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Calibration cone penetration testing in silty soils

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ABSTRACT: The Offshore Wind Industry's rapid expansion across the globe requires geotechnical modelling of sites that are often characterized by layers of silty sand and silt mixtures. The CPTU is the main *in situ* offshore investigation tool for defining the ground conditions and for establishing facility position and soil parameters for foundation design, but no simple and robust methodologies exist for characterizing transitional soils. This paper presents some results of CPTUs carried out in a large calibration chamber and in a centrifuge aimed at contributing to the development of guidelines for planning, specification, execution, and interpretation of CPTUs in transitional soils.

1 INTRODUCTION

After the installation of the first Offshore Wind Farm in Denmark in 1991, the Offshore Wind Industry (OWI) has been increasing exponentially in Europe and recently also in new markets such as the US East Coast and the Asia-Pacific Countries.

Soil modelling and spatial mapping for the design and installation of foundations for offshore wind turbines is generally based on the combined and staged use of seismic surveys, piezocone penetration testing (CPTU) and boreholes with soil sampling. However, in many regions where the OWI is expanding, layers of transitional soils, i.e. neither clean sand nor clay, are unexpectedly encountered and not predicted by the CPTU interpretation. This is mainly due to the lack of robust methodologies for characterizing silty sand and silt mixtures based on CPTU, as existing correlations between CPTU parameters and classification and engineering properties have been developed for sand and clay. Consequently, the cost and risk of developing offshore wind farms in these regions are high.

The goal of the CSi – CPTU in silty soils – Joint Industry Project is ultimately to develop guidelines for set-up, execution and interpretation of CPTUs in silty soils, see Augustesen et al. (2022). This goal is pursued by a combination of research activities including

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in situ testing, numerical modelling and using a significant number of CPTUs, carried out in a large calibration chamber and in a geotechnical centrifuge at the ISMGEO laboratory (Italy, Baldi et al. 1982, Baldi et al. 1986).

With the main aim of highlighting the impact of fines content on soil strength and stiffness, the tests are carried out on a clean sand and on the sands mixed with non-plastic fines to obtain 15% and 30% fines content (grain size < 0.063 mm). Some of the preliminary results of the calibration chamber and centrifuge tests are presented in this paper, together with a brief description of the testing apparatuses and procedures.

2 TESTING SOIL AND PROGRAM

2.1 *Ticino Sand and Ticino Filler*

The sand and silty sand used for the experimentation are Ticino Sand (TS) and Ticino Filler (TF). TS is a clean silica sand used extensively in the past for calibration chamber, centrifuge and laboratory tests (Baldi et al. 1982, 1986, Fioravante 2000, Jamiolkowki et al. 2003, Fioravante & Giretti 2016). The batch used for the CSi project is named TS11, which is a natural, coarse to medium clean sand, with principal components of quartz (36% by weight), feldspar (40%), mica (11%). TF is the natural flour obtained by sieving the coarser fraction of Ticino sand and has similar mineralogical composition (21% quartz, 47% feldspar, 16% mica).

Optical microscope analysis evidenced that in both materials quartz is mainly present in subangular, equidimensional grains, feldspars are in both round and prismatic form, while micas are in lamellae. A diffractometric study shows that the mineralogical composition of the two materials is compatible with dominant origin from metamorphic rocks. Stereo microscope observations denote a type of transport that is relatively low in energy and of short duration, compatible with poorly worked sand.

Grain size distribution of TS11 and TF is shown in Figure 1. Table 1 lists the main index properties.

In this paper the preliminary results of tests carried out on clean TS11 and on a mix of TS11 and TF characterized by 15% FC (MIX15%) are discussed, see Figure 1 and Table 1. The minimum and maximum void ratios reported in Table 1 were measured according to the method proposed by Knudsen et al. (2020), validated for silty sand with FC as high as 14%.

2.2 *Test program and procedure*

Tables 2 and 3 provide the main characteristics of the calibration chamber (CC) and centrifuge (CCC) models discussed in this paper. The values of void ratio e, relative density D_R and dry unit weight γ_d refer to the end of consolidation. The test layout is sketched in Figure 2. All the models were normally consolidated.

