A Methodology for Evaluating Liquefaction Susceptibility in Shallow Sandy Slopes

Une méthodologie pour l'évaluation de susceptibilité à la liquéfaction dans les pentes sableuses

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ABSTRACT: The paper illustrates a modeling approach for evaluating the liquefaction susceptibility of shallow sandy slopes. The proposed methodology consists of two main components: (i) a theoretical framework for undrained stability and (ii) the MIT-S1 constitutive model for simulating the response of sands. In the first part of the paper, the use of a stability index able to capture the onset of undrained failure in infinite slopes is illustrated. In the second part, the practical significance of the method is discussed by back-analyzing the series of flow failures in an underwater berm at the Nerlerk site. The reinterpretation of these events in the light of the theory of material stability confirmed that liquefaction was a plausible mechanism for the failures. In addition, the analyses have provided a prediction of the spatial distribution of the unstable masses which is compatible with what was observed through bathimetric surveys conducted after the events. This particular application of the theory supports the idea that realistic constitutive modeling is crucial for achieving consistent predictions of liquefaction potential under field conditions.

RÉSUMÉ: L'article illustre une approche de modélisation pour évaluer la susceptibilité à la liquéfaction des pentes sablonneuses peu profondes. La méthodologie proposée se compose de deux éléments principaux: (i) un cadre théorique pour la stabilité non drainée et (ii) MIT-S1, le modèle de comportement pour la simulation de la réponse des sables. La première partie du document illustre l'utilisation d'un indice de stabilité capable de saisir le début de la rupture dans des pentes infinies dans des conditions non drainées. Dans la deuxième partie, les implications pratiques de la méthode sont évaluées par rétro-analyse d'une série de ruptures par écoulement dans une risberme sous-marine sur le site de Nerlerk. La réinterprétation de ces événements, à la lumière de la théorie de la stabilité des matériaux, a confirmé que la liquéfaction est un mécanisme plausible pour expliquer ces défaillances. En outre, les analyses ont fourni une prédiction de la distribution spatiale des masses instables, qui est compatible avec ce qui a été observé par des mesures bathimétriques menées après les défaillances. Cette application de la théorie soutient l'idée qu'une modélisation réaliste du comportement est essentielle pour faire des prédictions cohérentes de potentiel de liquéfaction dans des conditions de terrain réalistes.

KEYWORDS: sands, static liquefaction, flow slides, material stability, theoretical analyses, constitutive modeling.

1 INTRODUCTION.

Landslides and slope failures are widely recognized as one of the major natural hazards affecting both the development of densely populated areas in rugged terrain and the design of artificial earthworks [Terzaghi 1957, Sladen et al. 1985b]. Within the general class of slope failures, runaway instabilities or flow slides represent impressive phenomena that still raise several open questions.

Even though various studies have been carried out on the subject [Sladen et al. 1985a, Lade 1993], there is still need for advanced tools of analysis that can explain catastrophic failures, evaluate hazard levels in landslide prone areas and define geotechnical design criteria. The purpose of this work is to propose a predictive modeling methodology to study flow slide phenomena. The proposed methodology aims to evaluate (i) the shear perturbations that can trigger a flow slide, (ii) the spatial distribution of soil masses prone to liquefaction and (iii) the characteristics of the post-failure response of the slope.

2 MODELING FLOW SLIDE TRIGGERING.

The evaluation of liquefaction conditions based on geotechnical criteria typically relies on the combined use of the critical state theory and empirical observations from laboratory experiments and in situ tests [Poulos et al. 1985]. Although these methods provide guidance to assist engineering judgement, they lack appropriate geomechanical foundations that can be applied to general cases.

Indeed, the application of stability criteria to field conditions requires accurate consideration of the realistic static-kinematic characteristics of the problem at stake. An important example is represented by shallow slopes, in which initial stress conditions and kinematics are highly anisotropic and cannot be appropriately represented through classical triaxial testing. One of the first approaches to consider the role of soil behavior through a comprehensive constitutive model was suggested by di Prisco et al. (1995). In order to study the onset of a flow slide, these authors considered the geometry of an infinite slope (Figure 1) and modeled sand behavior through simple shear simulations.

