

## **DYNAMIC PROPERTIES OF A LIMY CEMENTED GRAVELY SAND**

**S. Mohsen HAERI<sup>1</sup>, Mohammad Reza SHAKERI<sup>2</sup>, Majid GHAYOONI<sup>3</sup>**

### **ABSTRACT**

Cemented soils with inter-particle bonds are widely available in the world especially in the earthquake prone areas. In order to prevent misunderstanding of the soil behaviour under cyclic loads, research on the dynamic properties of cemented soils is inevitable. In this paper, two dynamic parameters including dynamic shear modulus and damping ratio considering the effects of cement content, confining pressure and cyclic deviatoric stress were investigated. These effects were studied on limy cemented gravelly sand using cyclic triaxial tests. The results show that by increasing the cement content shear modulus increases. Also higher confining pressures lead to higher shear modulus and lower damping ratio. Furthermore in higher number of cycles, shear modulus decreases.

Keywords: Cemented gravelly sand, Cyclic triaxial test, Shear modulus, Damping ratio

### **INTRODUCTION**

Characterising the behaviour of cemented soils that possess some degrees of bonding between their constituents has attracted worldwide research interest in recent years. Although many recent studies have made significant contributions in delineating the behaviour of these sediments, there is still paucity of information particularly on the cyclic behaviour of cemented soils.

Naturally cemented soils are widely available in alluvial regions and coastal areas. Misunderstanding of behaviour of such soils could lead to under or overestimate of the soil parameters. Cementation affects on the strength properties of soils especially in low confining pressures which are very common in most engineering purposes that it can help us in slope stabilities and foundation capacities. Natural cementation is a long process that consists of soil compaction, compressive dissolution, crystal growth and precipitation of cementing materials. Environmental factors such as heat and pressure have considerable effects on cementation process as well. In addition, artificial cementation is recently widely developed in order to improve soil properties.

Tehran, the capital of Iran, has a soil with cemented nature. The cementation percent varies in different parts from highly cemented in north to non-cemented in south. Investigations by geologists show that calcite, with carbonate origin, are the main cementing agent in Tehran deposit (Haeri et al., 2002). Furthermore Tehran is situated in earthquake prone area. Thus, considering Tehran cemented gravelly sand and its vulnerability to earthquake, characterization of dynamic properties of this cemented soil is inevitable.

Haeri and his co-workers (Haeri et al., 2002; Haeri et al., 2005; Haeri and Hamidi, 2005) started a variety research on Tehran cemented soil from 1998 at Sharif University of Technology. In these years they investigated on static behaviour of Tehran cemented gravelly sand using different cementing agent

---

<sup>1</sup> Professor, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran, Email: [smhaeri@sharif.edu](mailto:smhaeri@sharif.edu)

<sup>2</sup> Ph.D. Student, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran.

<sup>3</sup> M.Sc. Student, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran.

like lime, Portland cement and gypsum. In addition they performed some large scale tests on naturally cemented soil of Tehran. According to their researches, cementation generally increases the soil strength parameters and brittleness. Also, by increasing the confining pressure, the effect of cementation decreases which could be a result of degradation of cement bonds. However, the increase in brittleness may have reverse effects such as the sudden bond breakage and consequent sudden decrease in strength and increase in deformation, that might be unjustifiable for excavations, or structures supported on the cemented soils.

Cyclic response of cemented soils depends on many factors such as density, stress state, fabric, age, stress or strain history, cementation percent and cyclic loading conditions. Cyclic shear strength is defined as the deviatoric stress which leads to failure after a specific number of cycles (Poulos, 1980). In order to explain cyclic shear strength, researchers have proposed different cyclic stress ratios. Stress-strain relation of the soil under cyclic loading is also characterized with a hysteresis loop. This loop is followed by a backbone curve which shows the compression stage of the first cycle. Using the backbone curve and the hysteresis loop, and applying geometrical calculations, it is possible to obtain dynamic shear modulus and damping ratio of the soil. The procedure used in this paper will be explained later.

