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New Insights into the Failure Mechanisms of Liquefiable Sandy Sloped Ground During Earthquakes

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ABSTRACT

The effects of initial static shear (i.e. sloped ground conditions) on the liquefaction resistance of sand have long been investigated. Nevertheless, there are still uncertainties regarding its role on the failure mechanisms (i.e. failure induced by liquefaction and/or brought about a large deformation extent) of sand subjected to undrained cyclic shear loading. In this paper, to address this issue and to provide new insights into such failure modes, the undrained cyclic torsional simple shear response of loose Toyoura sand specimens undergoing various levels of initial static shear was examined. From the result of this study, the key factors governing the occurrence or not of liquefaction and shear failure of sand were identified and a simple and practical procedure was proposed for predicting the failure modes observed for loose Toyoura sand specimens under various levels of combined static and cyclic shear stresses in undrained torsional simple shear tests.

Introduction

Due to the presence of static shear, a soil element underneath sloped ground can experience partially-reversed or non-reversed shear stress loading conditions during an earthquake (Fig.1), which can have major effects on the cyclic response of sands. Predicting in a reliable manner the complicated undrained cyclic behaviour of sand within sloped ground is essential to develop effective countermeasures against liquefaction-induced slope failure. Nevertheless, this is not an easy task due to a number of concurrent key factors that need to be considered in the analysis, such as static and cyclic shear stresses, effective mean principal stress level, soil density state, and drainage conditions, loading conditions, etc. This is attempted in this paper.

Although the importance of static shear has been widely recognized, its effects on liquefaction resistance and cyclic strength have not been fully understood yet. According to the results of cyclic triaxial tests, the presence of initial static shear may be beneficial to the liquefaction resistance (Lee and Seed, 1967; Castro and Poulus, 1977; Vaid and Chern, 1983; Hyodo et al., 1991 and 1994; Vaid et al., 2001; Yang and Sze, 2011; etc). On the contrary, laboratory tests using simple shear conditions, which provide a better representation of stress in the field during earthquake shaking, have indicated the opposite tendency, implying that resistance against liquefaction is drastically reduced by static shear existence (Yoshimi and Oh-oka, 1975; Vaid and Finn, 1979; Tatsuoka et al., 1982; Chiaro et al., 2012). Moreover, while in these studies

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various types of failure modes (i.e. failure due to liquefaction or failure brought about by large extent of deformation) have also been reported, there are still uncertainties regarding the key role of initial static shear on the modes of failure of sand subjected to undrained cyclic loading (Hyodo et al., 1991; Yang and Sze, 2011; Chiaro et al., 2012).

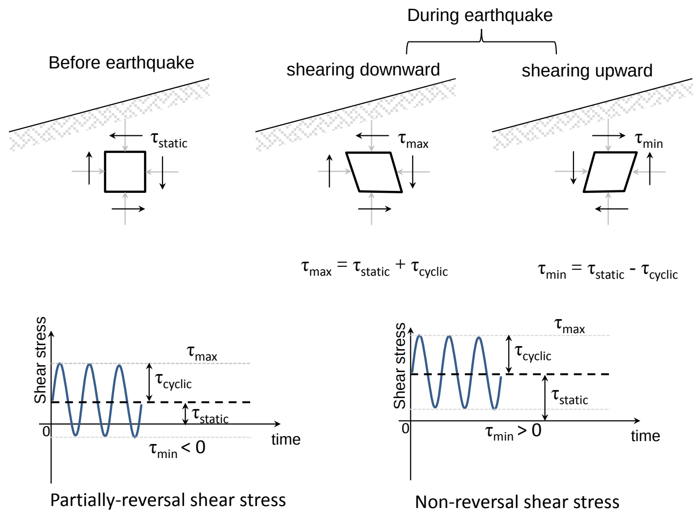

Figure 1. Stress conditions in sloped ground during earthquakes

In this paper, aimed at providing an insight into such failure mechanisms, the undrained cyclic torsional simple shear response of loose Toyoura sand specimens undergoing various levels of initial static shear investigated by the Authors (Chiaro et al., 2012) was further analysed. The key factors governing the occurrence or not of liquefaction and shear failure of sand were identified. Also, a simple and practical procedure was proposed for predicting the failure modes observed for loose Toyoura sand specimens under reversal and non-reversal stresses in undrained torsional simple shear tests. As far as the simple shear conditions are employed, this method can be used in the preliminary assessment of failure mechanisms of natural and artificial slopes or to analyse failures observed for sloped ground during past earthquakes.

