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The behaviour of desaturated sands under static and cyclic loading

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ABSTRACT: Static and cyclic behaviour of desaturated sands were experimented using a series of monotonic and cyclic triaxial tests. These tests were conducted by intruding compressed air into the pre-consolidated samples to reduce their degree of saturation. Soil water characteristic curves of the sand were predicted using the existing prediction model. This helped to maintain the suction in the tests and use the appropriate range within which the degree of saturation does not violate the use of Terzaghi's effective stress equation. The variation of peak undrained shear strength and excess pore pressures of the desaturated samples were inspected in both compression and extension loading condition. This study concludes with the use of conventional static tests to explain the effect of desaturation on the cyclic behaviour of the granular soils.

1 INTRODUCTION

Soil liquefaction is a concern for structures constructed on saturated sandy soils. When soil liquefies, it loses its strength and stiffness. Although the strength loss is of short duration, it is still sufficiently long to cause failure, deaths and significant financial loss. Liquefaction has caused damages in the past and probably got its share of importance after the 1964 Niigata earthquake in which huge loss of human life and economy occurred. There are other examples of liquefaction damages during the Turkey 2001, Chuetsu 2004 and the Christchurch 2011 earthquakes. Different soil improvement techniques to mitigate liquefaction have been used in the past, such as the vibro-flotation, dynamic compaction, deep mixing, dewatering by lowering the ground water level and grouting. If already there is an existing structure over the ground, it would be difficult to utilize much of the above methods, as they can cause ground subsidence or make the structure unusable or uneconomical. In this case, desaturation by air intrusion method would be a useful and cost-effective technique to reduce the soil's cyclic potential.

Over the recent years, desaturation of the ground by introducing air-bubbles has attracted significant attention and some studies have emerged on the use of this method. The inclusion of air bubbles can reduce the degree of saturation and consequently, will affect the liquefaction potential by a significant amount. It has been seen from the few investigations that the "intruded" air bubbles can last for a long-time within the ground and serve their purpose (e.g. Okamura et al. 2006, Juneja & Raghunandan 2011). There are several techniques with which air can be intruded in the ground at site. Yegian et al. (2007) used water-electrolysis method to introduce air within the liquefaction susceptible soils. Okamura et al. (2006) had observed that the air intruded in the ground during the installation of sand compaction piles causes additional and "new" improvement of the surrounding soils. Okamura et al. (2011) used 20 mm diameter air-injector using a 100 mm pipe. The pipe had a number of holes to intrude air up to the depth of improvement. He et al. (2013) used denitrifying bacteria to produce biogas bubbles in the soil. These bubbles were then shown to reduce the liquefaction potential.

Laboratory investigations on the use of air intrusion technique have been conducted using either shake table tests (e.g. Yegian et al. 2007, He et al. 2013) or cyclic triaxial tests (e.g. Yoshimi et al. 1989, Kamata et al. 2009, Okamura et al. 2011). In most of these tests, the samples were desaturated during their preparation that is, initial stage. In this study however, air was intruded after the consolidation of saturated samples. This was done to closely represent the desaturation methodology which is used in the field. Since liquefiable soils below the ground water table have traditionally been desaturated by intruding air bubbles. The present study also discusses the effect of soil and pore fluid characteristics on the static and cyclic behaviour of the granular soils. Correspondingly, monotonic compression and extension triaxial tests were performed on desaturated samples. Additionally, the soil-water characteristic curves of this sand were predicated using the existing empirical methods. Those results were used to get an insight of the cyclic behaviour of the desaturated soil sample.

2 MATERIALS AND METHOD

2.1 *Soil material*

Uniformly graded fine sand was used in the experiments. This soil was obatiend from Gujarat state where heavy liquefaction had occurred during the 2001 earthquake. Table 1 shows the index properties of this sand.