Dynamic shear modulus decreases with increase in the strain or the number of cycles. This subject is especially due to bond degradation for cemented soils. Idriss et al. (1978) proposed a degradation index ( $\delta$ ) to investigate decrease in the stiffness through increase in cycles. The index at each cycle is the ratio of the current shear modulus to the initial shear modulus. Yasuhara et al. (1997) followed the suggestion of Idriss et al. (1978) by proposing a linear relation for variation of degradation index with respect to the stress cycles, in a semi-logarithmic scale. On the other hand, the increase in cement content leads to higher dynamic shear modulus (Acar and El-Tahir, 1986). Sharma and Fahey (2003) and Ribay et al. (2004) also showed the increasing trend in shear modulus by increasing the confining pressure.

Regarding the damping ratio, Acar and El-Tahir (1986) showed that cementing of the soil reduces the damping ratio. Considering the effect of confining pressure on damping ratio of cemented soils, the results of investigations by various authors do not completely support each other. Although, confining pressure could reduce the damping ratio (Cai and Liang, 2004), Ribay et al. (2004) explained that confining pressure does not highly influence damping ratio.

## MATERIALS, SAMPLE PREPARATION AND TEST APPARATUS

### Soil and cementing agent

The soil which was used in this research is based on Tehran alluvium obtained from the northern part of Tehran. Figure 1 shows the grain size distributions of Tehran sandy gravel and gravely sand and the tested soil in this study. Considering scale factor for preparation of a cylindrical specimen with dimensions of 100 mm diameter and 200 mm height, the maximum grain size is limited to 12.5 mm. In order to recognize the soil characteristics, index tests were conducted according to ASTM; the test results are shown in Table 1.

**Table 1. Index tests results.**

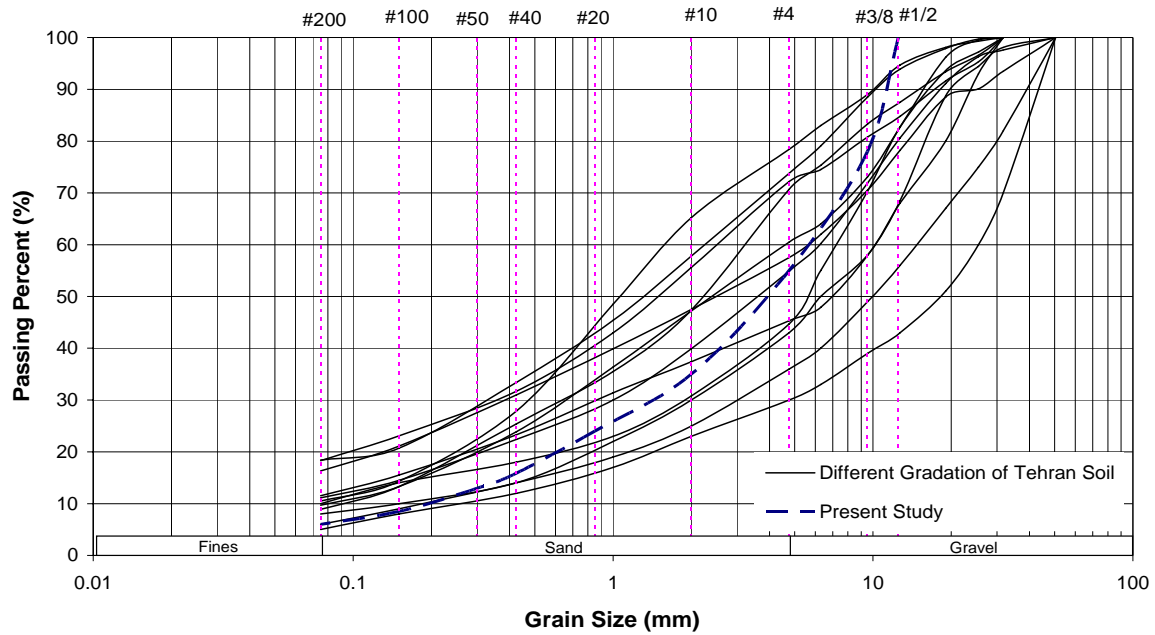
$C_u^*$	$C_z^{**}$	$G_s$	$\gamma_{d,min}$ ( $\text{kN/m}^3$ )	$\gamma_{d,max}$ ( $\text{kN/m}^3$ )	$\gamma_d$ ( $\text{kN/m}^3$ )	$w_{op}$ <sub>t</sub> (%)
28	1.8	2.57	16.14	18.78	17.75	8.5

\*  $C_u$ : Uniformity Coefficient

\*\*  $C_z$ : Curvature Coefficient

In order to provide some resemblance to the real cementation of Tehran cemented soil, the cementing

agent considered for this research was selected as hydrated lime.