Test apparatus, material and procedure

Torsional shear apparatus on hollow cylindrical specimen is recognized to be a good tool to properly evaluate liquefaction soil response (e.g. Tatsuoka et al., 1986; Arangelovski and Towhata, 2004). In particular, it offers the possibility to reproduce simple shear conditions, which are a close representation of field stress conditions during earthquakes. In this study, to achieve double amplitude torsional shear strain levels exceeding 100%, the torsional shear apparatus on hollow cylindrical specimens shown in Fig. 2 was employed. Large torsional deformations were measured by using a potentiometer with a wire and a pulley. The torque and axial load were detected by using a two-component load cell, which is installed inside the pressure cell. All the tests were performed on Toyoura sand, which is a uniform sand with negligible fines content (G_s = 2.656; e_{max} = 0.992; e_{min}= 0.632; F_c = 0.1%). Several medium-size hollow cylindrical specimens with dimension of 75 mm in outer radius, 45 mm in inner radius and 300 mm in height were prepared by air pluviation method at a relative density of about 50%.

After being saturated, the specimens were isotropically consolidated by increasing the effective stress state up to 100 kPa, with a back pressure of 200 kPa. Subsequently, a specific value of initial static shear was applied by drained monotonic torsional shear load. Finally, to replicate seismic conditions, a constant-amplitude undrained cyclic torsional shear stress was applied at a shear strain rate of 0.25%/min. The loading direction was reversed when the amplitude of shear stress, which was corrected for the effect of membrane force (Chiaro et al., 2012), reached the target value. During the process of undrained cyclic torsional loading the vertical displacement of the top cap was not permitted with the purpose of simulating as much as possible the simple shear condition that ground undergoes during horizontal excitation.

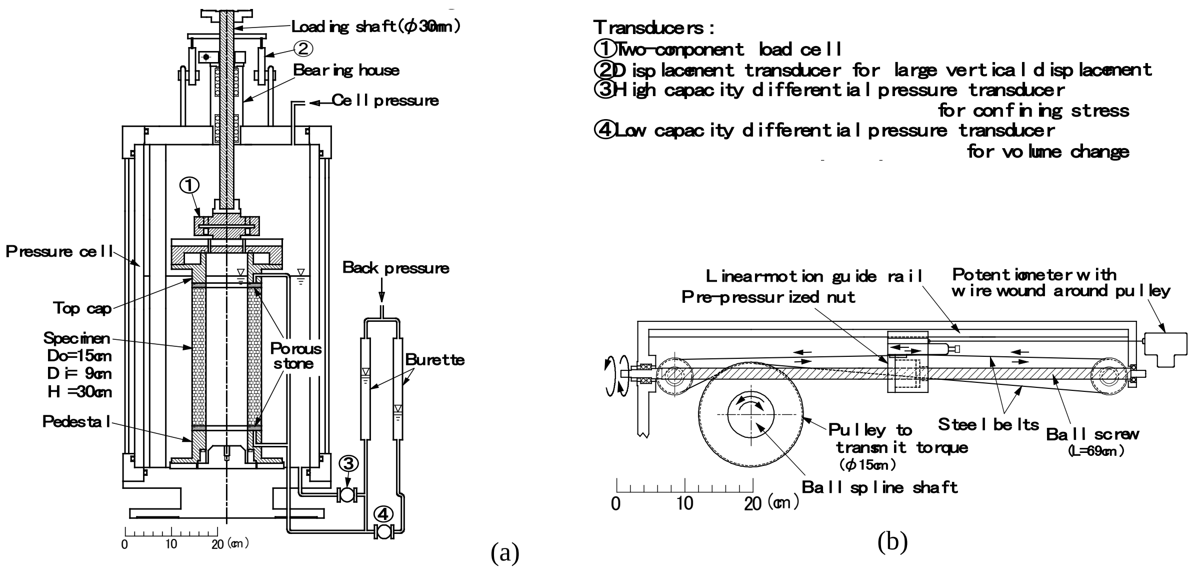

Figure 2. (a) Torsional shear test apparatus on hollow cylindrical specimen used in this study; and (b) plan view of torque-transmission part (after Kiyota et al., 2008)

Undrained cyclic response observed under reversal stress conditions

Under reversal stress conditions liquefaction is likely to occur (Hyodo et al, 1991; Yang and Sze, 2011, etc.), but its severity and consequent deformation development may vary significantly as described in detail hereafter. To investigate these issues, the cyclic undrained response of several isotropically consolidated specimens undergoing reversal stress conditions is analysed in terms of change in excess pore water pressure (PWP) and development of torsional shear strain with number of cycles.

