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Mechanical behavior of a cemented gravely sand under monotonic and cyclic loading-case study of Tehran alluvium

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Abstract

The major section of the city of Tehran has been developed on cemented coarse-grained alluvium. In order to understand the mechanical behavior of this soil, a series of undrained cyclic triaxial tests were performed on uncemented and artificially calcite-cemented samples. In this regard the effects of cement content, confining pressure and cyclic deviatoric stress were studied as well. In general by increase in the amount of cementation, maximum shear modulus increases and damping ratio show no significant variation. Also, increase in deviatoric strain results in the increase in damping ratio and decrease in shear modulus. In addition the higher confining pressures lead to higher shear modulus and lower damping ratio. Furthermore the shear modulus decreases with increase in number of cycles.
Keywords: calcite-cemented, gravely sand, shear strength, cyclic loading, Tehran alluvium

1. Introduction

Most of the alluvial deposit of Tehran, the capital city of Iran, has a soil with a cemented nature. The amount and characteristics of the cementation of the deposit varies in different parts from highly cemented in the north to non-cemented in the south. This deposit consists of gravely sand to sandy gravel with some cobbles and is dominantly cemented by calcite with carbonate origin (Haeri et al., 2002) [1]. On the other hand, Tehran is situated in a seismic region. Thus, characterization of dynamic behavior of the deposit is inevitable but undisturbed sampling from this soil for triaxial testing is virtually impossible. Therefore, a study on the dynamic behavior of Tehran deposit cemented artificially with calcite has been planned.

Previous studies conducted by Haeri and his co-workers on the static behavior of Tehran cemented gravely sand using different cementing agent like lime, Portland cement, gypsum show that cementation generally increases the static shear strength parameters and the brittleness of the soil, especially in low confining pressures (Haeri et al., 2002[1]; Haeri et al., 2005[2]; Haeri and Hamidi, 2005[3]; Haeri et al., 2007b [4]). However the influence of the cementation decreases as the confining pressure increases as a result of degradation of cemented bonds. The increase in shear strength mostly affects the cohesion and also slightly the friction angle. However, the increase in brittleness may have reverse effects as the sudden bond breakage and consequent sudden decrease in strength and increase in deformation might be unjustifiable for cuts in, or structures supported on cemented soils.

In cyclic loading, it is widely accepted that the stress–strain curve shows hysteresis and accumulation of irreversible strains with increasing number of cycles if the stress imposed during cyclic loading lies outside the true elastic range (Kokusho, 1980 [5]; Lo Presti et al., 1997[6]). Using the hysteresis loop, and applying geometrical calculations, it is possible to obtain dynamic shear modulus and damping ratio of the soil for compression and extension sections of loading. From further examination of the hysteresis loop of each cycle, dynamic shear modulus decreases with increase in the strain or the number of cycles. This subject is especially due to bond degradation and increase in pore water pressure for cemented and uncemented soils, respectively. Sharma and Fahey (2003) [7] and Ribay et al. (2004) [8] have showed the increasing trend in shear modulus by increasing the confining pressure. Various researchers have shown that shear modulus increases with the power form of effective confining pressure (Acar and El-Tahir, 1986 [9]; Saxena et al., 1988 [10]; Chang and Woods, 1986 [11]). However, Baig et al. (1997) [12] showed that G_{max} is independent on effective confining pressure for cemented sands. They found that degree of cementation and characteristics of grains skeleton along with cemented bond strength are the most effective parameters on shear modulus. On the other hand, the increase in cement content leads to higher dynamic shear modulus. Acar and El-Tahir (1986) [9] showed that degree of cementation and density highly control the stiffness degradation of cemented sands; and increase in shear strains due to consecutive failure of cementing bonds, decreases shear modulus. Ribay et al. (2004) [8] showed that effect of cementation on stiffness is considerable, especially in small strains ($<10^{-2}$%) and in large strains due to degradation of cementation bonds, shear modulus of cemented samples approach to uncemented samples. To investigate the decrease in the stiffness through the increase in cycles, a degradation index (δ) has been proposed by Idriss et al., (1978) [13] and Yasuhara et al. (1997) [14] based on the ratio of the current shear modulus to the initial shear modulus. The change in cyclic stress ratio changes the pattern of stiffness degradation. For samples subjected to a lower cyclic stress ratio, the rate of degradation of stiffness is slower than that for samples subjected to higher cyclic stress ratio (Sharma and Fahey, 2003) [7].