**Figure 1. Grain size distributions of northern Tehran alluvium and the tested soil.**

### Sample preparation

High strength PVC tubes of 100 mm diameter and 200 mm high were used as mould for sample preparation in this study. Each specimen was compacted in eight layers with determined gradation and added specified lime percent using wet tamping method. Specimens were prepared with different cement contents varying from 0 to 6 percent. For crystallisation of the lime, samples were cured in a curing tank filled with distilled water at 25°C for eight weeks. Some narrow longitudinally slots were made in the tubes to provide water current in the sample during curing time.

### Cyclic triaxial test apparatus and sample installation

In order to perform cyclic tests on cylindrical samples, a cyclic triaxial apparatus was used. The sample was extracted from the mould and installed on the pedestal in triaxial apparatus after curing time. 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 and compliance. After installation of the specimen, the cell together with cyclic actuator is located in the appropriate place and the cell is filled with de-aired water as a confining fluid. Saturation stage is then conducted to reach a B-value of greater than 0.95 by applying back pressure up to maximum 200 kPa.

## TEST SCHEDULE AND DATA PROCESSING PROCEDURE

The effects of three variables including cement content, confining pressure and cyclic deviatoric stress on two dynamic parameters of the tested soil including dynamic shear modulus and damping ratio were investigated. Totally 36 tests were conducted in this study. Confining effective pressures vary among 100, 300, 500 and 700 kPa and double amplitude cyclic deviatoric stresses range among 100, 150, 200 and 250 kPa. Some of the tests were re-examined to evaluate the repeatability of them, which showed an acceptable degree of repeatability. Stress control cyclic loading with a frequency of 1 Hz and up to 200 cycles are conducted on isotropically consolidated samples in undrained condition. The data that can be obtained directly from the tests were stress, strain, pore pressure and volume

change. By conducting a geometrical calculation as shown in Figure 2 dynamic shear modulus and damping ratio are obtained.

In the undrained triaxial stress conditions, the general stress invariants can be described and illustrated in q-p' space as defined below:

$$q = \sigma'_1 - \sigma'_3 = \sigma_d \quad (1)$$

$$p' = \frac{\sigma'_1 + 2\sigma'_3}{3} \quad (2)$$

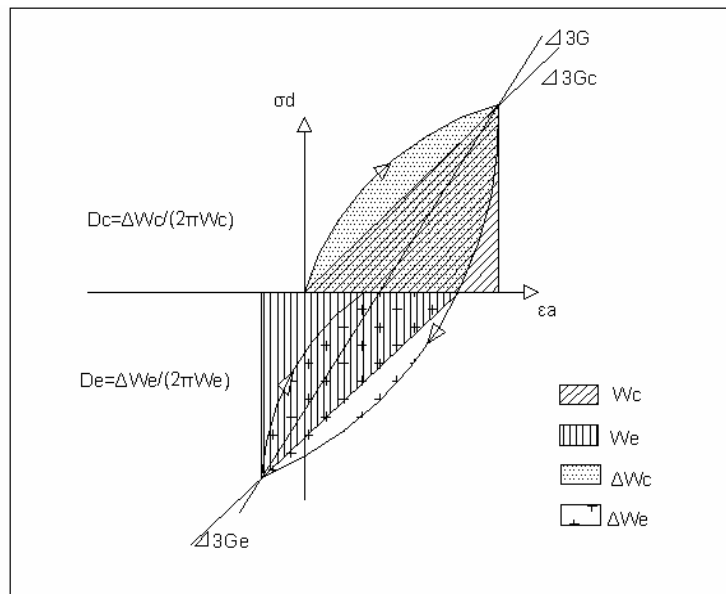
where,  $\sigma'_1$  and  $\sigma'_3$  are effective major and minor principal stresses. The shear modulus,  $G$ , and damping ratio,  $D$ , are also obtained by the Equations (3) and (4), respectively.

$$G = \frac{\sigma_d}{3\epsilon_a} \quad (3)$$

$$D = \frac{1}{2\pi} \frac{\Delta W}{W} \quad (4)$$

$W$  in equation (4) is the hatched area for each phase in Figure 2 which represents the stored energy for that phase and  $\Delta W$  is the area of the corresponding hysteresis loop.

