Finite element simulation of static liquefaction of submerged sand slopes using a multilaminate model

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Finite element simulation of static liquefaction of submerged sand slopes using a multilaminate model.

Simulation par éléments finis de la liquéfaction statique de pentes de sable immergées en utilisant un modèle multi-laminaire.

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ABSTRACT: Static liquefaction is one of the principal triggering mechanisms of failure in fully saturated loose sand slopes both in offshore and onshore regions. Static liquefaction induced landslides are known for their significant softening and a fluid-like behavior at the onset of failure. However, the literature lacks experimentally verified advanced numerical approaches which are capable of simulating static liquefaction. In this study, an advanced constitutive model based on the multilaminate framework is used in a finite element code. Multilaminate model accounts for significant features such as rotation of principal stresses, anisotropy in the material, strain softening due to static liquefaction and stress and strain dependency of the stiffness which enable us to achieve a more realistic soil behavior. The analysis results are verified by a set of large scale experiments of static liquefaction failures in submerged slopes under monotonic loading. Presented numerical approach can be used as a tool for further investigations of static liquefaction induced flow slides. This is useful for design and optimization of static liquefaction mitigation techniques.

RÉSUMÉ : La liquéfaction statique est l'un des principaux mécanismes de glissement des pentes en sable lâche saturé dans les zones marines ou terrestres. Les glissements de terrain déclenchés par la liquéfaction statique sont connus pour leur adoucissement substantiel et un comportement quasi-liquide lors de l'amorce de la rupture. La littérature manque d'approches numériques avancées, confirmées de manière expérimentale, qui permettent de simuler la liquéfaction statique. Dans cette étude, une loi de comportement avancée basée sur le cadre multi-laminaire est implémentée dans un programme par éléments finis. Le modèle multi-laminaire prend en considération des caractéristiques importantes, telles que la rotation des contraintes principales, l'anisotropie du matériau, l'adoucissement dû à la liquéfaction statique ainsi que la dépendance de la rigidité aux contraintes et déformations, permettant un comportement réaliste. Les résultats sont vérifiés par un ensemble de tests de liquéfaction statique à grande échelle pour des pentes immergées sous chargement monotone. L'approche numérique présentée peut être utilisée pour des analyses ultérieures de glissements de terrain causés par la liquéfaction statique. Cela peut se révéler utile pour que la conception et l'optimisation de mesures de mitigation.

KEYWORDS: Static liquefaction, submarine landslides, multilaminate framework, finite element, sands.

MOTS-CLES : Liquéfaction statique, glissements de terrain sous-marins, cadre multi-laminaire, éléments finis, sable

1 INTRODUCTION

The instability triggered by static liquefaction occurs in saturated granular soil due to abrupt reduction of effective stresses to zero caused by generation of excess pore pressure under monotonic loads (Sladen et al. 1985, Lade 1992, Ishihara 1993, Lade and Yamamuro, 1998, Jefferies and Been 2015). This phenomena is reported as one of the common triggering factors of the slope failures in both offshore and onshore regions (Kramer, Silvis and de Groot 1995, Blight and Fourie 2003, Okura et al. 2002, Hight and Leroueil 2003). Loose granular materials have been reported as the predominant soil type in numerous published case histories of liquefaction induced landslides (e.g. Kramer 1988, Lade 1993, Olson et al. 2000).

This type of instability has been the focus of numerous experimental studies in the literature. However, most of them are limited to element testing of saturated loose sands under undrained conditions (Chu et al. 2015). The limitation of element testing in simulation of realistic stress state in slope stability analysis highlights the need for large scale physical model tests and centrifuge testing of liquefaction. There is limited number of studies of the static liquefaction failures using physical modelling (Eckersley 1990, de Jager and Molenkamp 2012, Askarinejad et al. 2014). De Jager et al. (2017) report large scale physical modeling tests using a "liquefaction tank" performed at Delft University of Technology.

Since large scale physical model testing of the flow slides is very costly and time consuming, verified constitutive models implemented in numerical codes will be of great importance to

capture the coupled hydro-mechanical behavior of the soil. Several researchers compared and evaluated the available constitutive models (e.g. Hicks and Wong 1988) and others developed their own constitutive models or proposed frameworks which account for various material properties and stress-strain responses of soils (Manzari and Dafalias 1997, Wiltafsky 2003, Been and Jefferies 2004, Galavi 2007).

This paper focuses on evaluation of a generalized elastoplastic model within a multilaminate framework based on the works of Schweiger et al. (2009) as implemented in the finite element code of PLAXIS to simulate the static liquefaction failures using a laboratory flow slide model test results.

