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Numerical sensitivity analysis for stress-strain simulation and flow liquefaction assessment of tailings storage facilities using the NorSand constitutive model

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Article

Keywords
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Abstract

With the advent of critical state Soil Mechanics (CSSM), the void ratio began to be recognized as a key parameter, along with the stress state, which defines the mechanical behavior of soils and other particulate geomaterials by using the state parameter. The state parameter is the difference between the current and critical void ratio so that its definition requires the critical state line (CSL) identification. This work presents numerical calibration results, using the NorSand constitutive model, from three sets of triaxial compression tests selected from the literature. The SIGMA/W module of the Geostudio® System was adopted to perform the simulations of the triaxial compression tests, and the results showed adequate fit between real tests and numerical simulations. The parameters necessary for the modeling with NorSand model, defined from the numerical calibration, were used in a stress-strain evaluation of a hypothetical upstream tailings dam. These simulations allowed the evaluation of the differences in the tailings storage facility (TSF) responses in terms of both deformation behavior and flow liquefaction instability. Flow liquefaction instability is described in the literature as a complete loss in shear strength and the development of excessive strains due to the contractive response of tailings when subjected to low confining stress. The results suggest that the use of the NorSand model is, in general, a good option to reproduce the typical strain-softening behavior of such structures. Furthermore, it was clear the high sensitivity of the constitutive model parameters, drawing attention to the importance of best laboratory practices for carrying out triaxial tests to obtain reliable parameters for NorSand modeling.

1. Introduction

Catastrophic failures with tailings storage facilities (TSF) have accelerated the process of improving knowledge about the mechanical and hydraulic behavior of tailings generated in the mining process. Two of these recent TSF catastrophic failures, Fundão and B1, took place in Brazil due to the static (flow) liquefication failure mode according to their respective investigation panels (Morgenstern et al., 2016; Robertson et al., 2019).

Flow liquefication can be defined as a sudden and substantial loss of resistance of soft and saturated particulate matter, when subject to undrained loadings. Liquefaction in tailings dams usually lead to catastrophic failure, which could be partially explained by the absence of preliminary signals and by the fast movement of the tailings over the downstream zone. Liquefication is basically governed by deformation response of the particulate materials when subjected to changes in their stress state; therefore, to evaluate the TSF mechanical response, it is necessary to study the stress-strain behavior of these materials.

The Critical State Soil Mechanics (CSSM) (Schofield & Wroth, 1968) proposes an integrated approach to soil mechanical behavior, both in relation to deformability and shear strength, subjects treated separately by Classical Soil Mechanics. The aforementioned generalization has its application made possible by means of constitutive models that consider the Plasticity Theory (with hardening and/or softening on the yield surface). Constitutive models such as the Modified CamClay (Roscoe & Schofield, 1963; Roscoe & Burland, 1968; Schofield & Wroth, 1968) and NorSand (Jefferies, 1993) adopt the CSSM concepts and have numerical implementation codes available in most software.

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The application of critical state models, which allow the evaluation of the generalized behavior of soils and other particulate geomaterials, requires the experimental acquisition of parameters that describe the behavior of materials under different loading conditions. Most of these parameters can be obtained through laboratory tests as in the method proposed by Jefferies & Been (2016) based on triaxial compression tests. The quality assurance of these tests requires advanced equipment and trained professionals so that the results obtained are reliable and have repeatability. Reid et al. (2021) carried out a critical state round robin program to evaluate the variability of the critical state line (CSL) parameters obtained from triaxial tests performed by fifteen laboratories on gold tailings. Results from eleven laboratories had lower variability while four indicated considerable variations in CSL position and therefore they were disregarded.

The NorSand constitutive model (Jefferies, 1993), which adopts the critical state theory as the basis of its formulation, has been adopted by researchers and practitioners as a sufficiently reliable model for simulating the stress-strain behavior of particulate geomaterials (Silva et al., 2022).

This work reports a numerical calibration of the NorSand parameters adopting the results of three laboratory triaxial compression tests from Reid et al. (2021) for modeling of the raising process of a hypothetical tailings dam. The modeling results of the hypothetical upstream tailings dam from the experimental parameters of the different laboratories are compared to evaluate how the NorSand parameters variability can affect the TSF performance evaluation.