It is notable that there is a shift in each hysteresis loop with respect to the previous one as shown in Figure 2 and 3 which has been considered in the calculations throughout this study. Namely, the upper half of the loop and associated triangle are considered for compression and those for lower half are considered for extension. The calculation for secant values is based on the total area of the loop and the combination of the lower and upper triangles.



**Figure 2. Schematic hysteresis loop and the method of calculation of parameters in this study.**

## TEST RESULTS AND DISCUSSION

### Typical test results

Since all the tests follow the same trend, results obtained from one test are presented as a representative. This test was done on 1.5 percent cemented sample with confining pressure of 100 kPa and double amplitude cyclic deviatoric stress of 200 kPa. Figure 3 shows the hysteresis loops of this test for some cycles. The rightward shift explained before is obvious in this graph. Figure 4 also shows the variation of axial strain with respect to cycles. As it can be seen, strain increases as the number of cycles increases. This is mainly due to increase in pore pressure and decrease in stiffness by increase in the number of cycles.

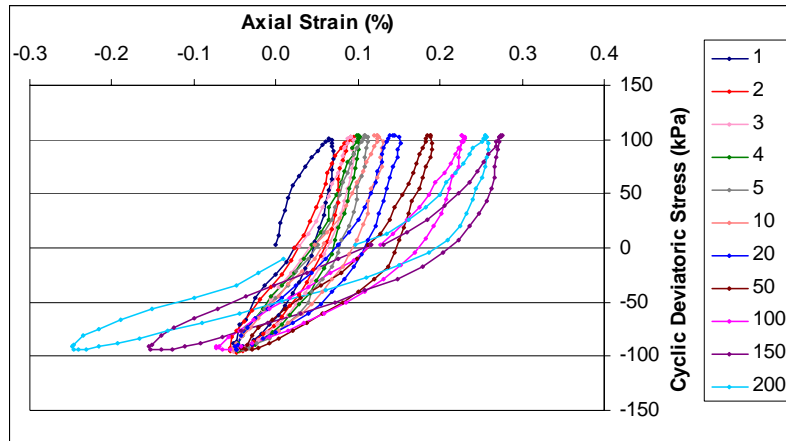


Figure 3. Representative hysteresis loops for a performed cyclic triaxial test in cycles of 1 to 200.