Cyclic liquefaction behaviour and potential large shear strain development

Fig. 3 shows the results of two tests in which progressive excess PWP generation besides a nearly zero shear strain development was observed until the full liquefaction state is reached at Δu = 100 kPa. Yet, significantly, after this point (i.e. post-liquefaction state), a sudden development of large shear strain clearly took place. This type of undrained cyclic response, which potentially may induce large post-liquefaction flow deformations, is commonly observed in loose/medium sands exhibiting a stable behaviour under monotonic loading (Fig. 5a).

Precisely, it is referred to as ***cyclic liquefaction*** (Chiaro et al., 2012) and may occur only if both the following two conditions take place concurrently: (i) reversal stress conditions ($\tau_{min} = \tau_{static} - \tau_{cyclic} < 0$); and (ii) maximum shear stress applied ($\tau_{max} = \tau_{static} + \tau_{cyclic}$) does not exceed the undrained shear strength of sand (τ_{und}). From a practical point of view, this kind of behaviour would be observed in the field only if an earthquake is strong enough to produce a considerable number of cycles (e.g. N = 15) and adequate shear stress amplitude to trigger liquefaction and subsequent large deformation development.

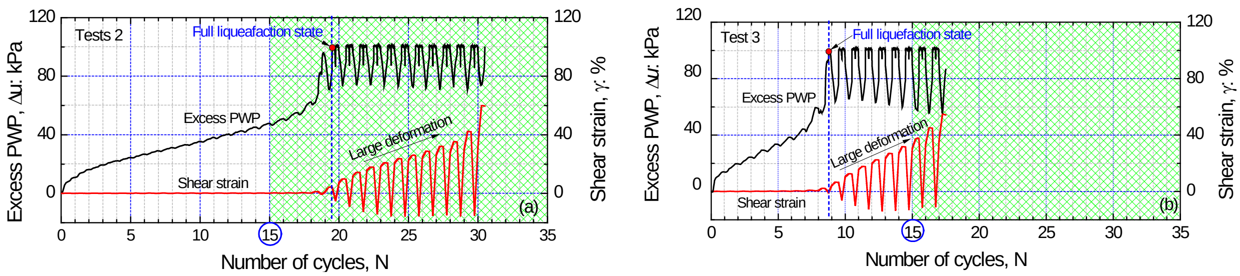

Figure 3. Cyclic liquefaction behavior: (a) Test 2 (τ_{static} = 5 kPa; τ_{cyclic} = 16 kPa; p_0' = 100 kPa; D_r = 45.5%) and (b) Test 3 (τ_{static} = 10 kPa; τ_{cyclic} = 16 kPa; p_0' = 100 kPa; D_r = 46.6%)

Liquefaction induced extremely large deformation behaviour (rapid flow liquefaction)

Instead, in the test shown in Fig. 4, immediate excess PWP generation was observed (i.e. full liquefaction state at Δu = 100 kPa was achieved in less than one cycle) and rapid development of large shear strain in less than 8 cycles. Similar to the case previously examined, this abrupt type of undrained cyclic response is also commonly observed in loose/medium sands exhibiting stable behaviour under monotonic loading (Fig. 5b). However, it is referred to as ***rapid flow liquefaction*** (Chiaro et al., 2012) and may occur only if the following two conditions are achieved: (i) reversal stress conditions ($\tau_{min} < 0$); and (ii) maximum shear stress applied (τ_{max}) exceeds the undrained shear strength of sand (τ_{und}). From a practical view point, the above described rapid flow liquefaction behaviour can be activated by a strong earthquake with a magnitude in the range of 7-8, which would produce 10-20 cycles of loading.

