Liquefaction Resistance of Desaturated and Partly Saturated Clean Sand

Dhanaji Chavan, T. G. Sitharam, and P. Anbazhagan

Abstract Induced desaturation has been emerging as a new liquefaction mitigation technique. Laboratory study carried out, so far, on induced desaturation has mainly focused on shaking table and centrifuge studies. In the present study, triaxial specimens of saturated clean sand have been desaturated by injecting air/CO_2 into it and stress-controlled undrained cyclic triaxial tests have been conducted on such samples. Few tests have been conducted on partly saturated samples as well. It is observed that the presence of air in the sample increases the liquefaction resistance of the sand. Further, desaturation affected not only liquefaction resistance but also dilative and contractive tendency of the soil. Slope of the phase transformation line on compression side initially increased and then decreased with reduction in degree of saturation whereas slope of phase transformation line on extension side initially decreased and then increased with reduction in the degree of saturation. In most of the cases, slope of the phase transformation line on extension side is found to be smaller than that on compression side.

Keywords Initial liquefaction · Desaturation · Phase transformation line

1 Introduction

Saturated loose sand when subjected to earthquake loading generates large pore water pressure and finally loses its strength and stiffness. This phenomenon is called as liquefaction [1]. Over the last few decades, various techniques such as explosive compaction, deep dynamic compaction and deep soil mixing have been invented to mitigate the liquefaction [2]. Induced desaturation is emerging as a new liquefaction mitigation technique over the last few years. In this technique, liquefaction susceptible saturated loose sand is desaturated by adopting one of the following techniques: (1) air injection; (2) microbial desaturation; (3) water electrolysis; (4) sand compaction pile; (5) use of sodium perborate; [3–6].

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Laboratory study carried out, so far, on induced desaturation has mainly focused on shaking table and centrifuge studies. No research has been carried out so far on air-injected desaturated triaxial specimens. Purpose of this study is: (1) to desaturate saturated triaxial specimen by CO_2 injection/air injection; (2) to assess change in liquefaction resistance on desaturation; (3) to study the effect of desaturation on contractive and dilative tendency of sample. In the present study, stress-controlled undrained cyclic triaxial tests have been conducted on CO_2 desaturated, air desaturated and partly saturated clean sandy soil.

2 Material and Methodology

2.1 Material

Original sand was collected from bed of Sabarmati River near IIT Gandhinagar campus, Gujarat, India. This is the area which severely suffered from 2001 Bhuj earthquake. Collected sand was passed through 2 mm IS Sieve. In the present study, sand passing through 2 mm IS Sieve and retained on 75 micron IS Sieve has been used. Gradation curve for this sand is shown in Fig. 1 and its rest of the index properties are given in Table 1. As per IS soil classification system soil comes to be poorly graded fine sand.