2 EXPERIMENTAL STUDY

2 .1 *Material characterization*

A very fine, uniform silica sand is used in the experiments of this study. A set of comprehensive geomechanical tests are performed to characterize the engineering properties of the sand. Table 1 summarizes the material properties.

Table 1. Geotechnical properties of the soil

Parameter	Values
D_{50} (mm)	0.11
$\varphi'_{residual}$ (Deg)	36
ψ (Deg)	13
Cohesion (kPa)	0.0
Angle of repose (Deg)	35
Permeability (m/s)	4.2E-5
Min-Max void ratio	0.64-1.07
Particle shape	Sub-rounded

Figure 1 illustrates the grain size distribution of the nine samples that were collected from nine different locations of the sand batch.

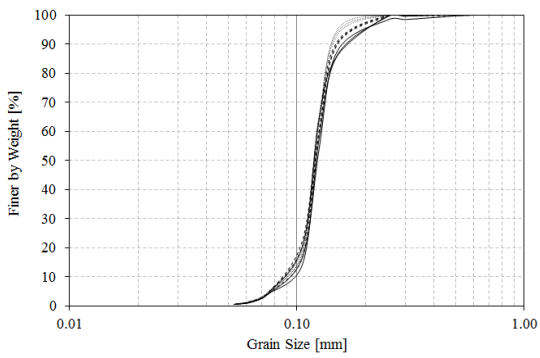

Figure 1. Grain size distribution curves of nine silica sand samples.

2 .2 *Large scale physical modelling*

The liquefaction induced failures in submerged sand slopes are simulated in a laboratory model test. The experimental test results are used for verification of the implemented numerical model.

The static liquefaction tank (de Jager et al. 2017), which was used in these experiments, is a 5 m by 2 m by 2 m inclinable container. The tank has two glass side walls which were designed for minimization of the side wall frictions and observation of the failure modes. The failure is initiated by tilting the tank. The titling process can be accurately controlled using hydraulic jacks at various rates (e.g. 0.1, 0.3 and 0.01 deg/sec). A horizontal layer of loose sand sample ($D_r \approx 30\%$) with the thickness of 0.5 m is prepared in the liquefaction tank using fluidization. The sand layer is remained fully submerged throughout the experiment. Fluidization technique was selected as the most uniform and the most repeatable sample preparation method in this research. The deposited sand in the liquefaction tank was fluidized by a controlled upward flow of water and afterwards allowed to settle down under self-weight of the particles. After stopping the fluidization, the relatively fast consolidation settlements under the self-weight of the sand particles with extremely compressive skeleton and settlements in the suspension phase wherein the soil particles are isolated and effective stress is not developed in the mixture occurred (Been and Sills 1981). All the tilting experiments of the liquefaction tank were preformed after the formation of the soil matrix after termination of the fluidization phase. Reproducibility of the experiment results were also verified by repetition of each test for three times which resulted in the same values both in terms of density and failure angle.

Figure 2 illustrates the initiation of two failures at the tilting rates of 0.03 and 0.1 deg/sec recorded by cameras from the side glass walls. It can be seen that the critical failure angles of the experiments significantly varies with the rate of loading (tilting).

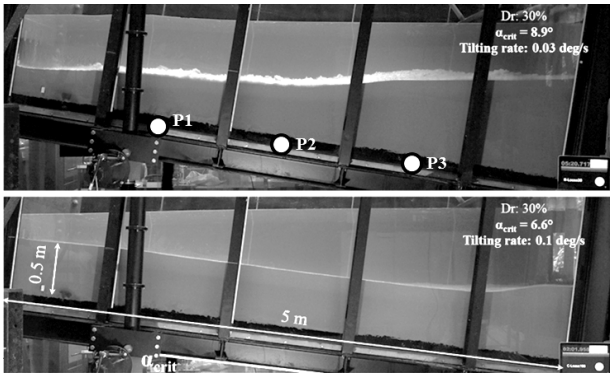

Figure 2. Illustration of two examples of liquefaction failure in loose samples (D_r = 30%) at two different rates of 0.1 deg/sec and 0.03 deg/sec.

Figure 3 shows the pore water pressure differences during the experiment, recorded by three pore pressure transducers (ppt) (P1, P2, and P3) installed on the base centerline of the liquefaction tank (ref. Figure 2 for the location of ppts).

