



## CYCLIC RESISTANCE AND POST LIQUEFACTION RESPONSE OF UNDISTURBED IN-SITU SANDS

S. Sivathayalan<sup>1</sup> & Y. P. Vaid<sup>2</sup>

### SUMMARY

Most of our understanding of the nature of the cyclic, and post liquefaction response of sands is derived from controlled laboratory tests on reconstituted specimens. However, the undrained response of soils is dependent on the fabric, in addition to the density, initial stress state, and the stress path during loading. As a result, uncertainties arise when characterizing the response of natural soils in-situ, based on the behaviour of specimens reconstituted in the laboratory, even if appropriate stress states and paths are duplicated.

This paper presents the cyclic and post liquefaction response of in-situ frozen, "undisturbed" sands from alluvial environments and compares them to the response of specimens reconstituted in the laboratory by water pluviation using the same sand. The data presented demonstrate that the response of alluvial in-situ sands may be treated within the same framework established in the literature using water pluviated specimens. The various mechanisms of deformation noted in these "undisturbed" sand specimens were consistent with those observed using pluviated specimens. The process of water pluviation mimics the natural deposition process in an alluvial environment, and as a result produces a fabric similar to that of alluvial sands.

It is shown that post liquefaction response of sand is dilative, even if the sand is contractive and strain softening during the cyclic loading. As a result, post liquefaction shear results in a continually stiffening response. Post liquefaction response is dependent on the density, stress level, and loading mode. The results presented suggest that the residual post liquefaction strength adopted in current practice (based on the empirical relationship between the back calculated shear strength and SPT  $N_{1,60}$  blow counts) is conservative.

### INTRODUCTION

Liquefaction susceptibility of sands is highly dependent on the fabric, stress state and the stress path during loading. Ideally, laboratory tests would be performed on "undisturbed" soil samples by appropriately simulating the field stress conditions. But, obtaining good quality "undisturbed" samples of granular soil deposits is a difficult, and expensive endeavour. As a result, specimens reconstituted in the laboratory are

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<sup>1</sup> Assistant Professor, Dept of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada.

<sup>2</sup> Adjunct Professor, Dept of Civil and Environmental Engineering, Carleton University, Ottawa, ON, and Professor Emeritus, University of British Columbia, Vancouver, BC, Canada.

often used to characterize the soils in-situ. Unfortunately different laboratory reconstitution techniques give rise to different soil fabric that result in different mechanical behaviour. This paper presents the cyclic and post liquefaction responses of in-situ frozen, "undisturbed" sands measured in the laboratory, and compares them to the response of specimens reconstituted in the laboratory by water pluviation using the same sand. Cyclic and post liquefaction undrained tests were carried out under triaxial and simple shear loading modes.

The spatial arrangement of the soil particles and the associated void space, termed soil fabric, plays an important role on the undrained response of sands. This has been clearly demonstrated using specimens reconstituted by different techniques in the laboratory [1, 2], and by comparing the response of reconstituted sands with "undisturbed" sand specimens [3, 4]. Most of our understanding of the undrained behaviour of sands has been based on moist tamped fabric, which strain softens virtually under all loading modes. However, water pluviated sands [5] rarely strain soften under triaxial compression loading [6]. Other reconstitution techniques, such as dry deposition may give rise to a different fabric, and thus different response. The observed differences clearly highlight the need to replicate the in-situ soil fabric in the laboratory if the results of the laboratory tests are to have any relevance to the sands in-situ. The reconstitution method that produces a fabric closest to that of in-situ sands should obviously be the preferred method of specimen preparation for fundamental laboratory studies.

"Undisturbed" sand specimens when restored to in-situ stress levels with minimal disturbance and subjected to in-situ loading paths closely mimic the state of the in-situ soil element. Therefore, the response of such specimens measured in the laboratory will be indicative of the response of the in-situ sand under field loading conditions. Static undrained behaviour of undisturbed in-situ frozen sands obtained from an alluvial environment clearly indicate that natural sands are inherently anisotropic [7]. Such inherent anisotropy is clearly exhibited by specimens reconstituted in the laboratory by water pluviation.

The monotonic undrained response of specimens reconstituted in the laboratory using water pluviation has been found to be qualitatively and quantitatively similar to that of the undisturbed alluvial sand specimens [3]. Both, undisturbed and water pluviated sands were found to be much more contractive in triaxial extension loading compared to triaxial compressions loading. Water pluviation technique yields uniform specimens only in relatively clean sands, and evidence available in the literature of such equivalence is limited to relatively clean sands. Direction dependent response of undisturbed sands has been reported by Ishihara et al. [8] as well. Hoeg et al. [4] have reported that moist tamped specimens paint a conservative and misleading picture of the in-situ strength of sands. They studied the response of silty sands, and concluded that moist tamped specimens should not be used to characterize the behaviour of in-situ soils.

The equivalency noted in the static undrained behaviour of undisturbed and water deposited sands is an indication that both sands possess similar fabric. Even though evidence available in current literature is mostly limited to monotonic loading, such similarities can be expected in cyclic and post cyclic loading as well, if field stress conditions are appropriately replicated. This paper presents the results of an experimental study to support this contention. A direct assessment of the cyclic and post liquefaction response of undisturbed in-situ frozen sands is made and the response is compared to that of the specimens of the same sand reconstituted by water pluviation in the laboratory. Cyclic resistance of undisturbed and water pluviated sands is evaluated and compared in simple shear, and the post liquefaction behaviour is compared under triaxial and simple shear loading modes.

## EXPERIMENTATION

An NGI type simple shear apparatus [9] was used to carry out cyclic and post liquefaction simple shear tests on approximately 70mm diameter x 20mm high specimens. Simple shear specimens are enclosed in steel reinforced rubber membranes, and thus can only develop insignificant lateral strains. The pore space in simple shear is open to atmosphere, and constant volume conditions are enforced during the shearing phase. The change in total vertical stress during shear in a constant volume simple shear test equals the excess pore pressure generated in an equivalent undrained test [10]. Cyclic shearing was applied under stress controlled loading mode, and post liquefaction loading under displacement control.