2. Materials and methods

This work was conducted by four steps of greater relevance:

- Selection of experimental data to be adopted in the study from the data published by Reid et al. (2021).
- Data processing: raw data evaluation from Reid et al. (2021), data processing and preparation of the various graphs to be used in the numerical calibration.
- Computational modeling and calibration process of laboratory tests: modeling of the tests in the SIGMA/W module of the GeoStudio® System (Geoslope) and development of the iterative process for calibration results.
- Computational modeling of the heightening process of a hypothetical dam: Elaboration of the hypothetical model for the seepage and stress-strain analysis in the SEEP/W and SIGMA/W modules of the GeoStudio® System, respectively.

3. Analysis and results

3.1 Tailing characteristics

As mentioned, this work adopted as reference three CSL results from a round robin program for CSL determination of gold tailings collected in an active TSF (Reid et al., 2021). The main characteristics of the gold tailings adopted are presented in Table 1. The tailings were characterized by Reid et al. (2021) as low plasticity and a mixture of predominately sand and silt-sized particles. Different laboratories characterized and evaluated the mechanical behavior of the material and the particle size distribution (PSD) curves obtained by these laboratories did not show relevant dispersion regarding the results.

The preparation of the tailings for shipment to the laboratories comprising the washing of the material with the use of deionized water to reduce dissolved solids, mainly salts. There is evidence that salts may affect the CLS of some tailings (Reid et al., 2021). After washing the material was dried to a moisture content of approximately 3% and was subsequently mixed to ensure uniformity.

3.2 Experimental data selection

Out of the eleven laboratory tests results presented by Reid et al. (2021), the set test results of the University of Porto (UPorto), the University of Toronto (UOT) and Klohn Crippen Berger (KCB) were considered for numerical studies development in this work. The choice for these three laboratories was based on the following criteria:

- The sample preparation method was performed according to the Moist-Tamping method which, in conjunction with the sub-compaction procedure for non-cohesive soils, allows the reconstitution of uniform and reproducible samples with the highest range of void ratios (Viana da Fonseca et al., 2021).
- End-of-test soil freezing method (EOTSF) was used to obtain the final void ratio. This technique, as mentioned by Viana da Fonseca et al. (2021), leads to a more rigorous determination of the sample volume, which consequently implies greater reliability in obtaining the void ratio in the different phases. The details of the test methods by the three selected laboratories are presented in Table 2.
- The adoption of the same loading rate in the tests.

Based on critical state parameters obtained by experimental test results between the three selected laboratories, a greater convergence of results from KCB and University of Porto is observed. It is noteworthy that the procedures of both University of Porto and the University of Toronto have similarities.

Table 1. Gold tailings characteristic (Reid et al., 2021).

Parameters	Symbol	Value
Specific gravity	G_s	2.78
Liquid limit (%)	w_L	18
Plasticity limit (%)	w_P	16
Plasticity index (%)	PI	2
% < 75 μm (%)	-	58
% < 38 μm (%)	-	44
Mean particle size (μm)	D_{50}	50

3.3 Numerical simulation of triaxial tests

The triaxial tests were modeled in the SIGMA/W considering an axisymmetric condition, which allows the simplification of the model by the adoption of a symmetrical structure in relation to the vertical axis, which consequently ends up optimizing the calculation time.

The diameters of the specimens adopted in the simulations were those presented by Reid et al. (2021). The modeling was performed in two steps. The first step to establish the confining pressure and the second one to simulate the shear phase. In the first step, three boundary condition were applied. At the inner face (vertical symmetric axis), a boundary condition that restricts horizontal displacements was applied, to simulate the restriction created by the other half of the specimen which is not represented in the axisymmetric model. At the base of the model, a boundary condition was inserted to restrict vertical displacements. On the external face and at the top of the model are applied the confinement pressure of each test which establish the initial condition for the shear phase. After this modeling, a 'daughter' model of the initial one is created through the software routine called 'Parente Analysis'. This routine allows importing from an initial model the stress state, pore pressure, displacements, and deformations. In this model, the final stress condition of the consolidation phase is used as input in the next step of the model (shearing phase).

The stress state calculated in the initial step is imported into the next step so the boundary conditions that simulate the confining pressure must be removed to prevent stress increments from being computed in the shear step. At the shear stage of modeling, the rigid borders are maintained, and a time dependent displacement boundary condition is used at the top of the model with maximum values equal to those values presented in the supplementary information by Reid et al. (2021).

