as illustrated in Fig. 3.

Aveiro test site is mainly composed by sand and silty sand with layers of mud at about 2-4 m and 10-12 m depth, and different lens of sandy mud and muddy sand roughly between 13-15 m and 16-19 m depth, characterized by low values of q_c and K_D.

Additional details on CPTu/SCPTu and DMT/SDMT results can be found in Rodrigues et al. (2014).

4 LIQUEFIABILITY ASSESSMENT

4.1 *Liquefaction Safety Factor (FS)*

The liquefaction analyses were carried out according to the "simplified procedure" introduced by Seed & Idriss (1971), based on the comparison of the seismic demand on a soil layer generated by the earthquake (cyclic stress ratio *CSR*) and the capacity of the soil to resist liquefaction (cyclic resistance ratio *CRR*). Indeed, the liquefaction safety factor *FS* was defined as the ratio between *CRR* and *CSR*.

4.1.1 *Cyclic Stress Ratio (CSR)*

The cyclic stress ratio CSR was estimated by Seed & Idriss (1971) formulation, evaluating the Magnitude Scaling Factor *MSF* and the shear stress reduction coefficient r_d according to Idriss (1999).

The peak horizontal acceleration a_{max} was defined considering the two seismic scenarios introduced in the Portuguese National Annex of the Eurocode 8 (NP EN 1998-1 2010, NP EN 1998-5 2010) for Aveiro site. The *Seismic Action 1* is characterized by earthquakes mainly with offshore epicenters (far source), low predominant earthquake frequency, high magnitude and long duration, while the *Seismic Action 2* refers mostly to inland epicenters (near source), high predominant earthquake frequency, moderate magnitude and short-duration. Table 1 summarizes the parameters that identify the two seismic actions: seismic zone, return period T_R, moment magnitude M_w, peak horizontal acceleration for stiff ground a_g, and peak horizontal acceleration at the ground surface a_{max}, estimated using a soil factor *S* based on ground type classification of Aveiro site.

Table 1. Seismic actions at Aveiro site.

	Seismic Action 1	Seismic Action 2
Seismic zone	1.6	2.4
T_R (years)	475	475
M_w	7.3	4.4
a_g (m/s^2)	0.35	1.10
a_{max} (m/s^2)	0.80	1.60

4.1.2 *Cyclic Resistance Ratio (CRR)*

The cyclic resistance ratio *CRR* was evaluated using different in situ techniques/parameters for a more reliable estimate of *CRR*, as stated by Robertson & Wride (1998), Youd & Idriss (2001) and Idriss & Boulanger (2004).

At Aveiro test site *CRR* was derived from CPTu, DMT and V_S measurements, considering respectively, at each depth, the normalized cone resistance $Q_{tn,cs}$, the horizontal stress index K_D, and the overburden-stress corrected shear wave velocity V_{S1}. In particular, the *CRR*-$Q_{tn,cs}$ correlation used was the one established by Robertson (2009), while three different *CRR*-K_D correlations, developed by Monaco et al. (2005), Tsai et al. (2009) and Robertson

(2012), were used. It has been observed that K_D is sensitive to stress history, prestraining/aging, cementation, structure, and it is related to relative density and state parameter (Monaco et al. 2005). Finally, the correlation CRR-V_S proposed by Andrus & Stokoe (2000) was used, introducing the values of fine content FC obtained from sieve analyses ($FC \leq$ 5-10 % for the phases 1A and 1B, $FC \leq$ 7 % for phase 2C).

The ground water table depth was assumed equal to 1.5-1.9 m for phase 1A and 1B tests, and of about 0.80 m for investigations related to phase 2C.