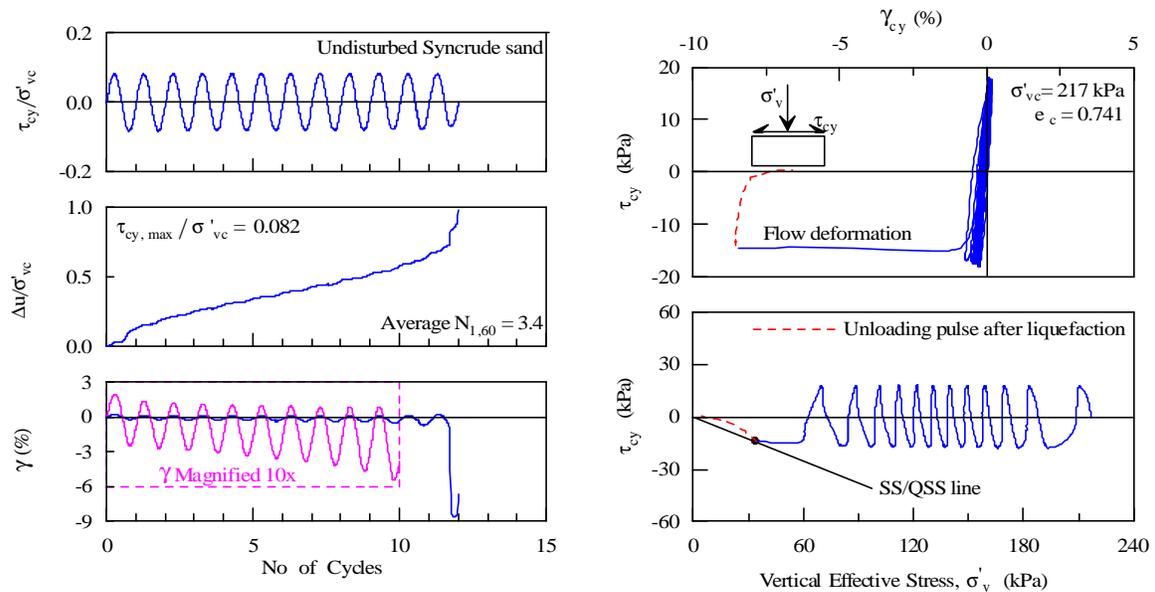
Post liquefaction response was also assessed under triaxial loading using the UBC cyclic triaxial device [11]. Triaxial tests were performed on approximately 63mm diameter by 125mm high specimens under displacement controlled loading. Liquefaction was triggered in triaxial specimens by static unloading following monotonic shearing to relatively large strain levels (5 to 10% axial strain). High resolution transducers and high speed 16 bit data acquisition system were used to accomplish confident measurements of strains with a resolution of about  $10^{-4}$  and stresses with about 0.2 kPa, both in triaxial and simple shear tests.

Undisturbed in-situ frozen sand specimens were obtained from three different sites (two natural sand deposits in the Fraser River Delta in British Columbia named Kidd and Massey sands herein, and one hydraulically placed tailings sand deposit in Alberta, named Syncrude sand) as part of the Canadian Liquefaction Experiment (CANLEX) cooperative research endeavour. Details of in-situ ground freezing, sampling and trimming techniques used in the CANLEX program are given in Hofmann [12]. Alternate thaw and consolidation techniques were evaluated to determine the method that would minimize the disturbance. Sivathayalan and Vaid [7] detail the setup procedure, and the methodology used to thaw and consolidate the specimens to the in-situ stress state.

### BEHAVIOUR OF UNDISTURBED SANDS UNDER CYCLIC SHEAR

Fundamental studies using reconstituted sand specimens have identified three different mechanisms that can be responsible for the development of large strains under cyclic loading [13]. The mechanism of true liquefaction and limited liquefaction are characteristic of sands that strain soften under static loading. Large deformations develop due to contractive deformation in both of these mechanisms. On the other hand, large deformations may develop during cyclic loading in dense, strain hardening sands on account of cyclic mobility associated with dilation. Similar characteristics were noted in undisturbed sands, depending on density and stress state.

Figure 1 shows typical response of undisturbed sand that strain softens during cyclic loading. The variation of the applied cyclic shear stress, and the developed excess pore pressure ratio and shear strain are plotted against the load cycles. In addition the stress strain curve and the cyclic stress path for the test are also

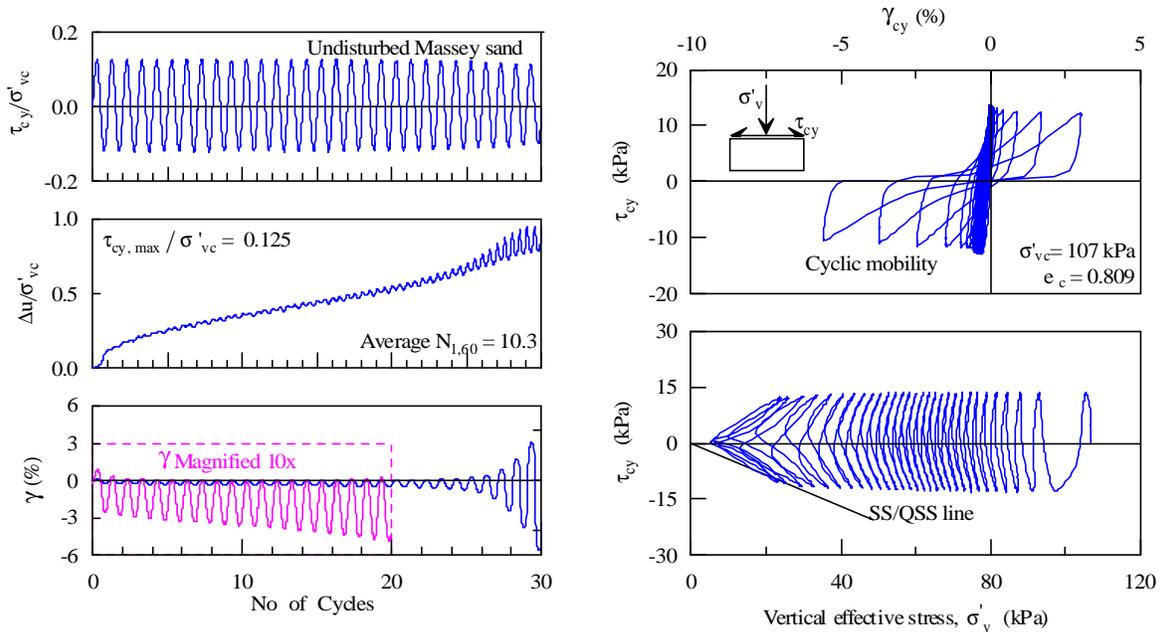


**Figure 1: Strain development due to contractive deformation in undisturbed Syncrude sand leading to flow failure.**

shown in the Figure. The sand develops just over half a percent maximum shear strain in the first 11 cycles, but suddenly “flows” in the 12<sup>th</sup> stress cycle. This type of response is typical of loose strain softening sands. These characteristics of deformation in undisturbed sand are similar to the “*true liquefaction*” type of deformation noted in reconstituted sands [13, 14]. The excess pore pressure continually increases during cyclic loading indicating no dilation during any state of the undrained shear. The triggering of strain softening leads to a steady state of deformation under constant effective and shear stresses. The sand would have deformed continually at this stress state (with an excess pore pressure of 84%), if not for the unloading stress pulse associated with the dynamic loading event. This unloading from the steady state induces 100% excess pore pressure, and thus a state of zero effective stress. The stress ratio mobilised at steady or quasi-steady state in monotonic loading is shown by the SS/QSS line in the stress path diagram. The effective stress ratio (and thus the friction angle) corresponding to the steady state of deformation under cyclic loading can be noted to be essentially equal to that under static undrained shear. Specimens reconstituted by water pluviation also exhibit similar equivalency between static and cyclic loading modes.

