Cyclic Behavior of Mixed Clayey Soils

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Abstract: *Mixed clayey soils occur as mixtures of sand (or gravel) and clay in widely varying proportions. Their engineering behavior has not been comprehensively studied yet. An experimental program, comprising monotonic, cyclic, and post-cyclic triaxial tests was undertaken on compacted clay-granular material mixtures, having different proportions of clay and sand or gravel. This paper presents the results of cyclic triaxial tests and explains the behavior of the mixtures based on number of loading cycles, cyclic strain amplitude, granular material content, grain size, and effective confining pressure. The results indicate an increase in degree of degradation and cyclic loading-induced pore water pressure as the number of loading cycles, cyclic strain and granular material content increase. Also the results show that the grain size has no significant effect on the degree of degradation and cyclic loading-induced pore water pressure in the specimens. The effect of granular material content on pore water pressure during cyclic loading in equal-stress-level was also examined. The pore water pressure increases with the increase of granular material content.*

Keywords: *mixed clayey soils, cyclic triaxial test, degradation, pore water pressure*

1. Introduction

Many natural and artificial soils contain combinations of fine-grained (i.e. clay and silt) and coarse-grained (i.e., sand and gravel) soils. Such soils are called intermediate or mixed soils, in which clay contents are more than about 20-30 %.

Foundations of offshore structures and earthfill dams are two examples, which comprise of mixed clayey soils. These structures are usually subjected to earthquake loading and/or cyclic wave loads. Such type of loading may result in loss of stiffness, strength and even stability of the structure in undrained conditions. Hence, it is necessary to characterize the behavior of mixed clayey soils under cyclic loading.

Over the past 30 years, the research focus has been mostly on the cyclic response of clays and sands; comprehensive studies on characterization of mixed clayey soils are scarce.

Nakase et al. studied cyclic behavior of "clay-sand" mixtures by conducting undrained stress-controlled cyclic triaxial testing [1]. They found that for a given number of cycles, excess pore water pressures in the mixtures increase as the sand content increases. Kimura et al. carried out undrained stress-controlled cyclic triaxial tests on Kawasaki clay-Toyoura sand mixtures and observed that for a given number of cycles, the excess pore water pressure increases with the sand content [2]. They also found out that when the sand content increases, the soil specimen fails at smaller number of loading cycles. The test results showed that the reduction in soils stiffness, with increasing the cycles, is more pronounced for the mixtures with the higher sand contents. Kuwano et al. investigated cyclic behavior of sand-kaolin mixtures under stress-controlled triaxial tests and found that the mixtures containing about 40 % clay demonstrate cyclic shear strength the same as that of the pure clay [3].

Jafari and Shafiee carried out strain-controlled cyclic triaxial tests on "kaolin-sand" and "kaolin-gravel" compacted specimens under different shear strain amplitudes and three initial consolidation pressures [4]. They observed that the higher values of excess pore water pressures are generated in the specimens with higher granular material contents. They also stated that cyclic loading, as compared to monotonic

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loading, highlights the effect of granular material content.

Based on the previous studies, except Jafari and Shafiee's research [4], all of the experimental studies have been carried out in stress-controlled conditions. In addition, the effects of grain size, effective confining pressure, and cyclic loading characteristics on the cyclic behavior of mixed clayey soils have not been studied sufficiently. In order to perform reliable stress-strain and stability analyses of soil structures made of clay-granular material mixtures, it is necessary to understand the evolution of the cyclic properties of mixed clayey soils as accurate as possible.

For this purpose, a number of undrained strain-controlled monotonic, cyclic, and post-cyclic triaxial tests were carried out on pure clay, "clay-sand" and "clay-gravel" mixtures. Results of the monotonic and post-cyclic tests have been published previously [5, 6, 7]. The main purpose of this paper is to present the results of the above cyclic tests. Effects of number of loading cycles, cyclic strain amplitude, granular material content, grain sizes, and effective confining pressure on the degradation of strength and deformability and pore water pressure behavior of the mixtures are evaluated. Moreover, the effect of granular material content on the cyclic loading-induced pore water pressure in equal-stress-level conditions is assessed.

