FAILURE MODES OF LOOSE TOYOURA SAND UNDER VARIOUS LEVELS OF STATIC SHEAR BY TORSIONAL SIMPLE SHEAR TESTS

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1. INTRODUCTION

Prediction of ground failure involving earthquake-induced liquefaction of sloped sandy deposits is a major challenge in geomechanics due to the great number of factors that need to be considered such as initial static shear stress (τ_{static}), cyclic shear stress (τ_{cyclic}), relative density (D_r), confining pressure (p_0'), loading conditions etc. Yet, such prediction is vital for researchers and practicing engineers to understand comprehensively the triggering conditions and consequences of liquefaction and to develop effective countermeasures against it.

This paper briefly describes the triggers (stress conditions) and the consequences (deformation behavior) for three distinct failure modes that can be produced by an earthquake on sloped ground consisting of loose saturated sand. Such failure mechanisms were observed in the laboratory by performing undrained monotonic and/or cyclic torsional simple shear tests on loose fully-saturated Toyoura sand specimens (Chiaro et al., 2012). Foremost, a practical method for assessing the failure behavior of sandy-sloped ground undergoing undrained cyclic shearing based on sand failure characteristics observed in the laboratory is also presented.

2. EXPERIMENTAL OUTLINE

To investigate the role which static shear stress (i.e. slope ground conditions) plays on the liquefaction response and large deformation properties of saturated sand, the authors performed a series of undrained cyclic torsional simple shear tests on loose fully-saturated Toyoura sand specimens (D_r = 44-50%; p_0' =100 kPa) under various combinations of static and cyclic shear stresses. From the study of failure mechanisms, three types of failure were identified based on the difference in the effective stress paths and the modes of development of shear strain during both monotonic and cyclic undrained loadings. Similarly to Hyodo et al. (1991), this study confirmed that to achieve full liquefaction state (p' = 0) the reversal of shear stress during cyclic loading is essential. Alternatively, when the shear stress is not reversed, large shear deformation may bring sand to failure. These failure modes are shown in Fig. 1. It is worth to mention that:

- τ_{max} (= $\tau_{static} + \tau_{cyclic}$) is the maximum shear stress during cyclic loading;
- τ_{min} (= $\tau_{static} - \tau_{cyclic}$) is the minimum shear stress during cyclic loading; and
- τ_{peak} is the transient undrained shear strength during monotonic loading.

where τ_{static} is the initial static shear stress and τ_{cyclic} is the cyclic shear stress.

a) **Cyclic Liquefaction ($\tau_{max} < \tau_{peak}$ and $\tau_{min} < 0$).** While undergoing a number of cycles between 1 and 15 (i.e. 15 is the number of cycles representative on an earthquake of magnitude 7.5, which in this study is taken as reference to define whether liquefaction occurs or not; hereafter, see also $NN_{(CLQ)}$ behavior), due to the excess pore water pressure generation, the effective mean principal stress progressively decreases and the stress state moves toward the failure envelope and finally reaches the full liquefaction state (p' = 0). Then, in the post liquefaction process, large deformations are developed. Hereafter, this type of failure is referred to as CLQ (Fig. 1(a)).

b) **Rapid Flow Liquefaction ($\tau_{max} > \tau_{peak}$ and $\tau_{min} < 0$).** Liquefaction takes place in-between the first cycle of loading and a rapid development of residual strain is observed. Herein, this type of failure is referred to as RLQ (Fig. 1(b)).

c) **Residual Deformation Failure ($\tau_{max} > \tau_{peak}$ and $\tau_{min} > 0$).** During cyclic loading large deformations are achieved rapidly, while in general liquefaction is not reached even after applying more than one hundred cycles. As a result, residual deformation brings the specimens to (shear) failure. Henceforward, this failure mode is referred to as RSD (Fig. 1(c)).

d) In addition to the three failure modes previously described, the following two cases in which neither failure nor liquefaction take place even after applying several tens of cycles were identified:
   (i) when $\tau_{max} < \tau_{peak}$ as well as $\tau_{min} > 0$ (Fig. 1(d)); and
   (ii) (ii) in the case of $\tau_{max} < \tau_{peak}$ and $\tau_{min} < 0$ (i.e. CLQ), but the level of τ_{cyclic} is very low so that liquefaction will occur in more than 15 cycles.

These two additional cases hereafter are referred to as NN and $NN_{(CLQ)}$, respectively.