2.2 *Testing procedure*

One hundred mm and 200 mm long samples were prepared by using dry pluviation (Raghunandan 2011). Using this method, uniform samples of relative density, RD approximately equal to 32% could be prepared. Carbon dioxide gas was then passed through the samples followed by flushing them with deaired water using a head of not more than 12 kN/m^2. The samples were then saturated using stepwise increments of cell and back pressures to achieve Skempton‘s (1954) B-factor of about 0.98. The samples were then consolidated under 100 kN/m^2 effective stress. After the completion of the consolidation, air bubbles were injected through the bottom drainage. Care was taken to maintain air pressure slightly greater than the back pressure but less than the confining pressure. Ogata & Okamura (2006) showed that the maximum injection pressure that could be applied to desaturate the soil without disturbing its structure was about 80% of the overburden. Figure 1 shows the schematic representation of the desaturation procedure used in this study. Injection of air bubbles resulted in the

Table 1. Index properties of the Gujarat sand

Specific Gravity	D_{50} (mm)	Cu	Cc	Minimum Dry Density (Mg/m^3)	Maximum Dry Density (Mg/m^3)
2.66	0.28	1.87	0.83	1.30	1.58

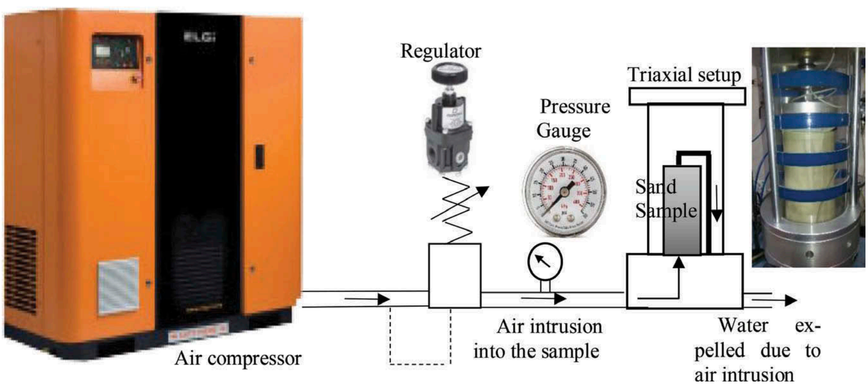

Figure 1. Desaturation procedure used in triaxial tests.

expulsion of water from the sample top. Volume of the expelled water was shown to depend upon the duration of the air pressure. After the expulsion of water, the drainage valves were closed to again measure Skempton's (1954) B-factor. Figure 2(a) shows the effect of expelled volume on B-factor. This plot was used to calibrate B-factor after each step of desaturation. Figure 2(b) shows the relationship between Skempton's (1954) B-factor and degree of saturation, S_r. These relationships were drawn using all previous studies and the present work. It can be seen that B-factor ranged from 1 to 0.3 when the degree of saturation reduced to 90%. The present data lies within the range of data collected from all prevous researchers. Therefore it seems that either the measure of B-factor or the measure of volume of expelled water are good indicators to describe the state of partially saturated samples (Kamata et al. 2009).

A comparison study was then performed between saturated and desaturated samples using bender element tests. This was done to estimate the effect of air injection on the possible disturbance in the soil structure and was considered a suitable method to measure changes in the soil structure due to air intrusion. Figure 3 shows the input and output signals received by the bender elements when a pulse of 15 kHz was applied at one end of the samples with B-factor equal to 0.98 and 0.7. The effective confining stresses on both the samples was 100 kN/m^2. The figure shows that the output signals of both the samples completely overlap and have the same arrival time. It can therefore be interpreted that there was no change in the soil structure due to air intrusion.

Monotonic undrained compression and extension and load controlled undrained cyclic triaxial tests were then conducted on saturated and desaturated samples. In order to verify that the Terzaghi's effective stress equation was applicable to these "desaturated" soils, the soil water characteristic curves (SWCC) of this sand were predicted. Figure 4 shows the predicted