2. Experimental Procedure

2. 1. Materials and Specimens Preparation

The sand and gravel, as the granular materials used in the mixtures, are sub-rounded with specific gravities (G_s) of 2.64 and 2.56, respectively. A commercial clay, namely Turkey Ball-clay, with the index properties of LL=42 %, PI=19 %, and G_S=2.72 was used as the cohesive part of the mixtures. The grain-size distributions of the materials are presented in Figure 1.

Clay-granular material mixture specimens were prepared by sand or gravel content of 0, 20, 40 and 60 % by volume. The specimens were named T100, ST80, ST60, ST40, GT60 and GT40, where S, G and T stand for the sand, gravel and clay, respectively; the numbers denote

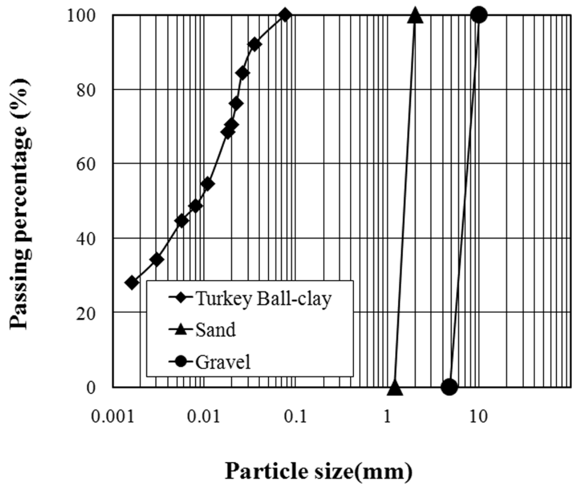

Fig. 1. Grain size distributions of tested materials

the volumetric clay percentage in the specimen.

Each specimen was compacted in six layers with a water content of 2% wet of optimum and 98% of maximum dry density, according to the standard compaction test [8]. Table 1 gives dry density and water content of the specimens before testing. The specimens were 7.1 cm in diameter and 15 cm in height.

2. 2. Consolidation and Shearing

The specimens were consolidated isotropically under effective consolidation pressures (σ'_c) of 100, 200 and 350 kPa in saturated conditions. Undrained cyclic strain-controlled triaxial tests were carried out on the specimens [9]. The tests were terminated after 50 cycles of constant cyclic strain amplitude (ε_c). The tests were conducted with three cyclic strain amplitudes, ε_c (i.e., ε_c = 0.25 %, 0.5 %, and 1% for the tests with σ'_c = 100 kPa, and ε_c= 0.5 %, 1 %, and 1.5 % for the tests with σ'_c= 200 kPa and 350 kPa). More details about the specimens and testing conditions are provided by Soroush and Soltani [7].

Since pore water pressures are not uniform within the cohesive soils immediately after stopping cyclic loading (Δu_{cy}), enough time was given for the equalization of Δu_{cy} after the completion of cyclic loading. To facilitate measuring reliable pore water pressures in the specimens, the frequency of cyclic loading was selected 0.1 Hz, which lies well in the range of frequency employed by the other researchers for testing on clay and clay-sand mixtures [1, 10, 11, 12, 13, 14, 4].

3. Test Results

For the purpose of brevity, only typical immediate results of the cyclic triaxial tests are presented. However, the compiled results of all the tests are analyzed and evaluated in the next sections.

Figure 2 shows the variations of deviatoric stress (σ_d=σ'_1-σ'_3) versus axial deformation during the tests with ε_c=1.0 % and σ'_c=350 kPa on T100, ST80, ST60, and ST40 specimens. It is observed that shear strength and stiffness of the specimens degrade during cyclic loading. The rate of degradation is comparatively more pronounced for the specimens with the higher granular material content (w_g). It is more obvious by comparing Figure 2d with Figure 2a.

For the above tests and loading, the variations of cyclic loading-induced pore water pressure with time are depicted in Figure 3. The figure shows that Δu_{cy} increases as cyclic loading continues and this increase are generally higher for the specimens with the higher sand contents.

