Liquefaction of clean sand using triaxial test

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ABSTRACT
This paper deals with investigation of initiation of liquefaction of soil using monotonic triaxial tests. Consolidated undrained static triaxial tests were conducted on clean sand for four initial relative densities: 30%, 40%, 60% and 70% with confining pressures of 50,100 and 200 kPa. Two different methods of sample preparation, viz. wet tamping method and IS-Code method were employed to test a total of twenty four samples. It was observed that deviator stress increases with increase in % strain; with maximum pore pressure reached between 1.0% and 1.5% of axial strain. Unstable zone is identifiable as the region that lies between effective stress failure line and the peak pore pressure line. The samples prepared by IS code method consistently exhibit dilative behaviour for all relative densities.

RÉSUMÉ
Este papel trata con investigación de iniciación de licuación de tierra que utiliza pruebas de triaxial de monotonic. Las pruebas undrained constantes consolidadas de triaxial fueron realizadas en la arena limpia para cuatro densidades 30%,40%,60% relativas iniciales y 70% con limitar las presiones de 50.100 y 200kPa. Totales 24 muestras fueron probadas utilizando dos métodos de preparación de muestra. Fue observado que énfasis de deviator aumenta como % aumentos de esfuerzo. La presión máxima del poro fue alcanzada en 1 a 1,5% del esfuerzo axial. La zona inestable ha sido considerada para ser el uno que está entre la línea efectiva de fracaso de énfasis y línea de presión de poro de pico. Las muestras preparadas por ES el método de código mostró dilative comportamiento para todas las densidades.

1 INTRODUCTION

Liquefaction is a phenomenon in which both strength and stiffness of a soil diminish by earthquake shaking or other rapid loading due to increase in the pore pressure. A reflection to the pertinent literature reveals that the principal approaches for assessing liquefaction potential comprise analytical models as well as certain experimental investigations. Experimentation chiefly employs the cyclic triaxial test in addition to a few other laboratory tests such as simple triaxial test, shake table test, shear wave velocity test etc.

Liquefaction of loose saturated sand can be triggered by cyclic and static undrained loading. The behaviour of sands under static loading has been extensively studied by Castro (1969,1975), Casagrande(1976), and by Castro and Poulos (1977). These studies probe the behaviour of saturated sands under monotonic undrained loading and further develop the steady state concept.

Hanzawa (1980), Ishihara *et al*. (1975), Sladen *et al.* (1985), Vaid and Chern (1985) have studied the stress conditions surrounding the initiation of liquefaction. In particular, Sladen *et. al* (1985) developed the concept of a “collapse surface” state on the basis of isotropically consolidated triaxial tests on loose fine sand. Yamamuro and Lade (1997,1998) and Covert (2001) proclaimed that complete static liquefaction in laboratory testing is most easily achieved in silty sands at very low confining pressures. Murthy *et al.* (2007) focussed on distinctive states of the monotonic undrained response of sand. Numerous studies (Ladd (1974),Vaid *et al.* (1999), Wood and Yamamuro (1999), Della *et al*.(2009)) deduced that the behaviour of sands under monotonic loading is significantly influenced by specimen reconstitution methods.

2 LITERATURE SURVEY

Experimental investigations to evaluate stress conditions and influence of various parameters to initiate liquefaction were carried out by Kramer and Seed (1988). Their triaxial test was conducted on clean and silty sand for relative densities 32%, 37%, 44% and 47% using the moist tamping method, whence it was inferred that the shear stress required for initiating liquefaction increased with increasing relative density and confining pressure whereas it decreased with increasing initial shear stress level. The distinction between the initiation and the effects of liquefaction was discussed and further, an expression for a factor of safety against the initiation of liquefaction was proposed in their work.