3.4 Calibration of NorSand model parameters

As described briefly in the Introduction, the NorSand Model was chosen to perform the stress-strain analysis due to its capacity of simulate the behavior of the material considering its initial state, stress and state parameter, according to the Critical State Soil Mechanics framework (CSSM). The calibration process was performed by iterative processes comparing the results of numerical modeling with the raw data triaxial tests provided by Reid et al. (2021). The modeling through the constitutive model NorSand in the SIGMA/W requires fourteen parameters. Nine of these parameters are necessary for the definition of the critical state line (Γ and λ), the behavior during the elastic phase (G and v) and during the plastic phase (M_{tc}, N, χ and H_0 and H_y). Table 3 shows the input values for each of the parameters necessary for the simulations, and the parameters Γ, λ, M_{tc} and γ are extracted directly from the experimental data (Reid et al., 2021).

Table 2. Summary of tests methods (from Reid et al., 2021).

Method	KCB	UPorto	UOT
Sample Preparation	Moist Tamping	Moist Tamping	Moist Tamping
Number of layers	11	6	6
Under-compaction ratio (%)	15	2	2
Initial sample diameter (mm)	69	72	51
Shear rate (%/h)	1	1	1
Gravimetric soil water content (%)	5	12	5
Lubricated diameter ratio	1.93	2.17	1.02
Oversized platen ratio	1.11	1.06	1.00
Top cap-loading ram conncetion type	Free to rotate	Embeded	Free to Rotate
M_{tc} interpretation method	Stress Dialatancy	End of Test	End of Test
Void ratio measurement method	EOTSF	EOTSF	EOTSF

EOTSF: end-of-test soil freezing.

Table 3. Parameters adopted in the simulations.

Parameter	Symbol	KCB	UPorto	UOT
"Altitude" of CSL defined at p' = 1 kPa	Γ	0.789	0.829	0.923
Slope of CSL defined on ln base	λ_e	0.035	0.046	0.058
Unit weight (kN/m^3)	γ	18	18	18
Poisson's ratio	ν	0.2	0.2	0.2
Volumetric coupling Parameters	N	0.2	0.2	0.2
Dilatancy parameter	χ	3.5	3.5	3.5

CSL: Critical State Line.

The dilatancy (χ) and volumetric coupling (N) parameters were fitted by means of an iterative process with the results of the three laboratories to find a single value. The values obtained for these two parameters are quite consistent with values provided by literature (Jefferies & Been, 2016; Cheng & Jefferies, 2020; Silva et al., 2022). The Poisson's ratio (ν) and the parameters required for calculating the shear module (p_{ref} and m) were deemed constant with average values as proposed by Shuttle & Jefferies (2010).

The initial void ratio (e_0) adopted in the modeling was the same of the triaxial tests. The values of the reference shear module (G_{ref}), the over-consolidation ratio (OCR) and the plastic hardening module (H_0 e H_y) were calibrated by interactive process and graphical comparison between the results of the triaxial tests and numerical simulations. The iterative graphical fitting comprised the comparison of the parameters as follows:

For drained tests:

i) Deviatoric stress (q) – mean effective stress (p'),
ii) Deviatoric stress (q) – axial strain (ε_a),
iii) Volumetric strains (εv) – shear strain (ε_q), and
iv) State parameter (ψ) – axial strain (ε).

For undrained tests:

i) Deviatoric stress (q) – mean mffective stress (p'),
ii) Deviatoric stress (q) – axial strain (ε_a),
iii) State parameter (ψ) – axial strain (ε), and
iv) Axial strain (ε_a) – pore pressure (u).

3.5 Triaxial tests numerical calibration: KCB

The numerical calibration of six out of seven tests from KCB (Reid et al., 2021) were carried out. The result of the test named TX CID4_KCB showed unusual strain behavior and was not object of the calibration process. The results of the TX CID5_KCB and TX CIU1_KCB test also showed variations that hindered an adequate fit in the calibration process.

The results of the TX CD1_KCB and TX CD2_KCB tests, which were performed under the same confining pressure (300 kPa) and similar initial void ratio (0.633 and 0.632, respectively), showed different behaviors. The TX CD2_KCB test initially showed a low axial strain in comparison with the TX CD1_KCB test, with a lower dilative behavior.

Figure 1 shows the graph with the numerical calibration results for the TX CD6_KCB test. The result of the numerical model is very close to those obtained in the real tests. It is noteworthy that the calibration process was carried out through numerous iterations with focus on the hardening module (H_0) and the reference shear module (G_{ref}).

There are many different combinations of these two parameters that can lead to a proper calibration, therefore it is important to use reference from the literature to choose the adequate values for these parameters.