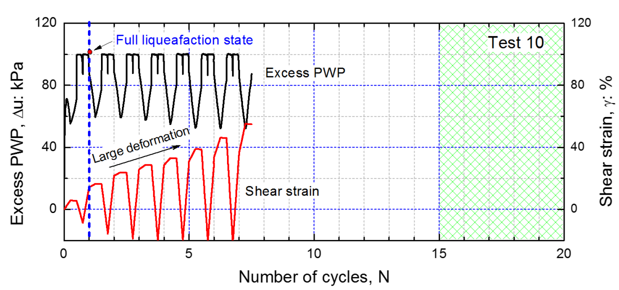

Figure 4. Rapid flow liquefaction behaviour:
Test 10 (τ_{static} = 10 kPa; τ_{cyclic} = 20 kPa; p_0' = 100 kPa; D_r = 45.6%)

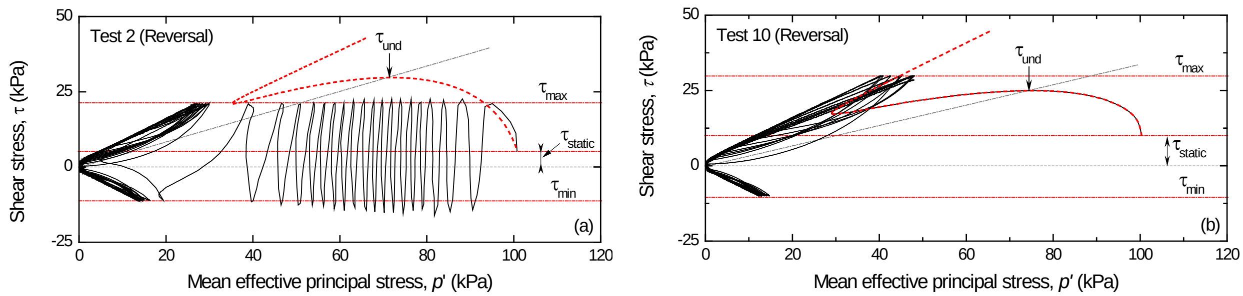

Figure 5. Comparison between cyclic and monotonic behaviours:
(a) Test 2 in Fig 3a ; and (b) Test 10 in Fig. 4

Undrained cyclic response observed under non-reversal stress conditions

Under non-reversal stress conditions, large deformation may bring loose sand to failure (Hyodo et al, 1991; Yang and Sze, 2011; etc.). However, this is not always the case. In fact, under certain conditions, loose sand may be very resistant against cyclic loading and not experience liquefaction nor shear failure as described in detail hereafter.

Accumulation of large residual shear deformation (i.e. shear failure)

In contrast, for the test shown in Fig. 6(a), despite gradual excess PWP generation, full liquefaction state is not reached (i.e. $\Delta u \approx 90$ kPa after more than 30 cycles). However, progressive development of large shear strain of almost 17% in 15 cycles was observed. In the actual tests, such large level of deformation brought the specimen to failure as shown by clear formation of shear band. This type of soil response is referred to as ***residual deformation failure*** or ***shear failure*** (Chiaro et al., 2012) and may happen only if, in conjunction to non-reversal stress conditions ($\tau_{min} < 0$), the maximum shear stress applied (τ_{max}) exceeds the undrained shear strength of sand (τ_{und}), as shown in Fig. 8. Under realistic earthquake conditions, shear failure induced by accumulation of large residual deformation would occur only if an earthquake produces a substantial number of cycles with large stress amplitude and the combined τ_{static} and τ_{cyclic} is significant.

No liquefaction and no failure

Fig. 6(b) refers to the cyclic undrained response of a second loose Toyoura sand specimen undergoing non-reversal stress conditions. In this test, despite undergoing 100 cycles of loading, only very limited excess PWP is generated. Significantly, it may also be observed that the achieved extent of shear strain is also very small (< 0.1 %). This type of ***no liquefaction and no failure*** cyclic behaviour has rarely been reported in the literature for loose sand. It may occur only under non-reversal stress conditions ($\tau_{min} > 0$) if the maximum shear stress applied (τ_{max}) does not exceed the undrained shear strength of sand (τ_{und}), as shown in Fig. 7(b). It may be argued that, in these types of tests, failure can potentially be reached by applying a number of cycles higher than 100. However, it is expected that an earthquake motion of magnitude 7.5-8 will produce no more than 15-20 cycles of uniform-amplitude shear loadings. Consequently, it is rational to state that, a slope of loose saturated sand will not experience failure in the field when shaken by an earthquake producing the same cyclic loading conditions here examined.