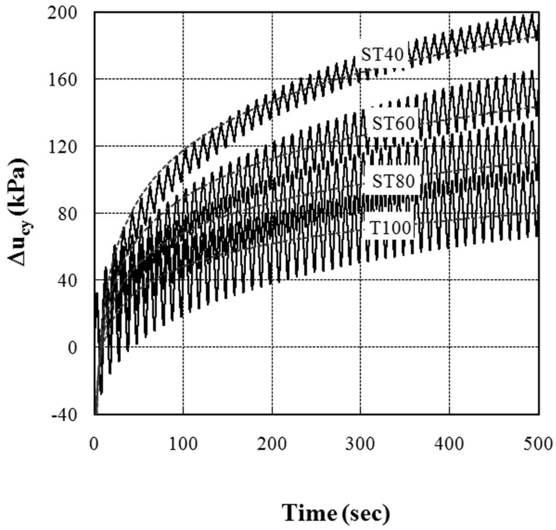

Fig. 3. Variations of excess pore water pressure versus time of loading (σ'_c=350 kPa and ε_c =1.0 %)

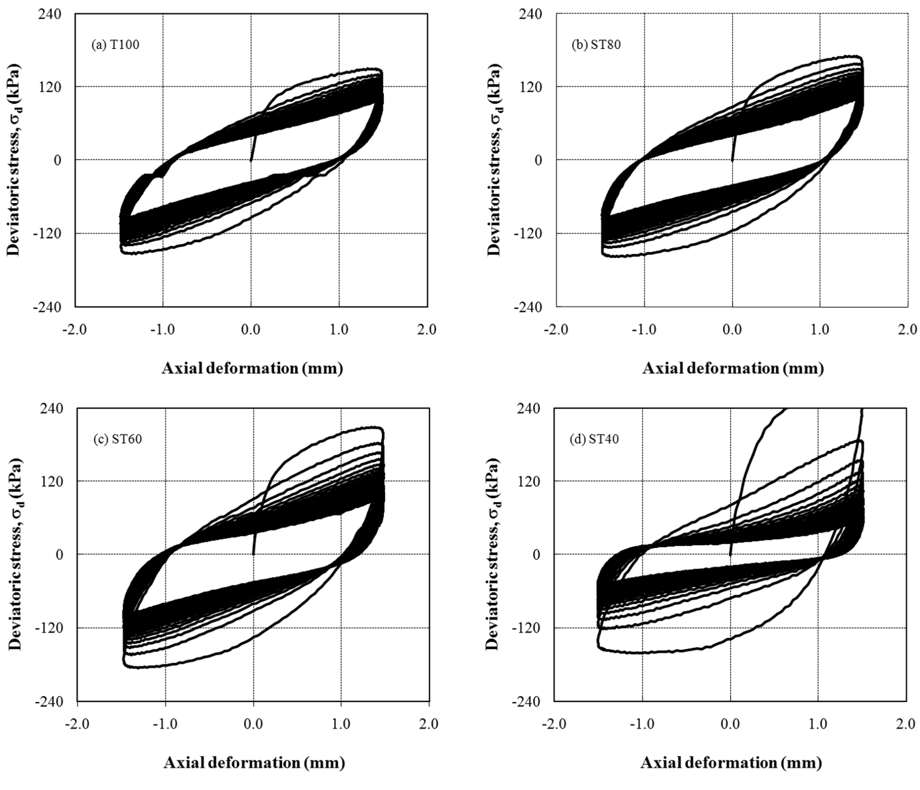

Fig. 2. Stress-deformation behavior of the specimens (σ'_c=350 kPa and ε_c =1.0 %)

