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Gabriele Chiaro
University of Wollongong, gchiaro@uow.edu.au

Junichi Koseki
IIS, University of Tokyo, koseki@iis.u-tokyo.ac.jp

A METHOD FOR ASSESSING FAILURE BEHAVIOR OF SAND WITH INITIAL STATIC SHEAR

Gabriele Chiaro[1] and Junichi Koseki[2]

1) Department of Civil Engineering, University of Tokyo
Ce202, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
e-mail: chiaroga@iis.u-tokyo.ac.jp
2) Institute of Industrial Science, University of Tokyo
Ce201, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
e-mail: koseki@iis.u-tokyo.ac.jp

INTRODUCTION

In sloped ground, soil elements are subjected to an initial static shear stress on the horizontal plane or an assumed failure surface. During earthquake shaking, these elements are subjected to additional cyclic shear stress due to shear waves propagating vertically upward from bedrock. The superimposition of static and cyclic shear stresses can have major effects on the response of the soil, leading to liquefaction-induced failure behavior of natural and artificial slopes of sandy deposits and the consequent development of extremely large ground deformation.

In order to address the above issue, in this paper, a method to assess the failure behavior of sand specimens with initial static shear under undrained cyclic shear loading is presented. Its applicability has been investigated on a wide range of combinations of static and cyclic shear stresses on very loose, loose and dense sand by referring to: (i) the results of undrained cyclic torsional shear tests carried out on saturated Toyoura sand specimens; and (ii) a number of single-element numerical simulations by employing an elasto-plastic constitutive model developed at the Institute of Industrial Science (IIS), University of Tokyo.

FAILURE CHARACTERISTICS OF SAND WITH INITIAL STATIC SHEAR

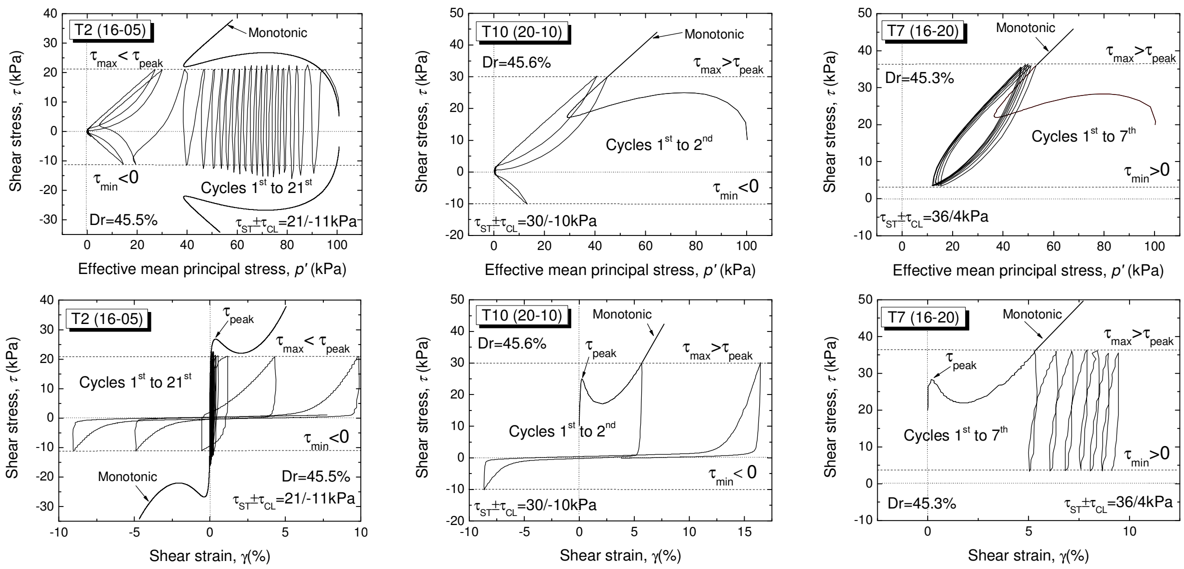
With the aim to better understand the role which the static shear plays on the undrained cyclic behavior of saturated sand, Chiaro et al. (2010) performed a series of undrained cyclic torsional shear tests on saturated Toyoura sand specimens under various combinations of static and subsequent cyclic shear stresses. While referring to Hyodo et al. (1991), depending on the magnitude of combined static and cyclic shear stress, the loading patterns were classified into three groups: stress reversal, intermediate and non-reversal. From the study of failure mechanisms, the observed types of failure were distinguished into liquefaction and residual deformation based on the difference in the effective stress paths and the modes of development of shear strain during both monotonic and cyclic undrained loading conditions. In case of the stress reversal and intermediate loadings, failure was associated with full liquefaction, followed by extremely large deformation during cyclic mobility. On the contrary, in the case of the non-reversal loading, it was found that residual deformation brought the specimen to failure (i.e., formation of spiral shear band) although liquefaction did not occur.