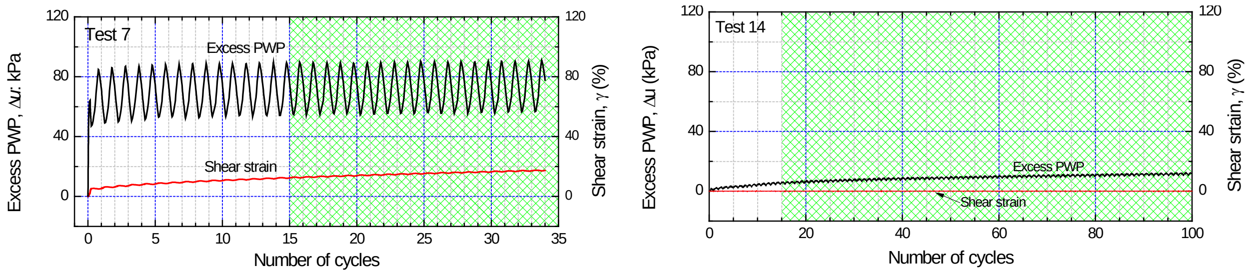

Figure 6. (a) Residual deformation failure (Test 7: $\tau_{static} = 20$ kPa; $\tau_{cyclic} = 16$ kPa; $p_0' = 100$ kPa; $D_r = 45.3\%$); and (b) no-liquefaction and no-failure behaviour (Test 14: $\tau_{static} = 15$ kPa; $\tau_{cyclic} = 12$ kPa; $p_0' = 100$ kPa; $D_r = 52.1\%$)

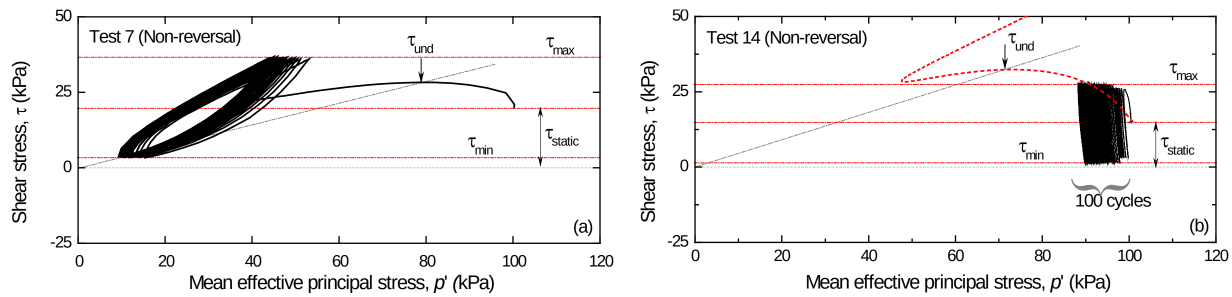

Figure 7. Comparison between cyclic and monotonic behaviours:
(a) Test 7 in Fig 6a; and (b) Test 14 in Fig. 6b

Predicting the observed liquefaction and shear failure behaviours

Prediction of ground failure involving earthquake-induced liquefaction of sloped sandy deposits is vital for researchers and practising engineers to comprehensively understand the triggering conditions and consequences of liquefaction, and to develop effective countermeasures against liquefaction. Nevertheless, it is still a major challenge in geomechanics due to the great number of factors that need to be considered such as initial static shear stress, cyclic shear stress, density state, confining pressure, loading conditions etc. For instance, post-earthquake field investigations and many laboratory tests, including the current one, suggest that soils susceptible to liquefaction consist mainly of saturated uniform sands, which are deposited in loose to medium dense states. Nevertheless, as show in this study, the fact that a soil is susceptible to liquefaction does not guarantee that liquefaction will be triggered during an earthquake. In fact, under non-reversal stress conditions saturated loose sand most likely will not experience liquefaction. Yet, this does not mean that loose saturated sand is very resistant against seismic loading, since a significant magnitude of combined static and cyclic shear stresses may cause failure of soil even though liquefaction does not take place.

To clarify this issue and provide a simple and useful tool for the preliminary assessment of liquefaction and shear failure of loose sand, a practical framework was developed (Fig. 7). It is known that the resistance to liquefaction of sands depends on the soil properties 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 was defined by means of three fundamental parameters namely: (i) static stress ratio, SSR (= τ_{static}/p_0'), which corresponds to the driving shear force induced by the inclination of slopes; (ii) cyclic stress ratio, CSR (= τ_{cyclic}/p_0'), that represents the inertial force exerted by earthquakes; and (iii) undrained shear strength ratio (USS = τ_{und}/p_0'), where τ_{und} is expected to vary depending on initial relative density (D_r) and effective mean principal stress level (p_0'), among other factors.

