Post liquefaction behaviour of saturated sand under simple shear loading

Comportement après liquéfaction d'un sable saturé chargé en cisaillement simple

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ABSTRACT: A study of post-liquefaction response of a saturated sand under simple shear loading is presented. The effects of initial density, confining stress level, the amplitude of maximum shear strain due to cyclic loading and the sense of post-cyclic strain in relation to that of residual strain due to cyclic loading are systematically assessed. The behaviour is compared under the triaxial loading conditions in order to assess possible stress path dependence of post-cyclic behaviour.

RÉSUMÉ: L'étude de la réponse après liquéfaction d'un sable saturé chargé en cisaillement simple est présentée. Les effets de la densité initiale, du niveau de pression latérale de confinement, de l'amplitude maximale des déformations de cisaillement sous chargement cyclique et la direction de la déformation post-cyclique sont systématiquement évalués. Le comportement sous chargement simple est comparé à celui sous chargement triaxial afin d'étudier la dépendance possible du comportement post-cyclique à la dispersion des forces.

1 INTRODUCTION

There are several documented cases of flow slides and large deformations of overlying structures associated with liquefaction of saturated sands during earthquakes. Comparison of earthquake induced displacements predicted using analytical techniques with those actually measured, in general, show large over-predictions. This has been amply revealed during the large scale liquefaction incidents in the January 1995 Kobe earthquake.

The prediction of earthquake induced displacements requires the knowledge of post-liquefaction behaviour of sand. The current analytical technique have modelled this behaviour within loading cycles by hyperbolic functions, which imply a modulus decreasing with strain (Prevost, 1981; Finn et al., 1986), and the steady state (or residual strength) during post-liquefaction loading remaining unaltered at the pre-liquefaction static value (Byrne et al., 1992). Recent experimental studies in the triaxial test (Vaid and Thomas, 1995), however, have shown that the post-liquefaction response involving transient states of zero effective stress during cyclic loading is, on the contrary, of the type in which modulus continuously increases with strain, and there is no approach to any residual strength equal to the pre-liquefaction value. These contrasting different responses are apparently the cause of overprediction in earthquake induced displacements.

This paper presents a study of the post-liquefaction response of a saturated sand under simple shear loading, characteristic of the shaking of horizontal ground by upward propagating shear waves. The dependence of post-liquefaction behaviour on initial density and confining stress, together with the maximum amplitude of shear strain induced during earthquake loading, and the sense of post-liquefaction strain in relation to the sense of residual strain following liquefaction is delineated in a comprehensive manner. Post-liquefaction response in simple shear is also compared to that reported by Vaid and Thomas (1995) under the triaxial stress conditions in order to emphasize the stress path dependence of post-liquefaction behaviour.

2 EXPERIMENTATION

An NGI type simple shear apparatus (Bjerrum and Landva, 1966) was used to carry out the experiments. The specimen was 71 mm diameter × approximately 20 mm high. The undrained tests were of the constant volume type. The porewater in these tests is always at the atmospheric pressure, and thus the change in total vertical stress during shearing equals the excess porewater pressure generated in an equivalent undrained test (Dyvik et al., 1987).

The test material, Fraser Delta sand, underlies the heavily populated and seismically active Fraser River Delta in Western Canada. The sand is composed of 40% quartz, 11% feldspar, 45% unstable volcanic rock fragments and 4% miscellaneous detritus. The sand fraction passing 1.0 mm sieve and retained on 0.1 mm sieve (98% of the original material) was used in the test program, and was identical to that used by Vaid and Thomas (1995) in parallel studies in the triaxial test.

Test specimens were reconstituted by water pluviation. It has been shown that the sand fabric ensuing upon water pluviation is similar to that of water deposited natural fluvial and hydraulic fill sands (Oda, 1972). Hence, laboratory studies on water pluviated sands provide a convenient method for studying behaviour of natural fluvial and hydraulic fill sands in-situ. Specimens were reconstituted in the loosest state and then densified, if needed, by low energy high frequency vibrations under a small seating load.