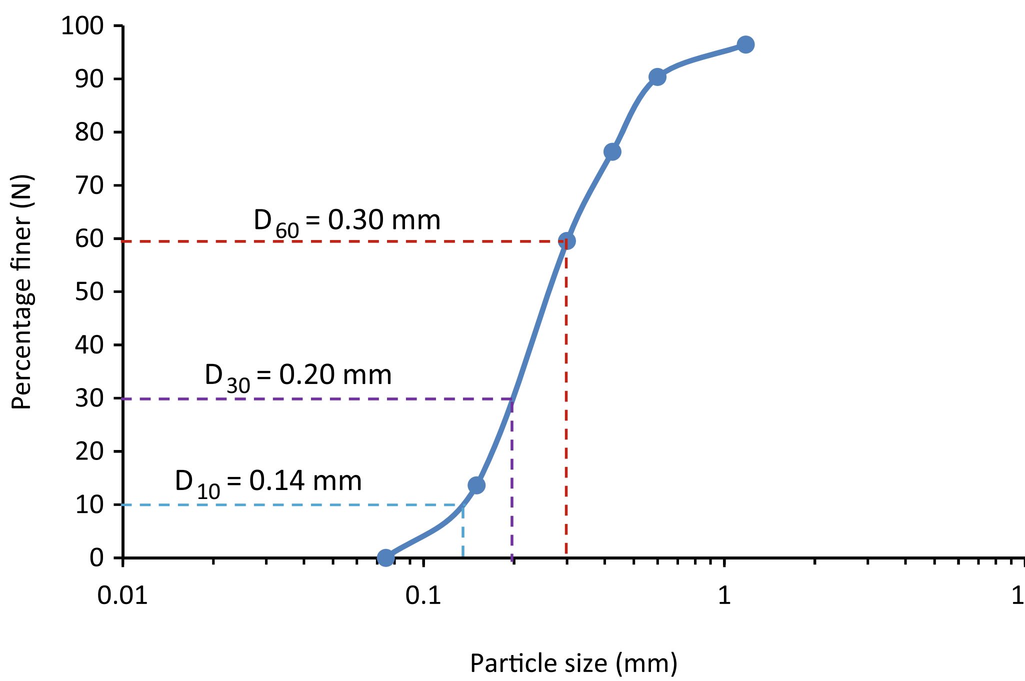


Fig. 1 Gradation curve of sand

Table 1 Index properties of the sand

G	e_{max}	e_{min}	ρ_{max}(gm/cc)	ρ_{min} (gm/cc)	D_{50} (mm)	C_u	C_c
2.65	0.84	0.45	1.83	1.44	0.27	2.14	0.95

2.2 Methodology

2.2.1 Sample Preparation

Sample was prepared by dry deposition method. Oven dry sand mass was deposited in the split mould in five layers with zero drop height. At the end of last layer little tamping and side tapping was done. Before removing split mould vacuum of 20 kPa was applied to the sample so that it can stand on its own even after removal of mould.

2.2.2 Saturation

Once sample was prepared as mentioned in above section, CO_2 gas was passed though the sample under vacuum of 20 kPa for 10 min. Then cell pressure of 20 kPa was applied and vacuum was released and again CO_2 gas was percolated through sample for another 20 min. This was followed by percolation of 1000 ml of distilled water. From several trials, it was found that this resulted into degree of saturation as high as 99%. From practical point of view, sample with degree of saturation of 99% can be considered as a fully saturated sample [7]

2.2.3 Desaturation

Once it was ensured that sample was saturated; it was desaturated by injecting/CO_2 from the bottom of the sample. The triaxial setup before and during desaturation is shown in Figs. 2 and 3. The detailed procedure adopted during desaturation is given in Fig. 4.

It should be noted that saturation and desaturation steps are not applicable to partly saturated samples. In case of partly saturated samples, once dry sample was prepared as mentioned in the "sample preparation" section, quantity of water in the range of 200–800 ml was passed through the specimen. Depending upon the quantity of water passed, different degrees of saturation were achieved. Both for desaturated and partly saturated sample, degree of saturation of the sample was computed from B parameter, using the following equation.