Therefore, by plotting the experimental data in terms of η_{max} (= (SSR+CSR)/USS) vs. η_{min} (= (SSR-CSR)/USS), a four-zone graph with well-defined boundary conditions was established. Each zone corresponds to the liquefaction/failure behaviours above described, namely *rapid flow liquefaction*; *cyclic liquefaction*; *no failure and no liquefaction* and *shear failure*. The identified boundary conditions have clear physical meaning as described henceforward: (A) zero static shear stress line (τ_{static} = 0 or SSR =0) representing the level ground conditions; (B) reversal stress line (η_{min} = 0). For η_{min} < 0 (left hand side of reversal line) liquefaction zone is located, while for η_{min} > 0 (left hand side of reversal line) shear failure zone is found; (C) zero cyclic shear stress line (τ_{cyclic} = 0 or CSR =0) representing the case of no earthquake (i.e. static/monotonic loading conditions); (D) undrained shear strength line (η_{max} = 1). For η_{max} > 1 (above this line) applied stress exceeds the available soil resistance, indicating the occurrence of liquefaction/failure; (E) limit liquefaction line, which defines whenever liquefaction (i.e. Δu = 100%) occurs or not in N cycles of loading. In this study it is defined for N =15 by combining results from experimental data and numerical simulations obtained using a state-dependent cyclic model for liquefiable sand (Chiaro et al., 2011).

As shown by Fig. 7, predictions obtained by the proposed graphical method are in agreement with those experimentally observed, which are shown as different symbols in the figure. Note that, in principle, for dense Toyoura sand as well as other sandy soils with fines or under partially saturated conditions, the soil behaviour may be different from that observed in this study. In such a case, the proposed methodology may be not readily applicable. To overcome this issue, the authors plan to conduct more investigations on a variety of sandy soils over a wide range of density states and stress conditions.

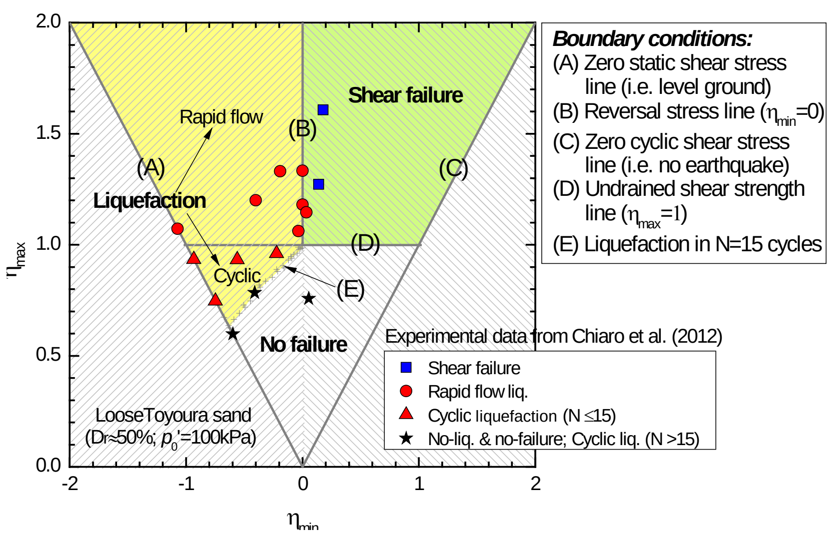

Figure 8. Agreement between observed and predicted failure modes for loose Toyura sand specimens subjected to undrained cyclic torsional shear tests with intial static shear

Conclusions

In this paper, the undrained cyclic torsional simple shear response of loose Toyoura sand specimens undergoing various levels of initial static shear was analysed and an attempt was made to identify key factors that govern failure of sandy sloped ground during earthquake shakings. Based on the difference in the effective stress path and the modes of development of cyclic residual shear strain during both monotonic and cyclic loading behaviours, the observed type of failure were classified into liquefaction (cyclic and rapid flow) and shear failure. In addition, the case of no failure/no liquefaction was also recognised.

Stress loading conditions (i.e. reversal or non-reversal stress), cyclic stress ratio (CSR = τ_{cyclic}/p_0'), static stress ratio (SSR = τ_{static}/p_0') and undrained shear strength ratio (USS = τ_{und}/p_0') were identified as the key factors governing the occurrence or not of liquefaction and shear failure of sand. Under reversal stress conditions, full liquefaction is likely to occur, but its severity and consequent development of extremely large strains will depend on the ratio between the maximum shear stress applied (CSR+SSR) and the undrained shear resistance of sand (USS). On the contrary, under non-reversal stress conditions, liquefaction does not take place and shear failure may be triggered by accumulation of residual deformation only if the maximum shear stress exceeds the undrained shear strength of sand.

Acknowledgements

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