3 TEST RESULTS AND DISCUSSION

A comprehensive study of static and cyclic liquefaction behaviour of Fraser Delta sand in simple shear, and its comparison to that observed under the triaxial stress conditions, has been reported by Vaid and Sivathayalan (1996). Herein, post-liquefaction behaviour in simple shear, together with its comparison with that under the triaxial conditions is presented. The softest post-liquefaction response in which the modulus continuously increases with strain ensues when the residual condition following cyclic liquefaction corresponds to a state of zero effective stress (Vaid and Sivathalayan, 1996). This invariably occurred following liquefaction of loose sands, and provided a certain minimum amplitude of shear strain developed during cyclic loading in denser sand.

3.1 *Typical post-liquefaction response following liquefaction-induced by cyclic loading*

Figure 1 shows typical post liquefaction undrained response of loose Fraser Delta sand. The sand had ended in a state of zero effective stress following development of a maximum shear strain amplitude of -10% during cyclic loading (see Fig. 1 for

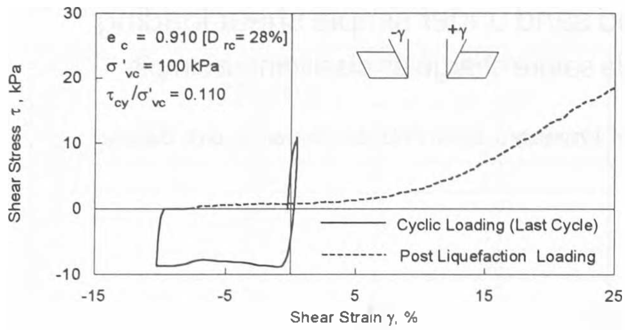

Fig. 1. Post-liquefaction response of sand that had realized a state of zero effective stress.

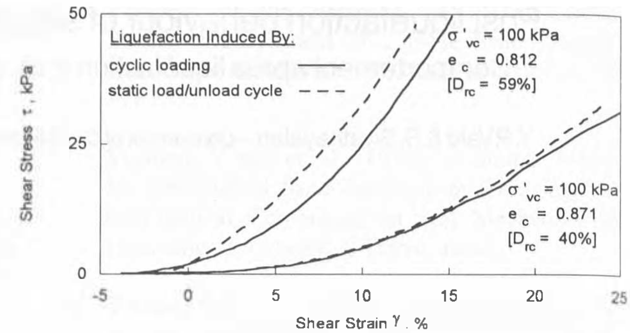

Fig. 2. Post-liquefaction response of sand liquefied by cyclic loading and by static load/unload cycle.

sign convention on shear strain). The residual strain from where post-liquefaction loading commenced was about -8% as a consequence of some strain recovery on final unloading of the peak stress amplitude to zero. Post-liquefaction undrained loading was carried out so as to strain the sand in the direction opposite to the direction of residual strain. As will be shown later, this type of loading resulting in strain reversal yields a much softer stress-strain response than further loading in the direction of residual strain. All post-cyclic data reported herein was of the type that involved strain reversal. The sand may be noted to deform with virtually zero stiffness in the beginning. The stiffness increases with straining, but at a very small rate until about +7% strain, whereafter the increase is at a faster rate. This type of behaviour is also apparent in the stress-strain loops at constant stress amplitude reported by Kuerbis (1985), Ishihara (1985), and in more recent studies by Yasuda et al. (1995) and Pradhan et al. (1995). The phenomenon of increasing stiffness with strain is opposite to the commonly assumed behaviour of soils, where straining is associated with a loss of stiffness. This unusual stress-strain response arises from the fact that on post liquefaction loading, the sand dilates all the way, causing the effective stresses to increase. The deformation occurs at a mobilized friction angle equal to the angle of maximum obliquity noted under static monotonic loading. The stress strain curve beyond about +10% shear strain becomes essentially linear, and there is no tendency towards an approach to a residual strength even after a total post-liquefaction strain of about 35%. For this initial density and stress state (e_c = 0.91, σ'_{vc} = 100 kPa), a residual strength condition was realized at a shear strain level of about 4% to 6% on static loading. The shear stress of 18 kPa at +25% strain in Fig. 1, is much higher than the residual strength of 10 kPa recorded in static loading.