Several standard penetration (SPT) and cone penetration (CPT) tests were performed at this site within a radius of about 3m from the location of the bore hole for the undisturbed sample. The standard penetration test  $N_{1,60}$  values from four different bore holes at the elevation of the tested specimen were 2, 3, 3, and 4, and the cone bearing was about only 20 bars [15]. Such a low  $N_{1,60}$  value is consistent with the sand liquefying at a low cyclic stress ratio of 0.08 at a confining stress level of about 200 kPa.

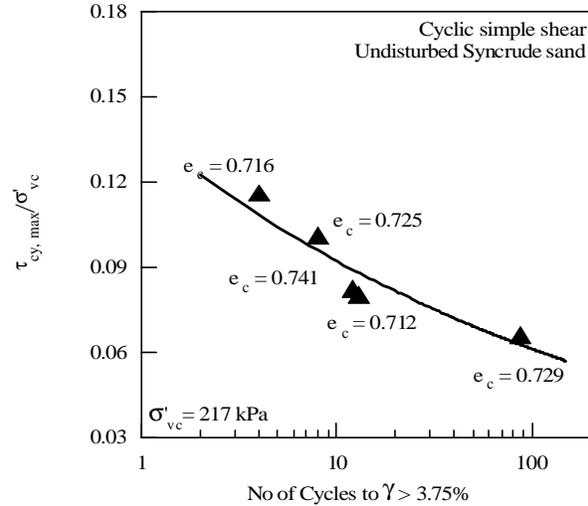
The behaviour of a dilative undisturbed sand specimen under cyclic shear is shown in Figure 2. The sand gradually develops larger strains, and is deemed to have liquefied after 30 stress cycles based on the strain criterion ( $\gamma > 3.75\%$  single amplitude shear strain) for liquefaction. Strain development is small until the pore pressure exceeds about 70%. This is consistent with the findings of Seed [16] that large strains develop only after the excess pore pressure exceeds about 60%. The maximum strain developed increases essentially linearly with loading cycles until about the 24<sup>th</sup> cycle (which corresponds to about 60% excess pore pressure development), but maximum strain increases exponentially with load cycles subsequently. Unlike in the tests on loose sands, the excess pore pressure can now be noted to go through cycles of increasing and decreasing phase. This implies that the sand is dilating during the loading pulses of the cyclic shear and contracting during the unloading pulses. The stress-strain loops noted in this undisturbed sand are typical of the reconstituted sands under cyclic mobility. The standard penetration test  $N_{1,60}$  values measured in two



**Figure 2: Strain development due to cyclic mobility in dilative undisturbed sand**

different bore holes at the elevation of the tested specimen were 12 and 8, and the cone bearing was about 50 bars [15].

The primary interest in cyclic behaviour of sands is the number of stress cycles of a given shear stress amplitude required to induce liquefaction. This cyclic resistance of sands is often expressed in the form of cyclic stress ratio vs number of load cycles. Figure 3 presents one such cyclic resistance curve for undisturbed Syncrude sand at a vertical consolidation stress of 217 kPa. There is no control over the void ratio of the undisturbed specimens, and therefore specimens with void ratios within a small range ( $e_c = 0.725 \pm 0.015$ ) were considered in defining the cyclic resistance curve. The rate of decrease in cyclic stress ratio with number of cycles is similar to those observed in the cyclic resistance curves of water deposited sands.

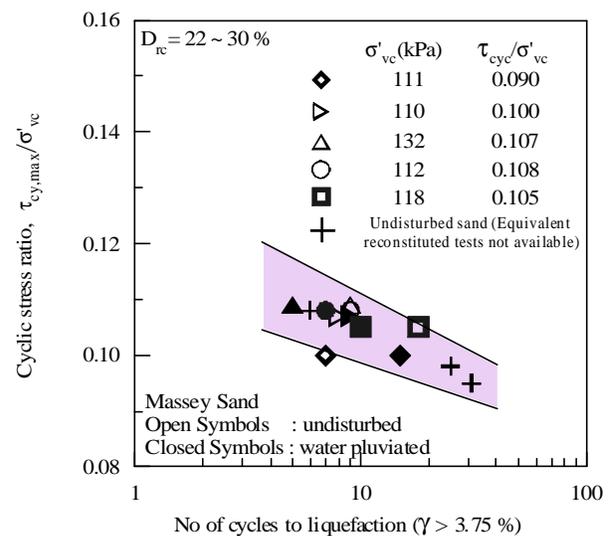


**Figure 3: Cyclic resistance of undisturbed Syncrude sand under simple shear loading**

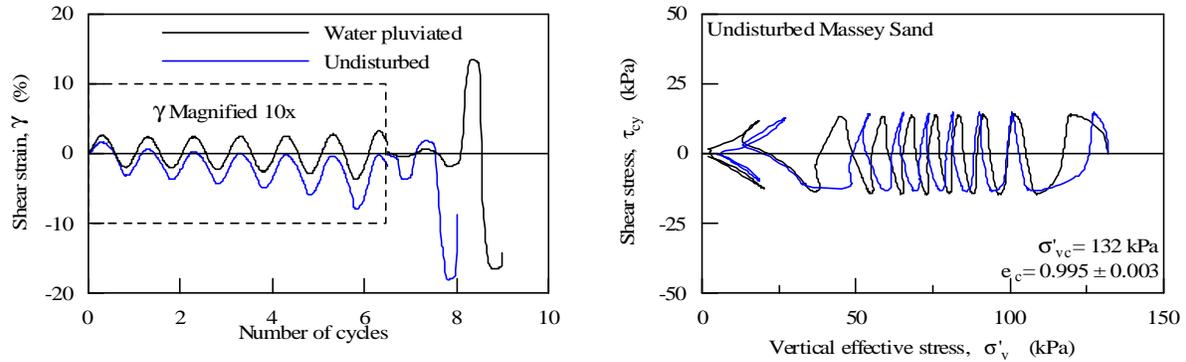
The equivalence in the cyclic resistance of undisturbed and water pluviated sands were assessed by performing cyclic simple shear tests on equivalent undisturbed and water pluviated specimens. Reconstituted specimens were formed using the entire solids retrieved at the end of the test on the undisturbed specimens. These reconstituted specimens were formed at a target initial density, such that the void ratio at the end of consolidation to the same stresses as the undisturbed sand would be close to that of the undisturbed sands. Thus, the initial stress and density states are virtually identical between the undisturbed and reconstituted specimens, and soil fabric is the only variable. The specimens were then subjected to the same cyclic shear stress amplitude as the undisturbed specimens until liquefaction. The undisturbed Massey sand specimens were sampled from adjacent boreholes within a radius of about one metre at depths ranging from about 10m to 13m. The specimens were consolidated under  $K_0$  conditions to the in-situ vertical effective stress (which varied between 110 kPa and 132 kPa depending on the depth) prior to the application of cyclic shear.