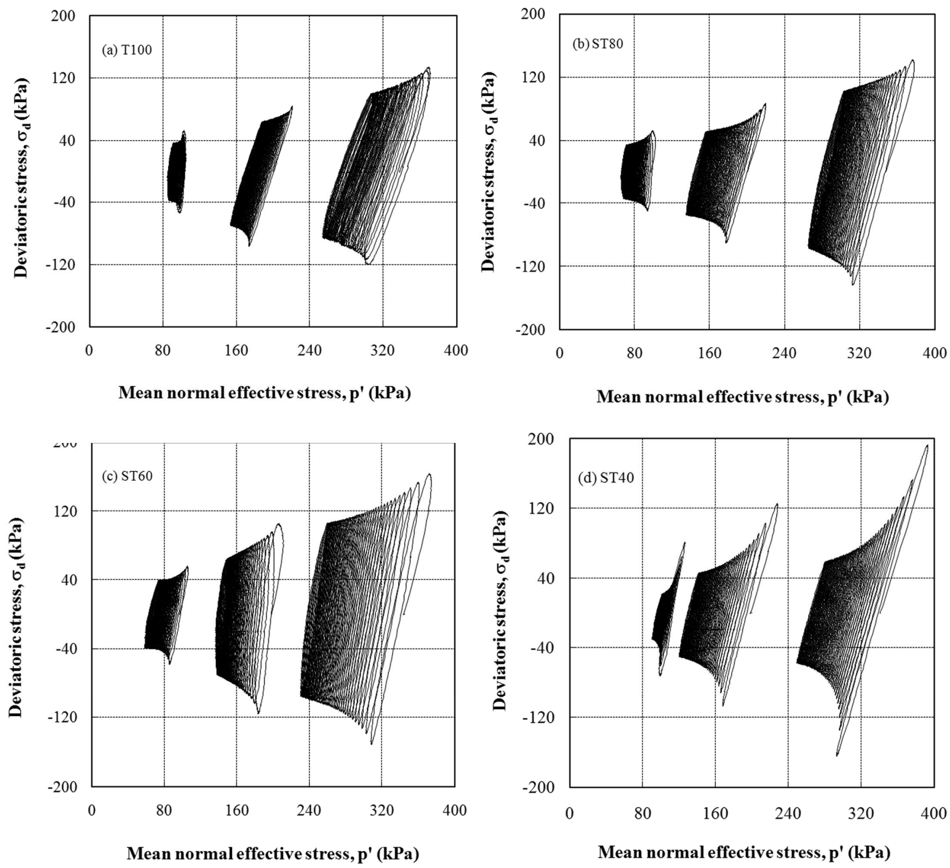

Fig. 4. Stress paths of cyclic tests with ε_c =0.5% at different consolidation pressures

The stress paths in the σ_d: $p' = (\sigma'_1+2\sigma'_3)/3$ plane for the tests with ε_c=0.50 % on T100, ST80, ST60 and ST40 specimens are illustrated and compared in Figure 4. The decrease of p′ values due to pore water pressure buildup is evident for all of the tests.

4. Analysis of Results

4. 1. Degradation Index

It is well known that normally and lightly overconsolidated saturated soils, subjected to undrained cyclic loading, degrade in terms of their shear strength and deformation modulus. Figure 2 shows this effect for the tests reported in this paper. In order to demonstrate quantitatively the above influence in triaxial tests, the degradation index (δ) introduced by Idriss et al. is adopted here [15]. For a cyclic strain-controlled triaxial test with given ε_c, this index is defined as follow:

$$\delta = \frac{G_{SN}}{G_{S1}} = \frac{\sigma_{dN}/\varepsilon_c}{\sigma_{d1}/\varepsilon_c} = \frac{\sigma_{dN}}{\sigma_{d1}} \qquad (1)$$

where G_{S1} and G_{SN} are secant deformation modulus at cycles 1 and N, respectively; σ_{d1} and σ_{dN} are the maximum cyclic deviatoric stresses corresponding respectively to the above-mentioned cycles. Lower values of δ mean the higher degrees of degradation.

The variations of degradation index (δ) and cyclic loading-induced pore water pressures (Δu_{cy}) in terms of cyclic strain (ε_c), number of loading cycles (N), and granular material content (w_g) are presented in the following.

4. 2. Effect of Number of Loading Cycles

The variations of degradation index (δ) and cyclic loading-induced pore water pressures (Δu_{cy}) versus number of loading cycles (in logarithmic