$$B = \frac{1}{1 + nK_s\left[S/K_w + (1 - S)/u_a\right]} \tag{1}$$

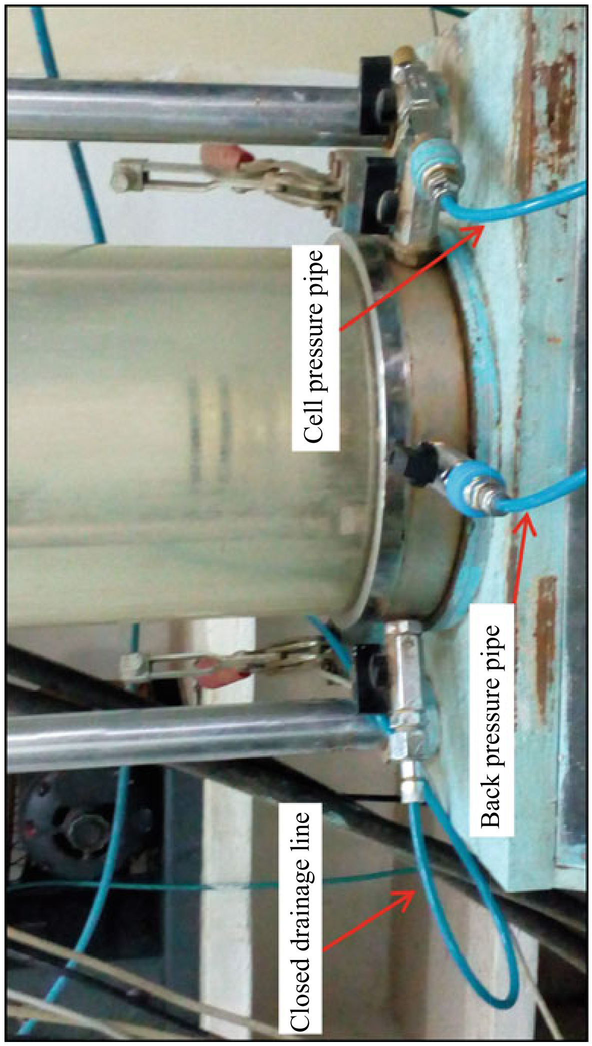


Fig. 2 Triaxial cell set up before desaturation

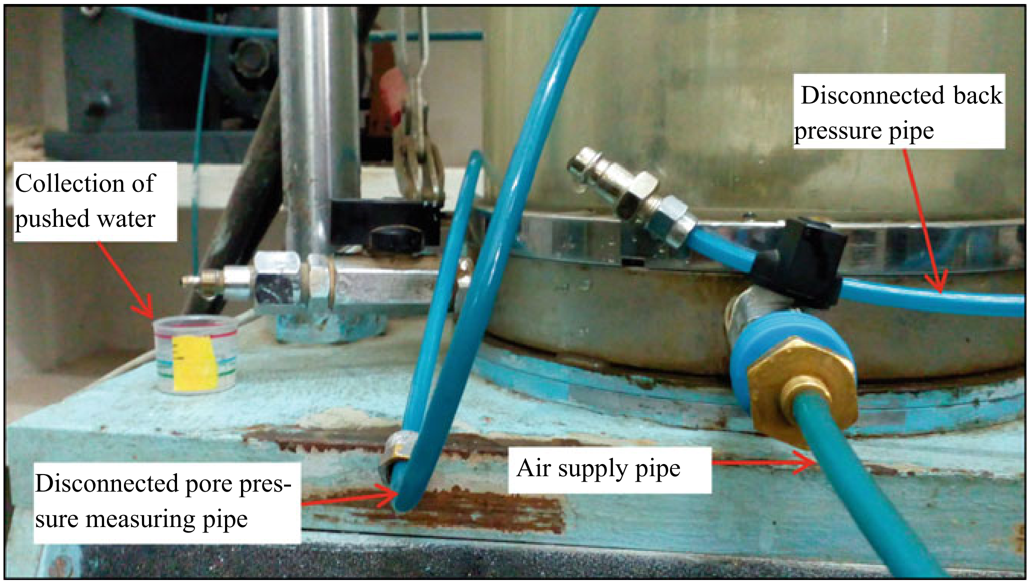


Fig. 3 Triaxial cell set up during desaturation

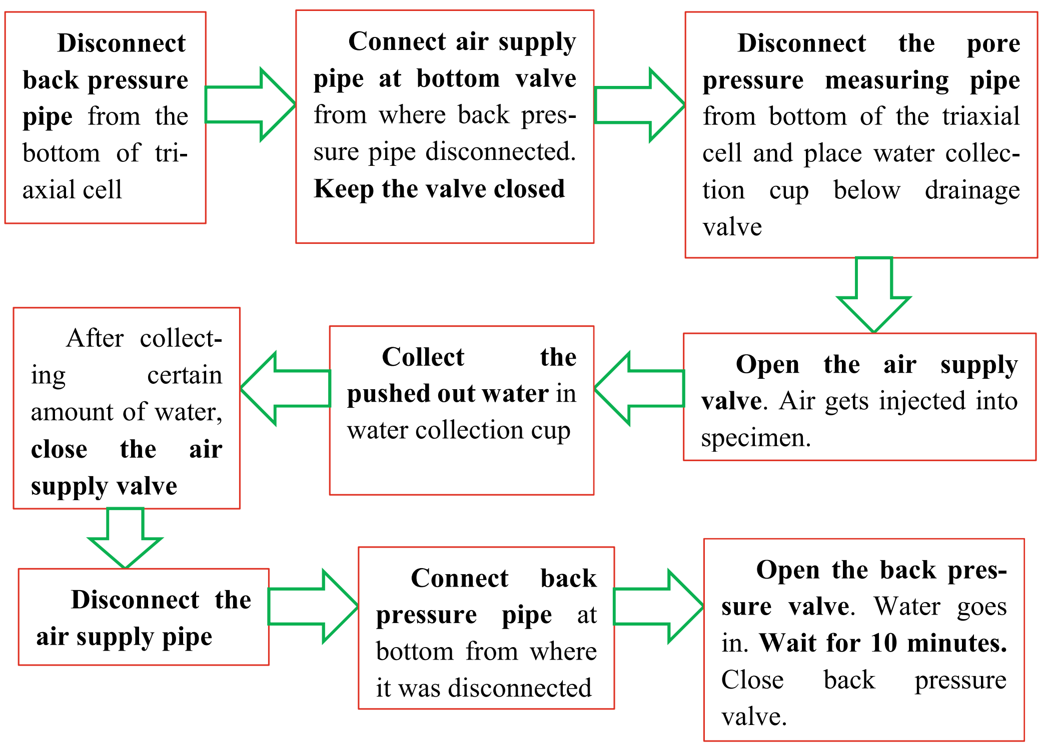


Fig. 4 Flow chart explaining steps adopted during desaturation

where, n is the porosity of the sample, S is the degree of saturation, K_s and K_w are the bulk modulus of soil skeleton and water, respectively and u_a is the absolute pore fluid pressure.

2.2.4 Application of Cyclic Loading

Back pressure valve was closed and pore pressure measuring device was connected at the drainage valve. Then, sinusoidal cyclic deviatoric stress was applied at the frequency of 0.1 Hz. Tests were conducted on samples of relative density (D_r) of 30, 40 and 60% at *CSR* of 0.175, 0.250 and 0.400.

3 Results and Discussion

3.1 Degree of Saturation and Initial Liquefaction

Cyclic tests were conducted on CO_2 desaturated, air desaturated and partly saturated samples. It was observed that number of cycles required for initial liquefaction (N_i) increased with decrease in degree of saturation. The trend was observed to be exponential for all three cases as shown in Fig. 5. Further, it was observed that CO_2 desaturated samples took least number of cycles and partly saturated samples took the most number of cycles for given degree of saturation to reach the initial liquefaction. Possible reason could be dissolution of injected CO_2 into the pore water during