The cyclic resistance of undisturbed and equivalent water pluviated Massey sands is presented in Figure 4. Data in the Figure falls within a narrow band indicating that the cyclic resistance of the undisturbed sands is reasonably similar to that of water pluviated sands. The essential equivalence in cyclic resistance is an indication that specimens reconstituted by water pluviation in the laboratory produces a fabric similar to that of the natural in-situ fabric of the Massey sand. Data in Figure 4 correspond to relative density states of  $26 \pm 4\%$ , and effective confining stress levels of  $121 \pm 11$  kPa. Even though these variations are minor and would not significantly affect the cyclic resistance they could be responsible for part of the scatter noted in Figure 4.

The actual shear strain and excess pore pressure development within each loading cycle in an undisturbed and an equivalent water pluviated sand specimen is compared in Figure 5. The undisturbed sand developed strains in excess of 3.75% in the last half of the eighth cycle, and the water pluviated counterpart developed large strains in the first half of the ninth cycle. Strain development was very small



**Figure 4: Comparison of cyclic resistance undisturbed and equivalent water pluviated sands**



**Figure 5: Comparison of effective stress path, and strain development in undisturbed and equivalent water pluviated sand**

until the end of the sixth cycle, and the large strains developed suddenly during the last cycle in both cases. The characteristics of the effective stress path during cyclic loading are similar, and significant excess pore pressures developed only during the last two cycles. This illustrates that in addition to the cyclic resistance, the deformation mechanism during cyclic loading is also similar between undisturbed and water pluviated sands.

Previous studies [1, 2] have shown that the cyclic resistance of sands is highly dependent on the method of specimen reconstitution (that controls the ensuing fabric in the laboratory). The cyclic stress ratio required to induce liquefaction in a given number of stress cycles (at a given density and confining stress level in a given sand) has been reported to vary by well over 100% depending on the soil fabric [2]. The scatter noted in Figure 4 is relatively insignificant and represents only about 10% variation in the cyclic stress ratio required to induce liquefaction in a given number of load cycles. Given that fabric is the only variable between the undisturbed and water pluviated sands, this clearly demonstrates that the fabric of the in-situ Massey sand is duplicated by the process of water pluviation in the laboratory. This study provides a direct evidence that water pluviated specimens closely duplicate the response of undisturbed in-situ sands under cyclic loading. The results presented in Figure 4 indicate that specimens reconstituted in the laboratory by water pluviation may be confidently used to assess the liquefaction susceptibility of in-situ sands under cyclic loading conditions. This would provide an inexpensive alternative to obtaining undisturbed sand sample for site specific characterization of cyclic resistance.

### LIQUEFACTION INDUCED DISPLACEMENTS

The initial attempts to model the seismically induced displacements treated the failed sand mass as a rigid plastic system [17]. Newmark's method was later refined and extended by several researchers [18-20]. Improved analytical techniques using effective stress analysis modelled the behaviour within loading cycles assuming hyperbolic stress strain relationship that implies modulus degradation [21, 22]. The usage of hyperbolic stress strain model was based on the observed modulus degradation with strain in sands during pre liquefaction, virgin loading. Systematic attempts to understand the mechanics of deformation of the liquefied soil have been rare, and an empirical approach based on case studies [23] has been widely used in practice to estimate the undrained strength of the liquefied soil. This database has been modified by Seed and Harder [24] to include more case studies. There are several uncertainties associated with this data since the undrained strength values were back calculated using limit equilibrium analyses assuming different failure surfaces to determine the lower bound strength. There is a very large scatter in the Seed and Harder data, and strength values between the lower bound and the 33<sup>rd</sup> percentile are often used by practising engineers [25]. However, direct site specific assessment of the post liquefaction behaviour at Duncan Dam, British Columbia has indicated that Seed's lower bound residual strength values are very conservative [26].

The first comprehensive study of the behaviour of liquefied soil in the laboratory revealed that the stress-strain characteristics of liquefied sand is considerably different from that of virgin sand [27]. Based on triaxial compression and extension tests on water pluviated sand, three distinct phases of deformation in liquefied sand as noted in Figure 6 were identified. During the early stages of post liquefaction deformation, the liquefied sand has a very small, essentially zero initial modulus, especially if liquefaction results in close to 100% excess pore pressure development. The initial modulus of the liquefied soil is several orders of magnitude smaller compared to the initial modulus of virgin sand. Considerable deformation occurs during this stage with negligible strength mobilisation. In stage two, the modulus increases with increasing strain, and the sand gradually mobilises its strength. Upon further straining the modulus reaches an essentially constant value that was noted to be close to that of the modulus at large strains in virgin loading.

Post liquefaction behaviour of sand in plane strain simple shear, in contrast to axisymmetric triaxial compression, also reveal similar stress strain characteristics with three distinct phases of deformation [28]. These studies further illustrate a dependency of the post liquefaction behaviour on the relative density of the sand, and on the loading mode. Figure 7 shows the range of post liquefaction response measured by Vaid and Thomas [27] at different initial density and confining stress levels during post liquefaction shear in triaxial compression and extension. The region of deformation at essentially zero stiffness has not been shown for clarity. Increasing density can be noted to yield higher strength at smaller strains. Considerable differences can also be noted between the range of response in compression and extension at a given density. This suggests that the initial inherent and subsequently induced anisotropic fabric has not fully disintegrated as a result of liquefaction, and it leads to direction dependant response even in the liquefied soil. The post liquefaction behaviour of sand liquefied by a static load/unload cycle has been reported to be similar to that liquefied by cyclic loading, at the same density and confining stress level [27, 28].

