Liquefaction resistance improvement of silty sands using cyclic preloading

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Abstract. Liquefaction induced damages are plenty and cause various levels of destruction to civil engineering infrastructure. It is possible to prevent liquefaction-induced hazards by understanding the mechanism and adopting some improvement techniques or design the structure to resist the soil liquefaction. In the present study, the influence of cyclic preloading on the liquefaction resistance of sand-silt mixtures is analyzed by conducting undrained cyclic triaxial tests on the cylindrical samples reconstituted at medium dense conditions ($D_r = 50\%$). All samples were tested at an effective confining pressure of 100 kPa by varying the cyclic stress ratios (CSR) in the range of 0.127 to 0.178 using a sinusoidal waveform of frequency 1 Hz. The results are presented in the forms of the pore pressure build-up, axial strain variation and liquefaction resistance curves. Test results indicate that the liquefaction resistance of silty sands is increased substantially with the application of preload under drained conditions.

1. Introduction
Liquefaction induced damages are plenty and cause various levels of destruction to civil engineering infrastructure. It is possible to prevent liquefaction-induced hazards by understanding the mechanism and adopting some improvement techniques or design the structure to resist the soil liquefaction. The first possibility is to avoid the construction on liquefiable soil deposits as far as possible. However, it is mandatory to utilize the available land for the various infrastructure developments due to scarcity in the availability of land even if it does not satisfy the required properties. Hence, the second option is to make the structure resistant to liquefaction by adopting deep foundations. Nevertheless, the deep pile foundations may not prevent liquefaction damages in all cases. Piles are causing to deflect in liquefaction susceptibility zones. Hence, the third option is liquefaction mitigation which involves improving the strength, density, and drainage characteristics of the soil. The selection of the most appropriate ground improvement method for a particular application could depend on many factors including the type of soil, level, and magnitude of improvement to be attained, required depth and extent of the area to be covered. This paper presents an experimental study regarding the applicability of preloading for the improvement of liquefaction resistance.

2. Literature review
Preloading of the soils occurs naturally (for eg., erosion, the flow of groundwater, etc) or artificially (purposeful preloading to improve the soil properties, demolition of structures, etc). A few researchers have analyzed the liquefaction resistance of preloaded soils. The details are given in Table 1.
**Table 1.** Studies reported by various authors

| Author                        | Remarks                                                                 |
|-------------------------------|-------------------------------------------------------------------------|
| Finn et al. [1]               | Cyclic preloading improves the resistance of sand                       |
| Ishihara and Okada [2]        | Cyclic preloading at higher amplitudes reduces the cyclic strength of sands |
| Stamatopoulos et al. [3]      | Preloading can decrease significantly the danger of liquefaction, at least in the free field. |
| Bouferra and Shahrour [4]     | Preloading at great amplitudes increases liquefaction susceptibility   |
| Wichtmann et al. [5]          | The samples with preloading experience the high liquefaction potential |
| Lopez and Modaressi [6]       | The usage of preloading reduces the rate of pore pressure which is build up in the soil (conclusion based on FEM analysis) |
| Stamatopoulos and Balla [7]   | Prestress ratio and cyclic shear strength are directly proportional     |
| Stamatopoulos et al. [8]      | Conducted field experiments to prove the effectiveness of preloading in liquefaction mitigation |

The above review highlights that in most cases, preloading improves liquefaction resistance; but some scholars reported contradictory findings [5]. Hence, this work attempts to study the influence of cyclic preloading on liquefaction resistance of sand and sand-silt mixtures.

3. **Methodology**

In this study, the authors utilized the soil combinations obtained by mixing various amounts of non-plastic fines by weight into the sand. The basic laboratory tests were performed on soil combinations to find the index properties. The gradation curves derived from the particle size analysis are shown in Figure 1. Table 2 summarises the obtained properties of soil combinations.

The cyclic triaxial testing (conducted in computerized triaxial equipment) involves various stages such as sample preparation, saturation of soil, consolidation, application of drained preloading and application of the undrained loading. A detailed description of each stage is given in [9].

