Comparison of the Monotonic and Cyclic Response of Tailings Sands with a Reference Natural Sand

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Abstract. This article considers the monotonic and cyclic behaviour of a tailings sand material, tested over a wide range of confining pressures and relative densities. The collated experimental data are used to interpret the behaviour of this material in the framework of Critical State Soil Mechanics (CSSM) and to calibrate an advanced bounding surface plasticity model. The response of this man-made material is then contrasted, within the same framework, to that of Toyoura sand, which is a well-characterised reference natural sand.

This process aims to identify the principal behavioural differences between the two types of geo-materials and the implications that these may have on the calibration process of an advanced constitutive model. Ultimately, the process also supports the numerical modelling of Tailings Storage Facilities under both monotonic and cyclic/earthquake loading.

Keywords: Numerical modelling · Mine tailings · Bounding surface plasticity

1 Introduction

Several recent failures (e.g. [6, 11, 15]) in tailings storage facilities (TSFs) spotlight the need for further research in these complex man-made structures. Their extensive use in countries of high seismicity, also renders necessary a good understanding of their seismic response. A systematic study on the response of TSFs requires advanced numerical tools and material characterisation data for their calibration. In practice laboratory strength tests (e.g. triaxial, simple shear) in tailings materials are usually restricted due to the mining companies' policies and therefore there is a scarcity of published test data (e.g. [2, 5, 8]). Site-specific calibrations of numerical models are rarely attempted due to the lack of data. Analysts of TSFs often adopt a "default" set of parameters, usually only adjusted to be compatible with CPT/SPT site data, following, for example, the process proposed by Boulanger & Ziotopoulou (2013) [1] for the PM4Sand model. A major limitation of this type of generic calibration processes is that they are based on natural sands. Hence, to understand the static and seismic behaviour of tailings dams, it is important to develop consistent calibration procedures for these artificial materials based on experimental data. Through the comparison of calibrations for a tailings sand and for a natural sand, this article aims to explore their most relevant characteristics, intending to assess the likely impact for subsequent seismic simulations.

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2 Sands Descriptions

Two sandy soils are analysed herein: El Torito tailings sand and Toyoura sand. The former is a cycloned tailings sand material employed in the construction of the El Torito tailings dam (Chile), while the latter is a well-known reference laboratory sand.

Due to various mining processes, mainly crushing of rock blocks, tailings can be treated as artificial soils where the particle shapes are typically sub-angular to angular, with presence of fines contents. The El Torito tailings sands cover a wide range of particle sizes with non-plastic fines content reported from 15% to 23%, which is mainly attributed to the mineralogy of copper tailings. On the other hand, Toyoura sand is a natural well-characterised sand consisting of rounded to subangular particles formed by natural processes. Toyoura sand shows a uniform particle size distribution without fines contents.

Figure 1 plots the particle size distribution (PSD) for both sands, also including the coarse fraction of the tailings sand which is very similar to Toyoura sand in terms of PSD.

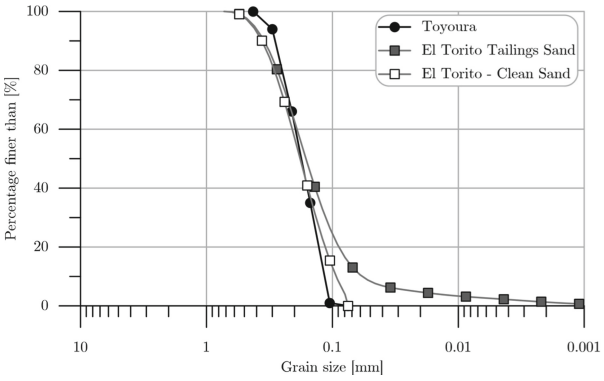


Fig. 1. Particle size distribution for Toyoura sand, the El Torito tailings sand and clean fraction

The characterisation of the El Torito tailings sands, which includes critical state strength, stiffness at small strains and cyclic strength, is presented and discussed in detail in Solans et al. (2019) [19]. Toyoura sand is well-known reference sand, with a large set of references available (e.g. [5, 7, 23, 24]).