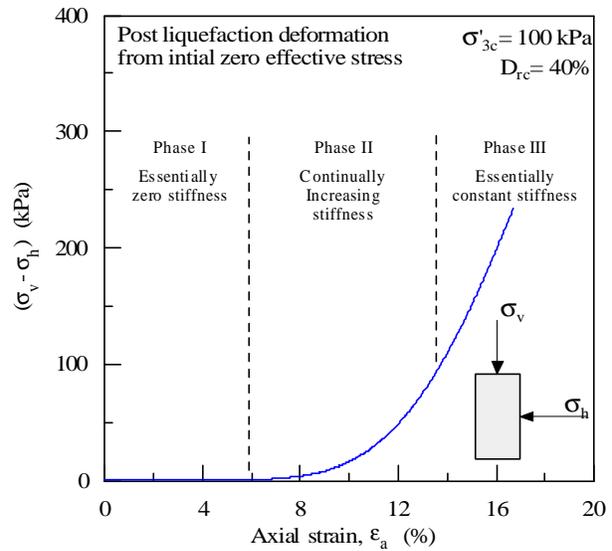


Figure 6: Post liquefaction stress-strain response of reconstituted Fraser River sand

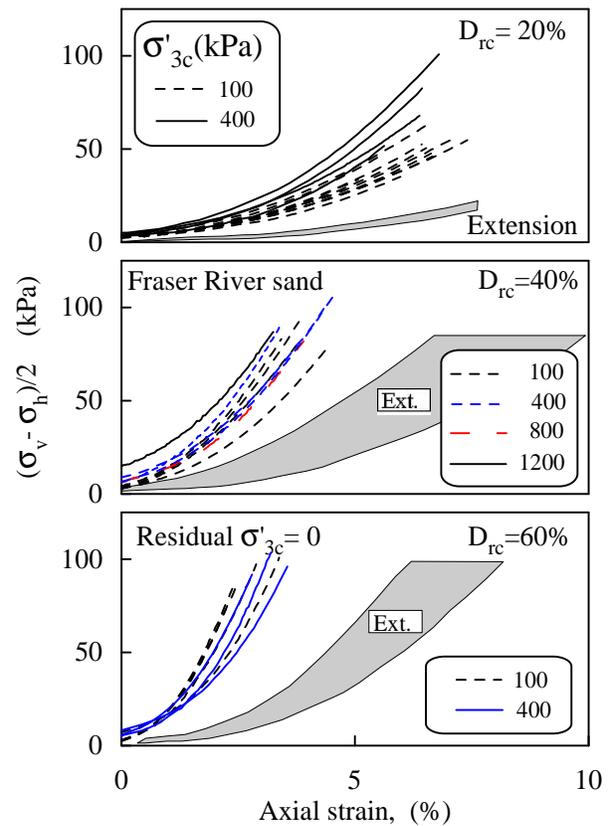
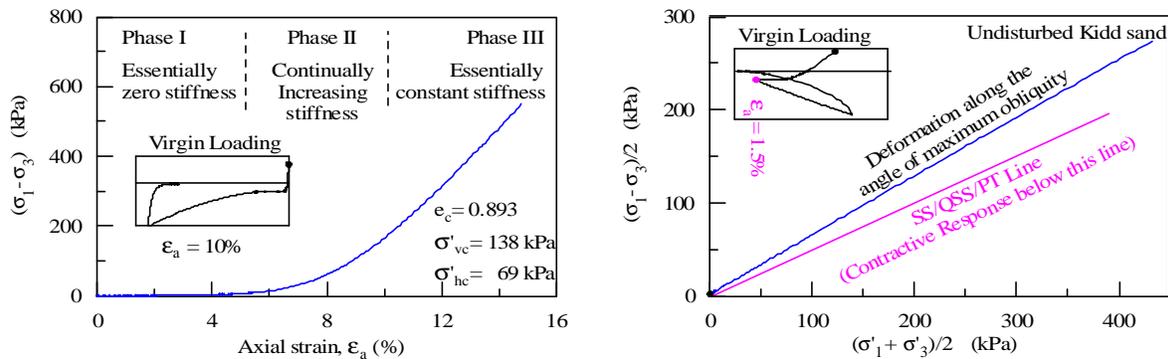


Figure 7: Range of post liquefaction response in triaxial loading (after Vaid & Thomas 1994)

## POST LIQUEFACTION RESPONSE OF UNDISTURBED SANDS

Figure 8 shows the post liquefaction stress strain curve, and stress path of undisturbed in-situ frozen Fraser Delta sand. The sand was loaded to about 10% axial strain in triaxial extension and then liquefied by static unloading. Upon unloading it developed almost 100% excess pore pressure, and was loaded at a constant rate of strain in post liquefaction. The sand deforms at essentially zero modulus and zero shear strength up to about 4% axial strain. Beyond this strain level the modulus increases with increasing strain, and the sand mobilises about 100 kPa shear stress at about 10% axial strain. The modulus remains essentially constant with further shearing. These characteristics are very similar to those observed in water pluviated sands [27]. The stress path in post liquefaction traverses along the line of maximum obliquity noted under static loading as the sand dilates all the way from a state of zero effective stress. There is no tendency towards a residual state even after shear strains in excess of 20%. The shear strength at the end of the tests was a high 240 kPa on account of the strong dilative response in post liquefaction loading, even though the initial confining stress was a low 70 kPa.

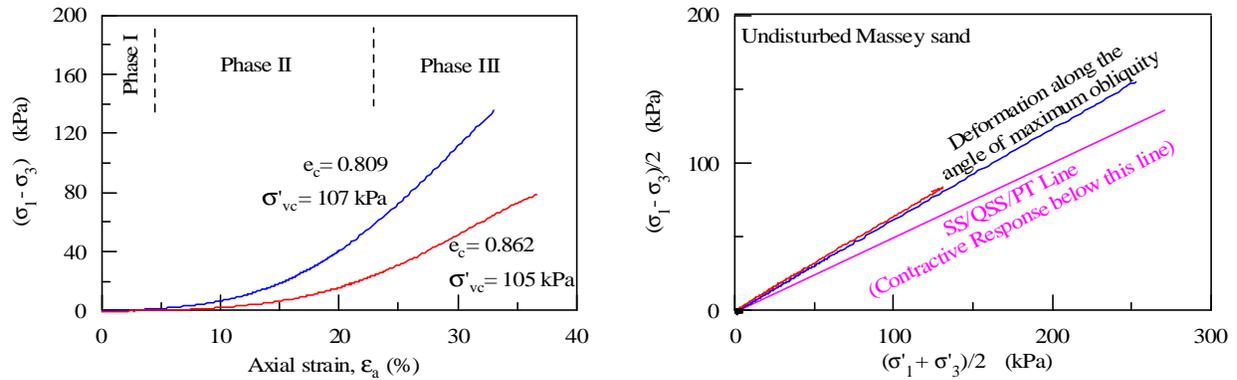


**Figure 8: Post liquefaction response of undisturbed Fraser Delta sand**

The phenomenon of increasing stiffness with strain is opposite to the commonly assumed behaviour of soils, where straining is associated with a reduction in modulus. However, such an increase in modulus with strain, but to a limited level, can be noted in the literature even during cyclic loading of the sands [13]. Just prior to the triggering of liquefaction by the static unloading pulse the specimen was deforming with an essentially constant tangent shear modulus of about 1.6 MPa in extension mode as shown in the inset in Figure 8. Following liquefaction, and subsequent shearing in triaxial compression the modulus gradually increased to an essentially constant value of about 6.5 MPa which is much higher than the modulus in extension.

