European Journal of Engineering and Technology Research
Vol 9 | Issue 3 | June 2024
ISSN 2736-576X

RESEARCH ARTICLE

Revisiting Brumadinho Dam Failure: A Methodology Study

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ABSTRACT

This is a methodology testing study that uses the case history of Vale Mining's Brumadinho Dam disaster and data from the Barcelona investigation report. This study aims to compare the results of two constitutive models for tailings: CASM and NorSand, running in the finite element program Plaxis 2D. The same senior authors carried out a previous study on four tailings dams and adopted the NorSand model and parameters obtained from piezocone and laboratory tests. Therefore, this paper aims to check if the same methodology would predict the Brumadinho Dam failure. The results show that both methods can predict Brumadinho failure, and the triggering mechanism suggested in the Barcelona report seems to be the cause of failure.

Keywords: Brumadinho failure, Liquefaction, NorSand, Tailings dams.

Submitted: March 27, 2024
Published: June 06, 2024

10.24018/ejeng.2024.9.3.3170

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1. Introduction

Any major failure can lead to tragedy and an opportunity to learn from past errors and avoid similar future events. This is certainly the case of the Brumadinho Tailings Dam (Figs. 1 and 2) disaster in early 2019, which took nearly 270 lives. This dam failure, also known as Vale's B1 Córrego do Feijão Dam, together with Samarco's Fundão Dam failure, was a turning point in dam safety measures [1]. Since then, government dam safety authorities have urged mining companies to increase safety using technical studies, risk classification, employing engineer of records (EoR), improving instrumentation, and monitoring systems, and decommissioning unsafe tailings dams.

The standard GISTM [2] brought up a series of best practices for tailings management. This document recommends the use of a stress-strain approach to analyse the behaviour and safety of existing tailings dams.

Ortigao *et al*. [3] analysed four upstream-built major tailings dams in late 2019 and spent three years using finite element analysis with the NorSand model [4], [5]. Two of them presented high liquefaction potential (LP), which correlated with low-stress reduction factors (SRF) above two. The other two presented unsafe behaviour with high LPs and lower SRFs.

These studies were based on a series of assumptions ranging from quantity and quality of site investigation to parameter selection to be used with the NorSand constitutive model. These authors also carried out laboratory tests on shallow tailings samples.

This paper presents a methodology test in which Ortigao *et al*. [3] methods and assumptions were tested at Brumadinho Dam. The specific questions to be answered were:

- Is NorSand's constitutive model capable of predicting Brumadinho dam behaviour, like the CASM?
- Is the characteristic value adopted by Ortigao *et al*. [3] for extracting the state parameter a valid methodology?

A wealth amount of data exists from Brumadinho failure published in the reports by Robertson *et al*. [6] and Arroyo *et al*. [7]. The first one blamed creep, a too-steep dam slope, and high porepressures as the leading cause of failure. On the other hand, Arroyo *et al*.'s [7] report was able to model the mechanism that triggered liquefaction, referred to here as the Barcelona model. They used the CASM (Clay and Sand Model) [8], [9] and wrote a *dll* (dynamic link library) for use with the Plaxis 2D software.

The Barcelona report led to different conclusions from the previous one: the triggering mechanism was a deep borehole carried out by Vale's drill rig (Fig. 3) through the dam slope and soft tailings. The borehole water level was too high, and this led to hydraulic fracture, which, in turn, should have triggered the disaster.

Fig. 1. Brumadinho Dam before failure.

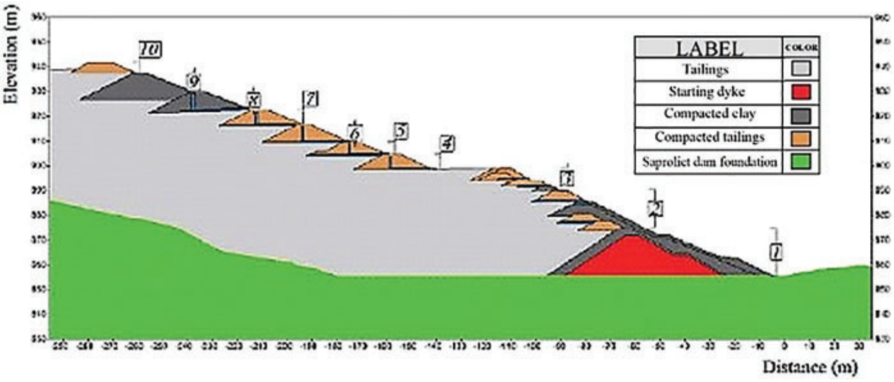

Fig. 2. Cross-section of Brumadinho.