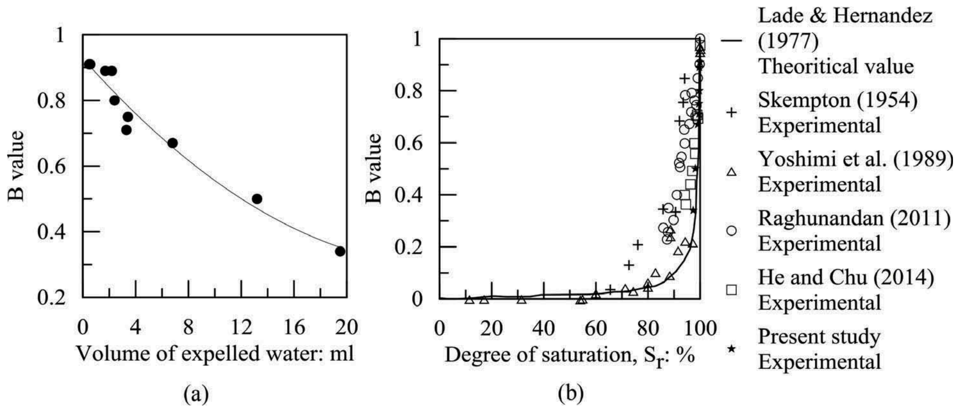

Figure 2. (a) Change in pore pressure coefficient B with expel of water during desaturation; (b) relationship between B and degree of saturation.

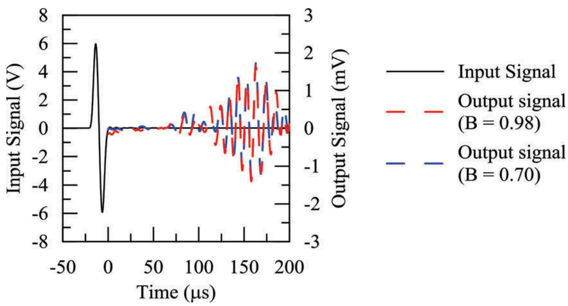

Figure 3. Comparison between saturated and desaturated sand sample using bender element test.

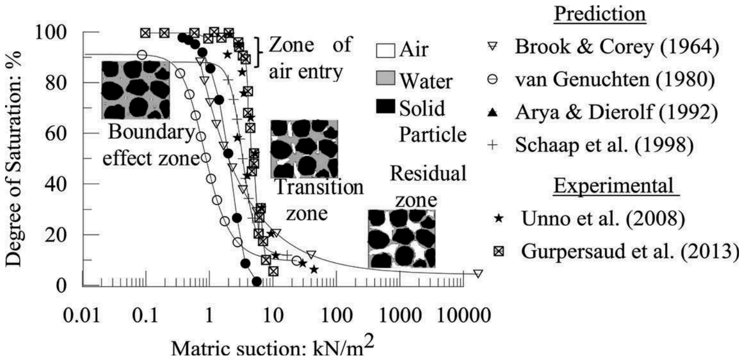

Figure 4. Soil water characteristic curve (SWCC) for Gujarat sand.

SWCC of the sand used in this study. This sand attained air-entry in between 90 and 95% saturation. At air entry zone, the largest pore of the soil is usually desaturated. Before that, the air remained as occluded air bubble form and it does not interact with soil structure. The predicted SWCC curves were also compared to the available experimentally measured results presented in the literature for almost similar grading of sand sample. The figure shows that the matric suction was negligible in this range. Upon the entry of air, the sample underwent a transition. Had the degree of saturation reached 50%, even then the matrix suction would not have exceeded a few kPas. It is seen that within the transition zone, the connectivity between the pore water reduced and matric suction increased. Matric suction in excess of 10 kN/m^2 occurred only when the degree of saturation dropped below 20%. The comparison shows a good agreement. It can therefore be stated that Terzaghi's effective stress principle is applicable to this sand even when its saturation falls to 90 to 100%.