3 Constitutive Model

A state parameter-based bounding surface plasticity model (BSPM) is employed herein, implemented in the Imperial College Finite Element Program ICFEP ([13]) by Taborda et al. (2014) [20] who introduced several modifications to the model originally proposed by Manzari & Dafalias (1997) [9]. The cyclic behaviour of the soil is simulated by means of a fabric variable influencing the hardening modulus ([12]), as well as by modifications introduced by Tsaparli (2017) [21] to the spherical part of the flow rule and the fabric

tensor aiming to improve the prediction of the cyclic strength. Further details of the model formulation can be found in Taborda et al. (2014) [20] and Tsaparli (2017) [21]. A summary of all model equations and a recent application can be found in Tsaparli et al. (2019) [22]. Table 1 summarises the model parameters obtained through the calibration process for both materials.

Table 1. Model parameters BSPM for Toyoura sand and El Torito tailings sand.

Component	Toyoura sand	El Torito tailings sand
Critical State	$p'_{ref} = 100$ kPa; $e_{o,ref} = 0.9325$; $\lambda = 0.019$; $\xi = 0.70$	$p'_{ref} = 100$ kPa; $e_{o,ref} = 1.105$; $\lambda = 0.2395$; $\xi = 0.205$
Small-strain parameters	$B = 840$; $n_g = 0.5$; $\nu = 0.15$	$B = 458$; $n_g = 0.55$; $\nu = 0.15$
Surface parameters	M^c_{cs} =1.25; $M^e_{cs} = 0.9$; $k^b_c = 1.1$; $k^d_c = 3.4$; $A_o = 0.9$	M^c_{cs} =1.50; $M^e_{cs} = 1.05$; $k^b_c = 2.0$; $k^d_c = 4.0$; $A_o = 0.80$ For flow rule mod: $A_o = 0.80$; $A_{o,min} = 0.0$; $b_d = 0.10$; $d_1 = 0.07821$; $d_2 = 0.00388$; $d_3 = 0.0$
Hardening modulus	$h_o = 0.1025$; $\nu = 0.02$; $\alpha = 1.0$; $\beta = -0.5$; $\gamma = 0.92$	$h_o = 0.13$; $\nu = -0.10$; $\alpha = 1.0$; $\beta = -0.5$; $\gamma = 0.92$ $d_1 = 3.83861$; $d_2 = 0.00538$
Fabric Tensor	Fabric: Ho = 55000; $\zeta = 1.55$; $C_f = 50$	Fabric: Ho = 14890; $\zeta = 0.317$; $C_f = 75$; For flow rule mod: Ho = 15000; $\zeta = 0.0$; $C_f = 75$

4 Calibration Results

The position of the CSL in the log p' – e plane is presented in Fig. 2 for both Toyoura sand and the El Torito tailings sand, along with the initial states (red and blue symbols) for the selected monotonic and cyclic tests to be simulated. For Toyoura sand, the position of the CSL is clear, with an only minor scattering in the data interpretation. Conversely, the El Torito tailings sand data presents high scatter with values of $\Delta e \sim 0.05$ to 0.1, which is consistent with the observed range reported for tailings by Fourie & Papageorgiou (2003) [4] and Reid et al. (2020) [14]. It is noteworthy that for both sands the void ratio was determined at the end of each test, following the procedure recommended by Verdugo & Ishihara (1996) [23].

In terms of the state parameter, ψ, , the monotonic tests selected include contractive ($\psi > 0$) and dilative ($\psi < 0$) conditions; while for the cyclic tests, only the dilative cases ($\psi < 0$) have been taken into account, due to the model formulation of the fabric tensor[1].