Fig. 3. Vale's drill-rig operating on the sloping berm of Brumadinho Dam drilling through the embankment and tailings (photo by Mr A Fanaya one week before failure).

In 2022, the Plaxis group significantly improved the software with NorSand model implementation. Therefore, the aim of these studies was:

- Reproduce the Barcelona model [7], [10] with CASM using the same parameters and the latest Plaxis 2D version.
- *idem*, but using NorSand.
- Analyse liquefaction potential through both models and compare the results.

2. Clay and Sand Model (CASM)

The Barcelona report used the CASM model for reproducing the tailings' brittle behaviour. It is not difficult to calibrate model parameters, and it has been successfully used for static liquefaction [10]–[12].

Mánica *et al*. [11] extended the original CASM to model viscous behaviour, as an attempt to model creep, which Robertson *et al*. [6] considered one of the major causes of Brumadinho failure.

The constitutive model has been compiled into a *dll* and implemented in the Plaxis software as a User Defined

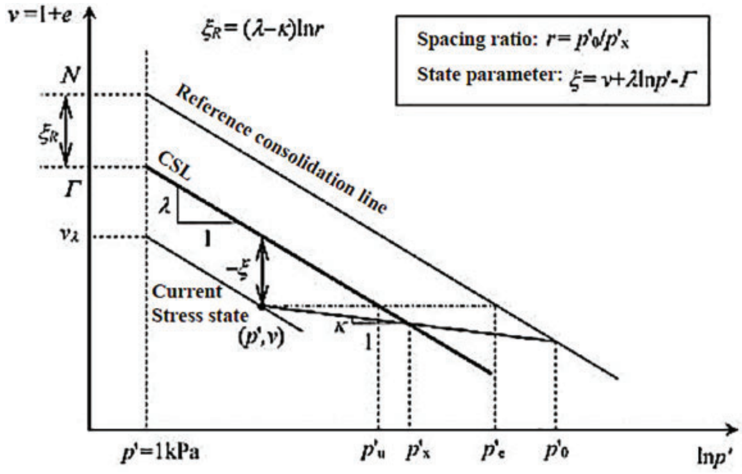

Fig. 4. CASM parameters (*e, r, G*) [8].

TABLE I: CASM Parameters

Parameter	Description	Range of values
λ	The slope of the CSL on the v : ln p' plot	0.1–0.2 for clays 0.01–0.05 for sand
κ	The slope of the unload-reload line on the v : ln p' plot	*
ν	Poisson's ratio	$0 < \nu \leq 0.495$
ϕ_{cs}	Critical state friction angle	$15° < \phi_{cs\ s} \leq 48°$
n	Shape control of the yield surface (Fig. 5)	$n \geq 1$
r	Spacing ratio (Fig. 4)	$r > 1$
m	The shape of the plastic potential function (Fig. 6)	$m > 2$

Note: *No reference data.

Soil Model (UDSM). The Barcelona report presents a full programme of validation of the constitutive model.

Fonseca *et al*. [13] present details of the extensive laboratory testing programme carried out at the University of Porto, Portugal, which enabled CASM parameter extraction.

The rate-independent model (i.e., CASM) requires eight material parameters and the viscoplastic extension requires only two additional ones (Table I).

In addition to the seven compulsory parameters, two of the four parameters below should be input, selected according to the available data. The alternatives are:

- Γ *and* ei_{ni}
- Γ *and po*
- Γ *and* ξ_{ini}
- e_{ini} *and po*
- e_{ini} *and* ξ_{ini}
- *po and* ξ_{ini}

where Γ is "altitude" of the CSL, given as the intersection of the CSL with the ordinate for a reference $p'_{ref} = 1\ kPa$,

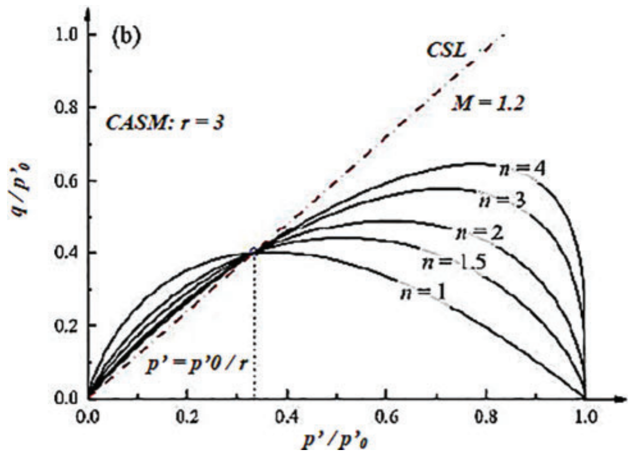

Fig. 5. Influence of parameter n on the yield locus [8].

