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Static liquefaction assessment of an offset-upstream tailings dam using NorSand in FLAC

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ABSTRACT

Geotechnical practice in tailings storage has evolved to incorporate deformation modeling to predict tailings dam performance. Static liquefaction can be triggered by a combination of mechanisms that are often challenging to identify in isolation. One commonly adopted approach is to bypass the triggering assessment step, assuming a liquefied shear strength for materials that are susceptible to static liquefaction. However, this approach can be overly conservative because it assumes all contractive materials would mobilize liquefied shear strengths simultaneously. By comparison, the advanced NorSand constitutive model (NorSand) has shown the capability of evaluating various potential triggering mechanisms of static liquefaction more realistically. NorSand incorporates a state parameter under the critical-state soil mechanics framework, which allows it to predict soil behavior based on the current soil state.

Two-dimensional (2D) static deformation modeling was performed on a study section evaluated for stability at an upstream tailings dam constructed offset the main impoundment embankment. Fine tailings were modeled using NorSand with all other materials modeled using Mohr-Coulomb. The behavior of the fine tailings observed in triaxial laboratory testing was used to calibrate the NorSand model parameters. The study section under existing conditions was then calibrated to screening-level CPT-based state parameter data. Modeling demonstrates that upon the planned deposition of fine tailings behind the offset-upstream dam, the instability ratio beneath the dam generally ranges between 0.20 and 0.30 with a maximum of 0.55. This indicates relatively low risk of static liquefaction. A sensitivity analysis was performed to evaluate the static liquefaction triggering threshold by gradually increasing the unit weight of newly deposited fine tailings. It was found that the offset-upstream dam would remain stable when the fine tailings unit weight was increased up to 3 times its realistic value.

INTRODUCTION

The tailings industry and standard-of-practice design guidance are rapidly evolving after several recent high profile tailings dam failures across the world such as at Fundão and Brumadinho in Brazil, and at Cadia in Australia (Morgenstern, N.R., et al., 2016; Robertson, P.K., et al., 2019; Jefferies, M., et al., 2019). Geotechnical practice in tailings storage has evolved to incorporate deformation modeling to predict tailings dam performance in response to various loads. Static liquefaction can be triggered by a combination of mechanisms that are often challenging to identify in isolation. One commonly adopted approach is to bypass the triggering assessment step, assuming a liquefied shear strength for materials that are contractive and susceptible to static liquefaction. However, this approach can be overly conservative because it assumes all contractive materials would mobilize liquefied shear strengths simultaneously and in a continuous fashion.

By comparison, the advanced NorSand constitutive model (Jefferies, 1993; Jefferies and Been, 2016) has shown the capability of evaluating various potential triggering mechanisms of static liquefaction more realistically. The primary advantage of NorSand is the incorporation of a state parameter under the critical-state soil mechanics framework, which allows it to predict soil behavior based on the current soil state (i.e., void ratio and stress condition). The soil behavior includes two major aspects: contraction or dilation in terms of volume change and the associated strain-softening or strain hardening response in terms of mobilized shear strength.

Although NorSand was developed nearly three decades ago, its use in deformation modeling is considered as an emerging analysis technique that has only gained popularity within the mining community over the past several years. It has been successfully applied to investigate major static liquefaction failure cases such as the Fundão failure in 2015 (Morgenstern, N.R., et al., 2016). This paper presents the results of a two-dimensional (2D) static deformation model using NorSand in the Fast Lagrangian Analysis of Continua (FLAC) software to simulate the response of an offset-upstream dam to undrained loading.

STUDY SECTION

The model geometry and stratigraphy of the study section used for this 2D deformation modeling is shown in Figure 1. The offset-upstream tailings dam is located approximately 300 meters upstream of the perimeter dam and it provides impoundment of fine tailings above the perimeter dam. The offset-upstream dam was constructed in a series of three lifts with each raise over the fine tailings deposit. The embankment contains a clay core surrounded by dam shell material (both borrowed from on-site sources of alluvial soil and weathered bedrock). The entire offset-upstream dam alignment is founded on previously deposited fine tailings and includes a filter buttress along its downstream toe. The top of the historic fine tailings deposition acting as the offset-upstream dam foundation is around Elevation 1,906 meters. The three lifts of the offset-upstream dam have elevations of approximately 1,911, 1,914, and 1,917 meters. All embankment lifts have a 4H:1V downstream and 3H:1V upstream slope. The native materials underlying the dams and fine tailings deposit are typically comprised of consolidated native soils (assorted clay, sand, and gravel) underlain by weathered siltstone and shale.