Drained and undrained triaxial tests were performed by Yamamuro and Lade (1997) on Nevada sand at relative densities 12, 22, 31, and 42% and on Ottawa sand at the relative density of 0%. Dry deposition and moist placement methods were used to prepare the samples with Nevada and Ottawa sands, where complete static liquefaction at low confining pressure is seen to occur. Similarly, four types of liquefaction behaviour were observed, viz. 1) static liquefaction 2) temporary liquefaction 3) temporary instability 4) instability (Fig. 1). As reported by Yamamuro and Lade (1997) with the increase in confining pressures, the effective stress paths indicated increasing resistance to liquefaction by exhibiting dilatant tendencies.

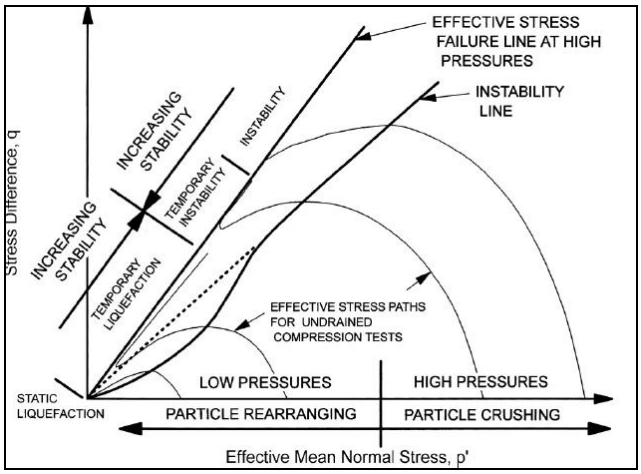

Figure1. Four distinct general types of undrained effective stress paths of loose silty sands shown in the p′-q diagram (Yamamuro and Lade1997).

Undrained behaviour of sand under low confining pressure was studied by Shaoli *et. al* (2003). Very loose sand samples (RD=4%) showed static liquefaction. On the other hand, Murthy *et al*. (2007) performed a series of triaxial compression tests on clean sand and silty sands. Using the slurry deposition and moist placement methods for sample preparation, they observed four distinctive states in undrained condition of sand such as critical state, phase transformation state, quasi steady state and undrained instability state. Della *et al.* (2009) conducted undrained triaxial test on Chlef sand for relative density of 28% and 80%. Dry funnel and wet deposition methods were adopted for sample preparation of size 70 mm diameter and 140 mm height. This study brought forth the fact that the resistance to liquefaction was affected by confining pressure and relative density. They also observed greater resistance to liquefaction for dry funnel pluviation method than wet deposition method.

Thus, the majority of the previous studies have been primarily dealing with evaluation of liquefaction susceptibility and properties of sand only subsequent to liquefaction. The present paper mainly focuses on assessment of initiation of clean sand under static loading for two different methods of sample preparation. A complete account of the laboratory investigation is presented in the subsequent sections.

3 MATERIAL TESTED

All tests carried out in this study have been performed on clean sand, characterized by the physical properties as summarized in Table 1. The clean sand is classified as uniformly graded sand as per I.S. classification. The grain size distribution is as shown in Fig. 2. The tests are conducted for four different initial relative densities 30%, 40% , 60% and 70% representing loose, medium and dense conditions and for three confining pressures of 50 kPa,100 kPa and 200 kPa.

Table 1. Properties of sand.

Properties of sand	Value	IS Code
γ_{max}	16.65 kN/m^3	IS :2720 (Part 14)-1983
γ_{min}	14.20 kN/m^3	IS :2720 (Part 14)-1983
G	2.765	IS :2720 (part 3 /sec1-1980)
e_{max}	0.909	IS :2720 (Part 14)-1983
e_{min}	0.629	IS :2720 (Part 14)-1983
D_{50} (mm)	0.30	IS :2720 (Part 4)-1985
D_{10}(mm)	0.175	IS :2720 (Part 4)-1985
D_{60}(mm)	0.32	IS :2720 (Part 4)-1985
D_{30}(mm)	0.24	IS :2720 (Part 4)-1985
C_c	1.028	IS :2720 (Part 4)-1985
C_u	1.82	IS :2720 (Part 4)-1985