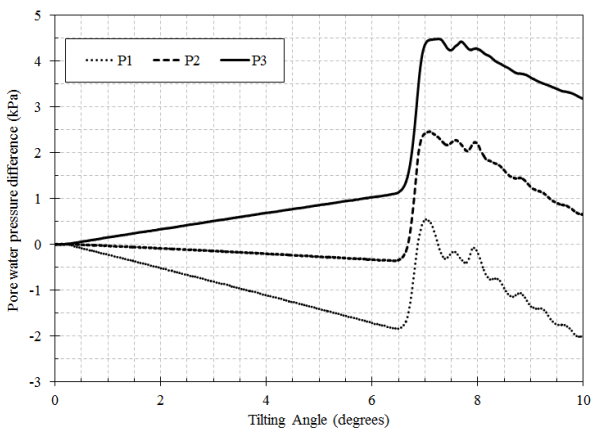

Figure 3. Simulation of the triaxial test with calibrated parameters.

The initial hydrostatic decrease in the pore water pressure measured at P1 and P2 is due to the location of these sensors with respect to the rotation center of the tank. The results

indicate that static liquefaction failure can be characterized by a sudden jump in the pore water pressures, which occurred at the angle of 6.2 (deg).

3 NUMERICAL ANALYSIS

The tilting slope model is numerically simulated using the finite element method. Not all the material models are capable of simulating the liquefaction induced failures and the post failure behaviour. In this study, a multilaminate model (Schweiger et al. 2009) is used as a material model in the finite element code of PLAXIS .

In the multilaminate framework, it is assumed that the overall deformation of a soil body can be obtained from deformation on so-called sampling planes which are distributed at various directions given by the employed integration rule. In order to calculate the global deformation of a soil element, numerical integration over all contact planes is performed. In this study, 66 (2×33) sampling planes are assumed in each stress point. As the sampling planes are independent from each other, the multilaminate framework can take into account the rotation of principal stresses and the combination of inherent and induced anisotropy (Schweiger et al. 2009). An extended Mohr-Coulomb yield surface with a non-associated flow rule is assumed in each sampling plane to account for shear hardening. The flow rule corresponds to the stress dilatancy theory by Rowe (1972) modified by Søreide et al. (2002). A dilatancy power parameter adjusts the relationship between mobilized friction angle and mobilized dilation angle at low mobilized friction angles (Galavi 2007).

The rotation of the liquefaction tank is simulated using the pseudo acceleration option in PLAXIS software. Each degree of rotation is modeled in a separate phase of staged construction mode in which the ground acceleration components and ground water level are adjusted accordingly. The consolidation type of calculation was selected to perform time dependent analysis of excess pore pressures in the model. In this type of calculation the accurately measured permeability and various time intervals for different tilting rates were introduced to the model.

Material parameters for the multilaminate model are calibrated using the experimental data. Table 2 summarizes the calibrated parameters and recommended values of each parameter to start the calibration.

Table 2. Calibrated soil parameters in the multilaminate model.

Parameters	**Calibrated values**
E_{oed}^{ref} (kN/m^2)	2000
E_{ur}^{ref} (kN/m^2)	6000
p_{ref} (kN/m^2)	4
m	0.22
ν'_{ur}	0.2
A_{mat}	$33*10^{-3}$
c' (kN/m^2)	0.5
ϕ' (Deg)	42
ψ (Deg)	14
R_f	0.95
$k_{0,nc}$	0.29

Figure 4 shows the simulations of direct shear test using the final calibrated parameters.

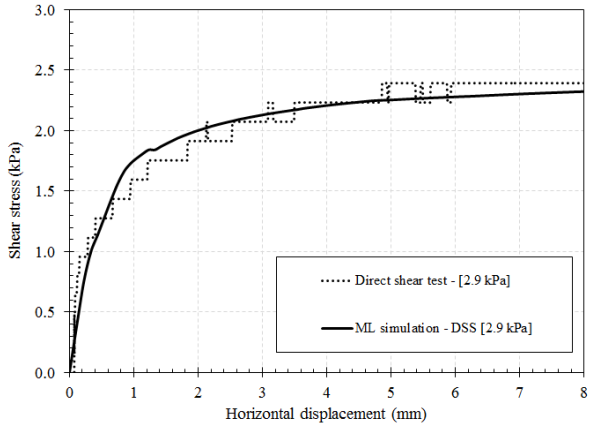

Figure 4. Comparison of element test and simulations after calibration.

Figure 4 presents the simulations of triaxial tests using calibrated parameters. This figure proves that hardening behavior in the material can be simulated using the implemented material model in finite element code.