[1] The fabric tensor is affected by the H parameter defined as: $H = H_o\left(\sigma'_{1,0}/p'_{ref}\right)\langle -\psi_o \rangle$, where $\langle\rangle$ corresponds to the Macauley brackets ($\langle x \rangle = x$ if x > 0 and $\langle x \rangle = 0$ if x < 0). (Taborda et al. 2014) [20]

Both sets of experimental data, Toyoura and El Torito tailings sands, were obtained for reconstituted samples formed using the moist tamping technique. The initial state conditions, $p'_o - e_o$, were defined aiming to cover a wide range of densities and mean effective stresses for Toyoura sand. For the El Torito tailings sand, the initial conditions aimed to reproduce the in-situ compaction state with an initial relative density of $D_{Ro} =$ 60%, a typical value for constructing cycloned tailings dams, and high p' values which are expected in TSFs for dams over 80 m height.

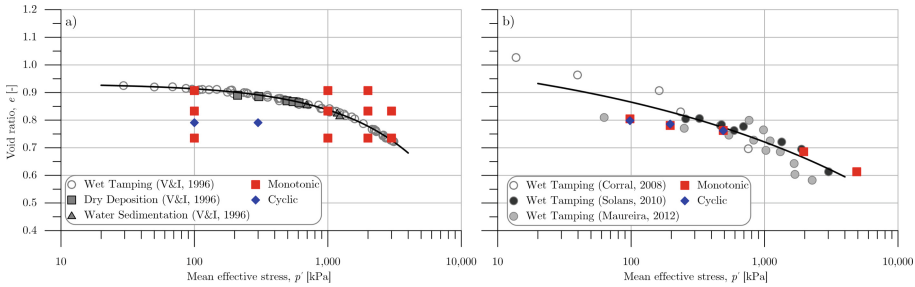


Fig. 2. Critical State Line and selected tests for: a) Toyoura sand ([23]), and b) El Torito tailings sand ([3, 10, 17])

Examining the two materials, the observed scatter evidences a bigger challenge to establish the CSL for the tailings than for the natural sand. It is noteworthy that no significant particle breakage was detected after the tests on the tailings sand, regardless of the high mean effective stresses applied ([19]).

4.1 Monotonic Response

The result of the model calibration is presented first for the monotonic response for both Toyoura and the El Torito tailings sands.

Figure 3 compares the experimental data ([23]) and the model simulations for undrained triaxial compression tests of Toyoura sand. The experimental data covers a wide range of mean effective stresses (p' from 100 kPa to 3 MPa) and void ratios (e from 0.735 to 0.907). The model simulations, indicated in solid lines, show a good agreement with the experiments, indicated with dotted lines, reproducing a variety of responses from highly dilatant to highly contractant. Also, the model reproduces well the phase transformation state and peak strength, typically observed in sandy soils.

A set of undrained triaxial tests for the El Torito tailings sand obtained from Solans (2010) [17] and Maureira (2012) [10] has been chosen for the numerical simulations, see Fig. 4. The selected tests cover a wide range of mean effective stresses (p' from 98 kPa to 4.9 MPa) and void ratios (e from 0.613 to 0.805). A major challenge in the calibration process is capturing the experiments for a wider range of mean effective stresses with a single set of parameters. The simulations provide a good agreement with the experimental data, reproducing the characteristic aspects (e.g. phase transformation) of the sand response. Better simulation results are obtained if the calibration is separated

for a low and a high range of p' ([18]). Complementary simulations, for both materials, under drained triaxial compression conditions can be found in Solans (2022) [18].