The tests on clean TS11 were meant to assess if CC and CCC cone penetration tests were comparable with each other and with previous studies carried out using TS and the same facilities. In addition, they were aimed at validating the use of the centrifuge as a calibration tool of CPTUs in sandy soils. Indeed, centrifuge CPTUs have the advantage, with respect to calibration chamber tests, of giving a q_c-profile over a wide range of vertical stress, rather than a single q_c value associated to the specific level of the applied stress of a single sample. This is under the condition that the effects of rigid boundaries and scale effects are minimised. In addition, CCC models are smaller and a test requires few days compared to about two weeks for a CC test. If validated, CCC CPTUs can be extensively used to explore the effect of variable density, fine content, stress level, overconsolidation ratio on the penetration resistance.

2.2.1 *The ISMGEO calibration chamber*

The calibration chamber specimens are 1.4 m high and 1.2 m in diameter. The CC is a flexible-wall chamber and it can impose four different boundary conditions (BC):

- BC1: constant vertical and horizontal stresses, σ_v = const and σ_h = const;
- BC2: zero vertical and horizontal strains, $\Delta\varepsilon_v = \Delta\varepsilon_h = 0$;
- BC3: constant vertical stress and zero horizontal strain, σ_v = const and $\Delta\varepsilon_h = 0$;
- BC4: constant horizontal stress and zero vertical strain, σ_h = const and $\Delta\varepsilon_v = 0$.

Two cells enclose the specimen. This allows obtaining a zero average lateral strain boundary condition by keeping the pressure in the outer cell equal to the pressure, developed by the specimen, in the inner cell. Vertical and horizontal stresses can be applied independently in a controlled manner to the boundaries of the sample. Vertical stresses are applied to the specimen through a piston (positioned at the bottom of the chamber) raised by pressured water and the horizontal stresses are applied by the pressure of water surrounding the specimen.

Table 1. Grain size and index properties of testing soils.

		TS11	TF	MIX15%
D_{60}	[mm]	0.49	0.098	0.43
D_{50}	[mm]	0.46	0.075	0.38
D_{10}	[mm]	0.32	0.009	0.028
U_c	[-]	1.53	11	15.4
G_S	[-]	2.695	2.772	2.721
*$\gamma_{d.max}$	[kN/m^3]	16.18	-	18.03
*$\gamma_{d.min}$	[kN/m^3]	13.05	-	13.93
e_{min}	[-]	0.634	-	0.48
e_{max}	[-]	1.026	-	0.916

* Knudsen et al. (2020)

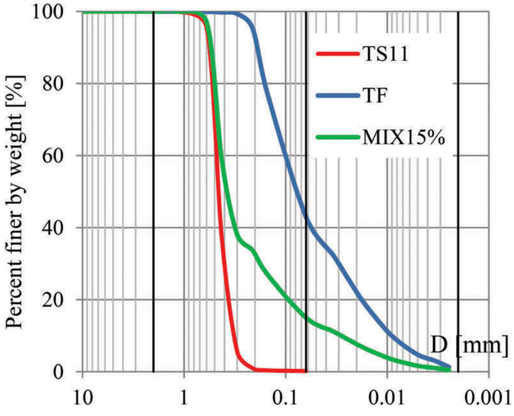

Figure 1. Grain size distribution of TS11, TF and MIX15%.

Table 2. CC Test Program.

test	Soil	D_R (%)	σ'$_v$ (kPa)	e (-)	γ_d (kN/m^3)	V*
1	TS11	48	50	0.84	14.39	V1&V2
2		49	200	0.83	14.41	V1&V2

* V1 = 20 mm/s, V2 = 100 mm/s

Table 3. CCC Test Program (N=63).

test	Soil	D_R (%)	σ'$_v$ (kPa)	e (-)	γ_d (kN/m^3)	V*
3	TS11	43	50-180	0.86	14.22	V1
4		44		0.85	14.26	V2
9	MIX15%	53	60-220	0.7	15.85	V1
11		53		0.7	15.85	V2

* V1 = 20 mm/s, V2 = 100 mm/s

The CC specimens are enclosed at the sides and base by a membrane, sealed at the top around an aluminium plate, which confines the specimen and transfers the thrust of the chamber piston from the specimen to a top lid. A 120 mm diameter hole is present in the centre of the lid; by changing the sealing hollow bush it is possible to press devices of different sizes into the specimen.