Studies on dynamic behavior of limy cemented gravely sand samples performed by Haeri et al. (2007a) [15] show that shear modulus increases with increase in cement content up to 4.5% lime content and then the shear modulus decreases for 6% lime. However, damping ratio does not show any clear trend with change in cement content; although a minimum value for damping ratio could be seen at about 3.0 to 4.5 % cement content. The studies also show that shear modulus increases with increase in confining pressure (in the range of 100 to 700 KPa) and degradation index has a decreasing linear relation to the number of cycles in semi-logarithmic scale for limy cemented samples.

In this paper, the results of a series undrained monotonic and cyclic triaxial tests performed on uncemented and calcite cemented gravely sands are presented to examine the effect of cementation, confining pressure and cyclic stress ratio on the shear modulus and damping ratio of uncemented and cemented gravely soils.

2. Test Procedure

The undisturbed sampling of naturally cemented coarse-grained alluvium of Tehran is extremely difficult and for triaxial testing is virtually impossible. Moreover, the deposit is heterogeneous both in grading and cementation. Therefore mechanical properties of this soil including dynamic shear modulus and damping ratio were investigated using artificially calcite-cemented samples. Cement content (C_C = 0.0 to 3.0%), effective confining pressure (σ_3 = 100 to 500 KPa) and single amplitude of cyclic axial deviatoric stress ($\sigma_{d,c}$) are the main controlling factors considered and tested in this research. Tehran alluvium alters highly in gradation and cementation. The soil used in this research is obtained from the northern part of Tehran alluvium. An average grain size distribution of Tehran alluvium, which is called the base soil, is applied for reconstituted samples (Haeri et al., 2002) [1]. Maximum grain size is limited to 12.5 mm to comply with 100 mm diameter and 200 mm height of the samples. The base soil is sandy gravel that classifies as SW-SM based on the Unified Soil Classification System. The index characteristics of the base soil are also given in Table 1.

Table 1- Index prosperities for tested material.

F_C [i] (%)	G_C [ii] (%)	D_{10} [iii] (mm)	D_{50} [iv] (mm)	C_U [v] $= D_{60}/D_{10}$	C_S [vi]	G_s	$\gamma_{d,min}$ (kN/m^3)	$\gamma_{d,max}$ (kN/m^3)	γ_d (kN/m^3)
6	45	0.2	4	28	1.8	2.57	16.14	18.78	17.75

[i] F_C: Fine Content
[ii] G_C: Gravel Content
[iii] D_{10}: Effective Grain Size
[iv] D_{50}: Medium Grain Size
[v] C_U: Uniformity Coefficient
[vi] C_S: Curvature Coefficient

Consolidated undrained monotonic and particularly cyclic triaxial tests on uncemented and artificially cemented samples of the base soil were planned. Each specimen was compacted in four layers with determined gradation and density using wet tamping method. Under-compaction of lower layers was also considered during preparation (Ladd, 1978) [16]. Based on the preliminary cyclic test results, under-compaction percent (U_n) varied linearly between 3.0% for the first layer and 0.0% for the forth layer. Uncemented samples were directly prepared on the pedestal by a two-split mould. Conversely, cementation with calcite is a time-consuming process that needs particular equipments. This process includes three stages. The first stage is the preparation of cemented samples with hydrated lime. Passing CO_2 through the moist sample for 7 days is the second stage. Finally, samples were cured under water in a curing tank filled with distilled water at 25ºC for 27 days for crystallisation and precipitation of calcite. Four special units including aluminium base, ring, porous disk and cap were designed for preparation of calcite-cemented samples (Figure 1). High strength PVC tubes of 100 mm diameter and 275 mm long were used as mould for calcite cemented samples. The cemented samples were extracted from the mould with an extruder after curing time and installed on the pedestal in triaxial apparatus. Prior to cover the specimen with rubber membrane, its periphery was coated with a very thin layer of sandy clayey mortar in order to prevent membrane penetration. After installation of the specimen, the samples were saturated by flushing CO_2 before gravitational flushing de-aired water. During this process a maximum cell pressure of 30 KPa was maintained on the sample. Saturation stage is then conducted to reach a B-value of greater than 0.95 by applying back pressure. After saturation, in the case of cyclic loading, the samples were isotropically consolidated and then cyclically sheared under undrained condition in stress control mode with a frequency of 1 Hz. Principal stress reversal is also occurred during cyclic loading for all tests. Some tests were re-examined to evaluate the repeatability of the tests.