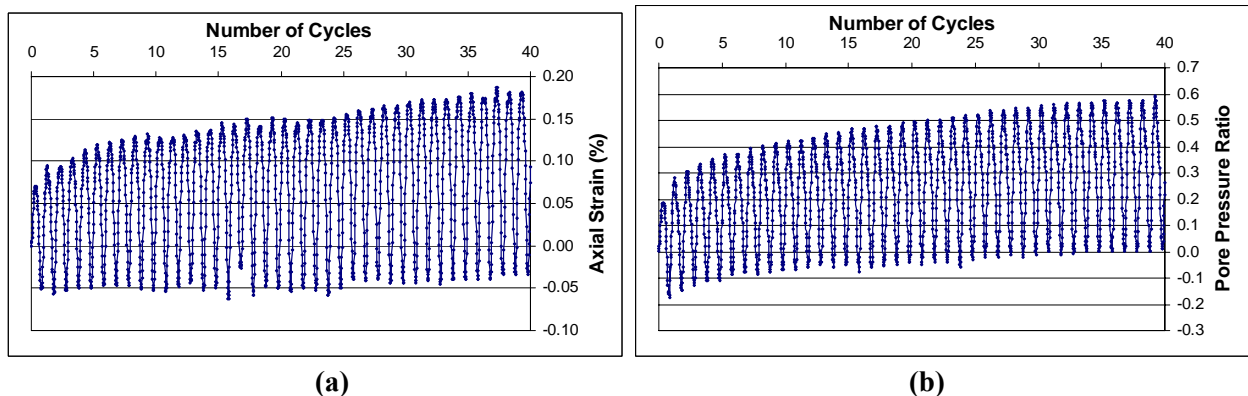


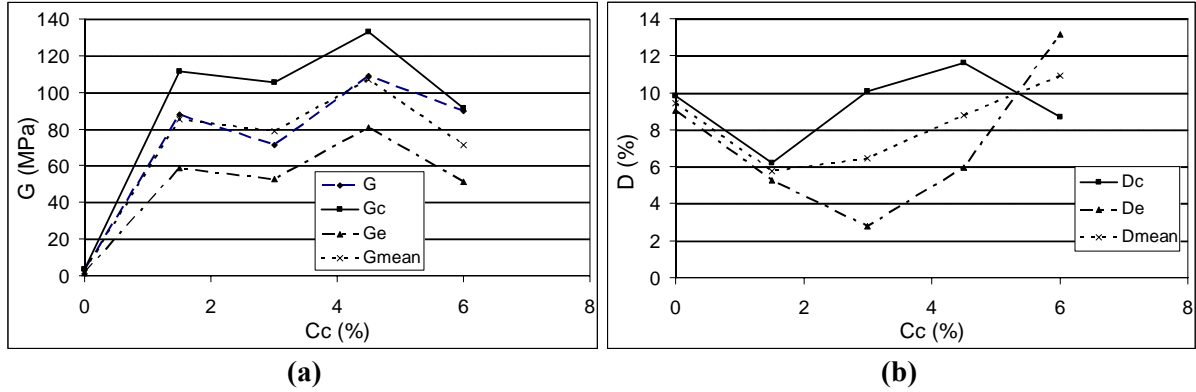
Figure 4. Typical variation of (a) axial strain and (b) pore water pressure versus cycles.

### Effect of cement content

In this part, the effect of cement content on the dynamic parameters is investigated. Figure 5-(a) shows the variation of different types of dynamic shear modulus, described before and shown in Figure 2 including  $G$  (secant shear modulus),  $G_c$  (compression modulus),  $G_e$  (extension modulus) and  $G_{mean}$  (mean values of compression and extension modulus) versus the cement content. This graph is drawn for 10<sup>th</sup> cycle of loading that axial strains vary between 0.04% (for  $C_c=6.0\%$ ) and 0.30% (for  $C_c=0\%$ ). As it can be seen in this graph, the higher cement contents generally leads to higher shear modulus, and consequently, stiffer samples. It is important to note that samples show an increasing trend in modulus with cement content up to 4.5% cement and a little fall in stiffness after that. Comparing different types of modulus in Figure 5-(a), it is notable that  $G_c$  is the highest and  $G_e$  the lowest value. However  $G$  and  $G_{mean}$  have approximately the same values.

Another dynamic parameter is damping ratio. Figure 5-(b) illustrates the variation of different damping ratios namely  $D_c$  (compression damping),  $D_e$  (extension damping) and  $D_{mean}$  versus the

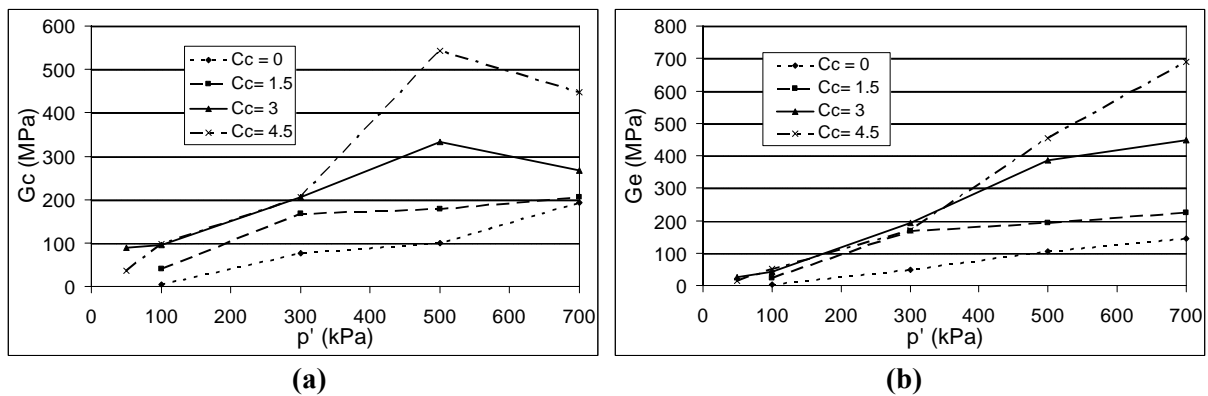
cement content. The results show that although  $D_c$  does not have a unique trend, the two other types of damping ratios namely  $D_e$  and  $D_{mean}$  have a minimum value in their variations. This could be the result of the fact that more solid samples which have higher shear modulus behave more elastic and have less damping ratio.