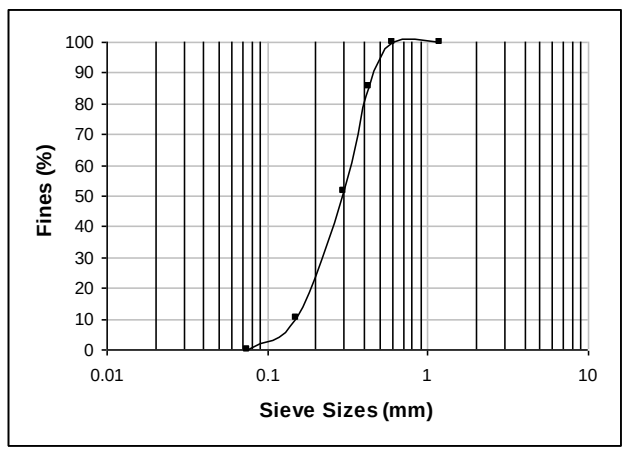

Figure 2. Grain size Distribution curve

4 EXPERIMENTAL INVESTIGATION

The apparatus used to perform the isotropically consolidated undrained triaxial compression tests includes: Load frame (Motorized) having 50kN capacity, triaxial cell stationary bushing, air water constant pressure system (Capacity = 7 Kg/cm^2) and data acquisition system for recording load, pore pressure and displacement.

4.1 Method of Sample Preparation

Triaxial tests were performed on cylindrical specimens admeasuring 38 mm diameter by 76mm height (H/D=2.0). Wet tamping and I.S. code [I.S. 2720 (part 12)-1981] methods were used to prepare sand samples in a fashion similar to the water sedimentation method put forth by Ishihara (1993). In this method sand was mixed with sufficient quantity of water. A glass rod was initially kept at the centre of the funnel and the sand mixture was placed with a spoon in the funnel. Later, with the glass rod removed, the sample was prepared by a continuous rapid flow of soil in the membrane as shown in Fig. 3(a). The desired density was achieved by gently tapping on the mould in symmetrical pattern.

Wet tamping method used in the present work is different from the procedure laid down by Ishihara (1993). In this method, a known quantity of sand and water for the desired density was mixed. The mixture was placed in five layers by tamping each layer with the help of a hammer as depicted in Fig. 3(b). Calibration was done for number of blows required to achieve the required specimen height.

Figure 3.(a) I.S. Code method

4.2 Test Procedure

After the specimens were prepared, their caps were placed and sealed with O-rings. A negative pressure of 10 kPa was applied to the specimens to reduce disturbance during removal of split mould and triaxial cell installation. When the cell was filled with water, the negative pressure was removed and a confining pressure of 50kPa was then applied to the specimens. For saturation of samples, cell pressure and back pressures both were simultaneously increased until an acceptable B-value was reached to ensure complete saturation. A

Figure 3.(b) Hammer used in Wet tamping

minimum B-value of 0.97 was achieved for all the specimens. The cell pressure was then slowly increased to provide the desired effective confining pressure. All the samples were then isotropically consolidated and loaded at the same axial strain rate of 1.2mm/min. For each effective confining pressure, readings of load, deformation and pore pressure were recorded using data acquisition system during the tests.

This test procedure was repeated for conducting tests on various samples prepared by both methods for all four relative densities(30%, 40%, 60% & 70%) with confining pressures of 50 kPa, 100 kPa & 200 kPa.