4.2 *Liquefaction Potential Index (LPI)*

According to Iwasaki et al. (1982) the liquefaction potential index LPI was introduced to estimate the vulnerability of site to liquefaction effects, as shown in Eq. (1):

$$LPI = \int_0^{20} F(z)w(z)dz \quad (1)$$

where z is the depth below ground surface, $F(z)$ is a linear function of the liquefaction safety factor FS, and $w(z)$ is a linear function of z. Iwasaki et al. (1982) defined four LPI ranges in liquefaction damage: (i) very low for $LPI = 0$; (ii) low for $0 < LPI \leq 5$; (iii) high for $5 < LPI \leq 15$; (iv) very high for $LPI > 15$.

4.3 *Liquefaction Severity Number (LSN)*

The liquefaction severity number LSN is a new calculated parameter developed by Tonkin & Taylor (2013) for 2010-2011 Canterbury earthquakes, New Zealand, to reflect the more damaging effects of shallow liquefaction on residential lands and foundations. LSN, as presented in Eq. (2), considers depth weighted calculated volumetric densification strain within soil layers, as a proxy for the severity of liquefaction land damage likely at the ground surface:

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz \quad (2)$$

where z is the depth to the layer of interest below ground surface, and ε_v is the calculated volumetric densification strain in the subject layer. The integral was calculated with the first 20 m depth. Tonkin & Taylor (2013) identified six LSN ranges for the liquefaction land effects: (i) little to no expression of liquefaction minor effects, for $0 < LSN \leq 10$; (ii) minor expression of liquefaction, some sand boils, for $10 < LSN \leq 20$; (iii) moderate expression of liquefaction, with sand boils and some structural damage, for $20 < LSN \leq 30$; (iv) moderate to severe expression of liquefaction, settlement can cause structural damage, for $30 < LSN \leq 40$; (v) major expression of liquefaction, undulations and damage to ground surface, severe total and differential settlement of structures, for $40 < LSN \leq 50$; (vi) severe damage, extensive evidence of liquefaction at surface, severe total and differential settlement affecting structures, damage to services for $LSN > 50$.

Zhang et al. (2002) proposed that ε_v can be obtained combining $Q_{tn,cs}$ for clean sand and the liquefaction safety factor FS, when $FS < 2$. In addition, Zhang et al. (2002) also defined the potential liquefaction-induced ground settlements index S, as shown in Eq. (3), assuming that the volumetric strain is roughly equal to the vertical strain:

$$S = \sum_{i=1}^{j} \varepsilon_{vi} \Delta z_i \quad (3)$$

where ε_{vi} is the postliquefaction volumetric strain for the soil sublayer i, Δz_i is the thickness of the sublayer i, and j is the number of soil sublayers.

At Aveiro test site a CPT-DMT correlation, Eq. (4), provided by Robertson (2012), was used in order to quantify the LSN and S indices not just for CPTu but for DMT as well:

$$Q_{tn,cs} = 25K_D \quad (4)$$

Eq. (4) is valid for $I_D > 1.2$ and $2 < K_D < 6$. Nevertheless, this formulation was used also for $K_D \leq 2$ and for values of K_D slightly higher than 6, verifying an acceptable agreement between the values of $Q_{tn,cs}$ for clean sand measured from CPTu and estimated from DMT.

4.4 *Lateral Displacement Index (LDI)*

An approach for estimating liquefaction induced lateral displacement was introduced by Zhang et al. (2004), defining the lateral displacement index LDI, as shown in Eq. (5):

$$LDI = \int_0^{Z_{\max}} \gamma_{\max} dz \quad (5)$$

where γ_{max} is maximum cyclic shear strain, z is the depth below ground surface, and Z_{max} is the maximum depth below all the potential liquefiable layers with a calculated $FS < 2.0$. According to Seed (1979) and to Ishihara & Yoshimine (1992), γ_{max} can be estimated in combination with the liquefaction safety factor FS and the relative density D_r.

At Aveiro test site, D_r was evaluated from Robertson & Cabal (2012) for CPTu and from Jamiolkowski et al. (2003) for DMT, considering Aveiro sands as normally consolidated freshly deposited sands.