**Figure 5. Variation of (a) various dynamic shear modulus and (b) various damping ratio with the cement content at the 10<sup>th</sup> cycle ( $\sigma_3=100$  kPa and  $\sigma_{d,cyc,DA}=200$  kPa).**

#### Effect of confining pressure

Figure 6 indicates that the increase in confining pressure results in the increase in shear modulus irrespective of the type of calculation of shear modulus. Also Figure 7 demonstrates downward trend for damping ratio with increasing confining pressure. Confining pressure constrains the sample laterally and as a result, axial strain decreases showing stiffer behavior. In such condition, the area of hysteresis loop reduces which shows a higher elastic behavior and reveals lower damping ratio. 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, this phenomenon has not been observed in this study.



**Figure 6. Variation of (a)  $G_c$  and (b)  $G_e$  with the confining pressure at the 10<sup>th</sup> cycle for different cement contents ( $\sigma_{d,cyc,DA}=200$  kPa).**

Figure 7 clearly shows the decrease in damping ratio with increase in confining pressure which supports the fact that as long as increase in confining pressure does not break the bonds it results in stiffening of the samples. Variation of axial strain versus confining pressure at the 10<sup>th</sup> cycle is illustrated in Figure 8 for different cement contents. The decreasing trend of axial strain with increase in confining pressure and cement content can be observed from this figure.

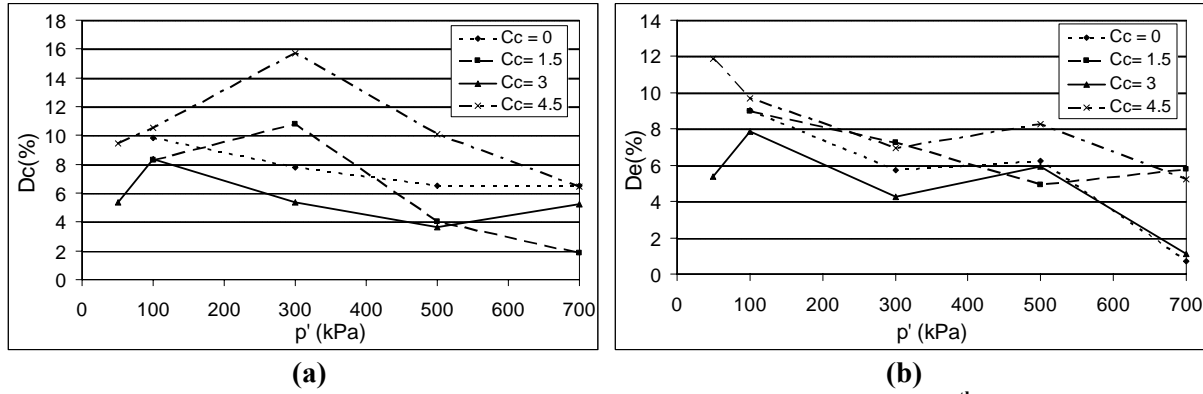


Figure 7. Variation of (a)  $D_c$  and (b)  $D_e$  with the confining pressure at the 10<sup>th</sup> cycle for different cement contents ( $\sigma_{d,cyc,DA}=200$  kPa).