The fine tailings deposition upstream of the Lift 3 embankment under existing condition has an elevation of approximately 1,913.5 meters and will be raised to elevation of 1,916.6 meters under future conditions. Static liquefaction may be triggered due to changes in the stress conditions during the future deposition process. As such, a 2D static deformation modeling was performed on the study section to evaluate the response of an offset-upstream dam to undrained loading. Other potential static liquefaction triggering mechanisms, such as change in the phreatic surface associated with ongoing depositional operations, are also possible but are beyond the scope of this study.

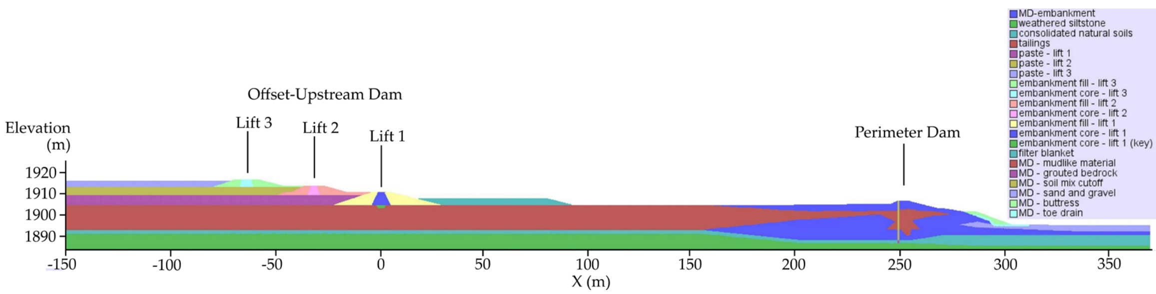

Figure 1 Model Geometry of the Study Section

METHODOLOGY

The deformation modeling presented in this paper was performed using the FLAC 8.1 program, which uses the finite-difference method to solve nonlinear stress-strain systems. In this method, materials are represented by elements, or zones, that form a grid to fit the geometry of the study section. Each element behaves according to the user-prescribed linear or nonlinear stress-strain model (i.e., constitutive model) in response to the applied forces and boundary conditions. In general, the deformation modeling involved a seepage analysis followed by a mechanical-only deformation analysis. Seepage calibration and analysis are beyond the scope of this paper, and therefore are not discussed herein. Solution from the seepage analysis under existing conditions was directly incorporated into the subsequent deformation analysis.

Fine tailings material was modeled using the NorSand (Jefferies, 1993; Jefferies and Been, 2016) constitutive model. For NorSand implementation, it is critical to first calibrate the behavior of the NorSand material against triaxial compression testing performed in the laboratory at element level. The next level of NorSand calibration involves a 2D model scale calibration to screening-level CPT-based state parameter data by replicating the phased construction of the embankment lifts. Specifically, the deformation model of the study section was developed with an initial geometry reflecting conditions prior to construction of the offset-upstream dam and the filter blanket at the dam toe. Pre-construction fine tailings materials were seeded with an initial state parameter, which evolved with the modeling of historic phase construction. The deformation model was run from the initial geometry up to the existing conditions with all three embankment lifts of the offset-upstream dam. The initial seed value of the state parameter was ultimately determined via an iterative trial-and-error process until the 80th percentile modeled state parameter matched with the 80th percentile in situ state parameter measured during recent field investigation under existing conditions. The results of both calibrations are discussed in the following sections. The Mohr-Coulomb constitutive model was applied for the remaining materials within the embankment and foundation that are not susceptible to static liquefaction.

MODEL PARAMETERS

Multiple geotechnical investigations have been performed on this site for stratigraphy verification, material characterization, and evaluation of in situ conditions. These field investigations generally consisted of test pit, seismic cone penetration test (SCPT), exploratory boreholes, field vane shear testing (FVT), among others. Extensive laboratory testing has also been performed to classify and characterize various materials at the site.