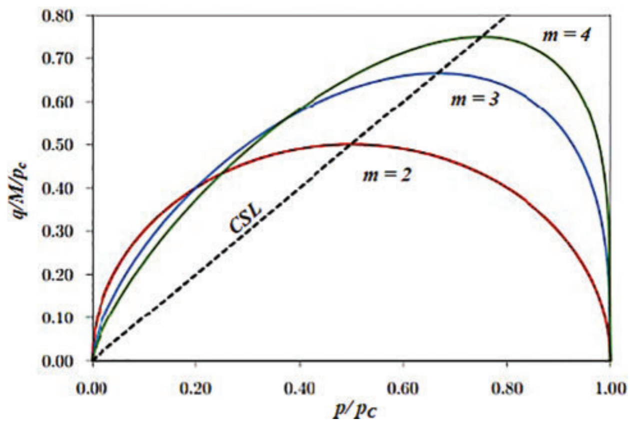

Fig. 6. Normalised plastic potential function for different m values [7].

ξ_{ini} is initial value of the state parameter, R is overconsolidation ratio $= p'_{max}/p'_o$.

There are other optional parameters to consider creep rate effects [7], not discussed in this paper. Table II presents the CASM parameters used in the Barcelona report and also in the following analyses, excluding parameters for rate effects.

In addition to the mechanical (stress-strain) formulation, it is necessary to account for the hydraulic behaviour of the tailings in both saturated and unsaturated states.

TABLE II: CASM Parameters for the Tailings (Arroyo *et al.* [6])

Parameter	Unit	Fine tailings	Tailings mix	Coarse tailings
λ	–	0.056	0.05	0.046
κ	–	0.019	0.019	0.019
n	–	0.3	0.3	0.3
f_{cs}	Degrees	35.7	34.2	33.08
n	–	3.25	4.9	5.1
r	–	5.18	12.3	75
m	–	2.367	2.48	2.465
Γ	–	2.14	2.05	2.353
R	–	1.05	1.05	1.05
N	–	5	5	5
η	m^2 day kN^{-1}	1.00E−09	4.00E−10	1.00E−11

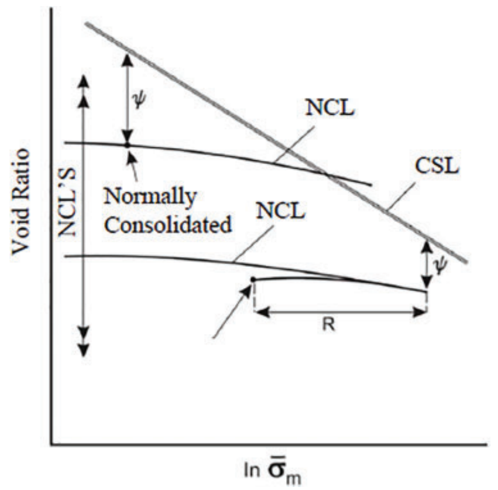

Fig. 7. State parameter in NorSand model.

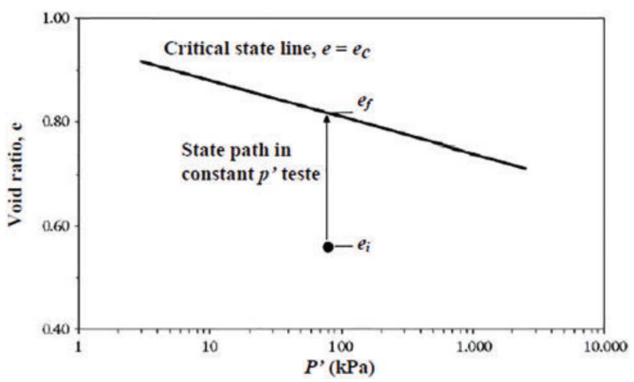

Fig. 8. Definition of the state parameter (Ψ) [4].

The saturated hydraulic behaviour of the tailings is simply characterized by a constant value of permeability. Permeability is assumed anisotropic with different values in the vertical and the horizontal directions.