Figure 1- Cementation units for four sample preparation.

3. Monotonic Tests

The effect of cement content on soil properties is a major concern in this research. This effect on the monotonic behaviour of gravely sand is summarised in figure 2. In general for a given confining stress, with an increase in cement content, peak strengths increase and the amount of excess pore water pressure decreases. Effect of cement content and confining pressure on secant shear modulus at shear strain level of 0.015% for undrained triaxial tests under monotonic loading have been shown in figure 3. It is evident that secant shear modulus increases by increase in confining pressure and cement content.

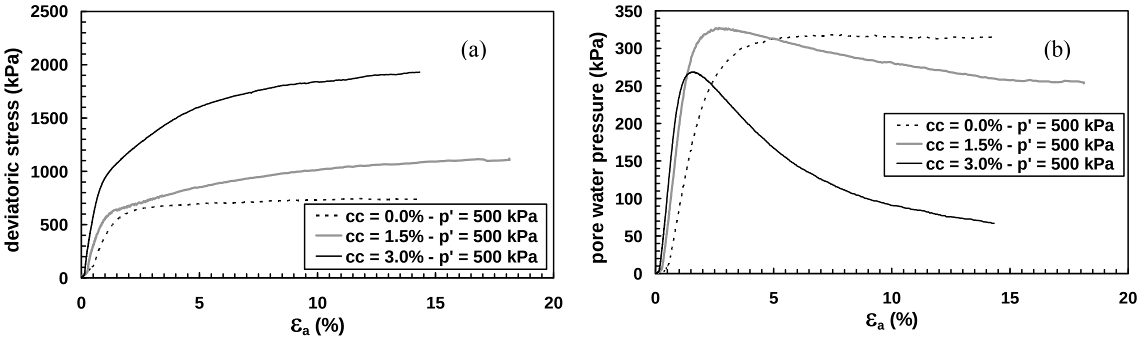


Figure 2- Influence of cementation on (a) shearing behavior for undrained samples, (b) excess pore water pressure generation during shear. (σ'_3=500 kPa)

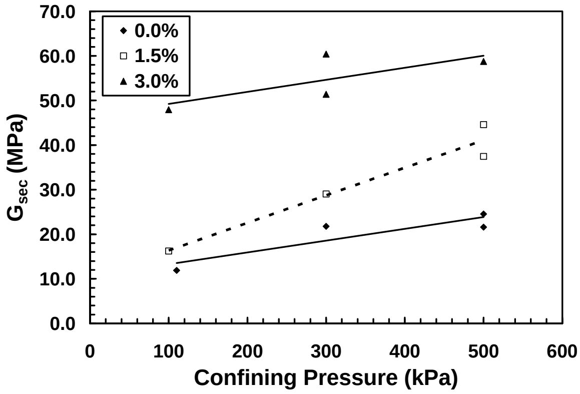
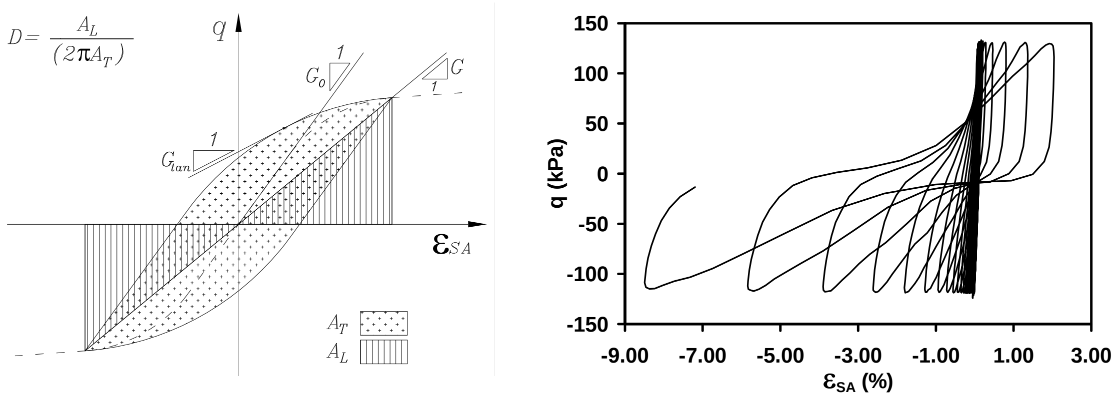


Figure 3- Influence of cementation and confining pressure on secant shear modulus in undrained triaxial tests under monotonic loading