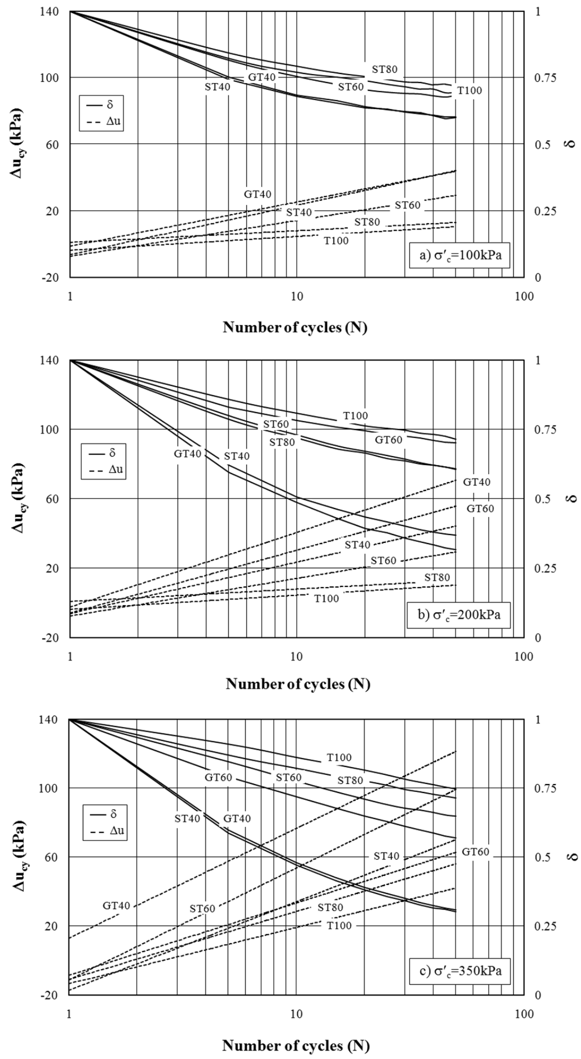

Fig. 5. Variations of degradation index and excess pore water pressure versus number of cycles (ε_c =0.50%)

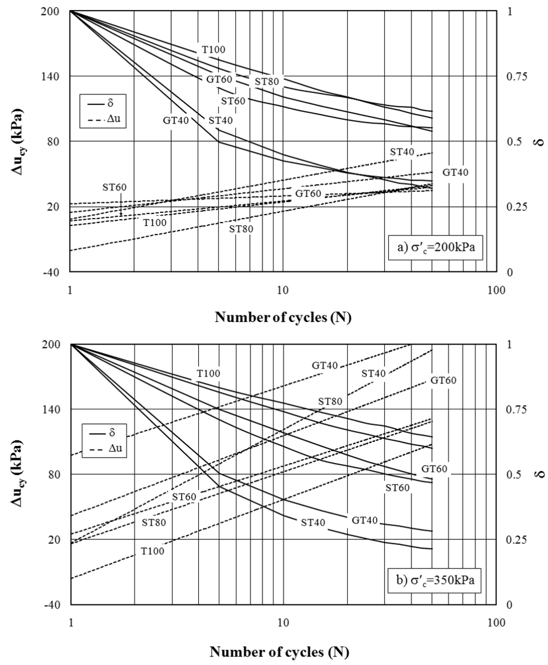

Fig. 6. Variations of degradation index and excess pore water pressure versus number of cycles (ε_c =1.0%)

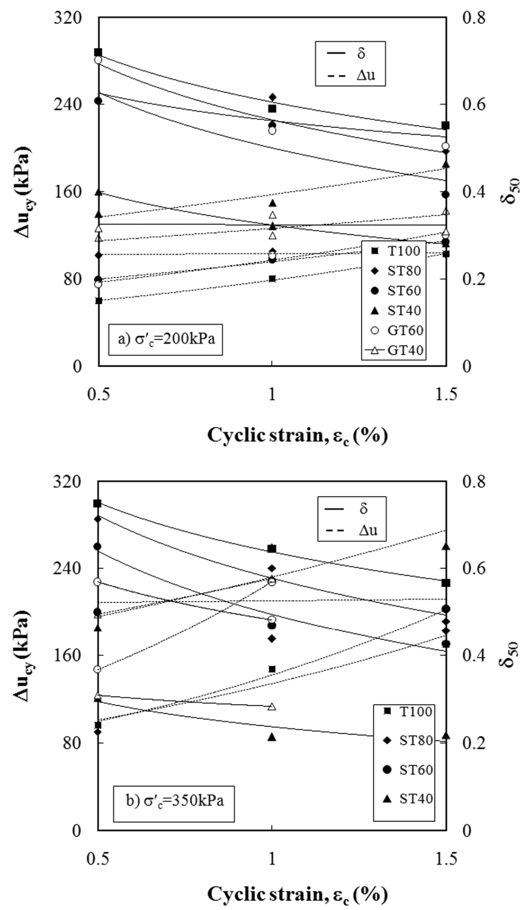

Fig. 7. Variations of degradation index and excess pore water pressure versus cyclic strain

scale) are shown together in Figures 5 and 6 for the tests with ε_c= 0.5 % and 1.0 %, respectively. Similar trends were observed for the tests with ε_c =1.5 %.