5 RESULTS AND DISCUSSION

5.1 Effect of Confining Pressure

Figs.4 (i) &(ii) display the results of deviator stress vs % strain for confining pressures of 50 kPa, 100 kPa and 200 kPa typically for 30% relative density with wet tamping method and IS code method respectively. It is evident from these plots that as confining pressure increases, the deviator stress also increases and for higher values of confining pressure the deviator stress attains a maximum. In both the methods of sample preparation essentially leads to similar trends, but the maximum value of deviator stress is found to be more in IS code method than the corresponding value in wet tamping method. This may be attributed to the amount of water in sample preparation in IS method being much more than that used in wet tamping method. It is also observed that deviator stress increases as % strain increases for all densities tested in the present work. Peak deviator stress is found to increase from 300 kPa to 600 kPa for wet tamping method whereas from 375 kPa to 1000 kPa for the IS code method as the confining

pressure increased from 50 to 200 kPa. This indicates that liquefaction resistance offered by sand is higher at

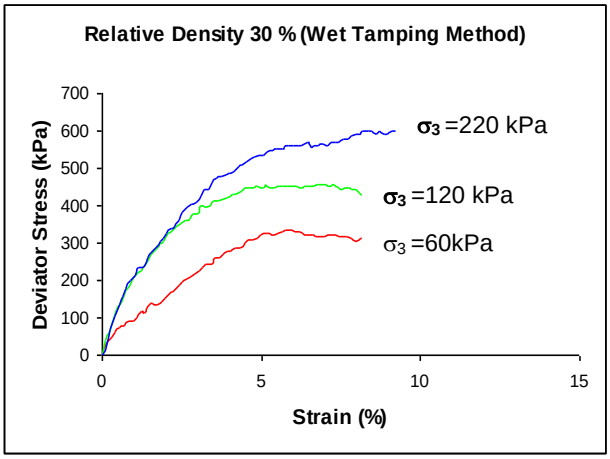

Figure 4.(i) Deviator stress vs % strain for a relative density of 30% and for different confining pressures (σ_3)

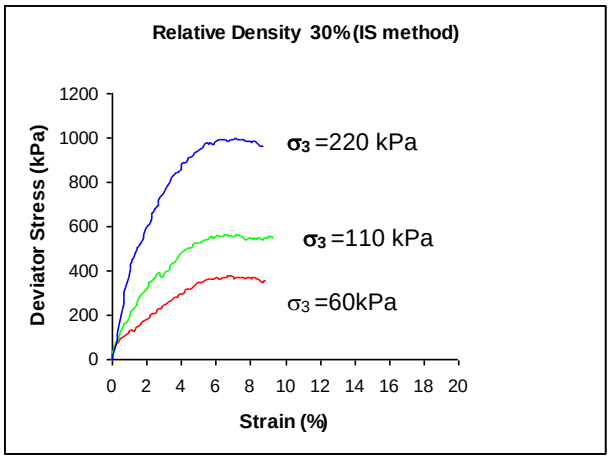

Figure 4.(ii) Deviator stress vs. % strain for relative density of 30% and for different confining pressures (σ_3)

higher confining pressure, in consonance with the findings of Kramer and Seed (1988),Yamamuro and Lade(1997) and Della *et al.* (2011). It is noteworthy that the peak value of deviator stress is reached at around 8% strain.

5.2 Effect of Relative Density

Fig.5 (i) shows a typical p′-q plots under the wet tamping method for four relative densities 30,40,60 and 70% for confining pressure 200kPa. The effective mean stress p′ is defined as $(\sigma'_1 + 2\sigma'_3)/3$, while q is given by the difference $(\sigma'_1-\sigma'_3)$. In case of wet tamping, contractive behaviour is observed only for relative density of 30%. Fig. 5(ii) portrays a p′-q plot with the IS code method of sample preparation typically for 200kPa confining pressure. It is seen that none of the samples indicates contractive nature, implying that identical samples with initial relative density 30% when prepared with IS code