4. Cyclic tests

Test Results and Discussions

Based on the results obtained from cyclic tests, dynamic shear modulus (G) and damping ratio (D) have been defined as illustrated in figure 4. In this figure, q is the stress invariant or cyclic deviatoric stress calculated from $q= \sigma'_1 - \sigma'_3 = \sigma_{d,c}$, where σ'_1 and σ'_3 are effective major and minor principal stresses. The parameter ε_{SA} is the corresponding shear strain invariant that is equal to axial deviatoric strain in undrained condition and calculated from $\varepsilon_{SA} =2/3(\varepsilon'_1 - \varepsilon'_3)$, where ε'_1 and ε'_3 are effective major and minor principal strains. In figure 4 (a), A_T represents the stored energy and A_L is the area of the corresponding hysteretic loop which used for calculation of damping ratio. The hysteretic loop Obtained from an uncemented sample is shown in Figure 4 (b) as a representative test. It can be observed that the amplitude of strain increases by increase in the number of cycles. This behavior is mainly due to increase in pore pressure and decrease in stiffness by increasing the number of cycles.



(a) (b)

Figure 4 (a) Schematic hysteresis loop and the method of calculation of parameters in this study and (b) Obtained hysteresis loops for an uncemented sample (*σ'$_r$=300 kPa, σ'$_{d,c}$=125 kPa*)

Effect of Cement Content

Figure 5 shows the variation of dynamic shear modulus and damping ratio calculated as the mean values for compression and extension of corresponding parameters. As it can be observed in this graph, the higher cement content generally leads to higher shear modulus, and consequently, stiffer samples. On the other hand, the results indicate that the damping ratio does not follow a decisive trend, but generally increase with cyclic strain. It is important to note that cemented samples with 1.5% cement have a very weak inter-particle bonding that leads to a similar stiffness to uncemented samples, especially in higher strains.

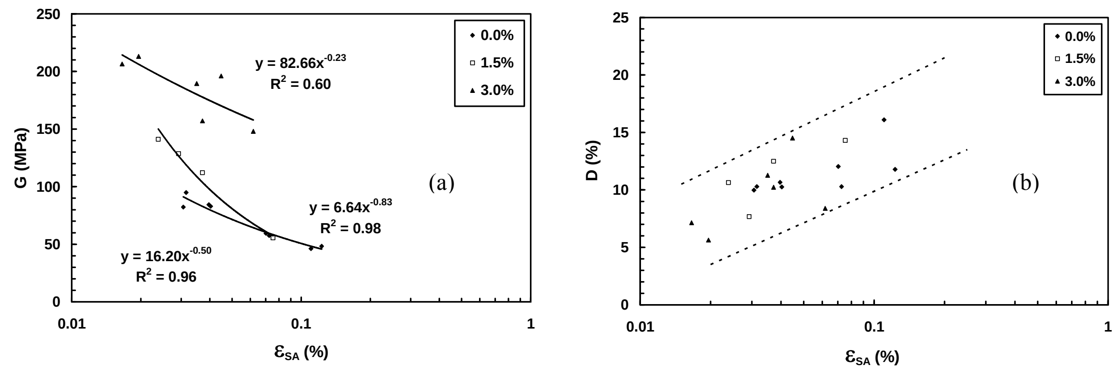


Figure 5- Variation of (a) shear modulus and (b) damping ratios with cyclic strain and cement content (σ_3=300 KPa).

The tests are conducted from small to large strains to get to failure. Variations of G (dynamic shear modulus) and D (damping ratio) versus single amplitude of axial strain are presented in Figure 6 in semi logarithmic scale for 1.5% cemented samples. The legends show the test names constituted from three parts that represent cement content, effective confining pressure and double amplitude deviatoric stress, respectively.

During the tests, with increase in the number of cycles, axial strain or shear strain gradually increases. As it is expected, the increase in amplitude of axial strain leads to decrease in shear modulus and increase in damping ratio by progressive degradation of cemented bonds. As mentioned above, cementation has a significant effect on the shear modulus. Since the amplitude of strain is very low in most cycles up to about failure, the density and scattering of the points regarding the damping ratios are very high in small strain range. At larger strains, damping ratio shows a rising trend with strain in semi-logarithmic scale. The maximum damping ratio obtained is about 25% for cemented samples and 27% for uncemented samples, at the failure cycle. Note that the single amplitude of axial strain at failure is in the range of 3.5% to 4.5%.