The loading frame, which counteracts the vertical load transferred to the lid during the compression of the specimen, also holds the hydro-mechanical press which pushes the test devices into the chamber during penetration tests. A hollow jack mounted inside the loading frame is used to counteract the vertical load; it is automatically controlled by a closed loop system, which equalizes the compression force in real time and allows to keep the lid position fixed and independent

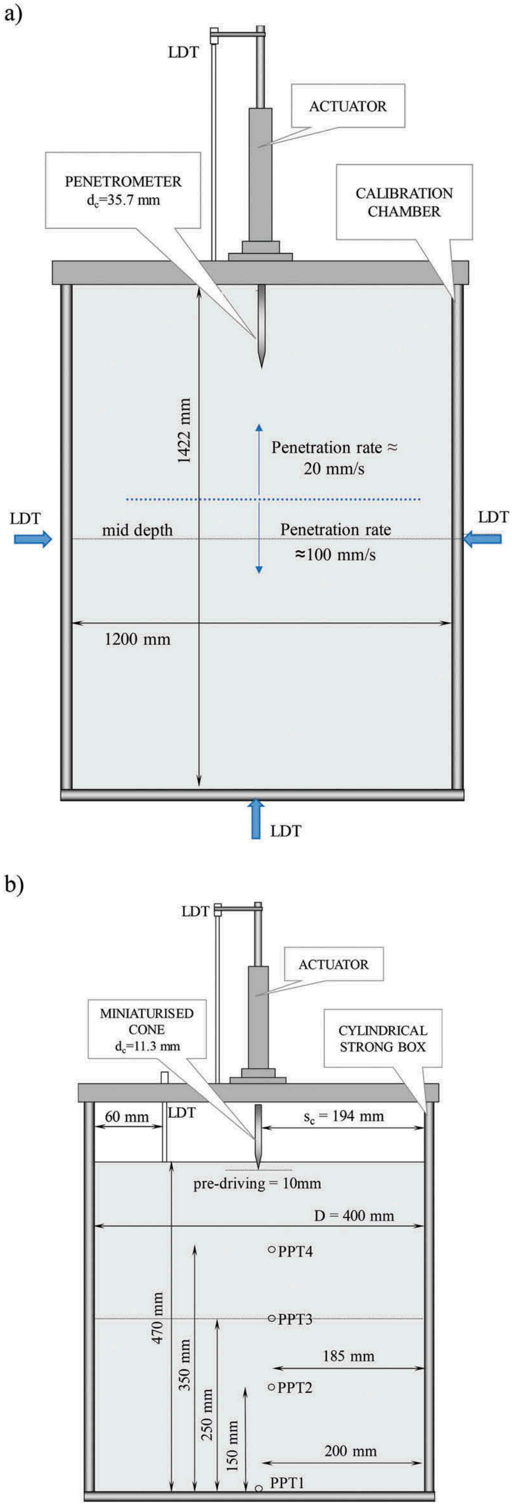

Figure 2. CC (a) and CCC (b) models.

from the frame deformations. Thus the specimen deformation can be monitored by measuring the chamber piston displacement.

The penetration probes used during the tests is a standard piezocone 35.7 mm in diameter, with a total area of 10 cm^2 and an apex angle of 60°. Two load cells measure the tip resistance and the lateral friction, independently; a pressure transducer measures the pore water pressure behind the tip (u_2).

The CC specimens were reconstituted in 15 strata using the undercompaction method (Ladd, 1978), Hereafter, they were saturated through an upwards flow of deaerated water and then by application of a back pressure. Reaching a Skempton B-value equal or larger than 0.95, the specimens were consolidated by applying the target vertical and horizontal stresses. To allow for comparison with the centrifuge tests, during which a rigid strong box houses the models and prevents the development of horizontal strains, the BC3 condition was adopted in the CC. In consequence, horizontal effective stresses imposed in CC were calibrated during the consolidation step to avoid radial deformations. A standard rate (V1 = 20 mm/s) was adopted in the upper part of the specimen and the maximum velocity possible for the loading system (V2 = 100 mm/s) in the lower part, see Figure 2a.

2.2.2 *The ISMGEO geotechnical centrifuge*

The ISMGEO geotechnical centrifuge is a beam centrifuge made up of a symmetrical rotating arm with a diameter of 6 m, a height of 2 m, a width of 1 m, and a nominal radius of about 2.2 m to the model base (Baldi et al.1988, Fioravante et al. 2021). The miniaturised piezocone used for the tests has a diameter d_c = 11.3 mm, an apex angle of 60° and a sleeve friction of 11 mm in diameter and 37 mm in length. One load cell measures the cone resistance and another one measures the cone resistance plus the shaft friction, up to forces of 9.8 kN. A pressure transducer is installed behind the tip for interstitial pressure measurements (u_2).