3. NorSand Model

The NorSand [4] is a critical state model that takes into account the void ratio (Figs. 7 and 8) Table III.

Hardening in the NorSand model is a function of the current state. The normal consolidation line (NCL) is also a function of the current state. Thanks to these changes to the Cambridge models, NorSand can simulate the behaviour of contractive and loose sands, being suitable to represent strain softening of sandy materials, thus ideal for liquefaction simulation.

TABLE III: NorSand Model Parameters (Jefferies & Been [4])

Parameter	Typical range	Remarks
CSL		
Γ	0.9–1.4	The altitude of CSL, defined at 1 kPa
l	0.01–0.07	The slope of CSL, defined on natural logarithm
Plasticity		
M_{tc}	1.2–1.5	Critical friction ratio, triaxial compression as the reference condition
N	0.2–0.5	Volumetric coupling coefficient for inelastic stored energy
H	25–500	Plastic hardening modulus for loading, often $f(\psi)$; as a first estimate for refinement, use $H = / \lambda$
χ_{tc}	2–5	Relates maximum dilatancy to ψ. Triaxial compression as the reference condition
Elasticity		
I_r	100–600	Dimensionless shear rigidity (G_{max}/p')
ν	0.1–0.3	Poisson ratio

TABLE IV: NorSand Parameters for Brumadinho Tailings

	Tailings		
	Course	Mixed	Fine
γ_{unsat} (kN/m^3)	22	22	22
γ_{sat} (kN/m^3)	27	27	27
$e_{initial}$	1.2	1.2	1.2
G_{ref} (kPa)	40000	40000	40000
p_{ref} (kPa)	100	100	400
n_G	0	0	0
ν	0.3	0.3	0.3
Γ	1.27	1.23	1.2
λe	0.04	0.046	0.053
M_{tc}	1.4	1.42	1.4
N	0.3	0.3	0.3
χ_{tc}	6	6	6
H_0	140	130	140
H_ψ	950	950	950
R	1	1	1
S	0	0,25	0
Ψ_0	0.05	0.12	0.16

4. The State Parameter Extraction

The in situ piezocone test (CPTU) has been the primary tool for obtaining the initial state parameter for loose sandy tailings [14]. The authors used the same methodology used by Ortigao *et al.* [3], adopting Robertson's [15] and a characteristic value corresponding to the first quartile (25% lower).

Table IV presents the NorSand parameters adopted for Brumadinho tailings. These data were derived from the Barcelona report and Fonseca *et al.* [13].

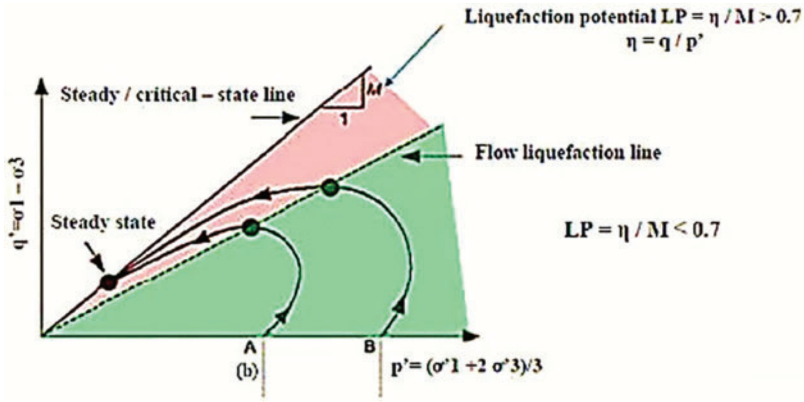

Fig. 9. Definition of liquefaction potential (LP) on the stress path.

5. Liquefaction Potential

The liquefaction potential (LP) is a parameter that indicates the proximity of the CSL (critical state line), also called the flow liquefaction line (Fig. 9). *LP* is given by the ratio:

$$LP = \eta/M$$

where η is q/p'.

LP values close to or above 0.7 indicate a high liquefaction potential and the possibility of the stress path turning to the left due to porepressure rise and drastically reducing strength.

6. Strength Reduction Method

The strength reduction method (SRM) [16], [17] is a well-known technique in which strength parameters are step by step reduced until large displacements take place in the model. The reduction factor is taken as the strength reduction factor (SRF) value. It works well on simple constitutive models like MC and HSM (Plaxis [16]) but has not been implemented in Plaxis for the NorSand model because a more complex model like NorSand may be influenced by other parameters.