Effect of Confining Pressure

Increase in confining pressure results in the increase in shear modulus irrespective of the type of calculation of shear modulus. However, there could be observed no trend of change in damping ratio with change in confining pressure. Figure 7 shows the results for the tests that confirms this behavior. Confining pressure constrains the sample laterally and as a result, axial strain decreases showing stiffer behavior. However, very high confining pressure can break the bonds and decrease the shear modulus. Therefore the shear modulus for different cemented samples may converge in very high confining pressures. However, because of the level of applied confining pressures in this study, this phenomenon has not been observed.

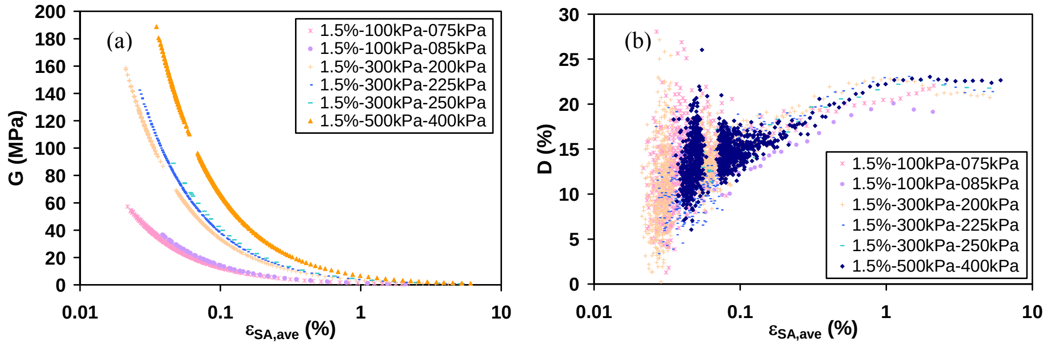


Figure 6- Variation of G and D with single amplitude axial strain for 1.5% cemented samples.

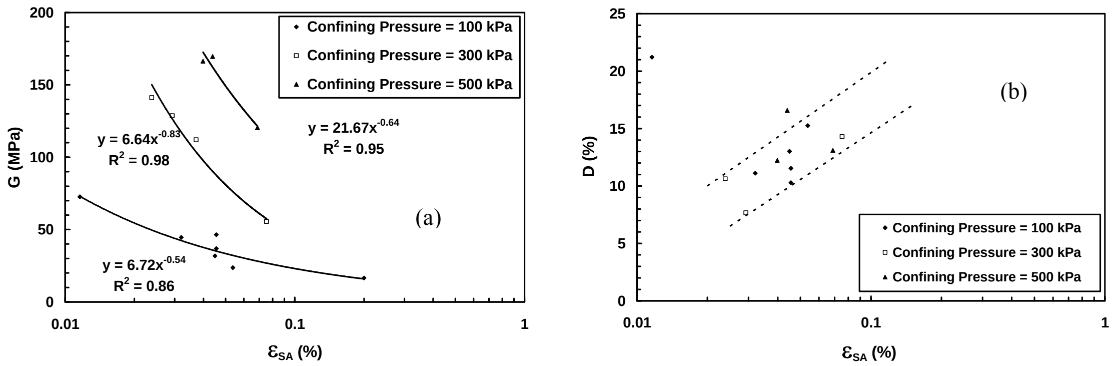


Figure 7- Variation of (a) G and (b) D with cyclic strain and confining pressure for 1.5% cement content.

5. Degradation

The decrease in stiffness and strength with the number of load cycles is named degradation. This phenomenon is clearly observed in Figure 6 due mainly to the building up of pore water pressure and bonding breakage. However, the cemented samples are not much affected by low amplitude cyclic loadings and depending on the amplitude of the cyclic load and the amount of cement content, degradation may happen. This fact is illustrated in Figure 8 for uncemented to 3.0% cemented samples. In this figure, the degradation index, is plotted against normalized number of cycle i.e. N/N_f and $r_{u,max}$; where the degradation index is the normalized shear modulus or G/G_{max}, G_{max} is maximum shear modulus, N_f is the number of cycles associated with the failure, $r_{u,max} = u_{max}/\sigma'_3$, u_{max} is the maximum excess pore water pressure in each cycle and σ'_3 is the effective confining pressure.

Yasuhara et al. (1997) suggested a linear relationship between degradation index and the number of cycles in logarithmic scale (i.e.: δ=1- α Log N). However, the results in this study show that almost a nonlinear relation for all samples is more appropriate. Figure 8 illustrates the relation between degradation index and the maximum pore pressure ratio that represents a rational trend.