It seems that for all the tests, δ decreases and Δu_{cy} increases with continuing loading cycles. It can also be seen that the decrease of δ and increase of Δu_{cy} are more pronounced for the tests with the higher initial consolidation pressure (σ'_c). The figures also show that most of degradations have taken place during the first 10 cycles.

4. 3. Effect of Cyclic Strain Amplitude

Figure 7 shows variations of the degradation

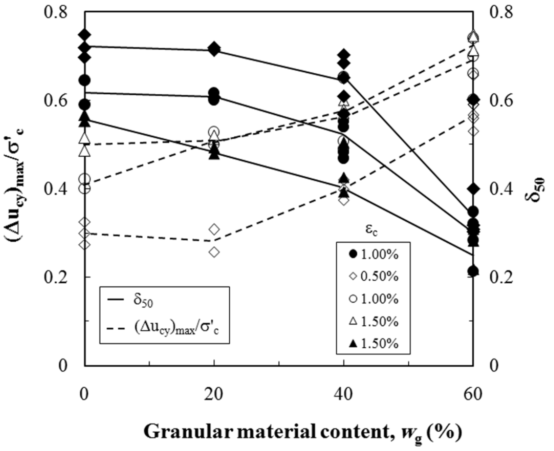

Fig. 8. Normalized maximum excess pore water pressure and degradation index versus granular material content

index and excess pore water pressure at the end of cyclic loading [δ_{50} and $(\Delta u_{cy})_{max}$] versus cyclic axial strain amplitude (ε_c) for the tests with σ'_c= 200 kPa and σ'_c= 350 kPa. It is obvious that for all of the tests, the degradation index decreases (i.e. excess pore water pressure increases) as ε_c increases.

4. 4. Effect of Granular Material Content (w_g)

Variations of the degradation index and normalized excess pore water pressure at the end of cyclic loading [δ_{50} and $(\Delta u_{cy})_{max}/\sigma'_c$] versus granular material content (w_g) for the tests with three values of cyclic strains (ε_c= 0.5%, 1%, and 1.5%) are presented in Figure 8. This figure indicates that in general δ_{50} decreases and $(\Delta u_{cy})_{max}/\sigma'_c$ increases with the increase of granular material content in the specimens.

As presented in this figure, for a given values of ε_c, the $(\Delta u_{cy})_{max}/\sigma'_c$ is approximately constant for w_g< 20%, while it is increased as w_g increases from 20 % to 60 %.

4. 5. Effect of Grain Size

The effect of grain size on the cyclic behavior of mixed clayey soils can be evaluated by comparing the variations of δ and Δu_{cy} versus number of loading cycles (Figures 5 and 6) for the specimens with the same w_g, but different grain sizes (i.e., sand versus gravel). With referring to these two figures, one may conclude that the grain size has no significant effects on the values of δ and Δu_{cy}. This conclusion is in agreement with the findings of similar researches [4].