For these SRM analyses, the Authors tested the GeoStudio program, which enables SRM calculation.

7. Brumadinho Geometry and FE Mesh

This investigation uses the same cross-section (Fig. 10) as the Barcelona report and the same materials. Fig. 11 presents the CPTU location on the same cross-section, Fig. 12, the tailings distribution, and Fig. 13 the finite element mesh used for Plaxis 2D analysis.

8. Dam Construction Simulation

The dam construction was simulated in 33 stages. The first is just to apply a $K_0 = 0.5$ to the foundation, and the second is to apply initial stresses and porepressures. From stage 3 onwards, all stages, including the dyke construction, followed by tailings filling. Tailings consolidation was applied at each stage, using the MC elastoplastic model with Mohr-Coulomb failure criteria.

The last phase, numbered 33, was when the dam no longer received tailings until failure occurred. At this moment, the tailings model was replaced by the CASM or NorSand models, but using the SSC Soft Soil Creep (Plaxis [18]) for the back of the reservoir, assuming that the elapsed time was not enough for the tailings to change its behaviour.

At this stage, all displacements were set to nil.

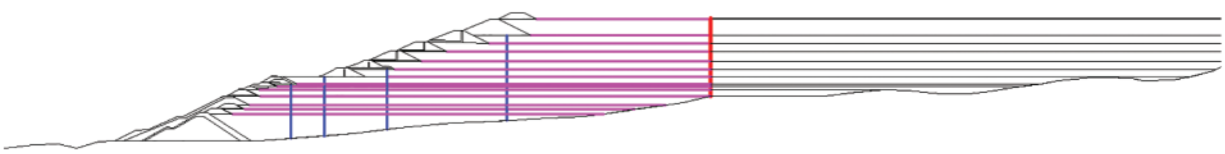

Fig. 10. Brumadinho Dam analysis cross-section.

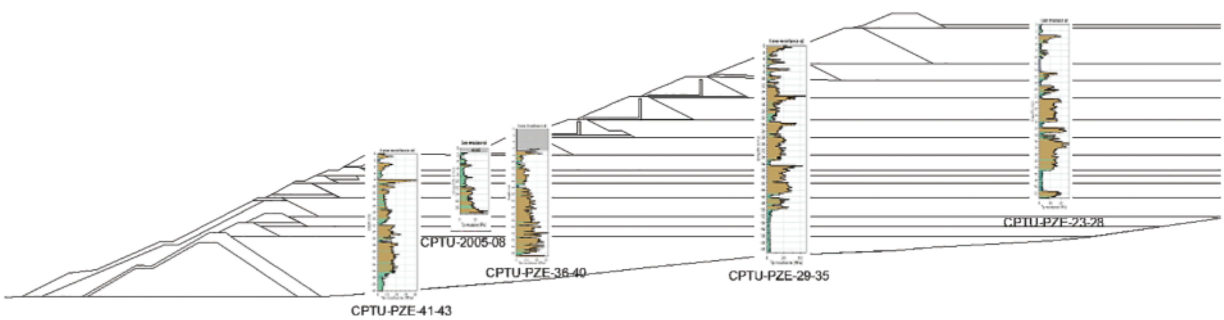

Fig. 11. CPTU's location on the analysed cross-section.

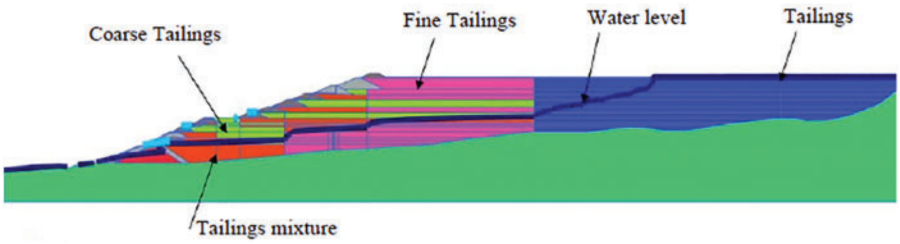

Fig. 12. Distribution of tailings in the cross-section [6].

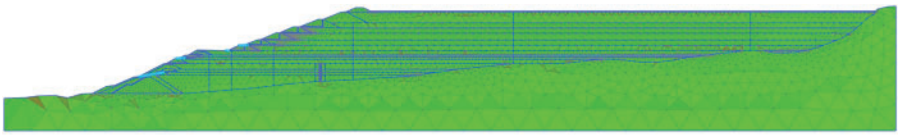

Fig. 13. Finite element mesh for Plaxis 2D analysis.