3.6 Triaxial tests numerical calibration: University of Porto

For the definition of *CSL*, the Laboratory of the Faculty of Engineering of the University of Porto developed seven triaxial tests, four of which were isotropically consolidated and drained (CID) and three isotropically consolidated and undrained (CIU). However, as presented in the supplementary information material by Reid et al. (2021), the undrained tests performed with low confinement (50 kPa and 200 kPa), when sheared, presented liquefied or strain-softening behavior. Therefore, the CSL was defined based on the four CID tests and one CIU test carried out under 800 kPa confining pressure.

The result of TX CID2_Porto test and the respective numerical calibration performed are presented in Figure 2. It is emphasized that the results of the four CID and one CIU tests carried out by the University of Porto were those whose numerical calibration required smaller iteration amounts.

3.7 Triaxial tests numerical calibration: University of Toronto

The University of Toronto performed six triaxial tests to obtain the CSL: four isotropically consolidated and drained (CID), one isotropically consolidated and undrained (CIU) and one K_0 consolidated and undrained (CK_0U). For the latter, named TX CK_0U1_Toronto, a K_0 of 0.5 was adopted as a reference for specimen consolidation.

For the TX CK_0U1_Toronto test, calibration attempts were made, but unsuccessful. However, the numerical calibration obtained good convergences for all isotropically consolidated tests as presented in Figure 3.

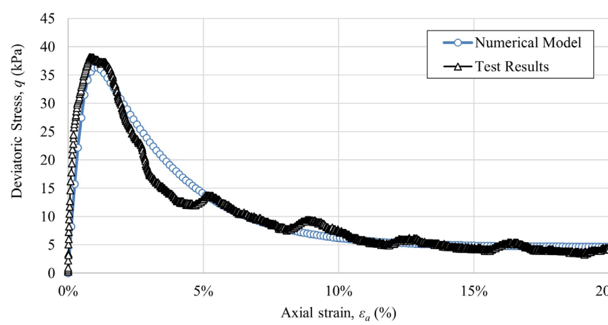

Figure 1. Deviatoric stress (q) *versus* axial strain (ε_a) − TX CD6_KCB.

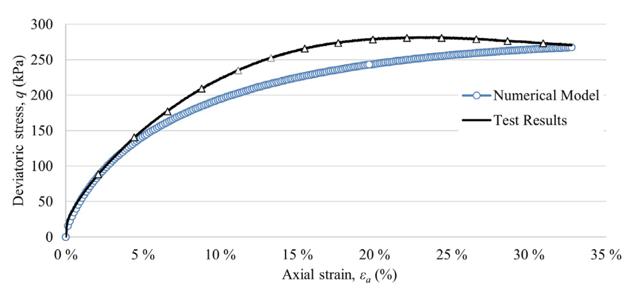

Figure 2. Deviatoric stress (q) *versus* axial strain (ε_a) − TX CID1_Porto.

4. Numerical model of an upstream tailings dam

Numerical modeling results are presented considering a hypothetical tailings dam, to simulate a dam behavior under similar boundary and stress conditions to a real structure, with successive upstream raisings, of which tailings were parameterized according to the results from the calibration of the experimental data presented before. For simplification, a homogeneous tailings disposal in the reservoir was adopted for the upstream tailings dam numerical simulations varying the experimental tailings NorSand parameters from the experimental data calibrated for the different laboratories (KCB, University of Porto, and University of Toronto).

4.1 Setting the numeric model

A hypothetical upstream raised tailings dam model with a total height of eighty meters was adopted, including a 20-meter starter dike and twelve upstream consecutive raisings, each five meters high, according to the cross section presented in Figure 4.

Starter Dam and raisings were modeled with a slope of 2.00 H:1.00 V (26.57°) and crest width of ten and five meters, respectively.

The foundation was established as rigid with the use of a boundary condition that prevents vertical and horizontal displacement. The foundation was modeled as rigid to reduce the model size and to facilitate the convergence. This boundary condition did not affect the model considerably according to stress and displacements calculated.

4.2 Numerical simulation of the raisings

The raising process was simulated by SEEP/W and SIGMA/W modules of Geostudio® (Geoslope) for seepage and stress-strain analyses, respectively. An analysis tree that allows piezometry, stresses and deformation conditions to be imported from previous analyses were adopted to simulate the incremental process of tailings disposal. The raising was simulated by 33 steps, one for simulating the implementation of the Starter Dike and thirty-two simulating increments of tailings layers with thicknesses of 2.50 meters each.