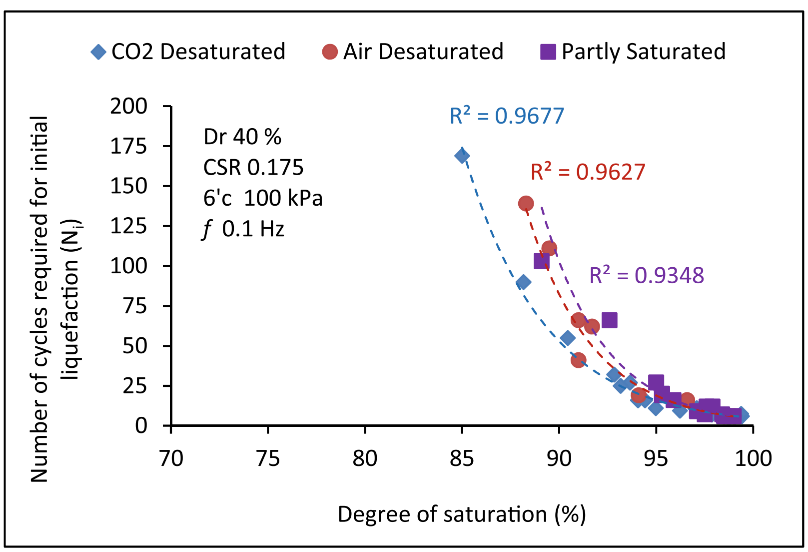


Fig. 5 Number of cycles required for initial liquefaction versus degree of saturation

the cyclic loading. The liquefaction resistance of air desaturated and partly saturated samples is very close to each other.

3.2 *Effect of Desaturation on Stress Ratio at Phase Transformation*

When saturated sand, dense of critical state, is subjected to undrained loading, initially it contracts and then dilates. Contraction results into increase in the pore pressure while dilation results into decrease into the pore pressure. This state results into elbow in effective stress path as shown in Fig. 6. Locus of all such point results into a straight line called as phase transformation line. It is a well-established fact that stress ratio at the phase transformation depends on void ratio and effective confining pressure. Stress ratio is the ratio of deviatoric stress and effective mean stress.

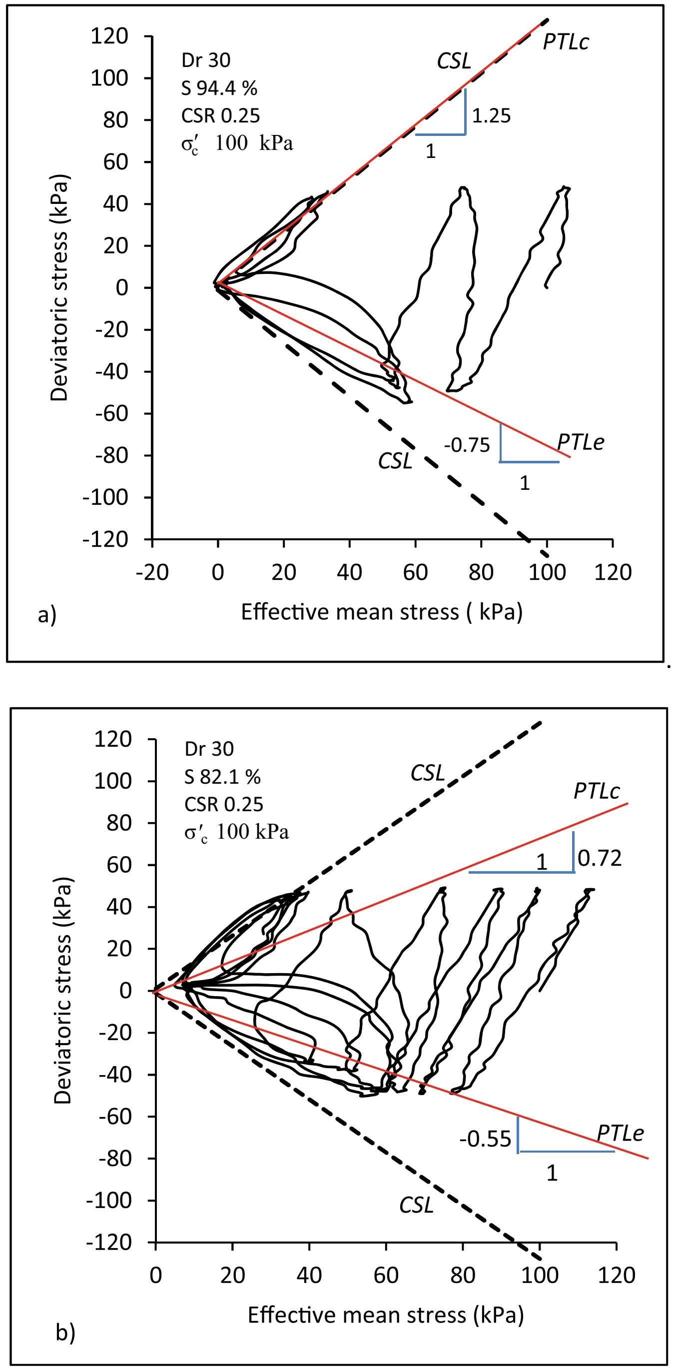
In the present study, it is investigated whether the presence of air in the voids, along with water, has any influence on the stress ratio at the phase transformation. Some of the effective stress paths are shown in Fig. 6. In this figure, *CSL* stands for critical state line, *PTLc* and *PTLe* stand for phase transformation line on compression side and phase transformation line on extension side, respectively. From the Fig. 6a, it is observed that, for given case, phase transformation line on compression side coincides with critical state line. Thus, the stress ratio for the *PTLc* equals the stress ratio for CSL, which is equal to 1.25. Further, stress ratio for *PTLe* is observed to be −0.75. For the case shown in Fig. 6b, phase transformation line on compression side is distinct from the corresponding CSL. Stress ratio for *PTLc* and *PTLe* is found to be 0.72 and −0.55 respectively. From Fig. 6, it is clear that slope of *PTLe* is less than that of *PTLc*.