The post-liquefaction response (Fig. 1) consists of three distinctive phases of deformation. In the initial phase the shear stiffness is essentially zero, and thus the sand deforms over a large range of strain without regaining much strength. In the second phase the stiffness increases rapidly that can be approximated by a parabolic function. The final phase is characterized by an essentially constant stiffness as is evident from the virtually linear stress-strain curve.

3.2 *Post-liquefaction behaviour following liquefaction induced by a static load/unload cycle*

The post liquefaction undrained behaviour of Fraser Delta sand liquefied by a static load/unload cycle (residual σ' = 0) is illustrated in Fig. 2. Two specimens reconstituted to different densities were loaded to sufficient strain levels so that on unloading a state of zero effective stress was realized. The post-liquefaction behaviour of identical specimens liquefied by cyclic loading, in which the maximum shear strain developed was approximately equal to that under static loading, are also shown for comparison. In order to facilitate comparison, the response of cyclically liquefied specimens was taken as the reference and so as to match the 2.5 kPa shear stress point on each curve. The post liquefaction response may be noted to be essentially similar at each relative density regardless of the manner by which the state of zero effective stress was realized. Thus, a convenient way of assessing post liquefaction response would be to use a static load/unload cycle instead of cyclic loading, to induce liquefaction. Similar behaviour was reported by Vaid and Thomas (1995) in triaxial tests.

3.3 *Effect of the sense of post-cyclic strain*

Figure 3 shows that the post-cyclic response is profoundly influenced by the direction of post-cyclic strain relative to the sense of residual strain following liquefaction. The behaviour of two essentially identical specimens liquefied by a single load/unload cycle is shown. The initial state corresponded to e_c = 0.890 and σ'_{vc} = 100 kPa, and γ_{max} during loading was 15%. The post-cyclic stress-strain behaviour is much stiffer with no leg corresponding to virtual zero stiffness when strain occurs in the same direction as the residual strain than when there is a strain reversal. The latter is thus much more conducive to the development of large earthquake induced displacement than the former.

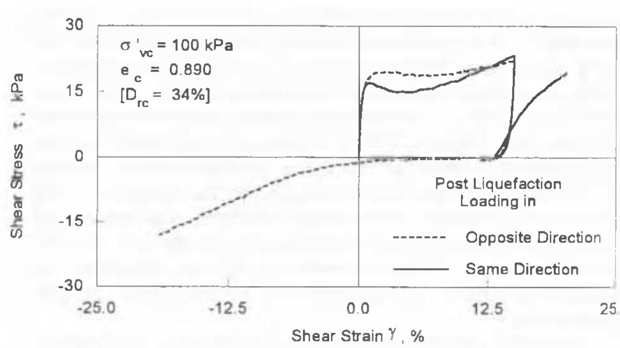

Fig. 3. Effect of the direction of strain prior to post-liquefaction loading.

3.4 *Comparison of pre and post liquefaction response*

Figure 4 compares undrained behaviour of Fraser Delta sand, at identical density and confining stress level, [D_{rc} = 50%; σ'_{vc} = 200 kPa] prior to and following liquefaction. In pre liquefaction (static) loading, the stiffness of the sand decreases with increasing strain level until peak. Beyond the phase transformation (PT) state, (Ishihara, 1975) the stiffness increases with further straining on account of the dilating tendency that is accompanied by an increase in effective stresses. In post liquefaction loading, the contractive (strain softening) region noted under static loading has been eliminated as a consequence of cyclic loading that lead to liquefaction. The post liquefaction response of a sand that is loaded from a state of zero effective stress is always dilative. As pointed out earlier, the stiffness is very small during the initial phase of loading, but increase with