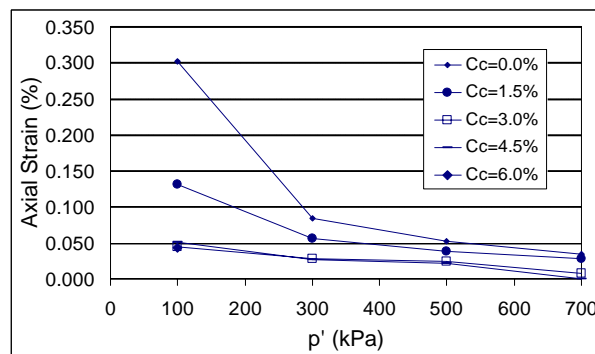


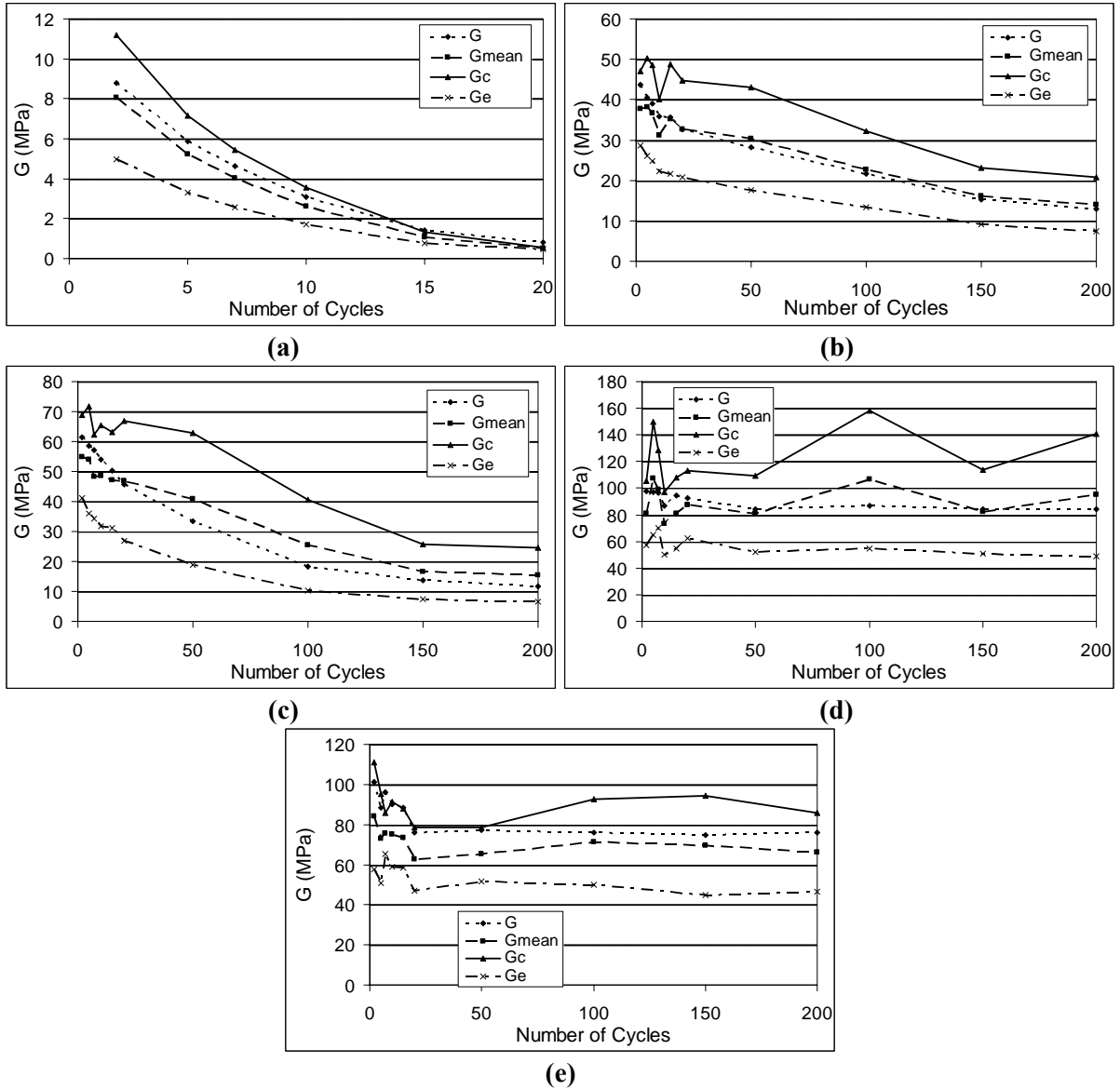
Figure 8. Variation of axial strain with the confining pressure at the 10<sup>th</sup> cycle for different cement contents ( $\sigma_{d,cyc,DA}=200$  kPa).