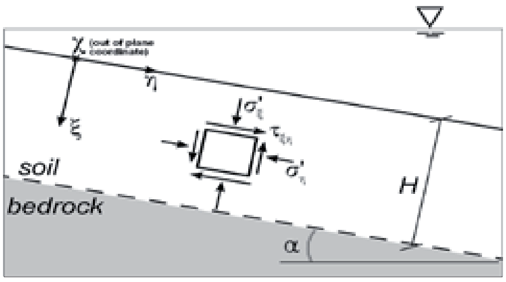

Figure 1. Reference system for a submerged infinite slope and initial stress conditions.

The present paper discusses a methodology which is inspired by this original idea, but tries to link it directly to the critical state of sands and in situ observations. The key contribution is the incorporation of a constitutive model with predictive capabilities for describing transitions from contractive to dilative volumetric behavior upon shearing. As a result, the approach is able to distinguish among different types of sand response induced by an undrained perturbation (e.g., complete liquefaction, partial liquefaction, etc.), which is an essential aspect to define the expected post-failure behavior of a sliding mass.

In order to define in appropriate mathematical terms the onset of failure in a shallow infinite slope, our methodology frames static liquefaction within the theory of material stability [Hill, 1958, Buscarnera et al. 2011, Buscarnera and Whittle 2013]. In particular, we introduce an index for undrained simple shear failure:

$$\Lambda_{LSS} = H - H_{LSS} \tag{1}$$

where H is the hardening modulus of the sand considered as an elastoplastic medium, while H_{LSS} is a kinematic correction factor that depends on the mode of deformation. Vanishing values of (1) indicate the onset of unstable conditions. In other words, H_{LSS} represents a critical value of the hardening modulus at which undrained simple shear perturbations are no longer admissible. More details about the derivation of the index (1) are given by Buscarnera and Whittle (2012). For the purpose of the current paper, it is sufficient to note that positive values of (1) at a given state of stress and density reflect a stable undrained response of the infinite slope, while vanishing/negative values indicate the loss of undrained strength capacity. In this way, the values of Λ_{LSS} (as well as its increment, $\dot{\Lambda}_{LSS}$) can be used to assess both the initial stability conditions prior to shearing and the critical triggering perturbations. More specifically, the simple shear response predicted by a constitutive model can be interpreted by means of (1), identifying the stresses at the initiation of a flow failure and the residual margin of safety. For example, Figure 2 illustrates two MIT-S1 simulations of undrained simple shear response at the same level of initial vertical effective stress but with different values of initial shear stresses (representing different slope angles).

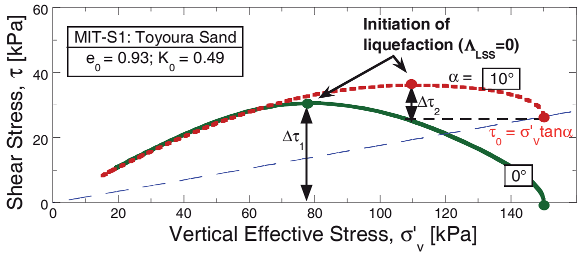

Figure 2. Example of simple shear simulations (loose Toyoura Sand simulated with the MIT-S1 model).

The results illustrate that the initial state of stress affects the magnitude of the shear perturbation required to induce instability ($\Delta\tau_1$ vs $\Delta\tau_2$). The onset of an instability coincides with the peak in the shear stress, and can be readily interpreted through the stability index (1).

As is well known, the undrained behavior of sands is also influenced by changes in the effective stress and density. For example, even very loose sands can exhibit a tendency to dilate at low effective stress levels, but will collapse for undrained shearing at high levels of effective stress. Hence, the prediction of liquefaction potential requires a constitutive framework that can simulate realistically the stress-strain properties as functions of stress level and density. To illustrate this aspect, Figure 3 shows MIT-S1 simulations for a pre-shear void ratio ranging from 0.87 to 0.94, with the model predicting a sharp transition from a stable behavior to complete collapse.

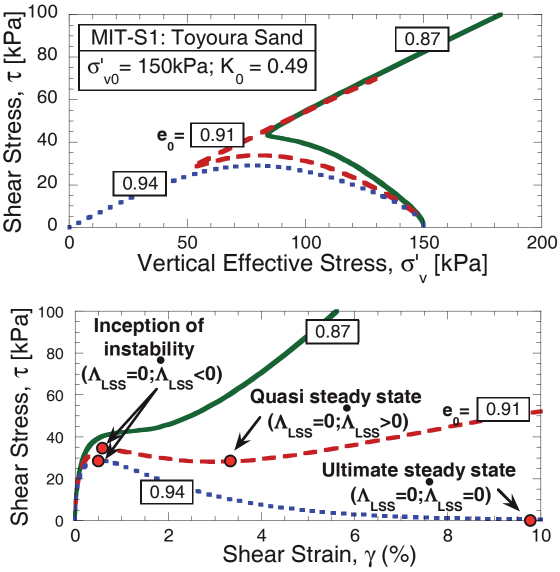

Figure 3. MIT-S1 predictions: effect of void ratio on undrained simple shear response of Toyoura Sand: a) stress path; b) stress-strain behavior.