Stress ratio at different degrees of saturation for various relative densities and cyclic shear stress ratio (CSR) is shown in Fig. 7. It is observed from Fig. 7a that stress ratio on compression side initially increases with decrease in degree of saturation and then decreases. On the other hand, stress ratio initially decreases and then increases with reduction in degree of saturation, during extension stage of loading as seen in Fig. 7b. Further, stress ratio for relative density of 60% is observed to be less than that for relative density of 30% and 40%, during compression stage of loading. On the other hand, during extension stage of loading, stress ratio for relative density of 60% is observed to be greater than that for relative density of 30 and 40% as seen Fig. 7b.

4 Conclusion

There is increase in the liquefaction resistance on desaturation. The trend is observed to be exponential. Further, the CO_2 desaturated samples took the least cycles while

Fig. 6 Effective stress paths showing effect of air desaturation on phase transformation



partly saturated sample took most cycles for given degree of saturation to reach the initial liquefaction. Desaturation affected contractive and dilative tendency of the sample as well. It was observed that stress ratio (i.e. slope) of the phase transformation line on compression side initially increases and then decreases with desaturation. On the other hand, slope of phase transformation line on extension side initially decreases and then increases with desaturation. Further, stress ratio for phase transformation line on extension side is found to be less than that for phase transformation line on