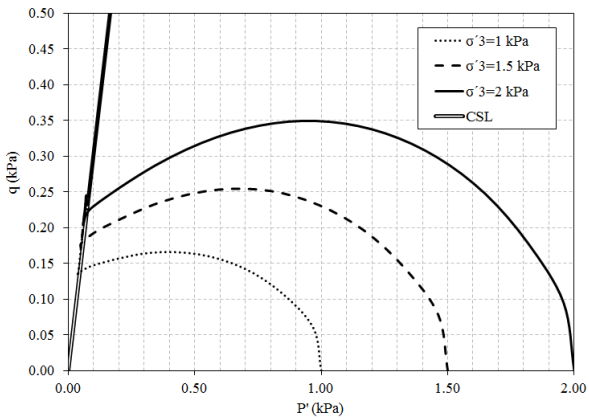

Figure 5. Simulation of triaxial tests with calibrated parameters.

4 DISCUSSION OF THE RESULTS

The proven rate dependency of instability and shear strength in localized failures in the soils highlights the need for having various rates of loading (Puzrin and Randolph 2015). Likewise, all the model test experiments performed at various rates resulted in different failure angles.

Nine reference points were selected to track the changes in stress paths in the soil body in the numerical simulations. The selected points, as shown in Figure 6, are at two different depths and on the left, centre, and right side of the tank. The stress paths of points A (0.22 m, 0.1 m) and A' (0.22 m, 0.3 m) are moving towards the critical state line with reduction of the mean effective and the shear stresses.

As it is depicted in the simulation of undrained triaxial stress paths in Figure 5, before reaching the critical state line the paths will enter an instability zone in which the material starts yielding before reaching the failure point. Extremely fast and instantaneous propagation of failure following the collapse of a metastable element in the soil matrix in liquefaction, can be associated with the observed failures in the liquefaction tank and simulated stress paths moving towards the critical state line and instability zone.

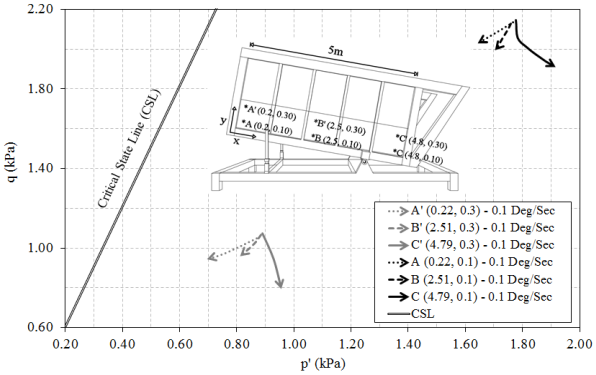

Figure 6. Stress paths of 9 different points in the tank during tilting tests.

In addition, the effect of the tilting rate on the stress paths in is investigated. Figure 7 shows that higher rates of tilting lead to generation of the excess pore pressures in a relatively high ranges comparing to increment of total mean stresses.

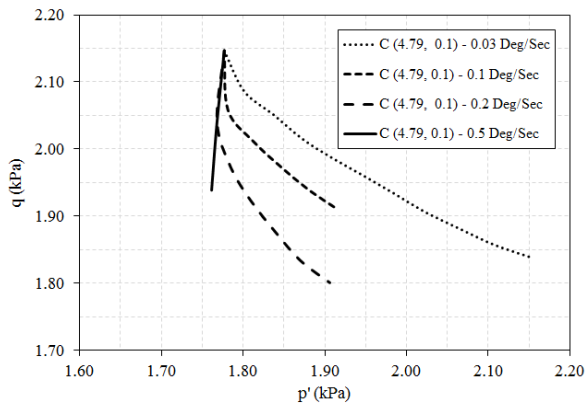

Figure 7. Rate dependency of stress paths for point C (4.79 *m*, 0.1 *m*).

Lower rates of both excess pore pressure generation and decrement of the effective stresses achieved in lower tilting rates, results in higher stability in the soil matrix.

5 CONCLUSIONS

In this paper, a set of laboratory model tests of static liquefaction induced failures in submerged loose sands are simulated using finite element method. The implemented constitutive model is based on a multilaminate framework which can simulate rotation of principal stresses, and strain softening in liquefaction failures. The simulations showed that taking the time and rate dependent behaviour of some material parameters along with the stress states into account will enable us to mimic more realistic stress strain behaviour. The multilaminate model proved to be able to simulate the undrained behaviour of loose sands at the available stress ranges. It should be taken into account that for a given sand material the model should be accurately calibrated based on the element test results and empirical correlations.

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