4.3 Piezometric and loading conditions

The piezometric conditions were defined through seepage analyses. The analyses were carried out adopting 100 meters as a premise for the minimum distance from the beach.

For the modeling in SEEP/W, two boundary conditions were used, one at the internal drainage output to direct the flow through this element and another to simulate the elevation of the lake in the reservoir. The pore pressure calculated in each step of seepage analysis were then imported into the respective stress-strain stages. The parameters needed for seepage modeling were obtained from the library available in the GeoStudio® system.

The SIGMA/W Module, at version 2021.4 of GeoStudio®, allows simulating the loading through four types of analysis: *In Situ*, Stress-Strain, Consolidation and Redistribution of Stresses. The first type was adopted for the first step to calculate the initial stress state of the Starter Dam. In the simulation of the heightening, the Stress-Strain analysis was adopted. Stress-Strain analysis allows evaluating the materials behavior when requested by forces or displacements.

4.4 Materials and parameters

The dam was modeled using three materials: Starter Dam, Elevations and Tailings. In the stress-strain analysis the same material was used to represent the Starter Dam earth fill and the horizontal drain to simplify the model. This adoption has little or almost no influence on the results. Except for the tailings, which was modeled using the NorSand model, the materials were modeled by isotropic linear elastic constitutive model.

For Tailings, the parameters were those provided by Reid et al. (2021) complemented by those from numerical calibration. The elastic parameters (G_{ref}) were defined based on the results of triaxial test calibrations with lower confining pressure to better simulate the behavior of the material on a TSF where the initial stresses are reduced. The initial void ratio of the tailings was calculated based on the fixed value of the state parameter, ψ = 0.15 which was considered a representative value to represent the soft conditions typically verified for hydraulic tailings disposal. The adoption of the fixed state parameter aims to standardize the initial state in all simulations (Table 4).

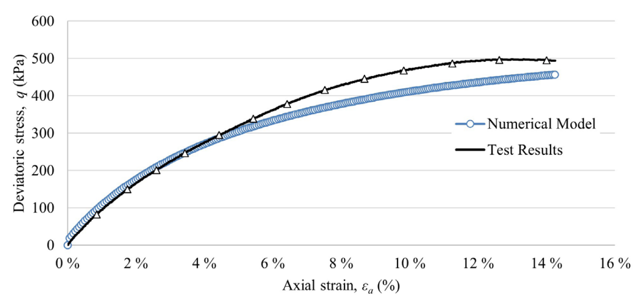

Figure 3. Deviatoric stress (q) *versus* axial strain (ε_a) – TX CID2_Toronto.

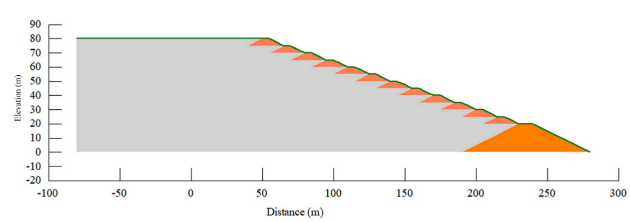

Figure 4. Cross section and geometry of the hypothetical dam.

Table 4. NorSand parameters for the tailings.

Parameter	Symbol/ Unit	KCB	U. Porto	U. Toronto
Initial void ratio	e_0	0.85	0.90	0.93
Unit weight (kN/m³)	γ	18	18	18
Over-consolidation ratio	OCR	1.10	1.10	1.10
Poisson's ratio	ν	0.20	0.20	0.20
Shear modulus (kPa)	G_{ref}	40,000	30,000	10,000
Critical state line slope ($q - p'$ plane)	M_{tc}	1.43	1.41	1.39
Volumetric coupling	N	0.2	0.2	0.2
Dilatancy	χ	3.5	3.5	3.5
Plastic hardening modulus	H_0	40	25	30
Additional softening parameter	H_y	0	0	0
Additional softening parameter		0	0	0
Specific void ratio at the critical state	Γ	0.7889	0.8225	0.9230
Critical state line slope ($e - \ln p'$ plane)	λ	0.035	0.046	0.058

4.5 Finite element mesh

The finite element mesh was configured with square elements of 1.25 meters. As the heights were sized with 2.5 meters this mesh provided a good configuration and fit to the geometry. This setting resulted in a Finite Element Mesh (FEM) with approximately 13,000 nodes.

The convergency of the model was verified by means of the Unbalanced Energy Method (GeoStudio, 2021) and the results, less than 1×10^{-5}, showed good convergency of the model according to the criteria of Sigma/W Module Guide (GeoStudio, 2013).