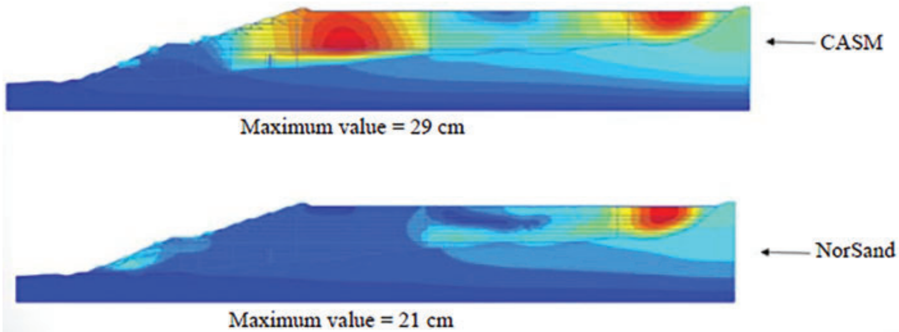

Fig. 14. Total displacements comparison between CASM and NorSand models

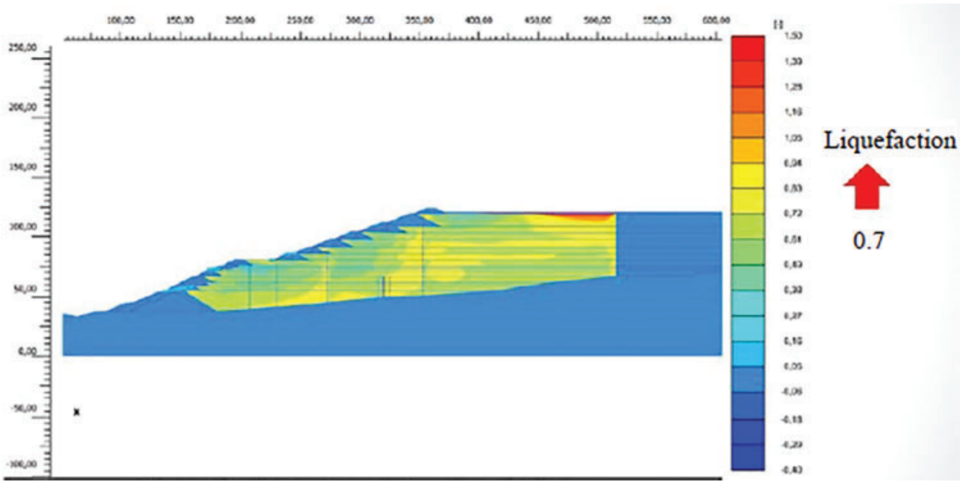

Fig. 15. Liquefaction potential (LP), NorSand model.

9. Flow Conditions

The flow conditions during construction were simulated by applying a hydraulic head, as recommended by Arroyo *et al*. [7], as there is not a lot of information during this phase of the structure. At the end of phase 33, the closed flow condition was then replaced by open borders to allow free flow, and the observed water level was applied. The dam was subjected to a precipitation of 1500 mm/year during construction and, after its inactivity, to 1100 mm/year, the same as in the Barcelona report.

10. Analysis Results

Fig. 14 compares the results of predicted total displacements at the end of constructions, and the maximum results seem to agree, although their location is quite different.

Fig. 15 presents the LP obtained through the NorSand model and shows very high values above 0.7 before failure. This is the key parameter to analyse liquefaction. As commented before, Plaxis does not use SRM for the NorSand model on the ground that a complex model, with many parameters, may not yield trustworthy results if only two strength parameters are reduced.