Material properties required for the Mohr-Coulomb constitutive model were developed directly from in situ field measurements and laboratory testing. Table 1 summarizes the unit weight, shear strength, and stiffness parameters of materials that were assigned to the Mohr-Coulomb constitutive model in the deformation analysis. Bulk and shear moduli were mostly based on empirical values in the literature for respective material type except for fine tailings, for which the shear modulus was correlated from the shear wave velocity measurement from SCPT soundings.

Table 1 Mohr-Coulomb Material Parameters Used in Deformation Analysis

Material	Shear Modulus (MPa)	Bulk Modulus (MPa)	Drained		Undrained (yield)
			c' (kPa)	φ' (deg)	s_u, or s_u/σ'_v
Embankment Fill	28.9	13.3	0.0	38.5	59.9 kPa
Embankment Core	28.9	13.3	0.0	33.0	50.3 kPa
Filter Blanket	83.3	38.5	0.0	33.0	—
Consolidated Natural Soils	6.7	3.1	0.0	26.0	95.8 kPa
Weathered Siltstone	Impenetrable				

The laboratory testing program has particularly focused on characterizing the critical state parameters of fine tailings to support the static liquefaction assessment presented herein. The behavior of the fine tailings observed in a total of ten triaxial laboratory tests was used to calibrate the NorSand model parameters, which is shown in Table 2 below. Limited by its length, this paper will not discuss what each of these parameters represents and the calibration procedure in details. Readers are referred to the book by Jefferies and Been (2016) which has covered these topics in detail.

As mentioned in the previous section, a critical model-scale calibration was performed against screening-level CPT-based state parameter data. The deformation model started with the initial geometry prior to the offset-upstream dam presence and replicated the phased construction of the three embankment lifts up to the existing conditions. Figure 2 compares the 80th percentile modeled state parameter distribution with the in situ measured distribution from the screening level method presented in Jefferies and Been (2016). Despite the modeled state parameter distribution showing a narrower band, the 80th percentile value of both the modeled and measured state parameter was determined as $\psi = +0.12$. The contours in Figure 3 show the distribution of the modeled state parameter in the offset-upstream dam area under existing conditions.

Table 2 Calibrated NorSand Parameters for Fine Tailings

Categories	Input Parameter	Symbol	Calibrated Value
Critical State Line Parameters	Material Constant	C_a	1.34
		C_b	0.60
		C_c	0.15
Elasticity Parameters	Reference shear modulus at reference pressure	G_0 (MPa)	28.0
	Material Constant	G_{power}	0.50
	Poisson's ratio	ν	0.15
Plasticity Parameters	Critical stress ratio under triaxial compression conditions	M_{tc}	1.50
	Volumetric coupling coefficient	N	0.10
	State-dilatancy parameter	χ_{tc}	2.20
	Basic plastic hardening modulus	H_0	45.0
	Plastic hardening modulus at corresponding soil state	H_ψ	300.0

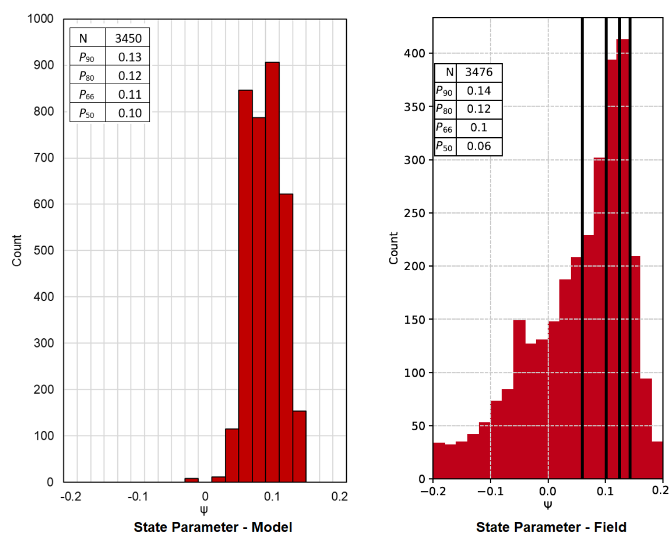

Figure 2 Comparison of the Modeled and Measured State Parameter Under Existing Conditions