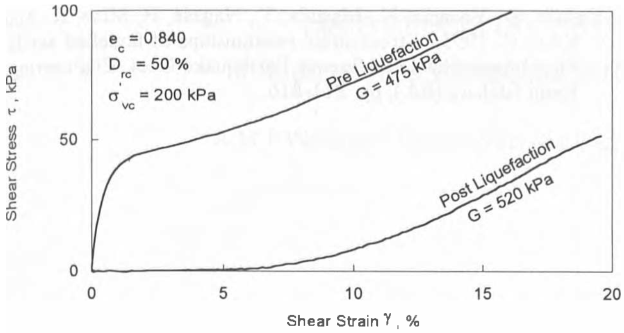

Fig. 4. Comparison of pre-liquefaction and post-liquefaction response.

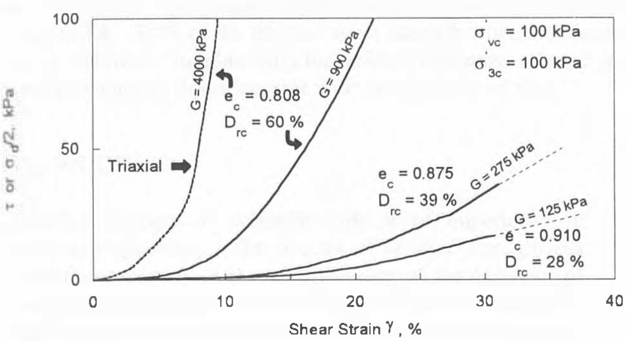

Fig. 5. Effect of relative density on post-liquefaction response.

increasing strain level until it reaches an essentially constant value at large strains. This large strain shear stiffness of the liquefied sand is of the same order of magnitude as the pre-liquefaction stiffness in the post PT state [shear modulus, approximately 500 kPa for the data presented in Fig. 3]. The sand exhibited similar comparative pre- and post-cyclic response at other relative densities and initial confining stresses, regardless of whether it was contractive, or otherwise, during static loading.

3.5 *Effect of relative density on post-liquefaction response*

Figure 5 shows post liquefaction undrained response at three relative densities. All specimens were consolidated to an effective confining stress level $\sigma'_{vc} = 100$ kPa prior to cyclic loading. Following cyclic liquefaction, all ended in a state of zero effective stress. To facilitate comparison of stress strain behaviour at these initial density states, zero strain is taken as the configuration at the conclusion of cyclic loading, with its associated residual strain. It may be noted that the sand initially deforms at virtually zero stiffness, irrespective of the density. However, the rate of stiffness increase is smaller for loose than that for dense sand. Thus, loose sand deforms at essentially zero stiffness over a larger range of strain. The shear strain required to mobilize a finite shear stress of 2.5 kPa was 17%, 13% and 5% at relative densities of 28%, 39% and 60% respectively. At large strains, the stress-strain curves become essentially linear, but the stiffness in this region does increase with relative density. The post-liquefaction deformation proceeds along the line of maximum obliquity observed in static undrained loading, regardless of the initial density state. In post liquefaction deformation analysis, the key factor will be the strain level needed for the sand to mobilize some finite strength. The results in Fig. 5 indicate that other conditions being equal, liquefaction induced displacements will be larger in looser sands. Figure 5 also shows the post-liquefaction response of an identical specimen at $e_c = 0.808$, $\sigma'_{3c} = 100$ kPa in triaxial compression. Even though the characteristics of the stress-strain curve are essentially similar to that in simple shear, triaxial response is much stiffer.