Keywords: Large deformation; Liquefaction; Static shear; Torsional shear tests; Toyoura sand
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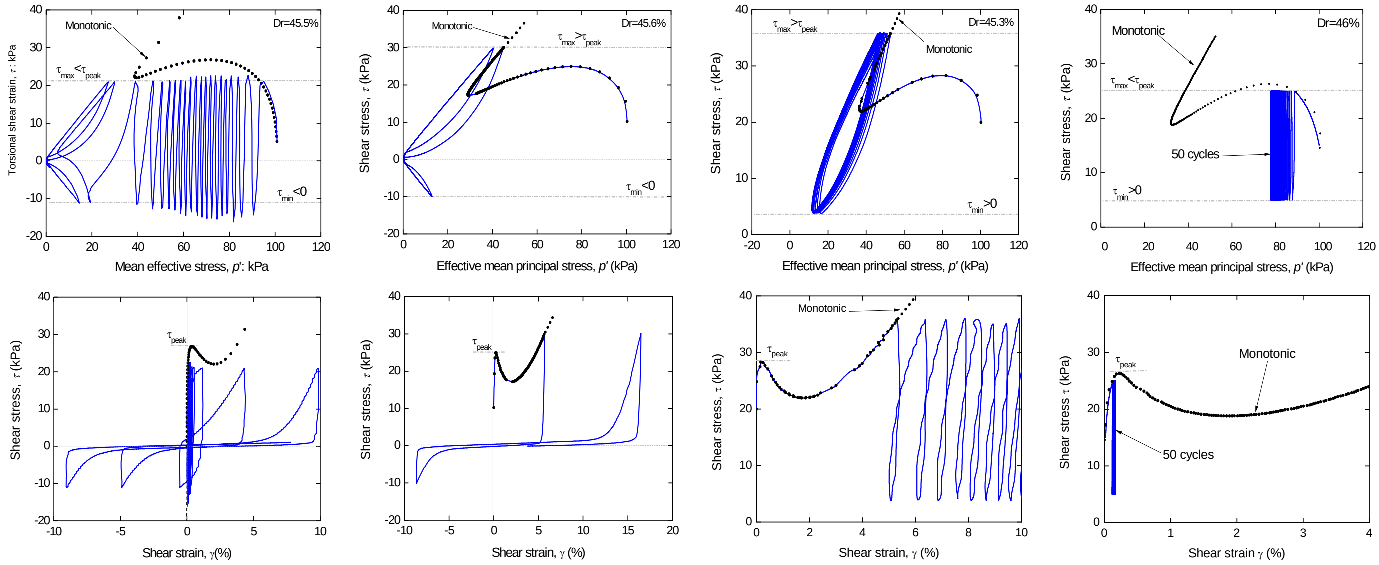

(a) Cyclic Liquefaction (CLQ) | (b) Rapid Flow Liquefaction (RLQ) | (c) Residual Deformation Failure (RSD) | (d) no failure & no liquefaction (NN)

Fig. 1 Typical liquefaction and failure mechanisms observed for loose Toyoura sand in torsional shear tests

3. PREDICTIVE METHOD

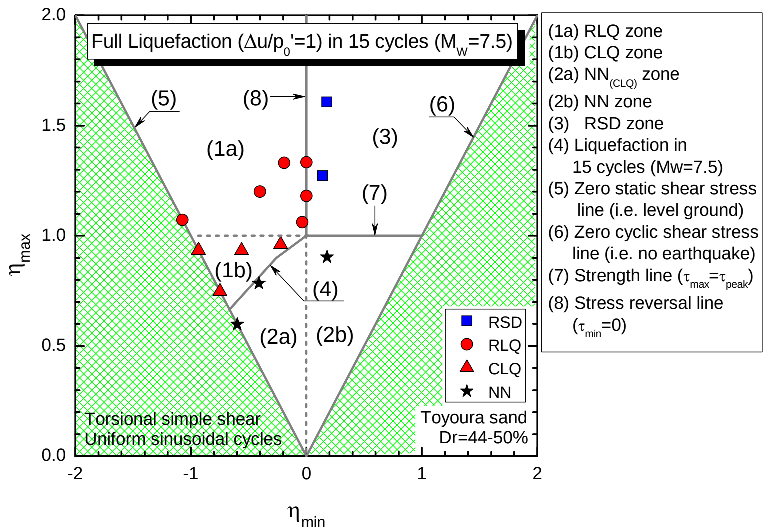

Fig. 2. Failure modes for loose Toyoura sand specimens subjected to undrained torsional simple shear loadings with/without static shear.

In this study, a method to identify the stress conditions that trigger the failure modes observed for loose Toyoura sand specimens in undrained cyclic torsional shear tests is presented. This is made by plotting experimental data) in terms of η_{max} (= τ_{max}/τ_{peak}) vs. η_{min} (= τ_{min}/τ_{peak}) parameters. Thus, as shown in Figure 2, five zones can be distinguished and boundary conditions with clear physical meaning can be established. Each zone corresponds to specific failure behavior (i.e. RLQ, CLQ, NN, $NN_{(CLQ)}$ and RSD).

As shown by Fig. 2, predictions obtained by the proposed graphical method are well in agreement with those experimentally observed, which is shown as different symbols in the figure.

4. CONCLUSION

Prediction of ground failure involving earthquake-induced liquefaction of sloped sandy deposits is essential for understanding comprehensively the triggers and consequences of liquefaction. In this paper, an attempt is made to identify key factors that govern failure of sandy sloped ground during earthquakes and a method to assess whenever liquefaction or shear failure occurs within a saturated sandy sloped deposit is presented.

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