The centrifuge specimens are 470 mm high and 400 mm in diameter and were reconstituted at 1g using the undercompaction method within a rigid strong box. They were saturated under vacuum using deaerated water and subjected in flight to an acceleration field of 63 g imposed at mid depth (geometrical scaling factor N = 63). The scaling factor and the angular velocity adopted allowed to obtain a vertical stress of about 50 kPa at a depth of 120 mm from ground surface (which is the depth at which the cone resistance q_c is no more affected by top boundary effects) and of 200 kPa at a distance of 150 mm from the container bottom (depth beyond which q_c can be affected by the rigid bottom boundary); 50 kPa and 200 kPa are the vertical effective stresses imposed in the calibration chamber (tests N. 1 and 2 in Table 2).

The CCC boundary conditions are: D/d_c = 35, where D is the internal diameter of the container and s_c/d_c = 17, where s_c is the distance between the CPT and the side wall. These values are sufficiently large to minimise any scale effects on the results (Bolton et al. 1999). The ratio of the cone diameter to the mean particle size is $d_c/D_{50} \approx 25$ for TS11 and $d_c/D_{50} \approx 30$ for MIX15%. CCC models were instrumented with pore pressure transducers (PPT in Figure 2), located at the base to monitor the water table and at three relevant depths of penetration, at a distance of one cone diameter from the penetration axis.

For each test condition two penetration rates were adopted; a standard rate V1 = 20 mm/s and a higher rate V2 = 100 mm/s (both velocities properly scaled).

3 TEST RESULTS

3.1 *CPTUs in clean TS11*

The results of the tests discussed in this section are shown in Figure 3 and were obtained from soil models of clean TS11 reconstituted at a relative density D_R slightly lower than 50%. In Figure 3 the corrected cone resistance q_t is plotted as a function of the vertical effective stress σ'_v. The tests are numbered according to Tables 2 and 3. The black and white squares represent the representative q_t measured in the CC specimens (Tests 1 and 2). For each CC test, two q_t values are plotted: one is the average value measured in the upper half of the model, with the probe penetrating at the standard rate V1; the second value refers to the faster rate V2 adopted in the lower half of the model. The black and grey lines in Figure 3 are the q_t profiles measured in the CCC (Tests 3 and 4). The vertical effective stresses in the centrifuge models are computed referring to: i) the average soil unit weight at the end of the in-flight consolidation, ii) the depth of the water table (estimated from PPT measurements) and iii) the acceleration field distortion. Figure 3 also shows the q_t profile (dashed line) estimated using the equation of Jamiolkowsi et al. (2003). This allows to express the cone resistance as function of the vertical effective stress and relative density, using correlation coefficients calibrated by the Authors for Ticino sand and accounting for the saturation effects. It is worth noting that the correlation was calibrated on the base of CC tests carried out using the same apparatus employed for the present experimentation. For the centrifuge tests, the u_2 profiles, compared with the hydrostatic lines derived from the PPT measures, are given in Figure 4.

The centrifuge test results show that the soil models were rather homogeneous and the tests are repeatable, as the two q_t profiles are almost superimposed. The penetration was, as expected, drained for both penetration rates, see Figure 4. A very good agreement between CC and CCC results can also be observed, see Figure 3. In addition, the measured cone resistance is very well described by the correlation proposed by Jamiolkowski et al. (2003). This is considered an important result, as it demonstrates that CC and CCC give comparable CPT results, which are also consistent with previous studies carried out using TS and the same facilities; these data

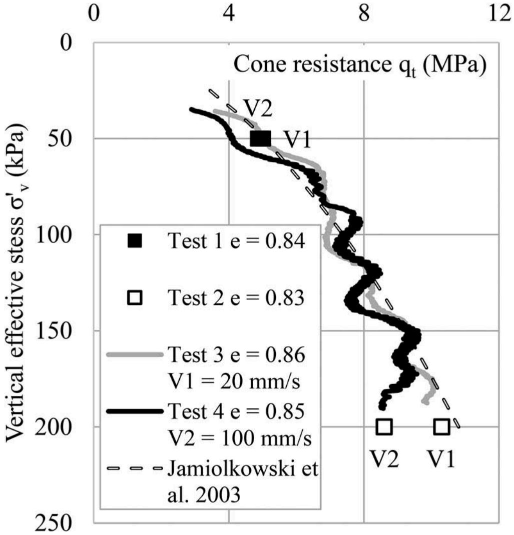

Figure 3. Centrifuge (solid lines) and Calibration Chamber (squares) CPTUs on TS11 - cone resistance q_t.