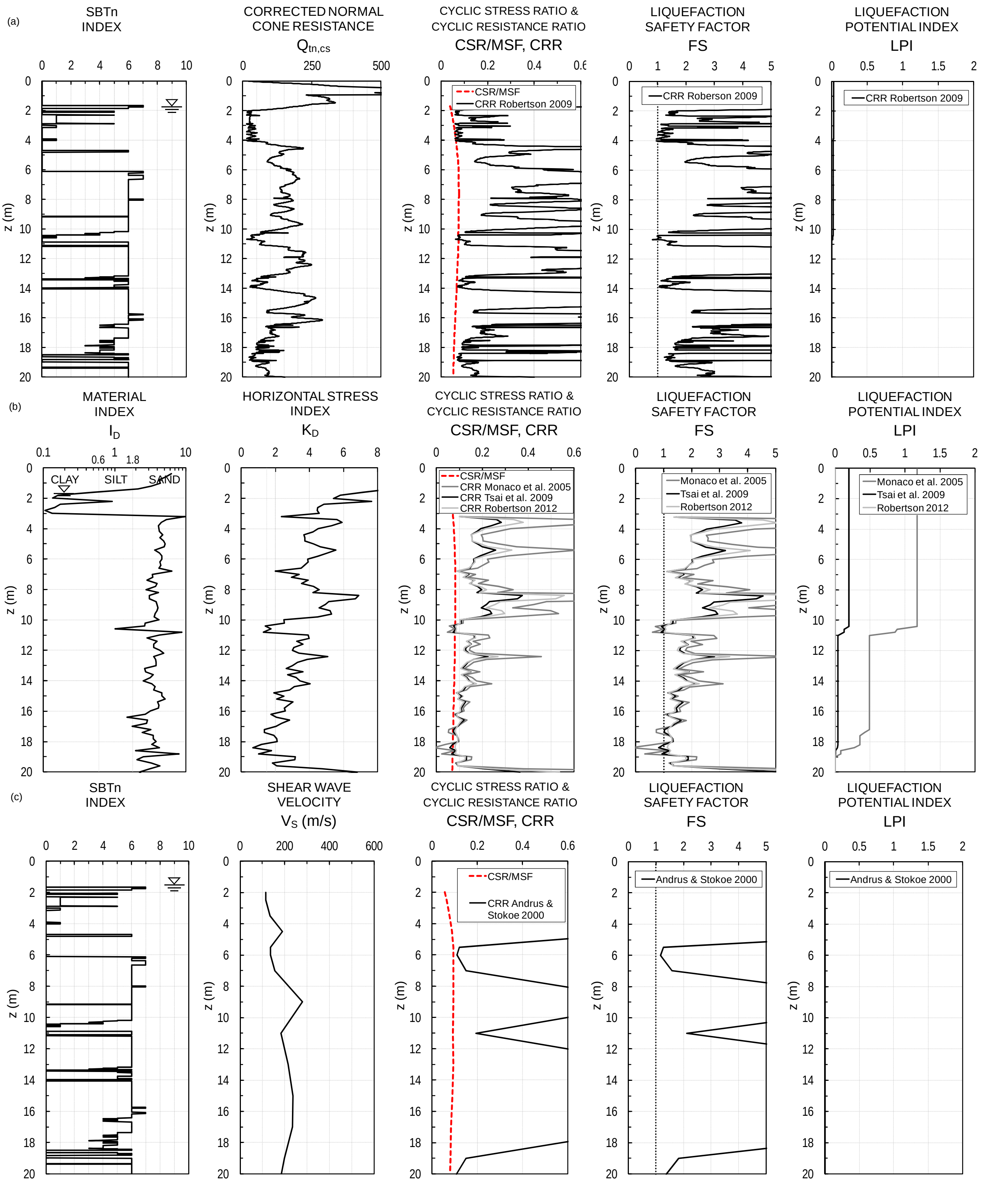

Fig. 4. *LPI* estimations from CPTu (a), DMT (b), and V_S measurements (c) for SCPTu2-1B and DMT4-1B tests, considering the Seismic Action 1 at Aveiro test site.