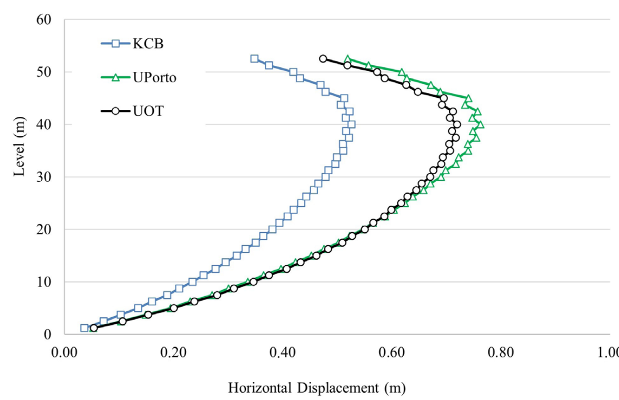

Figure 5. Horizontal displacements computed in a vertical one hundred away from the start dike crest.

4.6 Numerical modeling results

4.6.1 Horizontal displacements

The evaluation of horizontal displacements was performed by constructing graphs that present the horizontal displacements according to the depth in four vertical lines of 50, 100, 150 and 200 meters from the crest of the Starter Dam.

The largest horizontal displacements were verified in the vertical line one hundred meters far from the crest of the Starter Dike. These displacements can be seen in the graph shown in Figure 5.

The biggest displacements were recorded with the parameters obtained from the experimental data of the University of Porto and the University of Toronto. The maximum horizontal displacement from University of Toronto and University of Porto results were 37% and 45% higher than those of KCB, respectively. This behavior can be explained by the difference in the position of the critical states Line established by each laboratory. The CSL defined by KCB has a lower value of Γ and λ. The first parameter indicates the critical void ratio for a given reference stress, so considering that the initial state parameter adopted was similar for all samples, a lower Γ value means that this material starts with an initial void ratio smaller than the others (Figure 6).

4.6.2 State parameter (ψ) and Void Ratio (e)

Figure 7 shows the state parameter values calculated for the final configuration of the dam. In the modeling performed, the state parameter for the drained condition showed a small range with minimum values close to 0.10. The variation of the mean effective stress applied was around 700 kPa when analyzing an area at the base of the reservoir 200 meters away from the crest of the Start Dike, which can be observed in the graph in Figure 8.

4.6.3 Friction ratio (M) and Stress State ($\eta = q / p'$)

By comparing the stress ratio ($\eta = q / p'$) state with the friction ratio in the critical state (M_{tc}) it is possible to evaluate the shear strength mobilization and the potential for flow liquefaction. Unit values indicate that the critical state was reached, and continuous deformations were expected under constant shear stress and volume. If the material is in an initial condition considered "soft" ($\psi > 0$) the transition to the continuous deformation condition can occur to values smaller than the unit, within a range known as the instability zone for flow liquefaction, defined by the plane between the CSL and the instability line (IL). In the present work, for didactic purposes, a ratio of η / M_{tc}= 0.70 was adopted as a limit for the instability zone in terms of a flow liquefaction potential, emphasizing that for the simulation of real conditions this ratio should be carefully evaluated experimentally.

The models indicated that the stress states are lower than the limit considered for the instability zone (η / M_{tc}). The maximum values of the models range between 0.5 and 0.6 at the base of the reservoir near the Starter Dam (Figure 9). However, as both Starter Dam and Raisings Dikes materials were defined as isotropic linear elastic materials without an associated yield surface criterion, the results may not be sufficiently conservative, due to a new stress state distribution resulting from plasticization zones.