3 RESULTS AND DISCUSSIONS

Figure 5a-c shows triaxial test results of saturated (B = 0.98) and desaturated (B = 0.70) samples under monotonic loading. Figure 5b show dilative behaviour in undrained compression tests for the particular RD (32%). It happened due to the dilative behaviour of the sand sample (Jefferies & Been 2006). Figure 5(b) shows that positive excess pore pressures were generated during the initial phase of the shearing in saturated sample. The presence of the air bubbles in the pore water increased the compressibility of the pore fluid. This compressibility reduced the generation of the positive excess pore pressure for desaturated sample by an amount of 7 kN/m^2 at B = 0.70. It can be also observed from the figure that the axial strain for initialisation of dilation increased by about 0.5% with desaturation at B-factor of about 0.7. When the undrained behaviour of the saturated and desaturated samples in the positive excess pore pressure zone were compared with the drained behaviour in the positive volumetric strain zone, a better insight can be drawn. During the time of drained test, the volumetric compression of the soil grains and the voids in the initial stage of loading was responsible for positive volumetric strain. Whereas in the undrained test for a fully saturated sample, volumetric compression of the voids were negligible and peak positive excess pore pressure reached with a lesser axial strain compared to the peak volumetric strain in the case of drained test. Due to compressibility of the air bubbles, the desaturated sample reached to the peak positive pore pressure at an axial strain in between the above drained and undrained case. If it is considered that the air bubbles were compressed in that extra axial stain zone, the corresponding volumetric strain can be measured as 0.1% comparing the volumetric strain and excess pore pressure in that zone in Figure 5b. Due to the above compressibility of pore fluid, the desaturated sand sample showed more dense behaviour compared to the saturated sample in the initial positive pore pressure zone. Those behaviours also reflect in the stress path as shown in Figure 5c. Compressibility of the pore fluid also effects in the rate of dilation and the total

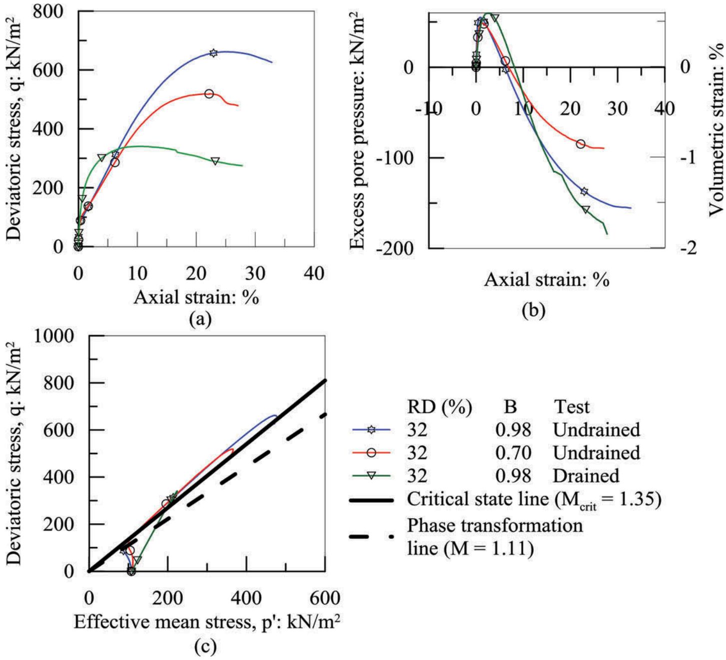

Figure 5. Effect of desaturation on: (a) stress strain behaviour; (b) excess pore pressure variation; (c) stress path in monotonic triaxial compression test.

dilation for the sample in undrained case. Rate of dilation and total dilation decreased with desaturation. Due to that the undrained shear strength of the desaturated sand sample decreased by 26% as shown in Figure 5(a). It can also be seen from the Figure 5(c) that the critical state line and phase transformation line were not affected due to desaturation when B-factor equalled 0.7.

Figure 6a-c shows the stress strain behaviour, excess pore pressure variation and stress path of monotonic triaxial undrained extension tests on both saturated (B = 0.98) and desaturated (B = 0.70) sand samples. The figures also show a contractive behaviour in undrained extension tests for that particular RD (32%) of the sample. As the soil behaviour is contractive, the peak undrained strength increased with desaturation as shown in Figure 6a. Undrained shear strength was increased by 32% with the change in B value from 0.98 to 0.70. It can be seen from the Figure 6b that the positive pore pressure at peak undrained strength decreased by 12 kN/m^2 and the corresponding axial strain increased by 0.08% for desaturated sample. In Figure 6c, instability lines are drawn for saturated and desaturated samples. The instability line joins the origin and the peak stress on the effective stress path for undrained condition. If the stress state crosses the instability line, a large strain generates and causes instability to the soil (Ladd 1992). He & Chu (2014) reported that the slope of the instability line increased with increase in relative density. Figure 6(c) shows that the slope of the instability line increased from 0.49 to 0.58 with decrease in B value from 0.98 to 0.70. It interprets that the compressibility of the pore fluid changes the behaviour of the sand sample more towards the denser state. Figure 7a-b shows the effect of the desaturation on the cyclic resistance of the Gujarat sand. Liquefaction criterion was considered as the condition when the excess pore pressure becomes equal to effective confining pressure. Figure 8a shows that the cyclic resistance increased by 20% with the decrease in B from 0.99 to 0.7. Figure 7b shows the effect of a change in B factor on the cyclic resistance of the sand. It can be observed that with a decrease in B from 0.98 to 0.60, the number of cycles requires liquefying increases almost with a linear proportion.