4.5 *Results*

Tables 2, 3, 4, 5 and 6 summarize the results of the liquefiability assessment executed at Aveiro test site for the investigation phases 1A, 1B and 2C. In particular, the results based on CPTu, DMT and V_S are represented in terms of *LPI*, *LSN*, *S* and *LDI*, following Eqs. (1), (2), (3) and (5), with *CRR* estimated from Robertson (2009), Monaco et al. (2005), Tsai et al. (2009), Robertson (2012) and Andrus & Stokoe (2000).

Table 2. Liquefiability assessment (Robertson 2009).

	Seismic Action 1				Seismic Action 2			
	LPI	LSN	S (cm)	LDI (cm)	LPI	LSN	S (cm)	LDI (cm)
SCPTu1-1A	1.32	9.59	10.44	88.81	0.07	4.02	4.23	5.82
SCPTu2-1A	0.46	8.45	10.33	44.32	0.00	1.60	1.96	0.72
SCPTu3-1A	0.05	2.74	1.30	6.27	0.00	0.55	0.24	0.77
CPTu1-1B	0.15	3.35	2.74	15.88	0.00	0.78	0.71	1.35
SCPTu2-1B	0.72	13.86	7.48	41.10	0.03	3.34	1.95	2.71
SCPTu3-1B	1.06	3.51	1.49	4.09	0.99	0.79	0.22	1.75
CPTu1-2C	0.00	0.24	0.15	0.80	0.00	0.00	0.00	0.24

Table 3. Liquefiability assessment (Monaco et al. 2005).

	Seismic Action 1				Seismic Action 2			
	LPI	LSN	S (cm)	LDI (cm)	LPI	LSN	S (cm)	LDI (cm)
DMT1-1B	1.40	9.79	15.64	82.18	1.17	7.83	12.22	60.77
DMT2-1B	2.77	347.1	145.26	70.62	2.45	371.9	153.7	57.45
DMT3-1B	1.70	4.31	5.01	32.28	1.60	4.04	4.71	31.37
DMT4-1B	1.17	8.20	11.90	77.80	0.88	6.51	9.16	54.95
SDMT2-2C	0.00	1.25	1.44	5.84	0.00	0.73	0.54	2.64

Table 4. Liquefiability assessment (Tsai et al. 2009).

	Seismic Action 1				Seismic Action 2			
	LPI	LSN	S (cm)	LDI (cm)	LPI	LSN	S (cm)	LDI (cm)
DMT1-1B	0.25	7.59	11.75	54.29	0.03	3.02	4.23	7.16
DMT2-1B	0.66	108.5	53.52	41.98	0.63	113.3	53.74	25.85
DMT3-1B	0.42	4.27	4.97	27.42	0.17	2.84	3.31	13.54
DMT4-1B	0.20	7.50	10.36	23.92	0.02	3.09	3.39	6.57
SDMT2-2C	0.00	2.56	2.62	11.86	0.00	2.18	1.63	8.14

Table 5. Liquefiability assessment (Robertson 2012).

	Seismic Action 1				Seismic Action 2			
	LPI	LSN	S (cm)	LDI (cm)	LPI	LSN	S (cm)	LDI (cm)
DMT1-1B	0.00	3.91	5.38	10.67	0.00	2.09	2.66	4.12
DMT2-1B	0.01	58.84	29.53	14.80	0.16	83.26	37.93	14.38
DMT3-1B	0.00	2.24	2.58	3.72	0.00	1.08	1.22	2.09
DMT4-1B	0.00	4.06	5.12	10.68	0.00	2.57	2.63	5.17
SDMT2-2C	0.00	2.85	2.96	12.47	0.00	2.30	1.87	8.18

Table 6. Liquefiability assessment (Andrus & Stokoe 2000).