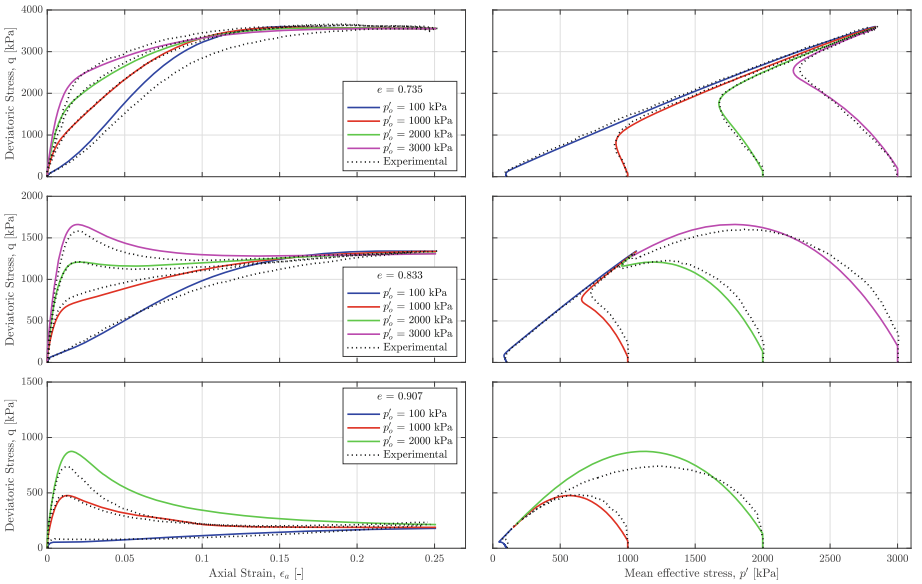


Fig. 3. Toyoura sand. Simulations compared with experiments in undrained triaxial tests ([23])

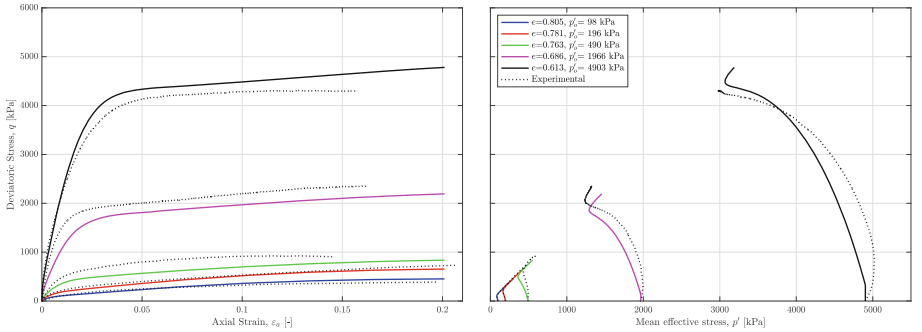


Fig. 4. El Torito tailings sand. Simulation compared with experiments in undrained triaxial tests based on ([17]) and ([10])

4.2 Cyclic Response

The cyclic response is assessed by undrained cyclic triaxial tests for both studied sands. The experimental data considered for Toyoura sand is published by Yang & Sze (2011) [24], while the tests of Solans (2010) [17] were used for the El Torito tailings sand.

The experimental data and the numerical simulations are summarised in Fig. 5 in terms of cyclic resistance curves. The calibration aims to reproduce the cyclic curves with reasonable agreement at around 10 to 15 cycles, considered as the relevant range for seismic applications. Another essential aspect to consider is the effect of mean effective stress in the cyclic response (often referred to as the overburden correction factor or K_σ ([16])).

The Toyoura sand simulations (Fig. 5.a) were performed employing the fabric tensor formulation described by Taborda et al. (2014) [20]. The experimental data uses the 5% double-amplitude (DA) axial strain as a liquefaction criterion. As some of the simulations did not reach the 5% DA criterion, it was necessary to include 90% of the excess of pore water pressure (PWP) build-up as a complementary criterion, typically employed in liquefaction assessment. The numerical simulations, plotted for 5%DA and 90% PWP criteria, provide satisfactory results compared to the experimental data, reproducing very well the K_σ effect for 300 kPa of confining stress.

Figure 5.b summarises the cyclic simulations for the El Torito tailings sand, where two calibration approaches were considered: (i) a fabric tensor formulation and (ii) a flow rule modification ([21]). Both the experimental data and the simulation employed the criterion of 90% PWP to define liquefaction. The original fabric tensor formulation provides good agreement for p' = 98 kPa, but as the mean effective stress increases, the simulated curves depart from the experimental data. For the flow rule modification, a good match is achieved at around 10 cycles, overestimating the cyclic strength for lower cycles and underestimating it for higher than 10 cycles, especially at $p' = 490$ kPa.