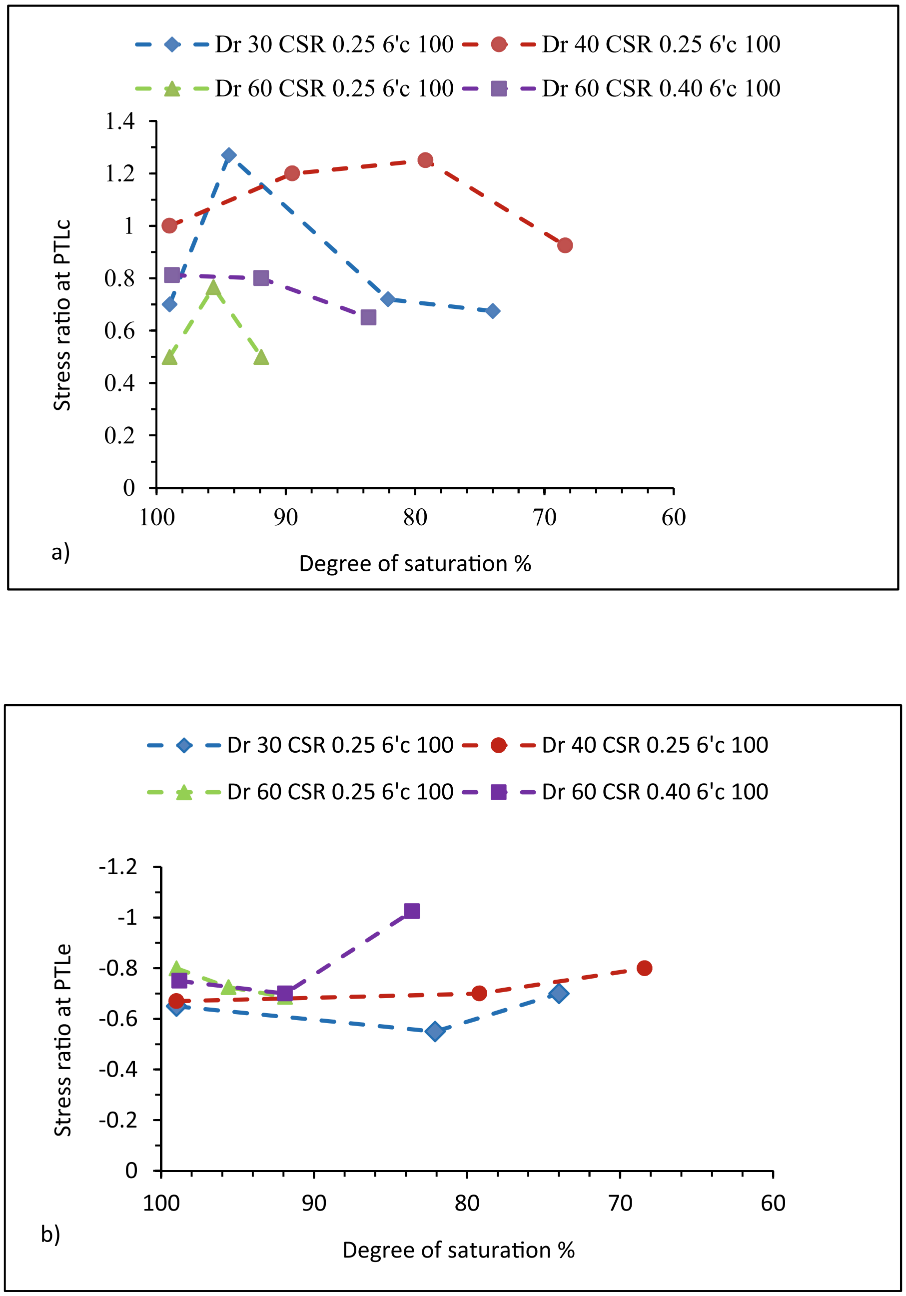


Fig. 7 Variation of stress ratio at phase transformation with degree of saturation

compression side. Comparison of stress ratio during compression shows that denser samples have smaller stress ratio while case is reverse during extension. Further study is required to have more deep insight of effect of desaturation on dilative—contractive tendency during undrained cyclic loading.

References

1. Kramer, S.L.: Geotechnical earthquake engineering. Pearson (1996)
2. Idriss, I.M., Boulanger, R..: Soil liquefaction during earthquakes. EERI (2008)
3. Okamura M, Takebayashi M, Nishida K, Fujii N, Jinguji M, Imasato T, Yasuhara H, Nakagawa E (2011) In-situ desaturation test by air injection and its evaluation through field monitoring and multiphase flow simulation. J Geotech Geoenviron Eng 137:643–652. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000483
4. Yegian MK, Eseller-Bayat E, Alshawabkeh A, Ali S (2007) Induced-partial saturation for liquefaction mitigation: experimental investigation. J Geotech Geoenviron Eng. 133:372–380. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:4(372)
5. Okamura M, Ishihara M, Oshita T (2003) Liquefaction resistance of sand deposit improved with sand compaction piles. Soils Found 43:175–187
6. He J, Chu J, Ivanov V (2013) Mitigation of liquefaction of saturated sand using biogas. Géotechnique. 63:267–275. https://doi.org/10.1680/geot.SIP13.P.004
7. Black D, Lee K (1973) Saturating laboratory samples by back pressure. J Soil Mech Found Div 99:75–95