Figure 8a-d shows the effect of desaturation on stress path behaviour, generation of excess pore pressure, stiffness degradation and accumulation of axial strain against damping ratio

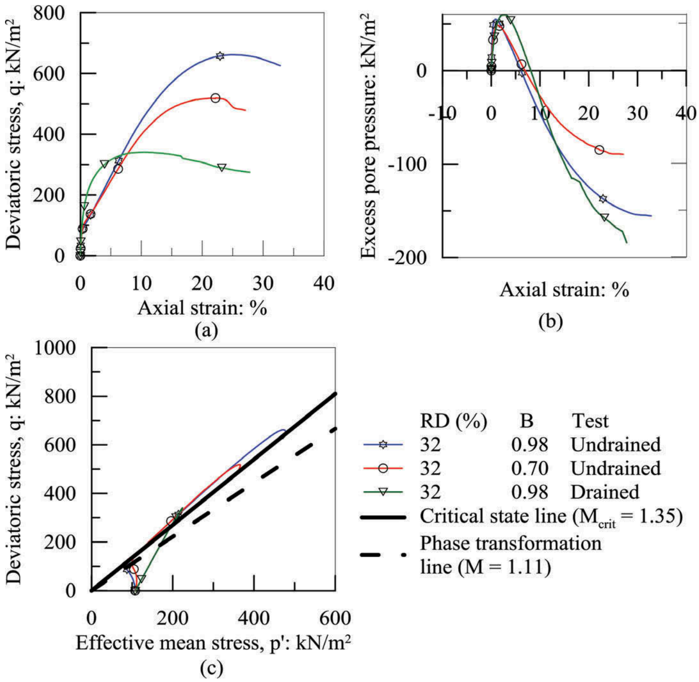

Figure 6. Effect of desaturation on: (a) stress strain behaviour; (b) excess pore pressure variation; (c) stress path in monotonic triaxial extension test.

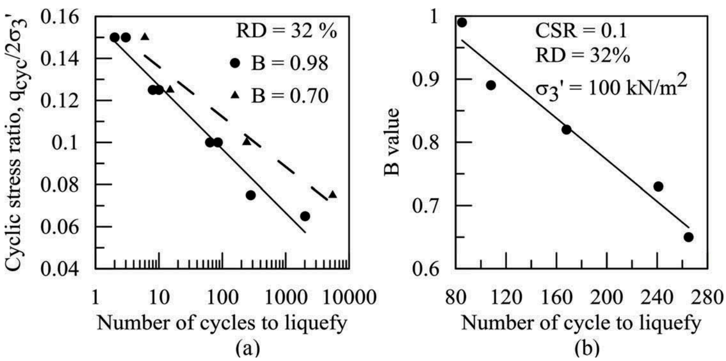

Figure 7. (a) Effect of desaturation on the cyclic strength of Gujarat sand; (b) B value vs number of cycles to reach liquefaction.

due to cyclic loading. Figure 8a shows that the stress state of the desaturated soil reached to the liquefaction more gradual manner compared to the saturated sample. It can be also seen from the figure that the saturated and desaturated sample failed after reaching their corresponding instability line in the extension direction. As the slope of the instability line for desaturated sample is higher compared to the saturated sample, the cyclic stress path can progress to lower effective mean stress state. That is why the corresponding threshold excess pore pressure before reached its liquefaction state, is higher in the case of desaturated sample as shown in Figure 8b. Compressibility of the air bubbles during cyclic loading reduced the generation of excess pore pressure per cycle. Figure 8c shows that the undrained Young's modulus increased with desaturation which was also described during the time of discussing the