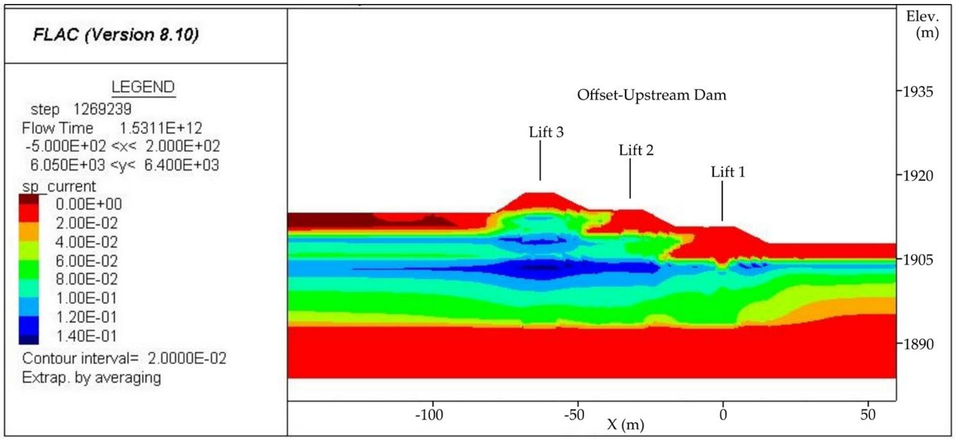

Figure 3 Modeled State Parameter Contour Under Existing Conditions

RESULTS AND DISCUSSION

The calibrated soil state under existing conditions that was presented in Figure 3 was used as the initial condition to evaluate the effect of future fine tailings deposition behind the third embankment lift of the offset-upstream dam. Figure 4 shows the mobilized instability ratio contour from an undrained loading scenario that assumed the future fine tailings was deposited under fully undrained conditions. The term mobilized instability ratio is defined as the mobilized stress ratio, η, of any soil element, normalized by the critical state stress ratio, M_{tc}, under triaxial conditions. The mobilized instability ratio essentially measures the distance of any soil element from the CSL in p'-q stress space. Therefore, a mobilized instability ratio close to 1.0 is considered to approach a rapid instability condition (i.e., static liquefaction triggering). The maximum value of mobilized instability ratio in Figure 4 was approximately 0.8, which was approaching the instability condition. However, the contours presented in Figure 4 also indicate the zones with high mobilized instability ratio (dark blue color) were predominately upstream of Lift 3 and not connected through embankment foundation to embankment slope surface. Modeling demonstrates that upon the planned deposition of fine tailings behind the offset-upstream dam, the instability ratio beneath the dam generally ranges between 0.20 and 0.30 with a maximum of 0.55. This indicates relatively low risk of static liquefaction.

Finally, a sensitivity analysis was performed to evaluate the static liquefaction triggering threshold by gradually increasing the unit weight of newly added fine tailings. It was found that the offset-upstream dam at the study section would remain stable when the fine tailings unit weight was increased up to 3 times its realistic value. The embankment experienced failure when the fine tailings unit weight was further increased to 3.5 times its realistic value. Figure 5 shows contours of the mobilized instability ratio (with value up to 0.9) from the hypothetical triggering scenario that assumed 3.5 times of original unit weight for the fine tailings material. The contour lines shown in Figure 5 represents the shear strain increment, which indicates a logarithmic type of failure mechanism and the critical slip surface exited at toe of the third embankment lift. The large mobilized instability ratio values are generally 0.9 along the shear band. It should be emphasized that this study only evaluated one of the most common potential triggering mechanisms (i.e., undrained loading). As previously discussed, static liquefaction can be triggered by various individual mechanisms or a combination of mechanisms such as pore pressure change, creep, erosion, excavation at toe, and so on. The sensitivity scenario presented herein was intended to demonstrate the amount of stability redundancy in this tailings storage facility in terms of undrained load triggering.