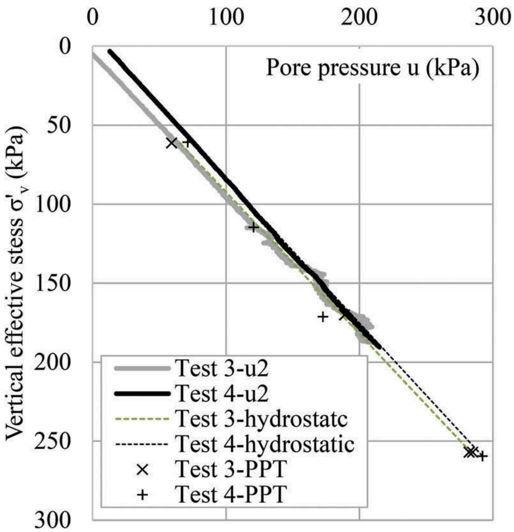

Figure 4. Centrifuge CPTUs on TS11 – PPT measures, hydrostatic line, pore pressure u_2.

are used as benchmark for the following testing stages and, in the first instance, used to evaluate the effect of 15% FC on the cone resistance, for the same relative density and stress state.

3.2 *CPTUs in MIX15%*

Two centrifuge tests (9 and 11 in Table 3) on MIX15% were carried out using the same test conditions as those of tests 3 and 4, i.e. similar relative density (about 50%), stress range and penetration rate. Test 9 was carried out using the standard rate V1; test 11 was run at V2. Figures 5 and 6 show the results. Inspecting the u_2 profiles (Figure 6), the penetration appears to be practically drained irrespective of the penetration rate, similar to the results on TS11.

However, as to the effect of FC on the penetration resistance (Figure 5), MIX15% had a penetration resistance about 40% lower than TS11, even though the void ratio is higher and the relative density is lower for TS11 compared to MIX15% (see Table 3). It's worth noting that drained and undrainded triaxial tests on reconstituted samples indicate a shearing resistance angle at critical state of 36° and 35° for TS11 and MIX15%, respectively. On the other hand, the two materials proved to have different volumetric behavior during shearing. The results of 4 drained triaxial tests carried out on medium dense TS11 and MIX15% samples are shown in Figure 7, in the void ratio e – mean effective stess p' and in the stress deviator q – p' plane. All the samples were reconstituted in strata at medium density (similar to the CC and CCC specimens, see Table 2 and 3) and were K_0-consolidated under a vertical stress of 50 and 200 kPa. While MIX15% manifested a contractive behavior, TS11 dilated.

In general, the cone penetration resistance q_t of an uncemented and unaged soil depends on the material properties and the state of the soil (stress level and density). The state of the soil governs the direction of volumetric strains, (dilation or contraction) during shearing, which, in turns, controls the stress increment around the tip. Consequently, a dilative soil will develop a larger stress increment around the tip and will oppose larger resistance to penetration than a contractive material, as observed for TS11 and MIX15%.

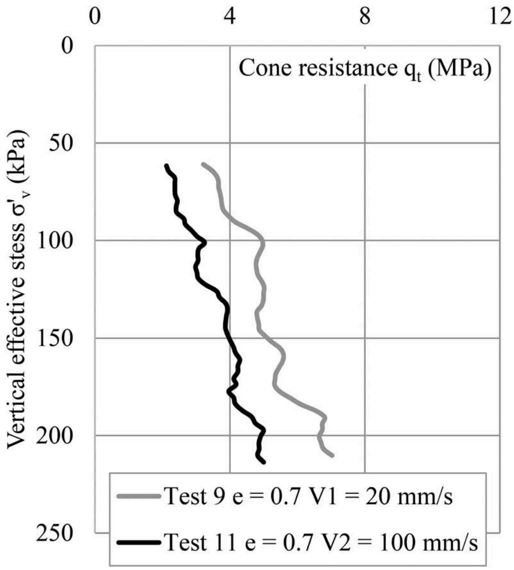

Figure 5. Centrifuge CPTUs on MIX15% - cone resistance q_t.