The post liquefaction simple shear behaviour of two undisturbed Massey sand specimens at different density states are compared in Figure 9(a). Both specimens were consolidated to essentially identical effective confining stresses and were subjected to the same cyclic shear stress amplitude. The denser sand liquefied in 30 cycles with a maximum shear strain of about 5.5%, and the looser sand in 7 cycles with a maximum shear strain of about 6.5%. Post liquefaction stress strain response can be noted to be significantly influenced by the density level in these otherwise similar sands. However, the response in the stress space is unique, since the angle of maximum obliquity is independent of stress level, density and loading mode [6]. The range of post liquefaction behaviour measured in undisturbed and water pluviated Massey sands shown in Figure 9(b) also reflects the influence of density. In addition, the response of both undisturbed and equivalent water pluviated sands can be noted to be in the same range.

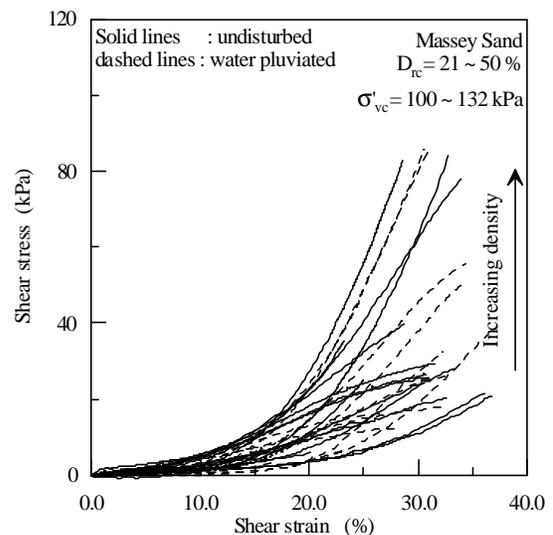
The influence of loading mode on the post liquefaction response is assessed in the data presented in Figure 10. Undisturbed specimens of Syncrude sand consolidated to essentially identical void ratio and confining stress levels were liquefied by static unloading with a maximum shear strain of about 10%. The differences



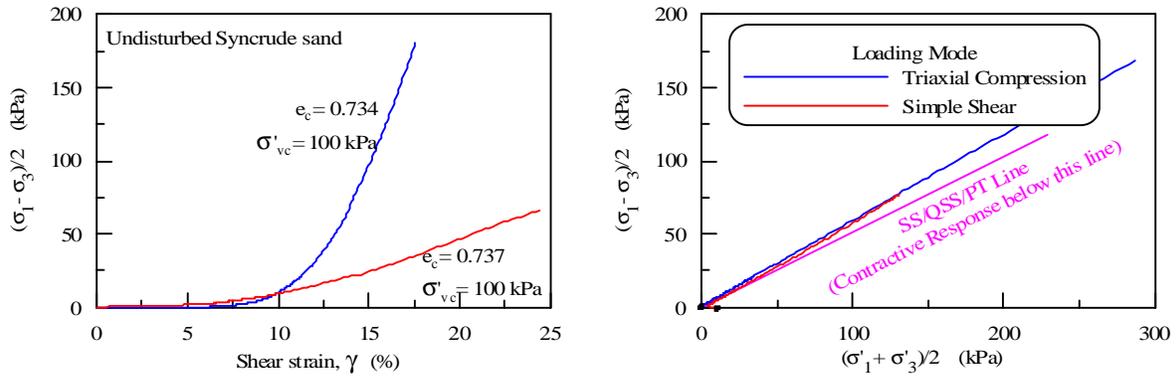
**Figure 9(a): Effect of relative density on the post liquefaction response of in-situ sand**

in the behaviour during the initial phase of deformation at essentially zero stiffness is not very significant. However, the modulus increases at a much faster rate in triaxial compression compared to simple shear during the second phase of deformation. The increase in shear modulus with an increase in density and its dependency on the loading mode are both characteristics of water pluviated sand as well [27, 28]. The sand mobilises a shear strength in excess of 150 kPa in triaxial compression, but only about 50 kPa in simple shear. It is also prudent to note that shear stiffness in simple shear is lower compared to triaxial even in virgin sands. The stress path in post liquefaction shearing, however, is independent of the loading mode, and it moves along the line of maximum obliquity. The uniqueness of the line of maximum obliquity has been well established in the literature. There appears no tendency to reach a residual state either in triaxial compression or simple shear. As noted earlier, the direction dependent post liquefaction stress strain behaviour is an indication that the anisotropic nature of the natural soil is not altered by liquefaction. Both inherent and induced anisotropy contribute to direction dependence in post liquefaction loading. It appears that neither the large shear strain (about 15%) nor the state of zero effective stress has fully altered the anisotropic nature of the undisturbed sand.

The post liquefaction behaviour of undisturbed Syncrude sand under multiple unload-reload cycles is shown in Figure 11. Liquefaction was initially triggered by the development of 100% excess pore pressure by a static load-unload cycle in triaxial extension. On post liquefaction loading in compression the sand required about 8% shear strain to mobilize a shear strength of a mere 5 kPa, before entering the second phase of deformation where the modulus increased with strain. However, after the second unload cycle in compression which also terminated in 100% excess pore pressure, the sand mobilized the same 5 kPa strength in only about 1% strain in its subsequent reloading in compression. This implies that the amount of post liquefaction deformation required for the sand to exhibit commencement of any appreciable modulus increase with strain is dependent on the sense of post liquefaction loading with reference to the loading that induced liquefaction. A change in the direction of strain increment upon liquefaction results in an increase in modulus compared to straining in the same direction. The shear modulus during the third phase of deformation in each cycle changes only by about 50% as the shear strain increases from about 15% to 25%.