These tests results, in terms of effective stress path, stress-strain relationship and associated failure behavior, could be reasonably well simulated by single-element numerical computations using an elasto-plastic constitutive model developed at IIS, University of Tokyo (De Silva, 2008; and further modifications), which can describe the behavior of sand with initial static shear under drained/undrained monotonic/cyclic torsional shear loading conditions. Therefore, in this study, this model was used to investigate the failure behavior of Toyoura sand on a wide range of combinations of static and cyclic shear stresses on loose and dense conditions.

Hereafter, the failure modes observed by Chiaro et al. (2010) and their simulations as typically shown in Fig. 1 and Fig. 2, respectively, are examined in detail.

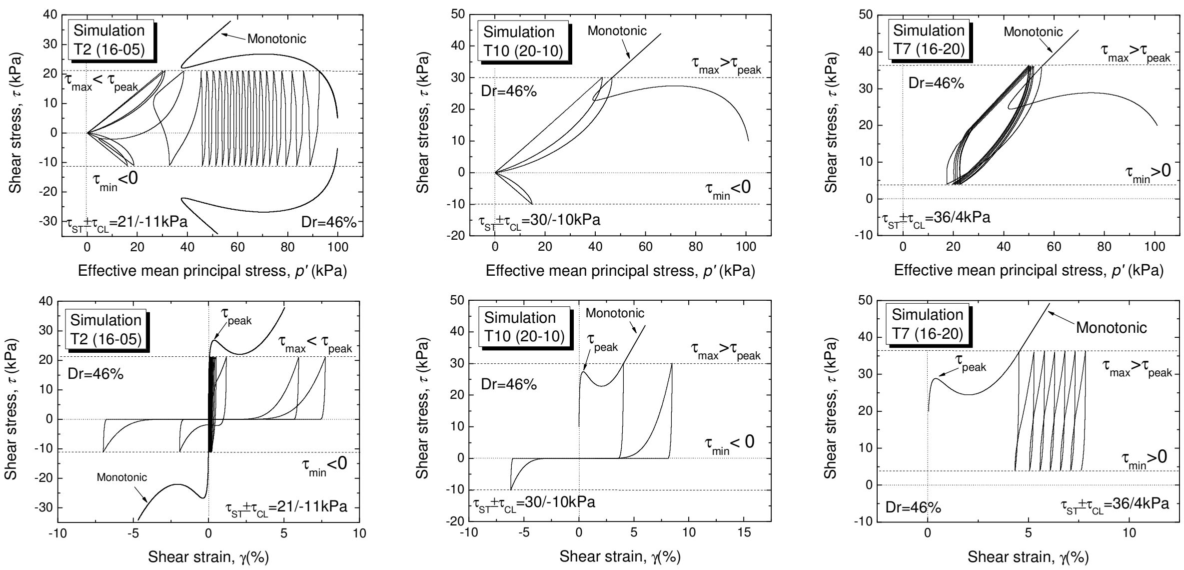
Cyclic Liquefaction Failure (LQ). In some cyclic tests, the shear stress reached a maximum value (τ_{max}) which was lower than the peak stress during undrained monotonic loading (τ_{peak}); in addition, the minimum shear stress value was negative ($\tau_{min}< 0$). Under these stress conditions (i.e., stress reversal), while undergoing several tens of cycles, due to the excess pore water pressure generation, the effective mean principal stress progressively decreased and the stress state moved toward the failure envelope and finally reached the full liquefaction state *(p'=0)*. Then, in the post liquefaction process, large deformations were developed. Hereafter this type of failure is called cyclic liquefaction failure.

Rapid Liquefaction Failure (RF). In other tests, the shear stress reached a maximum value which was higher than the peak stress during undrained monotonic loading ($\tau_{max} > \tau_{peak}$), while due to stress reversal conditions the minimum shear stress value was negative ($\tau_{min} < 0$). As a result, liquefaction took place in-between the first cycle of loading and a rapid development of residual strain was observed. Herein, this type of failure is called rapid liquefaction failure.