The effect of confining pressure and density on the undrained response of sands implies that the perturbation shear stress ratio, $\Delta\tau/\sigma'_{v0}$, associated with the initiation of liquefaction is not only a function of the slope angle, but must be evaluated at the depth of interest. This information can be encapsulated in appropriate stability charts of the triggering perturbations. Figure 4 gives an example of such charts, and uses MIT-S1 simulations for a constant value of the initial void ratio to show the effect of the stress level on the predicted triggering perturbations.

In general, such charts should be evaluated at any depth of interest, being they a function of the values of density and stress state at that specific location. Once the stability charts expressing the shear resistance potential have been obtained, it is possible to define the variation of the triggering perturbation at any depth. These capabilities are illustrated in the next section by applying the theory for a case study involving flow failures in a sandy deposit.

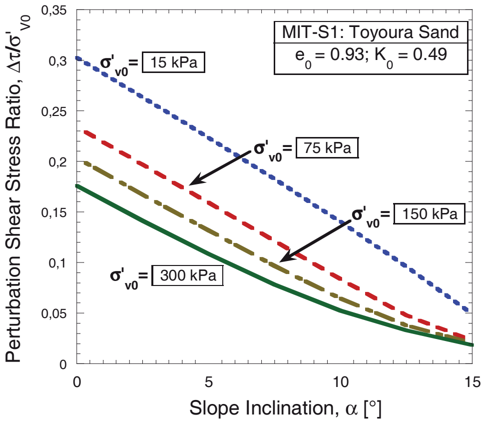

Figure 4. Effect of effective stress level on the stability charts (all points in the chart are characterized by Λ_{LSS}=0).

3 EXAMPLE OF APPLICATION: THE NERLERK CASE.

The Nerlerk berm case history refers to an impressive series of slope failures that took place in 1983 during construction of an artificial island in the Canadian Beaufort Sea (Sladen et al., 1985b). We have used the MIT-S1 model to investigate potential static liquefaction mechanisms in the Nerlek berm. In order to apply the theory to the Nerlerk case, it is assumed that the local behavior of the sides of the berm can be approximated by considering stress conditions in an infinite slope. Although this choice represents an important simplification of the real geometry, this assumption allows an immediate mechanical evaluation of possible incipient instabilities within the fill and provides an insight on the type of expected undrained phenomena.

The application of the methodology is based on the calibration of the MIT-S1 model parameters for the site-specific properties of the Nerlerk sands. Given the lack of data, the calibration procedure required a number of approximations. Here only some key aspects of the calibration process are described, while more details are available in Buscarnera and Whittle (2012). First, the parameters governing the critical state of the Nerlerk sands have been evaluated on the basis of the available literature data (Sladen et al., 1985a). Then, the critical state properties of the Nerlerk sands have been compared with those of similar Arctic sands (Figure 5), for which one-dimensional compression data were available.

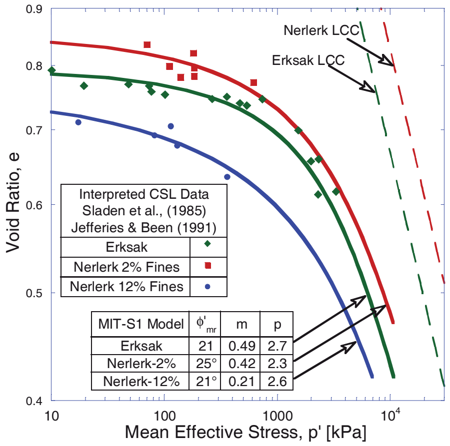

Figure 5. Comparison of Critical State Lines (CSL) and Limit Compression Curves (LCC; dotted lines) for Erksak and Nerlerk sands (while fines content affects the CSL of Nerlerk sand, no influence on the LCC is assumed given the lack of data).