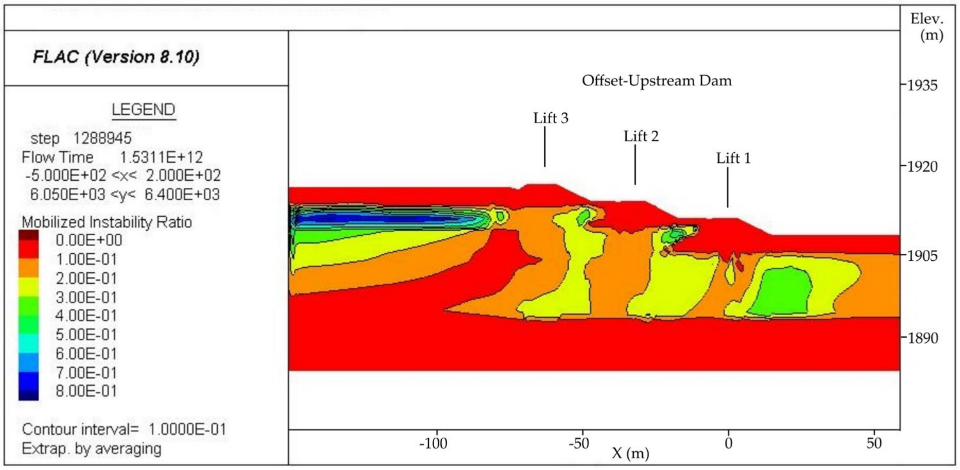

Figure 4 Mobilized Instability Ratio Contour Under Future Conditions (Adding Fine Tailings Deposition Behind the Third Embankment Lift Under Fully Undrained Conditions)

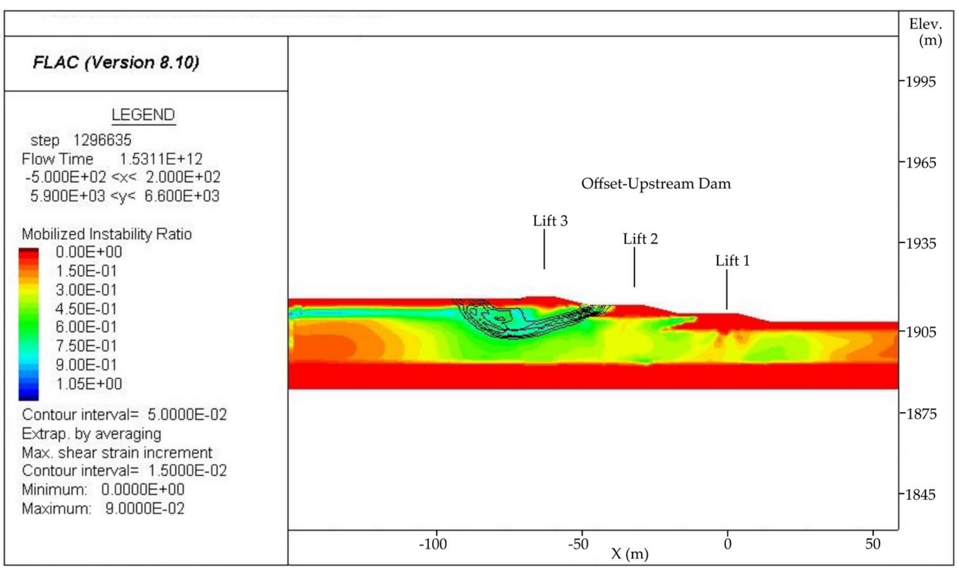

Figure 5 Mobilized Instability Ratio Contour from Hypothetical Triggering Threshold Scenario (Adding Fine Tailings with 3.5 Times of Realistic Unit Weight under Fully Undrained Conditions)

CONCLUSION

Deformation analyses using NorSand were performed on a study section to evaluate the response of an offset-upstream tailings dam to undrained loading from future fine tailings deposition in the basin. Model results indicated that filling the upstream basin would be unlikely to induce static instability in the offset-upstream dam area. To test a scenario in which stability would be compromised, the unit weight of the newly deposited fine tailings was increased progressively until instability was initiated. The onset of instability occurred at just over 3 times the actual unit weight of the fine tailings deposited upstream of the dam.

NOMENCLATURE

γ_{moist}	moist unit weight
γ_{sat}	saturated unit weight
c'	effective cohesion
φ'	drained frictional angle
s_u	yield undrained shear strength
σ'_v	effective vertical stress
η	stress ratio, q/p'
p'	effective mean stress
q	deviatoric stress
M_{tc}	critical state ratio under triaxial conditions

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