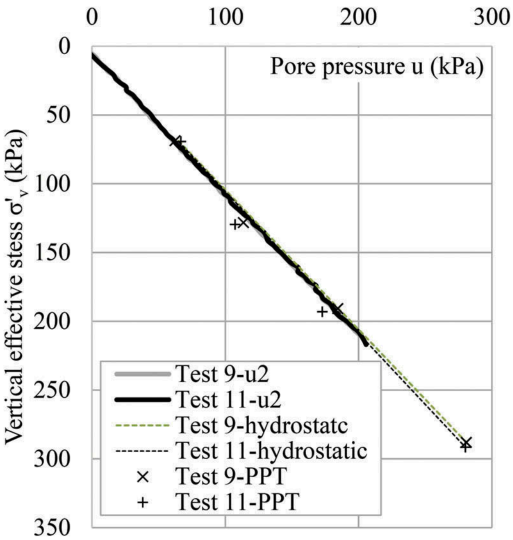

Figure 6. Centrifuge CPTUs on MIX15% – PPT measures, hydrostatic line, pore pressure u_2.

4 CONCLUSIONS

A very good agreement between results of CC and CCC CPTUs in clean TS11 was observed and the measured cone resistance is very well described by the correlation proposed by Jamiolkowski et al. (2003).

The sand mixed with none plastic silt experiences a drop of cone resistance in the centrifuge, which cannot be attributed to effect of partial drainage during penetration, as the measured u_2 profile is straight and coincident with the hydrostatic line and no excess pore pressures developed neither at the standard penetration rate nor during the faster penetration.

The drop of cone resistance is attributed to contractive behaviour of the silty sand at the test density and stress in contrast with the dilative behaviour of the clean sand.

The centrifuge has proved to be a reliable CPT calibration tool in clean sand, alternative to the calibration chamber, with the advantage of providing a continuous cone penetration resistance profile over a wide range of stress level in significantly less time. If a good agreement between centrifuge and calibration chamber results will be gained also for the MIX15%, the centrifuge alone will be employed in a further stage of experimentation, during which 10 additional calibration CPTUs will be carried out on a mix of TS11 and TF characterized by 30% FC (MIX30%). Samples will be reconstituted varying soil density and overconsolidation ratio and will be tested varying the penetration rate. The calibration CPTUs and the complementary laboratory tests will be interpreted in the frame of CSi project with the final goal of contributing to the development of acknowledged, simple and robust guidelines for specification, execution and interpretation of CPTUs in silty soils/silt mixtures.

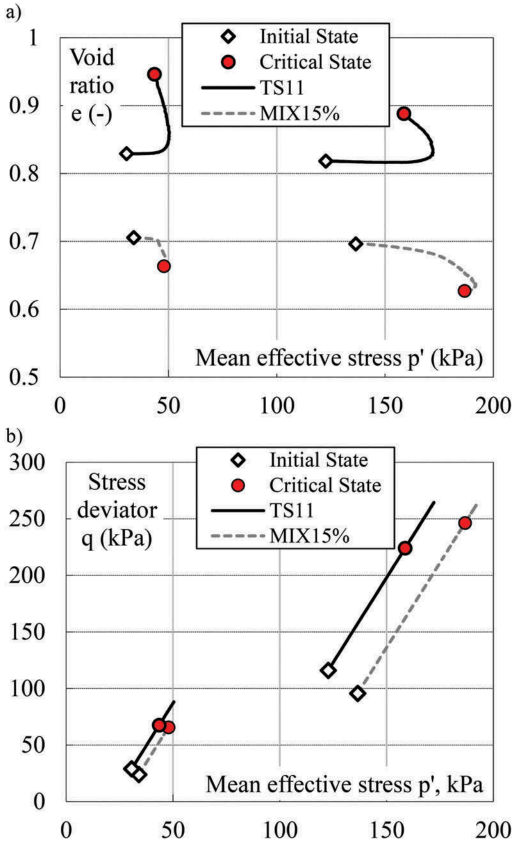

Figure 7. Drained triaxial tests on TS11 and MIX15%: a) e-p' plane; b) q- p' plane.

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