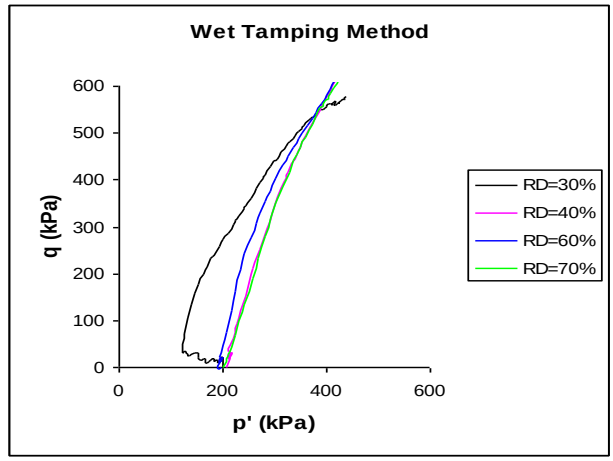

Figure 5.(i) p′-q Plot for wet tamping method

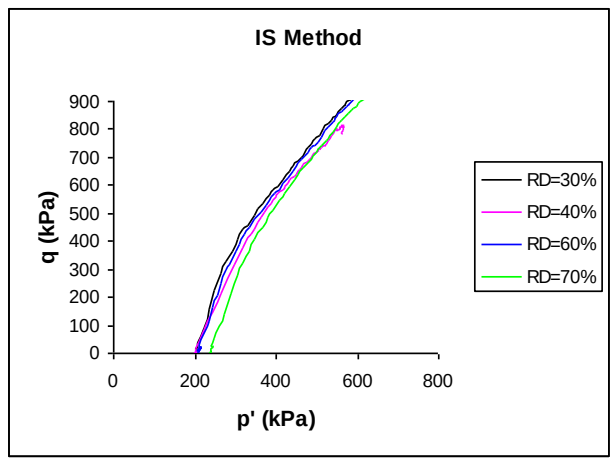

Figure 5. (ii) p′-q Plot for the IS method

method show the contrast behaviour as compared with their counterparts with the wet tamping method being employed for sample preparation. Such dilative nature in the water deposited state (under the IS code method) may be ascribed to soil grains rolling down into stable positions at lower densities: *cf.* Terzaghi and Peck (1967), and Been *et al.* (1988). Enhanced liquefaction resistance of sands is clearly discernible with increase in the relative density for both wet tamping method and IS code method.

The foregoing discussion makes it evident that the liquefaction behaviour of clean sands varies with the method of sample preparation, as quantified in the forthcoming subsection.

5.3 Effect of Sample Preparation

Figs. 6 (i) and (ii) illustrate effective stress paths for the

two sample preparation methods described above, for all confining pressures typically with the relative density of 30% for wet tamping and IS code method respectively. Chu *et al.* (2003) have also reported instability zone for sand having dilative nature which as zone between the critical state line and the constant stress ratio line (CSRL). In the present work the Mohr Circle at failure for each specimen was plotted and from the maximum shear-stress value for each of the Mohr Circles the p′-q values were deduced, which were then plotted on the p′-q diagram. The straight line joining these points with the origin is thus appropriately termed as the Effective Stress Failure Line, delineated in Figs. 6(i) and (ii). Corresponding to each peak pore pressure points recorded during the test p′-q values obtained are plotted to obtain the line passing through origin, which represents the peak pore pressure line. Thus the zone between the effective stress failure line and the peak pore pressure line can be regarded as Unstable. Effective stress path shows contractive behaviour of soil with wet tamping method at relative density 30%. Further, as confining

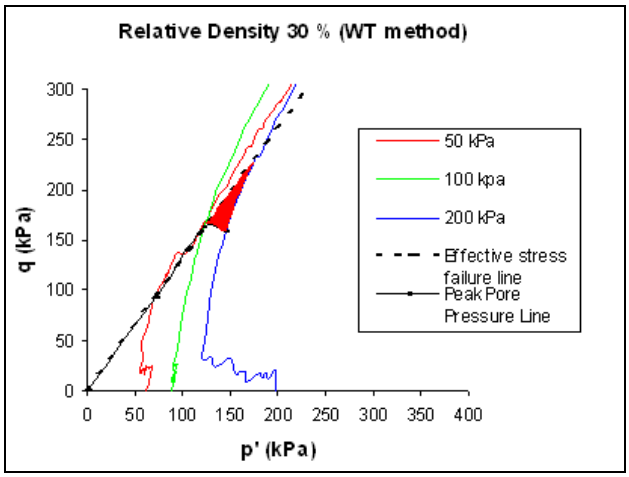

Figure 6. (i) Wet tamping method (RD=30%)