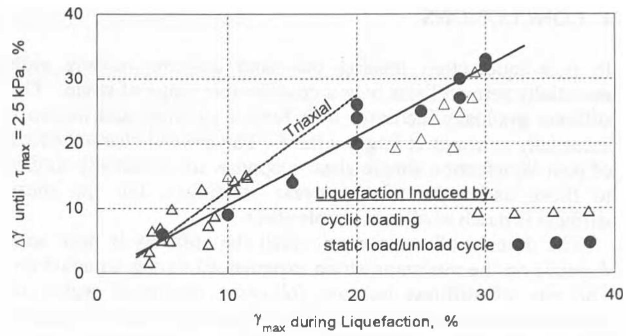

Fig. 6. Variation of Δγ with maximum strain during liquefaction.

3.6 *Effect of maximum strain during liquefaction on post-liquefaction response*

The deformation at essentially zero stiffness in the first phase of post-liquefaction response, is considered to be taking place from the instant of the development of the state of residual zero effective stress until the strain level at which a measurable small shear stress of 2.5 kPa is mobilized. Figure 6 shows the magnitude of shear strain ($\Delta\gamma$) required to mobilize this shear stress of 2.5 kPa as a function of the maximum strain developed during liquefaction (γ_{max}). The data includes all tests regardless of the manner in which liquefaction was induced (cyclic or static load/unload), different initial relative densities and confining stress levels. Static load/unload liquefaction tests, with more than one load/unload cycle are also included. This enabled simulation of successively larger γ_{max} by repeated liquefaction of a single specimen. It is interesting to note that $\Delta\gamma$ is essentially linearly related to γ_{max} only. Clearly, the larger the maximum strain developed during liquefaction, the greater would be the liquefaction induced displacement regardless of the initial density and confining pressure level. It is interesting to note that the relationship between $\Delta\gamma$ and γ_{max} in triaxial loading is essentially identical to that in simple shear.

3.7 *Comparison with triaxial behaviour*

Post-cyclic behaviour of Fraser Delta sand in simple shear is compared with triaxial compression behaviour (Vaid and Thomas, 1995) in Fig. 7, at a relative density of 40%. Only the curved portions of the response, which start at a maximum shear stress of 2.5 kPa and extends to the beginning of the linear segments, are shown. Like triaxial behaviour, simple shear post-cyclic response also does not appear to show a strong dependence on the level of initial confining stress. The shear stiffness under simple shear, however, is considerably smaller than under the triaxial conditions. The use of post-liquefaction data from triaxial tests will, thus, underestimate earthquake induced displacements in horizontal ground that experiences simple shear loading.

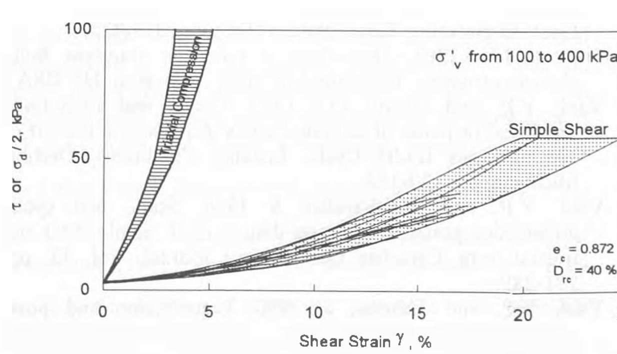

Fig. 7. Comparison of the range of post-liquefaction behaviour in simple shear and triaxial compression.

4 CONCLUSIONS

In post-liquefaction loading the sand deforms initially with essentially zero stiffness over a considerable range of strain. The stiffness gradually increases with further straining and becomes essentially constant at larger strains. The general characteristics of post liquefaction simple shear response are essentially similar to those under the triaxial stress conditions, but the shear stiffness is much smaller in simple shear.

The domain of strain over which the stiffness is near zero depends on the maximum strain experienced during liquefaction. The rate of stiffness increase following the initial region of essentially zero stiffness increases with relative density. The pre-cyclic contractive response, if any, is eliminated as a consequence of excursion through a state of zero effective stress following cyclic liquefaction. There is no tendency towards an approach to a residual strength even after shear strains in excess of 30%. Post liquefaction response does not depend on whether the sand was liquefied by cyclic or a static load/unload cycle.

5 ACKNOWLEDGEMENTS

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