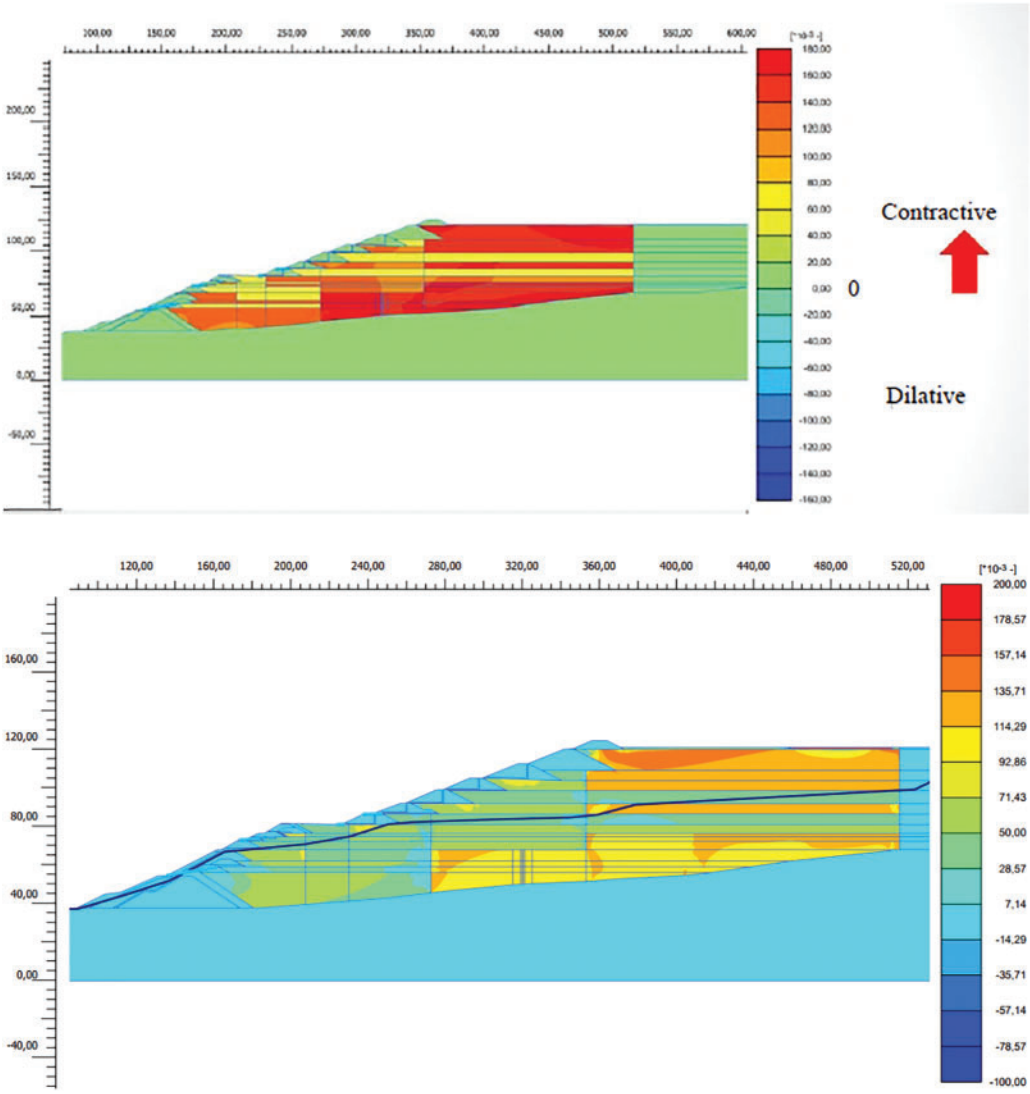

Fig. 16. State parameter, NorSand model (top) and CASM (bottom).

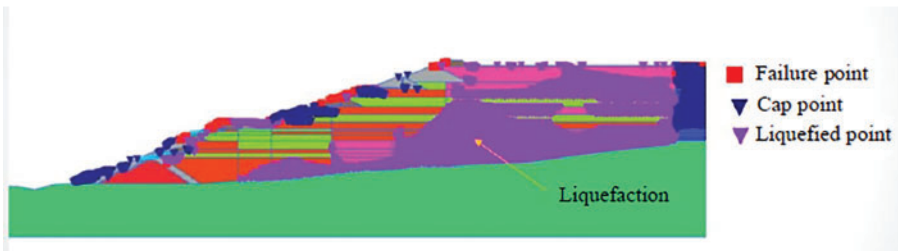

Fig. 17. Plastic points, NorSand model.

Fig. 16 presents the state parameter values at the end of construction, showing a very contractive tailings behaviour.

Fig. 17 shows the plastic points and liquefied points, as predicted by the NorSand model in Plaxis.

11. Liquefaction Triggering Mechanism

Following the Barcelona report, this investigation also analyses the same trigger mechanism by increasing pore-pressures to 28 m head at the same location (Fig. 18).

Fig. 19 shows the results for both constitutive models. On the left, it shows the initial conditions just before hydraulic fracturing; on the right the moment the pore-pressures were increased, leading to high shear strains and liquefaction.

12. Conclusions

Both CASM and NorSand models predicted the failure mechanisms well, following the footsteps of the Barcelona report.