The differences in the cyclic strength curve simulations and the experiments may be attributed to the inherent scatter for the CSL and to very low initial state parameter values, ψ_o, observed for the El Torito tailings sands. If these conditions are controlled, as it is the case for Toyoura sand, it is possible to improve the model performance achieving low B_{CRR} values ($CRR = A_{CRR}N^{B_{CRR}}$).

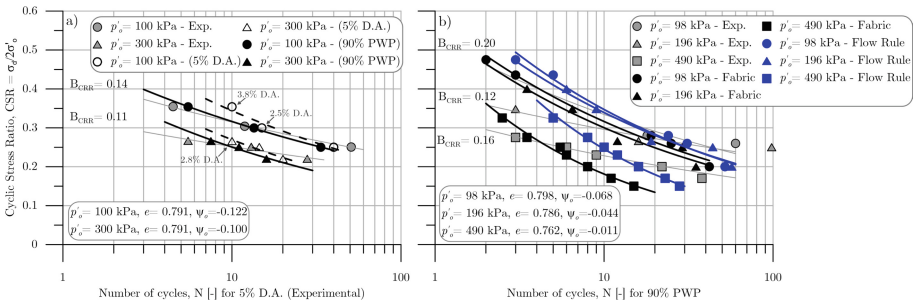


Fig. 5. Cyclic strength curves and simulations for: a) Toyoura sand, and b) El Torito tailing sand

Figure 6 shows the excess of pore water pressure (PWP) build-up of two cyclic tests. The experimental data in both tests indicate approximately 7 cycles to reach the 90% PWP liquefaction criterion, while the simulations predict higher number of cycles. In the case of Toyoura sand, the model simulation follows a PWP rate consistent with

the experiment. The PWP rate obtained from the flow rule approach is closer to the experiment for the El Torito tailings sands simulation.

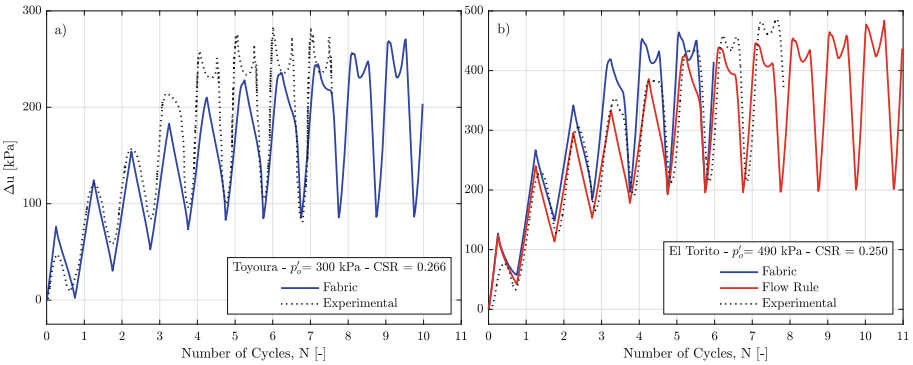


Fig. 6. Excess of pore water pressure build-up for: a) Toyoura sand, and b) El Torito tailings sand

5 Conclusions

This article presents and contrasts the calibration of an advanced state parameter-based bounding surface plasticity model for the El Torito tailings sand and for the well-known natural Toyoura sand.

Despite the fact that tailings sands are inherently variable, the model simulations for monotonic conditions compare well with the experimental data in the wide range of mean effective stress considered. For the cyclic response, reasonable simulation results are obtained for mean effective stress around 100 to 200 kPa. Important differences are observed for $p' = 490$ kPa, which may be explained by the low ψ_o values (proximity to the CSL), and the inherent scatter of the CSL, expected for this kind of material.

Finally, regardless of the variability of the tailings sand studied, the BSPM employed reproduces most of the behavioural features of this kind of material with reasonable accuracy. However, the use of this model formulation in boundary value problems should take into account the challenging calibration process at element level, to predict reasonable results in dynamic analysis of tailings sands dams.

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