(a) Cyclic Liquefaction Failure (LQ) (b) Rapid Liquefaction Failure (RF) (c) Residual Deformation Failure (RD)

Fig. 1. Typical failure behaviors of Toyoura sand specimens by undrained cyclic torsional shear tests.



(a) Cyclic Liquefaction Failure (LQ) (b) Rapid Liquefaction Failure (RF) (c) Residual Deformation Failure (RD)

Fig. 2. Failure behaviors obtained by simulating the test results shown in Fig. 1.

Residual Deformation Failure (RD). On the other hand, in some tests the shear stress reached a maximum value which was higher than the peak stress during undrained monotonic loading ($\tau_{max} > \tau_{peak}$), as well as the minimum shear stress value was positive ($\tau_{min} > 0$). Under these stress conditions (i.e., non-reversal stress), during cyclic loading large deformations were achieved rapidly, while in general liquefaction was not reached even after applying a hundred cycles. As a result, residual deformation brought the specimens to failure. Therefore, henceforward this failure mode is called residual deformation failure.

No Failure - No Liquefaction (NN). Since there was not experimental results, the following two cases in which either failure or liquefaction did not take place even after applying several tens of cycles were defined by means of numerical simulations: (i) when the maximum cyclic shear stress was lower than the monotonic peak stress ($\tau_{max} < \tau_{peak}$) as well as the minimum shear stress was positive ($\tau_{min} > 0$), as typically shown in Fig. 3; and (ii) in case of reversal loading in which the level of cyclic stress was very low. These two additional cases hereafter are called No Failure-No Liquefaction.

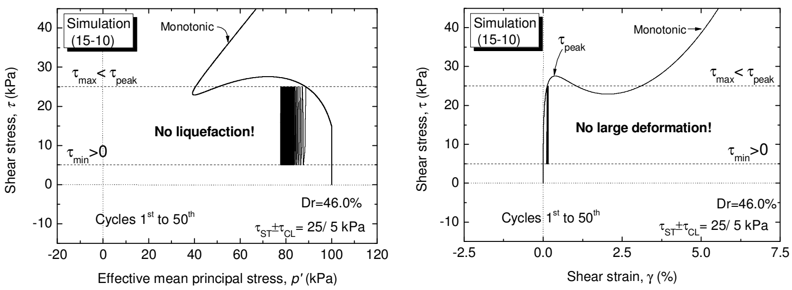


Fig. 3. Typical No failure - No liquefaction behavior of Toyoura sand obtained by numerical simulation.

A METHOD FOR EVALUATING SAND FAILURE BEHAVIORS

In this study, a method for assessing the failure behavior of sand specimens with initial static shear under undrained cyclic shear loading is presented.

It has been recognized from previous studies that the resistance to liquefaction of sands depends on the soil properties (e.g., relative density, degree of saturation, fines content, over-consolidation ratio, etc) as well as on the stress conditions such as confining pressure, cyclic shear stress and initial static shear stress.

In order to take the above factors into account, the proposed method is defined by means of three parameters namely: (i) static stress ratio $SSR = \tau_{static} / p_0'$, (ii) cyclic stress ratio $CSR = \tau_{cyclic} / p_0'$, and (iii) undrained monotonic peak stress ratio $MPSR = \tau_{peak} / p_0'$; where p_0' is the initial effective confining pressure. The *SSR* corresponds to the driving shear force induced by the inclination of slopes; the *CSR* represents the inertial force exerted by earthquakes; while the *MPSR* takes into account the strength of soil which depends on the soil properties (e.g., relative density, etc) and the stress conditions. In order to have a unique framework for analyzing the failure behavior of sands irrespective of the relative density of samples and other soil properties, the *SSR* and the *CSR* are normalized by the *MPSR*.