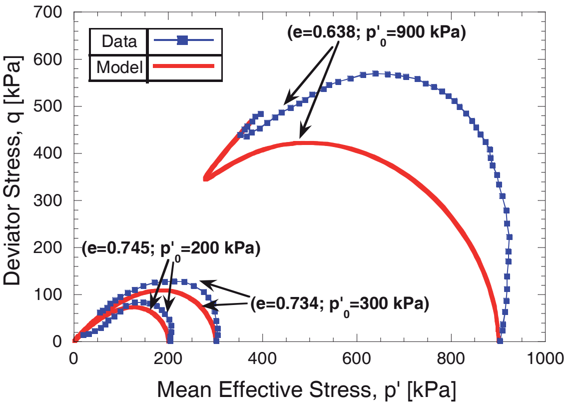

Figure 6. Comparison of computed and measured undrained shear behavior for Nerlerk Sand with 12% fines.

Such comparisons, together with empirical considerations compiled for a broad set of sands (Pestana and Whittle, 1995), allowed the definition of a set of parameters for the compression response of Nerlerk sands. The remaining model constants were calibrated using data on the undrained response (Figure 6).

In order to use the calibrated MIT-S1 model for the Nerlerk berms it is finally necessary to define the in situ void ratios along the slope profile and evaluate the stability charts of the Nerlerk berm for several depths within the slope. The first step is largely dependent on a reliable interpretation of the available in situ tests. Several CPT tests were performed on the hydraulic fills at Nerlerk, with the aim of estimating the in situ density. For consistency with prior studies (Sladen et al. 1985b; Lade 1993), the current analyses assume that relative density (D_r) can be estimated using the CPT correlation proposed by Baldi et al. (1982). It is clear that the choice of a specific interpretation method for CPT test results will affect the estimation of relative density (and, in turn, the model predictions). This uncertainty, however, is probably unavoidable in any method of interpretation. Figure 7 shows that the estimated values for D_r range from 30 to 55 %, while Figure 8 illustrates the distribution of these initial states relative to the CSL of Nerlerk sands with 12% fines content.

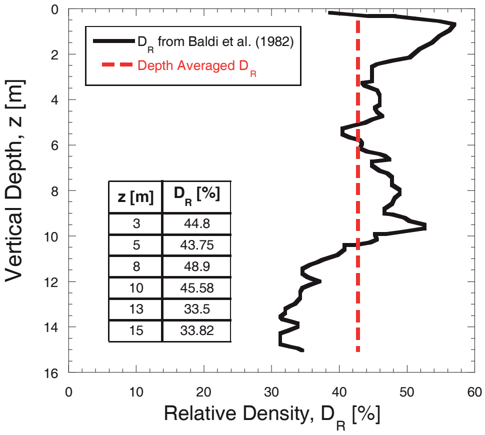

Figure 7. In situ relative density from CPT tests (Baldi et al. 1982)

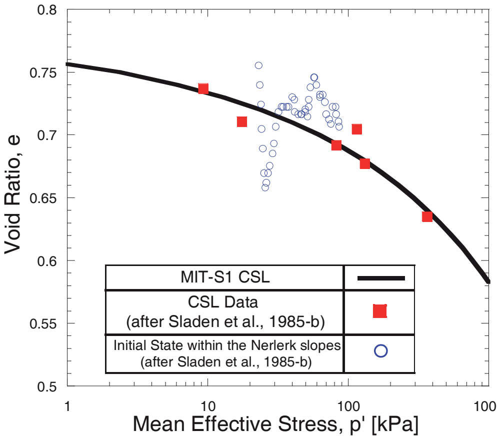

Figure 8. Relative location of in situ and critical states for Nerlerk sands

Figure 9 shows the computed stability charts at selected depths for infinite slopes in Nerlerk sand, while Figure 10 illustrates the undrained response predicted by the MIT-S1 model at various depths for a slope made of the same material and characterized by a slope angle α=13°.

The results show that the magnitude of the shear perturbation needed to cause instability can be significantly affected by the selected depth within the slope profile. More specifically, the analyses define the initial state of stability within the Nerlerk berm slopes in a proper mechanical sense, allowing a prediction of the critical inclination for incipient instability. Since the Nerlerk berm was constructed at slope angles in the range α=10°-13°, these results suggest that the Nerlerk slopes were likely not in an incipient state of instability, and additional shear stresses were required to trigger flow failures. In other locations where steeper slopes were recorded, however, only very small perturbations in shear stress could have triggered failure. This result suggests that an undrained collapse triggered by rapid deposition can be considered as a mechanically feasible failure mechanism for the berm.