	Seismic Action 1 - LPI	Seismic Action 2 - LPI
SCPTu1-1A	0.00	0.00
SCPTu2-1A	6.27	7.83
SCPTu3-1A	3.80	4.56
SCPTu2-1B	0.00	0.00
SCPTu3-1B	1.82	2.80
SDMT1-2C	0.11	0.65
SDMT2-2C	0.00	0.00

The liquefaction potential index, as well as the liquefaction severity number, commonly recognizes low liquefaction damage, slightly higher for Seismic Action 1 than for Seismic Action 2. Postliquefaction vertical settlements at the ground surface are also confined on average within 5-10 cm, while the lateral displacements can reach almost 90 cm. A relevant discrepancy by *LPI*, *LSN*, *S* and *LDI* estimations can be detected for DMT2-1B. Instead, a general countertrend can be observed between the liquefaction potential index *LPI* (low values) and the estimated settlements *S* and lateral displacements *LDI* (both large). This aspect could be related to the site-dependency of *S* and *LDI* formulations, evaluated for contained number of case histories data.

The liquefaction vulnerability appears generally lower for the investigation phase 2C, where rare potential liquefiable layers were detected and higher values of $Q_{tn,cs}$, K_D and V_S were obtained. CPT liquefiability assessment is on average in acceptable agreement with DMT and V_S interpretation for phase 1B, while it provides opposite results compared to V_S analyses for phase 1A. The latter aspect could be due to the scarce sensitivity of the shear wave velocity to the stress history (Jamiolkowski & Lo Presti 1992). For phase 1B CPTu analyses usually detect potential liquefiable layers in the shallow and deeper muddy sands, while DMT results identify liquefaction beyond 10 m depth, except for DMT2-1B.

DMT liquefiability assessment gives different liquefaction estimates, evaluating the cyclic resistance ratio from each one of the three CRR-K_D formulae. Tsai et al. (2009) usually fits quite well CPTu values, in terms of *LPI*, *LSN*, *S* and *LDI*, while Robertson (2012) ranges around zero (except for phase 2C), and Monaco et al. (2005) gives significantly higher results, reaching very low CRR values for $K_D < 2$, as identified for a thin layer during phase 1B. Nevertheless, it appears to be important to use all the three CRR-K_D relationships as long as the CRR-K_D case history database would increase introducing a more consistent liquefaction curve, which could also consider the fine content influence using the material index I_D.

In addition, the estimates of *LSN*, *S* and *LDI* from DMT could be also refined using $Q_{tn,cs}$ and D_r from CPT interpretation formulae.

The availability of SPT tests could complete liquefaction analyses from in situ tests and the possible execution of cyclic triaxial tests could support further research on liquefaction vulnerability of Aveiro site.

Finally Figs 4 and 5 show an example of the complete analysis performed for SCPTu2-1B and DMT4-1B tests, considering the Seismic Action 1. Figs 4a, 4b and 4c provide the profiles with depth of: (1) the soil behavior type index I_c (from CPTu) or the material index I_D (from DMT); (2) the parameter used in each case for evaluating *CRR*: $Q_{tn,cs}$ (from CPTu), the horizontal stress index K_D (from DMT) or the shear wave velocity V_S; (3) the *CSR*, divided by the *MSF*, compared to the *CRR*; (4) the liquefaction safety factor *FS*; (5) the liquefaction potential index *LPI*. Instead, Fig. 5 refers only to CPTu and DMT data, illustrating the profiles with depth of: (1) the corrected normal cone resistance $Q_{tn,cs}$ for clean sand (measured by CPTu, estimated by DMT using Eq. 4); (2) the relative density D_r; (3) the potential liquefaction-induced ground settlements index *S* ; (4) the lateral displacement index *LDI*; (5) the liquefaction severity number *LSN*.