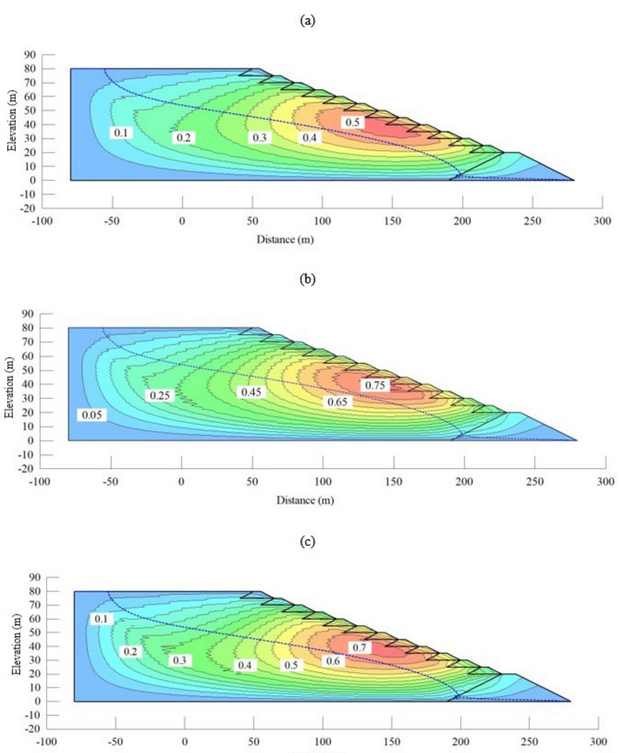

Figure 6. Values of horizontal displacement (m) of the modeling performed with the parameters obtained by KCB (a), University of Porto (b) and University of Toronto (c).

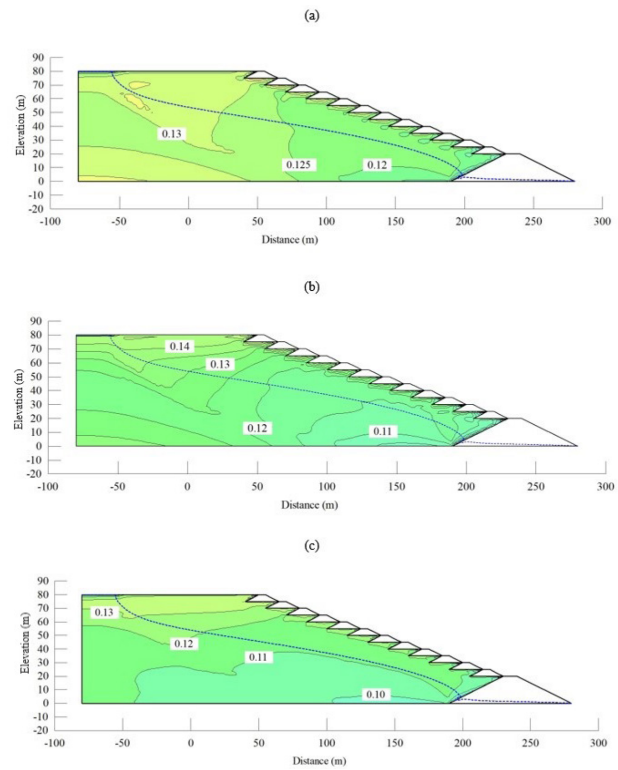

Figure 7. State parameter values for modeling with the results of KCB (a), University of Porto (b) and University of Toronto (c).

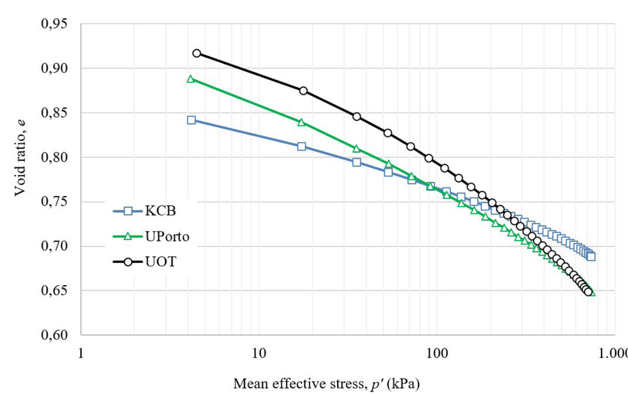

Figure 8. Variation of the void ratio (e) with the mean effective stress (p') at the base of the reservoir.