The LP is the key parameter to predict liquefaction, but only NorSand runs smoothly in Plaxis 2D [18] and yields results of very high LP taking place just before failure.

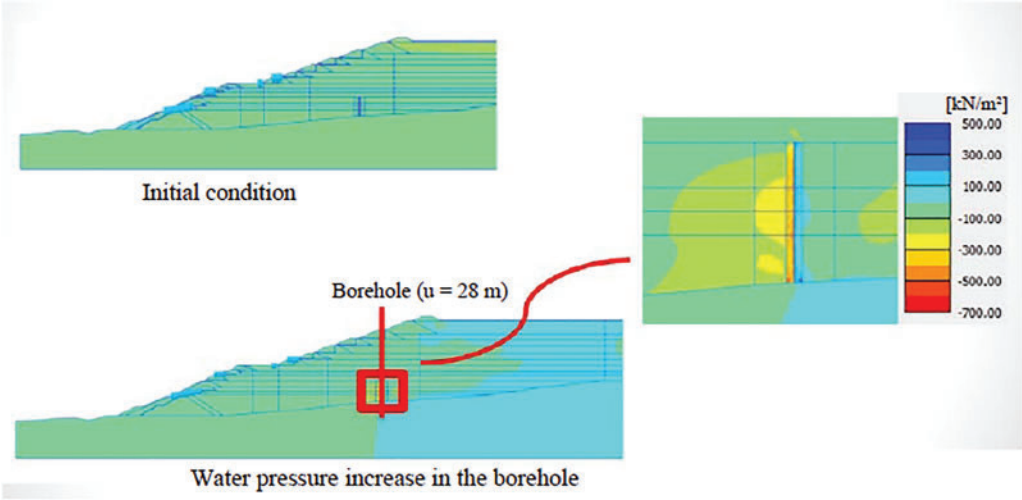

Fig. 18. Simulation of water pressure increase of 28 m head in the borehole.

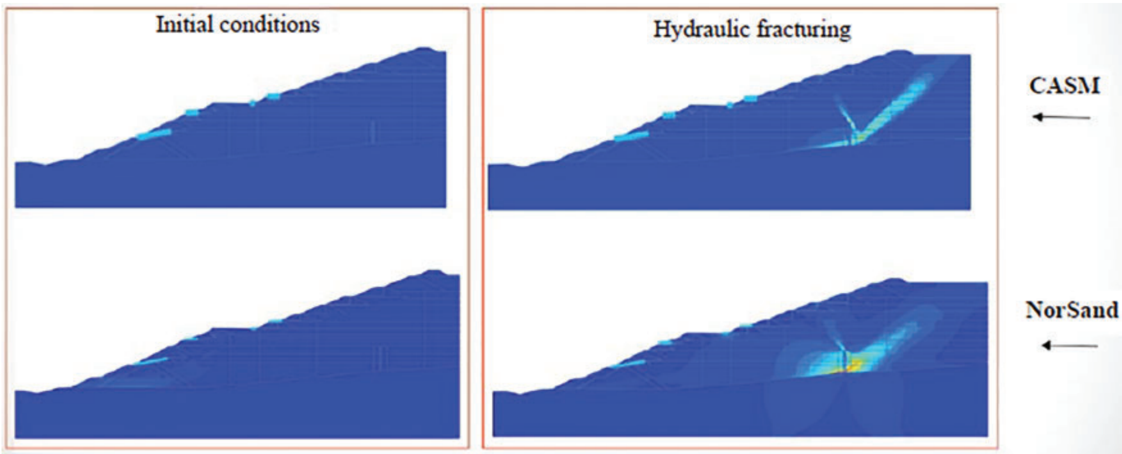

Fig. 19. Resulting shear strains in both CASM and NorSand models due to hydraulic fracturing.

Both models also agree that the hydraulic failure triggered liquefaction.

Finally, the methodology of selecting a characteristic value for the state parameter seemed to lead to acceptable results.

Acknowledgment

This research was supported by Prof Marcos Arroyo from the University of Cataluña, who kindly supplied the CASM *dll* and helped the junior Authors to run the model. Mr Leonardo Mesquita, an expert civil engineer of the Federal Police in charge of the criminal investigation of Vale's Brumadinho disaster, provided site investigation raw data. Finally, André Fanaya, a geotechnical engineer at Tecnogeo Ground, made available the photographs of the drill rig taken just one week before the failure. Victoria Germano helped with the manuscript and figures. The authors express our gratitude for their support.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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