CRR estimations, as well as *FS* and *LPI* values, from DMT4-1B and SCPTu2-1B seem to highlight that DMT tend to give lower results than CPTu estimation, and DMT profiles appear to be closer to each other than to CPTu. Focusing on *CRR* curves from DMT4-1B, it turns up that Monaco et al. (2005) provides always higher peaks when $K_D > 2$, and lower ones when $K_D < 2$. This aspect is related to *CRR*-K_D equation from Monaco et al. (2005) that presents larger amplitude when $K_D > 2$, and a more conservative prediction when $K_D < 2$, than Tsai et al. (2009) and Robertson (2012) formulations that are reasonably closer each other.

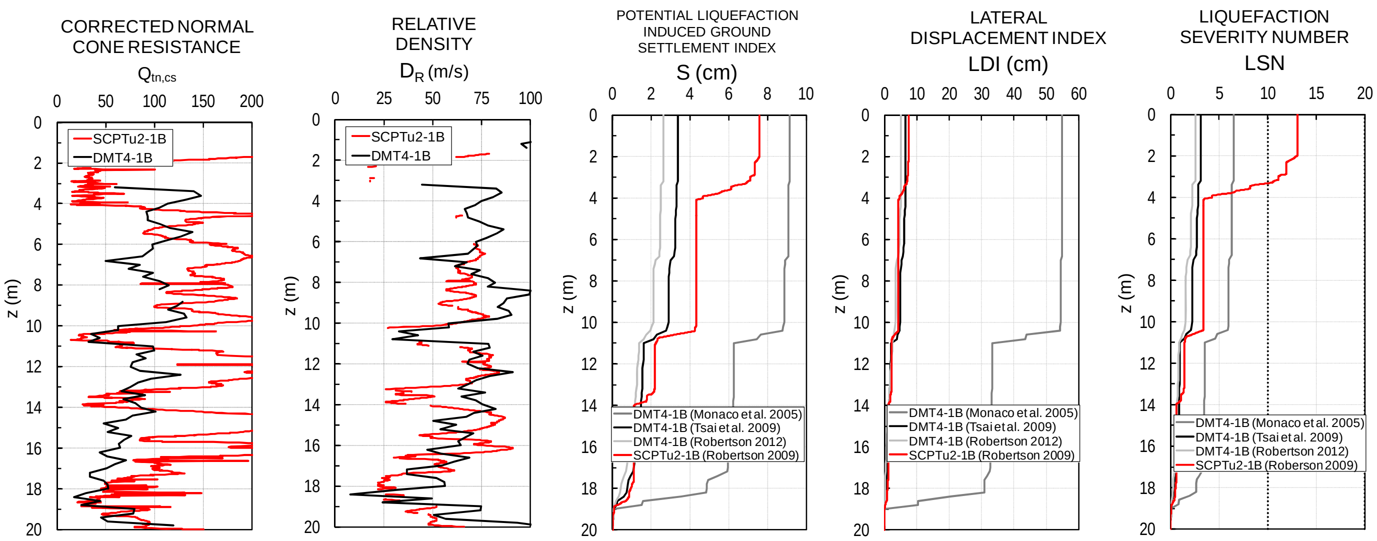

Fig. 5. *S*, *LDI* and *LSN* estimations for SCPTu2-1B and DMT4-1B, considering the Seismic Action 1 at Aveiro test site.

5 CONCLUSIONS

Liquefaction assessment from CPTu, DMT and in situ V_S measurements provides a low liquefaction vulnerability for the industrial site of Aveiro (Portugal).

The estimate of the cyclic resistance ratio *CRR* from DMT appears to be interesting since the horizontal stress index K_D is sensitive to a number of factors which are known to increase liquefaction resistance. Nevertheless, the *CRR*-K_D case history database needs to be implemented in order to introduce a more consistent liquefaction curve that could also consider the fine content influence using the material index I_D.

The availability of SPT tests could complete liquefaction analyses from in situ tests and the possible execution of cyclic triaxial tests could support further research on liquefaction vulnerability of Aveiro site.

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