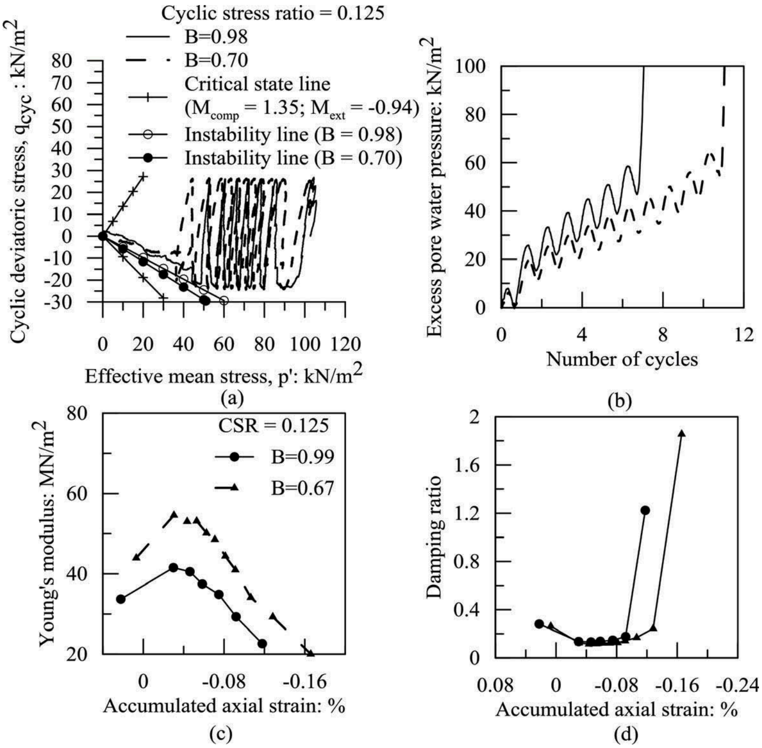

Figure 8. Effect of desaturation on: (a) cyclic stress path; (b) generation of excess pore pressure; (c) stiffness degradation; (d) accumulation of axial strain against damping ratio.

monotonic tests results. The degradation rate of Youngs modulus with cyclic loading also decreased with desaturation. When the soil reached to the liquefaction state, its damping ratio exceeded exponentially. Figure 8d shows that the damping ratio variation with accumulated axial strain during cyclic loading. It can be seen that the accumulated axial strain increased by almost 0.5% for desaturated sample to reach the position from where the damping ratio start to increase significantly. This was nearly similar to the axial strain of the desaturated sample to reach peak positive pore pressure condition compared to the saturated sample in monotonic undrained compression test. It was possible because the amount of the threshold excess pore pressure generated due to cyclic loading before it reached its liquefaction state was almost similar to the peak positive excess pore pressure generated during undrained monotonic compression loading for both saturated and unsaturated sample.

4 CONCLUSION

This paper discusses the effect of desaturation on monotonic and cyclic behaviour of the sand sample. The degree of saturation varied in between 90 to 100% for desaturation test and corresponding matric suction was negligible in that range of degree of saturation. Therefore Terzaghi's effective stress principal was applicable for the analyses of the results. The compressibility of the air bubbles present in the pore water due to desaturation was responsible for the significant change in the mechanical behaviour of the sand sample in static and cyclic loading. Peak undrained compressive strength, peak positive excess pore pressure, rate of dilation and total dilation decreased with desaturation when the sand sample was dilative in nature in monotonic compression loading. Whereas the peak undrained extension strength increased but the excess pore pressure at peak strength reduced with desaturation when the sand sample was contractive in nature in monotonic extension loading. The slope of the instability line increased with desaturation. Due to this cyclic stress path moved to more low effective mean stress state in undrained cyclic loading and corresponding threshold excess pore pressure before jumping to the liquefaction state was also increased. The initial Youngs modulus of the sample was increased but rate of degradation of Young's modulus was decreased with desaturation. The accumulation of axial strain before reaching to the liquefaction stage was also increased due to desaturation which indicates the compression of the air bubbles during cyclic loading.

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