**Figure 9(b): Range of post liquefaction stress-strain response in simple shear**

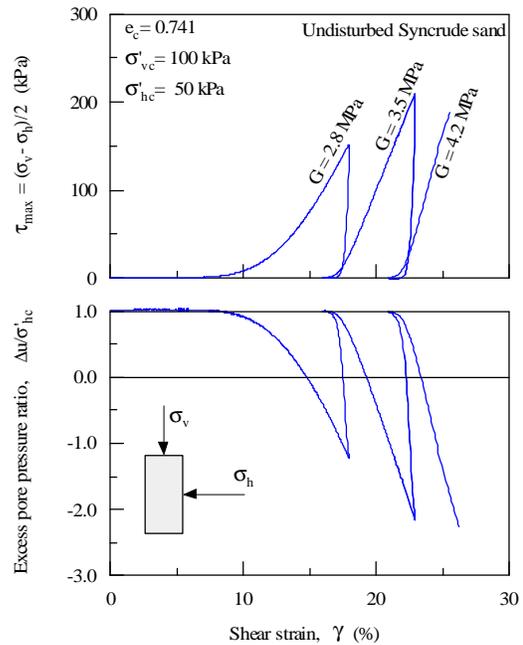


**Figure 10: Effect of loading mode on the post liquefaction response of in-situ sand**

The magnitude of the shear strain required in post liquefaction simple shear loading to mobilize a small arbitrary shear strength of 2.5 kPa is plotted as a function of the maximum shear strain developed during liquefaction in Figure 12. Results for both undisturbed and water pluviated sands are shown. This figure reflects the influence of the strain history prior to the initiation of the post liquefaction loading on the subsequent post liquefaction deformation. The data suggests that the strain range during which the sand deforms with essentially zero stiffness is dependent on the maximum shear strain developed during liquefaction. The large scatter in the data signifies that other parameters such as the relative density and confining stress level, may also influence this phase of deformation. Similar influence of the strain history on the stress strain characteristics of liquefied reconstituted sands has been reported in triaxial [29] and simple shear [30] loading. Recent studies on reconstituted ASTM C-109 graded Ottawa sand show that the magnitude of strain during this first phase of post liquefaction deformation is dependent on maximum strain history, and consolidation stress level, but not on the relative density [31].

The post liquefaction behaviour does not appear to be dependent on the deformation mechanism, viz. true liquefaction or cyclic mobility that was the cause of strain development. Even if large deformations develop as a result of true liquefaction, the unloading pulse of the dynamic load causes an essentially zero effective stress state in the sand. All subsequent deformation from a state of zero effective stress is associated with strain hardening where the sand dilates all the way from its initial zero effective stress state. This strain hardening response does not show any tendency to diminish, so as to reach a residual state, even when the sand is sheared in excess of 20% shear strain.

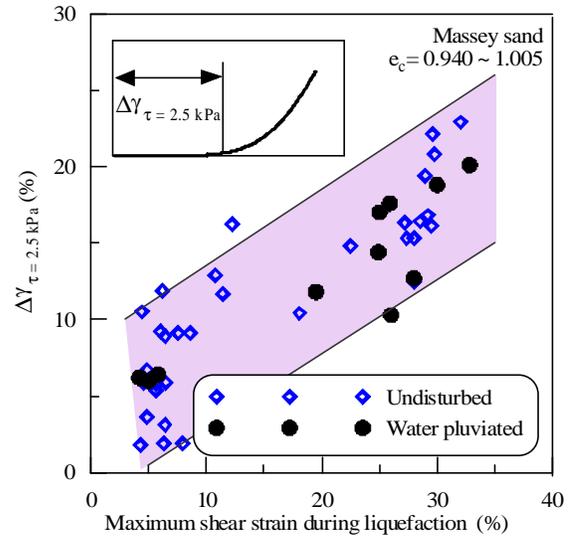
Figure 13(a) shows the post liquefaction behaviour of undisturbed Syncrude sand that exhibits true liquefaction type of response during cyclic loading. The sand reaches the steady state of deformation in the twelfth loading cycle, and deforms at a constant residual strength of about 15 kPa. The unloading pulse in the applied cyclic load terminates the steady state deformation at about 8% strain. In post liquefaction loading the sand strain hardens and deforms at an essentially constant modulus after a strain of about 15%



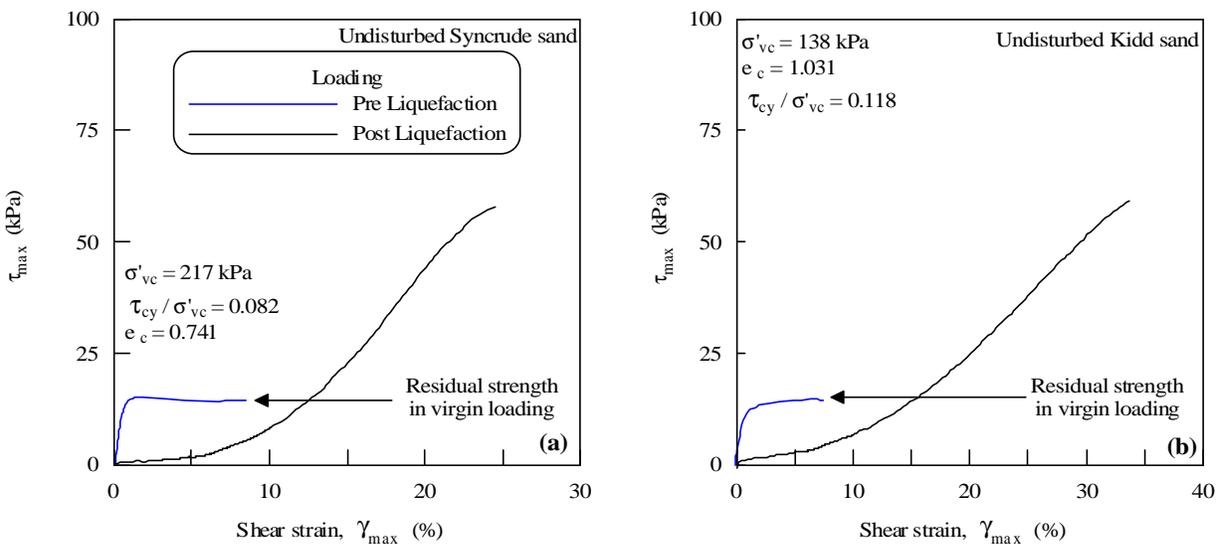
**Figure 11: Effect of multiple unload/reload cycles on post liquefaction response**

without any approach to a residual state. The steady state strength of the sand in virgin loading does not appear to be a limiting strength on post liquefaction loading. Similar behaviour of undisturbed Kidd sand is shown in Figure 13(b). These results imply that a sand may yield higher strength after liquefaction, compared to the minimum undrained strength of the virgin sand. The stiffness, especially in the early stages of deformation, is much smaller in post liquefaction and therefore very large strains develop in post liquefaction. It appears that a sand that originally exhibited steady state type of response that led to liquefaction will not realise a steady state in post liquefaction loading, even at strains of about 25%. The tests shown in Figure 13 were terminated at these strain levels because of apparatus limitations. If we assume that the sands may realise a residual state with further straining, then the residual strength may be several folds (at least a factor of 5 for the two sands tested) higher than the minimum undrained strength of the virgin sand. However, it is essential to recognize that it is almost impossible to load soil specimens to such large strains in laboratory apparatuses without introducing excessive non uniformities that may render the interpretation of test results questionable. It should also be noted that even though the sand realises a higher strength following liquefaction, very large strains are required to mobilise this strength. Post liquefaction design, therefore, should be based on deformation analysis, and not on the ultimate strength.