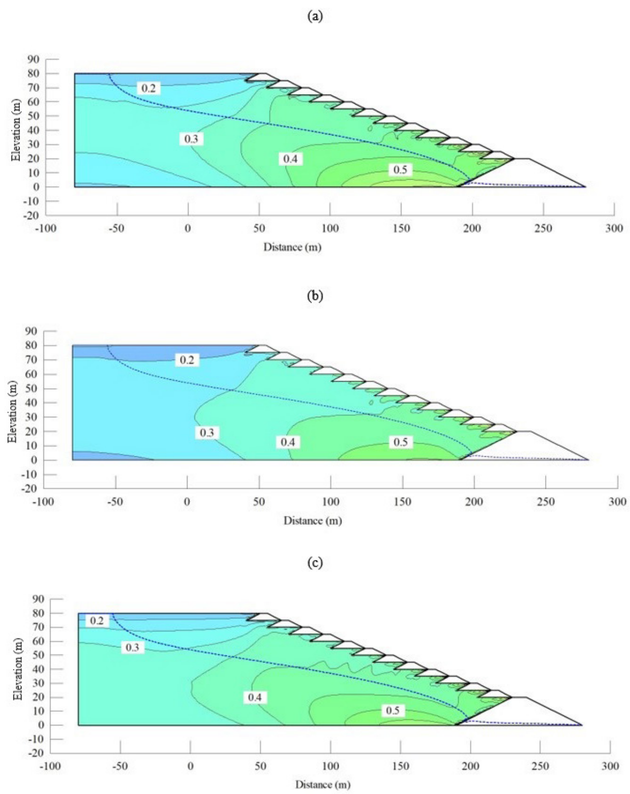

Figure 9. Values of the coefficient η / M_{tc} for the modeling with the results of KCB (a), University of Porto (b) and University of Toronto (c).

It is recommended that in real projects such aspects be considered, incorporating constitutive models with associated yield criteria and representative of the stress-strain behavior of the materials.

5. Conclusions

The main objective of this study was to evaluate how the results obtained by different laboratories for the same material can impact the stress-strain and flow liquefaction of tailings storage facilities from CSSM approach by NorSand constitutive model.

The hypothetical upstream tailings dam modeling in the SIGMA/W (Geostudio®, version 2021.2) presented instability for the consolidation coupled analyses, which considers the variation of pore pressure in time. Therefore, it was adopted the drained condition through stress-strain analysis, trying to verify possible constraints in terms of variation of the ratio η / M_{tc}.

The use of the Sigma Module (Geostudio®, version 2021.2) for the calibration of triaxial tests generated results considered satisfactory and the program presented relatively fast convergences in the iterative process. The results indicated that, from the experimental data adopted from the three selected laboratories, two presented very similar responses (University of Porto and University of Toronto), and the third, from KCB, presented relevant differences.

Considering the horizontal displacements, which may be a crucial factor for the evaluation of the TSF performance, mainly for upstream dams, maximum values of 0.76 and 0.72 meters were verified for the results of the Universities of Porto and Toronto, respectively, and 0.53 meters for the analyses performed from the experimental data of KCB. Although the strain values obtained do not exceed 1%, considering the total height of the hypothetical tailings dam analyzed, this difference between the results, greater than 35%, suggests the importance of reliability and repeatability of laboratory tests for the definition of the critical state line.

About the evaluation of the state parameter variation, it was verified that the maximum reduction was of 0.05 and that the void ratio variation with the mean effective stress was low enough to verify an almost parallelism with the CSL in almost all stress states. It was found that above 400 kPa there was a slight change in the material behavior.

In all analyses the values calculated for the coefficient η / M_{tc} do not suggest the occurrence of flow liquefaction instability. However, it is observed that the simpler models for the other dam materials may be producing still unconservative results.

The NorSand model was, in general, able to adequately simulate the experimental behavior verified for the tailings tested in the different laboratories. However, some aspects such as the very dense initial conditions and the behavior under specific stress paths such as both K_0 consolidation and high shear stress levels, need to be further investigated.

Declaration of interest

The authors have no conflict of interest to declare. All co-authors have observed and affirmed contents of the paper, and there is no financial interest to report.

Authors' contributions

Filipe Fernandes Souza Costa: conceptualization, data, curation, methodology visualization, writing – original draft. Bruno Guimarães Delgado: validation, writing – review & editing. Breno de Matos Castilho: review & editing.

Data availability

The datasets produced and analyzed in the course of the present study are available from the corresponding author upon reasonable request.

List of symbols

e	Void ratio
e_c	Critical void ratio
p'	Mean effective stress
q	Deviatoric stress
Dr	Relative density
G	Shear modulus
H	Plastic hardening parameter in NorSand.
H_0	Plastic hardening parameter
H_y	Plastic hardening parameter
K	Bulk modulus
M	Critical friction ratio
M_{Tx}	Critical friction ratio with triaxial s a reference condition
N	Volumetric coupling parameter
Γ	Altitude of CSL defined at p'=1kPa
ε	Strain
ε_s^e	Elastic shear strain
ε_v^e	Elastic volumetric strain
η	Stress ration
λ_e	Slope of CLS at ln base
λ_{10}	Slope of CLS at log10 base
ν	Poisson's ratio
χ	State–dilatancy parameter
ψ	State parameter

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