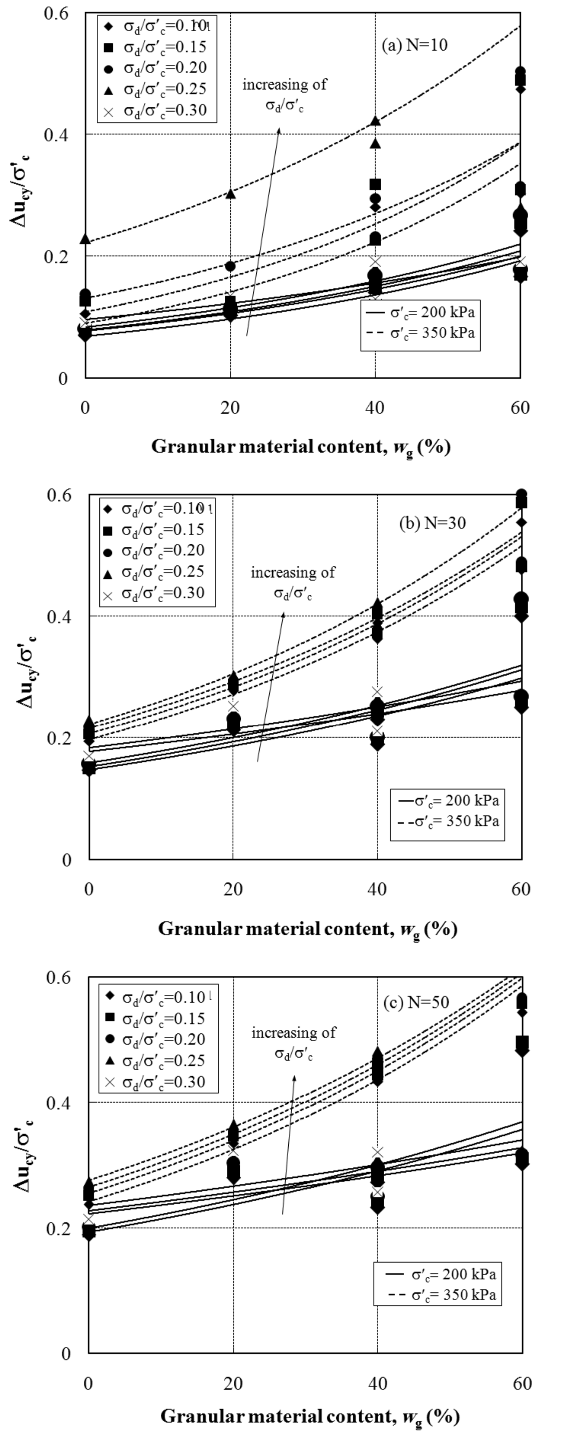

Figure 9. Effect of granular material content on excess pore water pressure in different equal stress levels for cyclic tests with ε_c = 1.0 %

4. 6. Equal Stress Level Condition

In practice soil structures exist in which stress-controlled (versus strain-controlled) conditions are dominant. In order to examine the effect of granular material content on the normalized pore water pressures generated during cyclic loading ($\Delta u_{cy}/\sigma'_c$) at equal stress levels (σ_d/σ'_c), the results of the tests, which are basically carried out in the strain-controlled conditions, are compiled and presented in Figure 9. Figures 9a, 9b and 9c show trends of variations of Δu_{cy} versus wg for the tests with ε_c=1.0, at five stress levels (σ_d/σ'_c = 0.1, 0.15, 0.2, 0.25 and 0.3) for N= 10, 30, and 50, respectively. It is obvious that for a given N, $\Delta u_{cy}/\sigma'_c$ increases as w_g of the specimen increases. It is worthy to note that this trend is similar to the trend observed in the strain-controlled conditions (see Figure 8).

5. Summary and Conclusions

A number of undrained cyclic triaxial tests were carried out on the clay-granular material mixtures to study the cyclic behavior of mixed clayey soils. The specimens of the mixtures consisted of 0, 20, 40 and 60 % sand or gravel, as granular materials. Degradation and excess pore water pressure behaviors of these soils were evaluated in terms of number of loading cycles, cyclic strain amplitude, granular material content, and grain size. The main findings are as follow:

- Mixed clayey soils degrade due to cyclic loading and their undrained shear strength and secant deformation modulus decrease as the number of loading cycles increase.
- The inclusion of sand and gravel grains into clay matrix leads to increasing of the degree of degradation and pore water pressure build up during cyclic loading.
- Degradation index decreases as number of loading cycles and cyclic strain increase. The major parts of degradations have taken place during the first 10 cycles. Also the degree of degradation is higher for the tests with higher values of cyclic strain.
- In equal-stress-levels, Δu_{cy} increases when granular material content of the specimens increases.

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Notation

G_S = Specific gravity
G_{S1} and G_{SN} = Secant deformation modulus at cycles 1 and N, respectively.
LL = Liquid limit
PI = Plasticity index
p' = Mean normal effective stress
w = Water content
w_g = Granular material content
Δu_{cy} = Cyclic-induced excess pore water pressure
$(\Delta u_{cy})_{max}$ = Cyclic-induced excess pore water pressure at the end of cyclic loading
δ = Degradation index
δ_{50} = Degradation index at the end of cyclic loading
ε_c = Cyclic axial strain
γ_d = Dry density
σ'_c = Effective consolidation pressure
σ_d = Deviatoric stress
σ_{d1} and σ_{dN} = Cyclic deviatoric stresses at cycles 1 and N, respectively

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