Vaid & Thomas [27] and Sivathayalan [30] have reported that the minimum undrained strength of the virgin contractive water pluviated sand does not represent a cap on the post liquefaction strength. Both water pluviated and undisturbed sands exhibit similar characteristics in this regard as well. This dramatic change apparently occurs because such a sand in the virgin state could undergo contractive deformation, whereas its deformation in post liquefaction loading is always dilative. On virgin loading, a contractive sand deforms at a constant friction angle  $\phi_{QSS,SS}$  during steady state, but in post liquefaction it deforms at all times



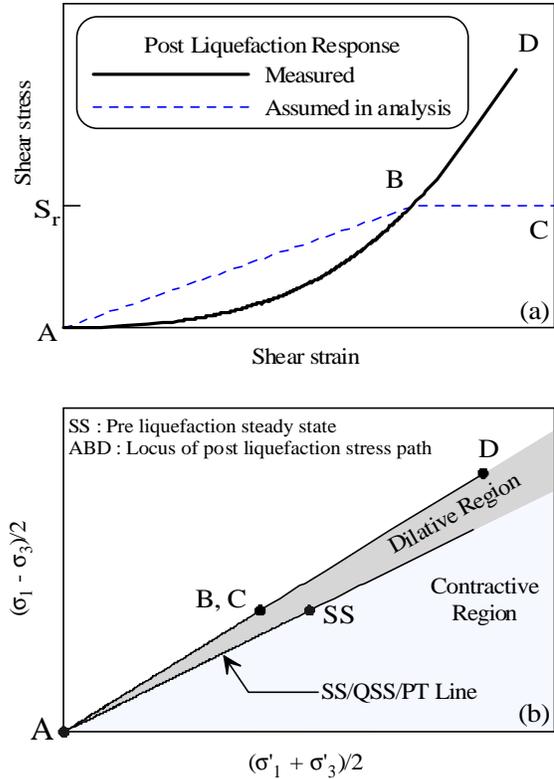
**Figure 12: The effect of maximum strain during cyclic loading on the post liquefaction response**



**Figure 13: Pre liquefaction and post liquefaction undrained behaviour of (a) Syncrude sand, (b) Fraser Delta sand in simple shear**

at a mobilized friction angle  $\phi_f$  that is a few degrees higher than  $\phi_{QSS/SS}$  for all sands.

But in most of the analytical methods the estimation of post liquefaction displacements is based on the assumption that post liquefaction residual strength is either equal to or slightly lower than that of the virgin sand. Furthermore, the current analytical methods for determining liquefaction induced displacements often assume the stress strain relationship of the liquefied soils as shown schematically in Figure 14. The earlier methods assumed a linear relationship until the residual state. The recent models however, do consider the stiffness increase with strain in order to estimate the post liquefaction deformations. Both approaches, however, limit the maximum post liquefaction strength at a residual value, that is often assumed to be slightly smaller than the strength of the virgin contractive sand. The test data on the undisturbed sands (Figure 13) do not exhibit such a residual state in post liquefaction loading even up to about 30% shear strain. Therefore, applying a limiting strength in post liquefaction may amount to conservatism, and may result in over prediction of earthquake induced displacements. Sands that exhibit true liquefaction type of response never dilate on virgin loading. Their effective stress path is bound within the contractive region below the steady state line as schematically shown in Figure 14. However, upon unloading after a controlled amount of steady state of deformation and on subsequent reloading in post liquefaction the deformation occurs due to dilation. The locus of the stress path in post liquefaction loading stays confined along the line of maximum obliquity associated with strain hardening. The higher strength in post liquefaction is apparently caused by the imposition of deformation in the dilative region as a result of initial zero effective stress on the sand that would have otherwise deformed within the contractive region under virgin loading. It is routinely postulated that strain hardening sands (both dilative and limited liquefaction type) could ultimately realize steady state at very high stresses after all dilation is complete. Continued dilation and the associated negative pore pressure development would increase the confining stress to a very large value, which in turn would make the sand respond contractively to reach a steady state. Such large negative pore pressures, however, cannot develop in the field because the maximum negative pore pressure will be limited to the initial pore pressure + 1 atm in sands. Cavitation of pore water would occur at this pressure and the sand would then deform drained, and not undrained. However, it is essential to recognize that very large strains would be required to mobilise the strength in post liquefaction loading.



**Figure 14: Schematic illustration of the post liquefaction response**

## CONCLUSIONS

The undrained behaviour of undisturbed in-situ frozen sands in cyclic and post liquefaction loading is presented, and compared to the behaviour of water pluviated sands. It has been demonstrated that cyclic undrained loading of undisturbed sands can lead to unidirectional flow (true liquefaction), or cyclic mobility depending on the initial state, much in the same manner as water pluviated sands. The cyclic resistance of undisturbed sands were found to be essentially similar to those reconstituted by water pluviation in the laboratory. This equivalence was noted with regard to both the number of cycles to liquefaction, and the

mechanisms of strain and pore pressure development within load cycles. The observed similarities in the mechanical behaviour clearly indicate that water pluviation technique produces a fabric similar to that of the alluvial in-situ sands tested.

The characteristics of the post liquefaction stress strain response of undisturbed sands is akin to those of water pluviated sands. Strength mobilisation in liquefied soil occurs on account of dilation. The shear modulus increases with increasing strain, in stark contrast to the modulus degradation in virgin sands. The relative density of the liquefied sand plays a dominant role on post liquefaction strength; denser sands mobilise higher strength with small strain development. Further the strength mobilises at a faster rate in triaxial compression than in simple shear or triaxial extension. This direction dependent behaviour implies that the sand does not fully lose its anisotropic nature even after liquefaction.

The pre liquefaction minimum undrained strength of the undisturbed sand does not appear to limit the post liquefaction strength. This occurs possibly on account of the fact that deformation after liquefaction occurs solely within the dilative region in stress space, unlike in pre liquefaction loading that occurs within the contractive region. Deformation in post liquefaction loading progresses along the line of maximum obliquity regardless of the loading mode. However, much larger strains are required in post liquefaction to mobilise the strength.

The results presented herein clearly demonstrate that the cyclic and post liquefaction behaviour of undisturbed sands is qualitatively and quantitatively equivalent to those reconstituted by water pluviation in the laboratory. This suggests that our understanding of these phenomena based on water pluviated sands is fully applicable to the sands in-situ. Further, comprehensive site characterization of alluvial or fluvial sand deposits may be performed by testing water pluviated sand specimens. This presents a highly attractive economic alternative to testing expensive undisturbed in-situ frozen sands.

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