![Particle size distribution curves](image-url)
Table 2. Basic properties of various soil combinations [9]

| Notation   | FS | SS10 | SS20 | SS30 | SS40 |
|------------|----|------|------|------|------|
| Fines content (%) | 0  | 10   | 20   | 30   | 40   |
| $G$         | 2.62 | 2.66 | 2.71 | 2.72 | 2.69 |
| $D_{50}$, mm | 0.28 | 0.26 | 0.23 | 0.2  | 0.15 |
| $C_u$       | 2.36 | 4.00 | 4.67 | 6.25 | 7.33 |
| $C_c$       | 0.87 | 1.28 | 1.17 | 0.72 | 0.74 |
| $\rho_{\text{max}}$, g/cc | 1.66 | 1.71 | 1.81 | 1.86 | 1.79 |
| $\rho_{\text{min}}$, g/cc | 1.41 | 1.44 | 1.48 | 1.52 | 1.42 |
| $\rho_{\text{test}}$, g/cc | 1.52 | 1.56 | 1.62 | 1.67 | 1.58 |

4. Results and Discussions
Cyclic triaxial tests were performed on the silty sands with and without preloading. The samples were prepared by combining the moist tamping - under compaction procedure [10] at medium dense conditions and consolidated at an effective pressure of 100 kPa. Initially, the samples were subjected to 5 and 10 cycles of preloading with CSR = 0.076 in drained conditions. The samples were then subjected to the cyclic stress amplitude of 0.127, 0.152 and 0.178 in undrained condition until failure.

Figures 2 to 6 show the effect of cycles of preloading on the undrained response of silty sands (tested at CSR = 0.178). Table 3 summarises the effect of cycles of preloading on undrained response and liquefaction resistance of silty sands. The number of cycles to liquefaction (i.e., when the excess pore pressure becomes equal to the effective consolidation pressure) is given in the table.

It is evident from the figures that the pore pressures build up and axial strain propagation become more gradual in the soils which are subjected to drained preloading than in the soils without preloading. Preloading slows down the build-up of pore pressures during undrained cyclic triaxial loading. Also, it is worthy to note that the soil samples with cycles of preloading experience both the compression and extensional strains whereas the samples without preloading only experience compression strains. The samples become more resistant to liquefaction and withstand large deformations when they are subjected to preloading in drained conditions. Similar trends were observed in other tested CSRs too.

Figure 2. Results of FS sample
Figure 3. Results of SS10 sample

Figure 4. Results of SS20 sample

Figure 5. Results of SS30 sample
Figure 6. Results of SS40 sample

Table 3. Summary of results

| Soil | Cycles of preloading |
|------|----------------------|
|      | CSR = 0.178 | CSR = 0.152 | CSR = 0.127 |
|      | 0  | 5  | 10 | 0  | 5  | 10 | 0  | 5  | 10 |
| FS   | 28 | 38 | 49 | 53 | 68 | 77 | 85 | 113 | 133 |
| SS10 | 20 | 33 | 38 | 43 | 58 | 65 | 77 | 101 | 116 |
| SS20 | 10 | 24 | 30 | 33 | 47 | 59 | 71 | 89  | 104 |
| SS30 | 8  | 19 | 23 | 24 | 39 | 51 | 66 | 81  | 99  |
| SS40 | 4  | 14 | 18 | 14 | 28 | 44 | 62 | 76  | 89  |
Figure 7. Liquefaction resistance curves

Figure 7 shows the effect of cycles of preloading on the liquefaction resistance curves of all soil combinations. The CSR corresponding to 20 cycles is found from this and is used to evaluate the effectiveness of preloading on liquefaction resistance. Figure 8 plots the variation of CSR at N_L = 20. The figure clearly shows that the CSR values are increasing as the number of cycles of preloading is increasing, irrespective of the soil type.

Figure 8. Improvement of CRR values

5. Summary and Conclusions

The authors studied the liquefaction resistance of silty sands subjected to initial preloading. The analysis of test results allow to draw the following conclusions:

- The low amplitude drained preloading slowed down the buildup of pore pressure and propagation of axial strain.
- The samples subjected to preloading experience both positive and negative strains.
- From liquefaction resistance curves, CSR corresponding to 20 cycles is found and it is used to evaluate the effectiveness of preloading on liquefaction resistance. CSR values increase as the number of cycles of preloading increases, irrespective of the soil type.

However, to make consistent conclusions, liquefaction susceptibility is to be investigated by varying, among others, the consolidation pressures, relative density, frequency of loading.
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