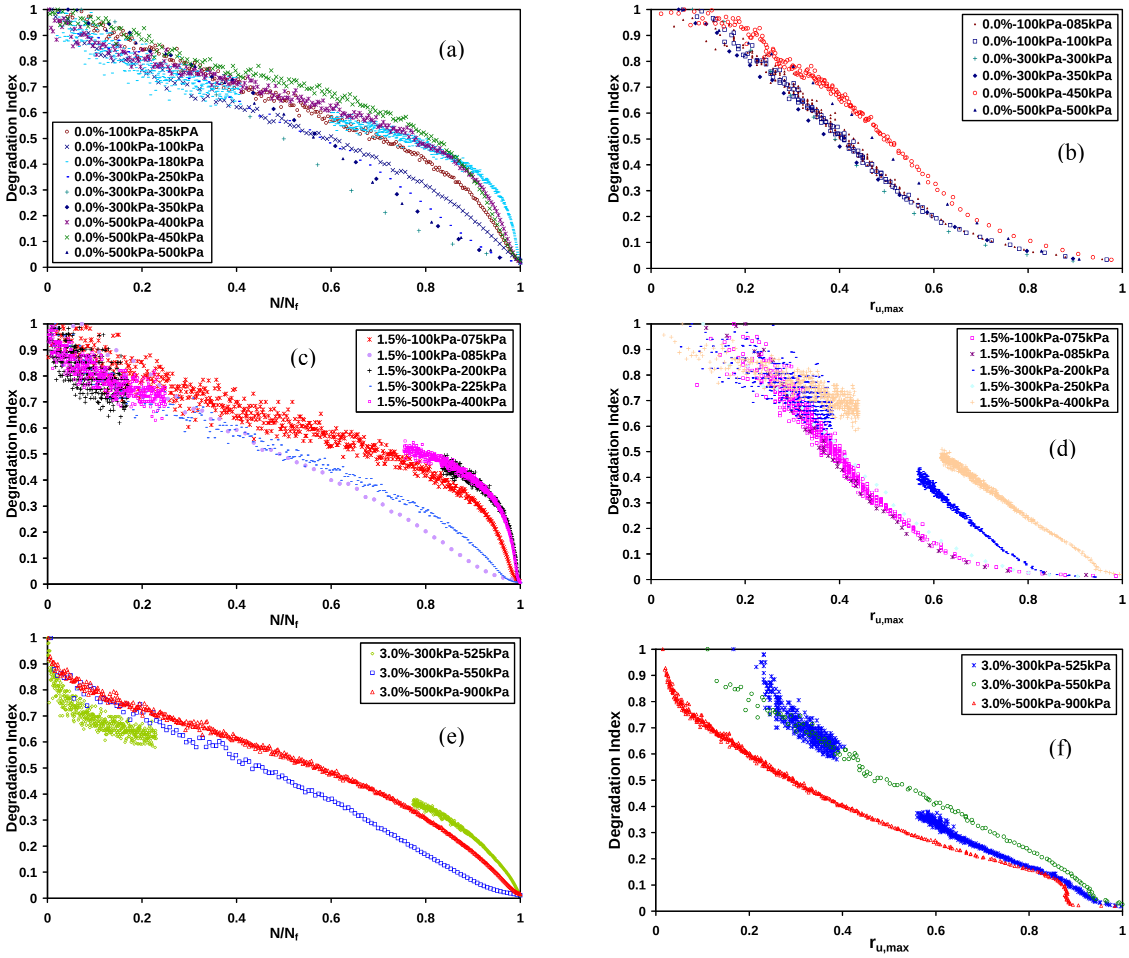


Figure 8- Variation of degradation index with N/N$_f$ and r$_{u,max}$ (a) and (b) uncemented sample, (c) and (d) 1.5% cement and (e) and (f) 3.0% cement.

6. Conclusion

Considering the results obtained from the tests, the following items can be concluded:

• Dynamic and monotonic shear modulus and peak strengths in monotonic loading of tested calcite cemented gravely sands increases with increase in cement content.

• Damping ratio does not show a decisive trend with change in cement content.

• Shear modulus rises continuously with increase in confining pressure. However, the performed tests show no clear trend for damping ratio versus confining pressure.

• In contrast to shear modulus, damping ratio increases with amplitude of axial strain.

• Degradation index has a decreasing nonlinear relation to the number of cycles.

7. References

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