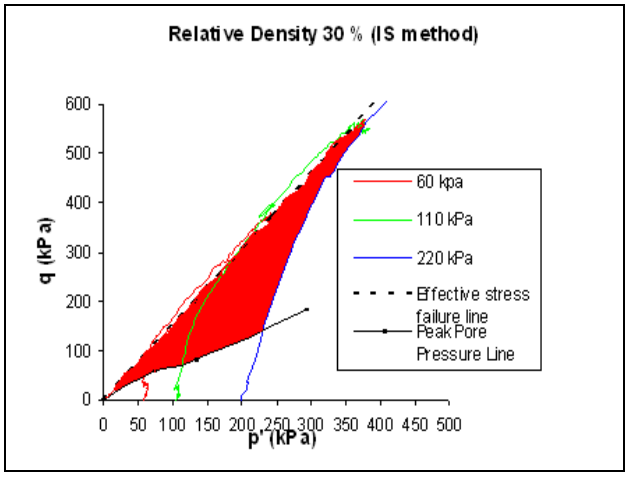

Figure 6.(ii) IS code method (RD=30%)

pressure increases from 50 kPa to 200 kPa, effective stress path shifts towards right on p′-q plot. Similar trend is observed for IS code method of sample preparation. However, the nature of effective stress path is more dilative as compared with that in the wet tamping method.

5.4 Generation of Maximum Pore pressure

Fig.7 sketches pore-pressure vs. % strain for different confining pressures. It has been observed that as confining pressure increases peak pore pressure also

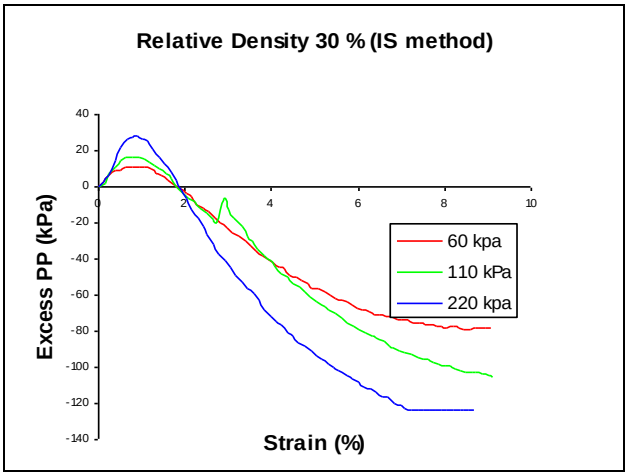

Figure 7. Pore pressure vs. % Strain for different confining pressure.

increases for all densities tested in the present work. Peak pore pressure is reached at 1% to 1.5 % strain for all confining pressures.

6 CONCLUSION

Consolidated undrained triaxial test conducted on clean sand in the present experimental work shows dilative behaviour for samples of all relative densities under the IS code method of sample preparation. However, samples of 30% and 40% relative density showed contractive behaviour by wet tamping method. Thus, method of sample preparation plays a crucial role in assessing liquefaction behaviour of clean sand when tested in undrained triaxial test. The peak value of deviator stress is higher in IS code method as compared with corresponding wet tamping method. For sand in loose condition the peak value of deviator stress is found to reach at around 8% strain. Further, it is noticed that liquefaction resistance increases with relative density and confining pressure for both methods of sample preparation. Initiation of liquefaction could be identified in the zone located between effective stress failure line and peak pore pressure line. For both sample preparation methods, the peak pore pressure reached at 1.0% to 1.5% strain for all confining pressures.

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