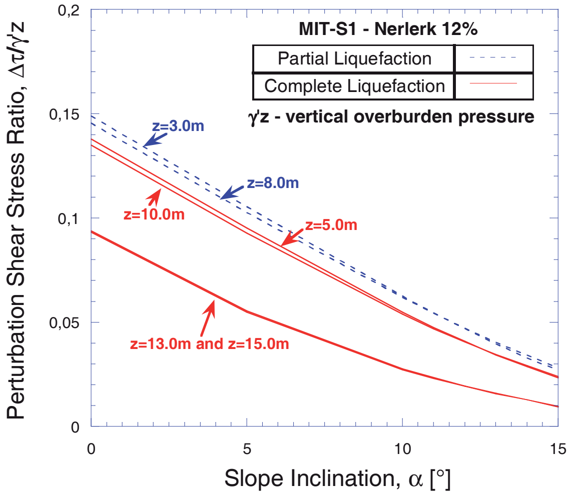

Figure 9. Stability charts for the Nerlerk berm.

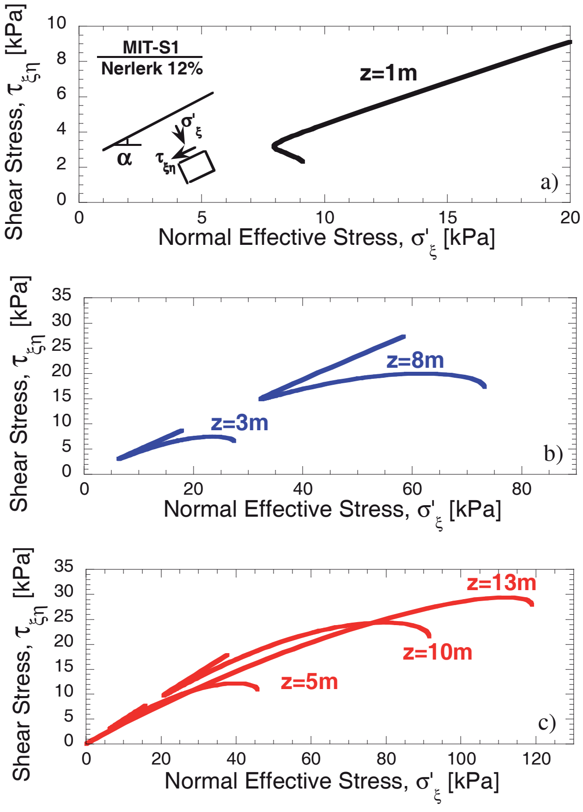

Figure 10. Predictions of undrained response across the Nerlerk berm section (α=13°): a) no potential for liquefaction; b) limited potential for liquefaction; c) high potential for liquefaction.

4 CONCLUSIONS

This paper has presented a framework for evaluating the triggering of flow slides in infinite slopes by modeling the undrained shear behavior using the anisotropic MIT-S1 model. The selected soil model is able to simulate realistic transitions in the contractive/dilative response of sands and enables the prediction of the shear perturbations able to induce instability, as well as the location of potentially unstable zones within the soil mass. In this paper, these features have been used to derive stability charts of triggering perturbations for different combinations of initial density and stress state.

In practice the model needs to be calibrated for the site specific properties of the soil, and requires reliable data on in situ density in order to make predictions of liquefaction potential. In order to show the capabilities of the proposed approach, the methodology has been applied to the well-known case of slope failures in the Nerlerk berm. A general picture of the distribution of liquefaction susceptibility on the Nerlerk slope profile has been obtained. The analyses have been based on the calibration of model input parameters against published laboratory test results, while empirical correlations for CPT data have been used to define the initial density conditions prior to shearing. The results show that there were two zones within the slope that were vulnerable to flow failure. Although some sections of the berm were oversteepened, most were deposited with a slope angle α=10°-13°. For these slope angles, the current analyses show that instability could have been triggered by the undrained perturbations possibly induced by the rapid deposition of hydraulic fill. Thus, static liquefaction is likely to have contributed to the observed failures, confirming earlier hypotheses by Sladen et al. (1985b).

The analyses presented in this work illustrate a unified methodology that combines the theory of material stability, the critical state framework for sands and data from in situ tests. As a result, the proposed methodology offers a simple, consistent and complete geomechanical framework for interpreting and predicting the triggering of flow slides that can be easily applied to other similar engineering cases.

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