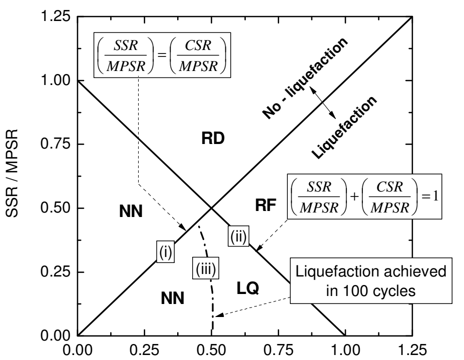
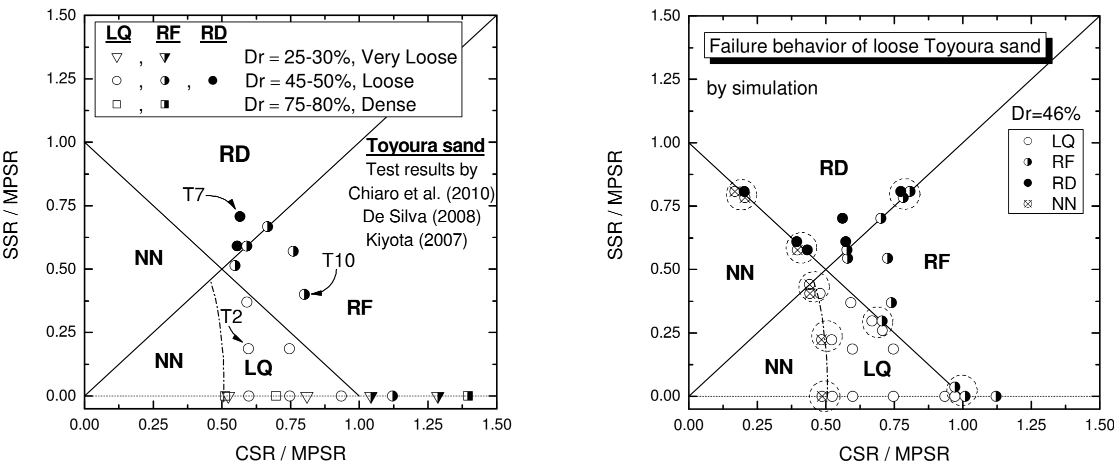


Fig. 4. Definition of boundary conditions

The scheme of the proposed method is shown in Fig. 4. There are four regions that identify the four above described failure modes, which are delineated by the following boundary conditions: (i) $\{(SSR/MPSR)=(CSR/MPSR)\}$ characterizes the boundary between the liquefaction and no-liquefaction zones, as well as the boundary between reversal and non-reversal loading conditions; in fact, in accordance with test results by Chiaro et al. (2010), among others, for liquefaction to occur the reversal of stress during cyclic shearing is necessary; (ii) $\{(SSR/MPSR)+(CSR/MPSR)=1\}$ defines whether the monotonic peak stress state is achieved or not, which is unique irrespective of the soil properties (e.g., relative density, etc), confining pressure and static shear level; (iii) numerical simulation results show that in the case of reversal tests in which the level of cyclic stress is very low, liquefaction occurs after applying even more than a hundred cycles. Therefore, considering that usually an earthquake is characterized by less than 20-30 cycles, under these stress conditions the probability that liquefaction takes place during an earthquake is very limited. Hence, to take the limit of liquefaction into account, an additional boundary that defines whether liquefaction is achieved or not by applying 100 cycles of loading was introduced in the proposed method.

The relevance of the proposed method has been investigated on a wide range of combinations of static and cyclic shear stresses on very loose, loose and dense sand by referring to: (i) the results of undrained cyclic torsional shear tests performed on hollow cylindrical Toyoura sand specimens; and (ii) a number of numerical simulations by employing the elasto-plastic constitutive model developed at IIS.

Fig. 5(a) summarizes the failure behaviors as observed in laboratory tests; on the other hand, Fig. 5(b) shows respectively the predicted failure behavior of the loose samples in Fig. 5(a) obtained by numerical simulations. In the latter plot the additional cases (within the dotted circle) are simulated in order to confirm the validity of the boundary conditions used to define the proposed method.



(a) (b)

Fig. 5. Applicability of the proposed method: (a) Undrained cyclic torsional shear test results; and (b) Results of numerical simulations on loose sand.

CONCLUSIONS

A method to assess the failure behavior (i.e., cyclic liquefaction, rapid liquefaction or residual deformation failure modes) of saturated Toyoura sand specimens with initial static shear under undrained cyclic shear loading is presented. Its applicability has been investigated using a wide range of combinations of static and cyclic shear stresses on very loose, loose and dense sand by referring to: (i) the results of undrained cyclic torsional shear tests carried out on saturated Toyoura sand specimens; and (ii) a number of single-element numerical simulations by employing an elasto-plastic constitutive model developed at the Institute of Industrial Science, University of Tokyo.

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