### Degradation

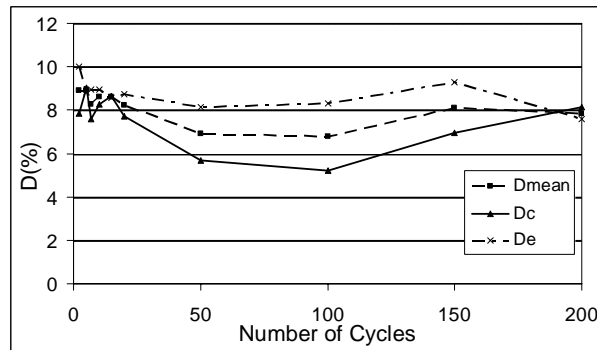
In undrained tests on saturated granular soils, the shear modulus decreases with increase in the number of load cycles due mainly to the building up of pore water pressure, and the sample may get to yield or failure after a number of load cycles, depending on the intensity of the load. The decrease in stiffness and strength with number of load cycles is called degradation. 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 in some tested samples (with 1.5% and 3.0% cement content); whereas the stiffness of some samples (with 4.5% and 6.0% cement content) do not visually change. This fact is illustrated in Figure 9.

Figure 10 shows the variation of damping ratio for sample with 1.5% cement as a representative of all samples; as there is no visual change in damping ratio with the number of cycles for all studied cases.

Figure 11 illustrates the variation of shear modulus with strain in semi logarithmic scale. As illustrated in Figure 11-(a) the variation of shear modulus with logarithm of axial strain is fairly smooth. Note that for uncemented samples the maximum strain of each cycle is in the range of 0.4% to 8% strain. However, the variation of shear modulus with logarithm of axial strain is very sharp for the



**Figure 9. Variation of  $G$  with the number of cycles for (a) uncemented sample, (b) 1.5% cement, (c) 3.0% cement, (d) 4.5% cement and (e) 6.0% cement ( $\sigma_3=100$  kPa and  $\sigma_{d,cyc,DA}=200$  kPa).**

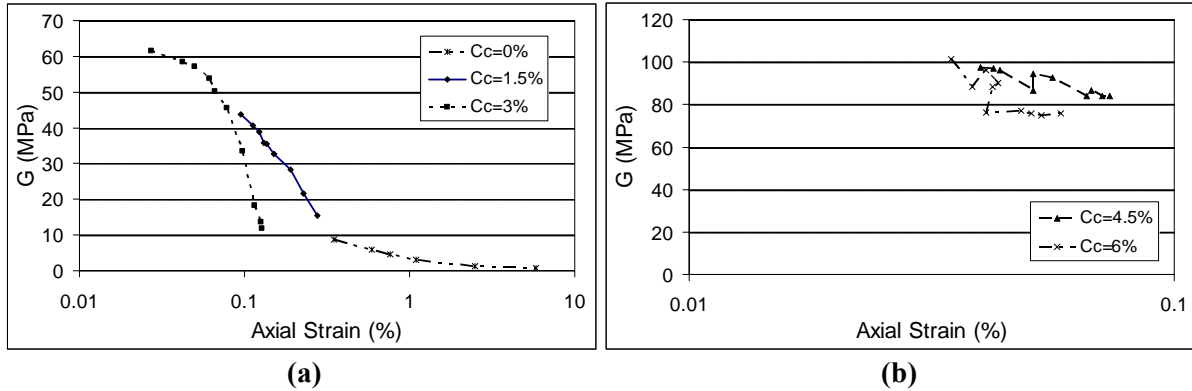


**Figure 10. Variation of  $D$  with the number of cycles for 1.5% cemented sample ( $\sigma_3=100$  kPa and  $\sigma_{d,cyc,DA}=200$  kPa).**

samples cemented with 1.5% and 3% lime, indicating a sharp degradation of cemented bonds for these samples. Note that the maximum strain associated with 1.5% cemented samples is in the range of 0.1%



to 0.4%, and that with 3% cemented sample is in the range of 0.03% to 0.15%. Ironically as can be seen from Figure 11-(b), the shear modulus do not show clear and smooth change with strain, although a general gentle decrease in stiffness could be seen with increase in strain level. This phenomenon can be attributed to the fact that the cemented bonds in samples of 4.5% and 6% lime are strong enough that can bear strains associated with low to medium amplitude cyclic loadings. Note that the maximum strain associated with 4.5% and 6% cemented samples is in the range of 0.05% to 0.08% which is very small.

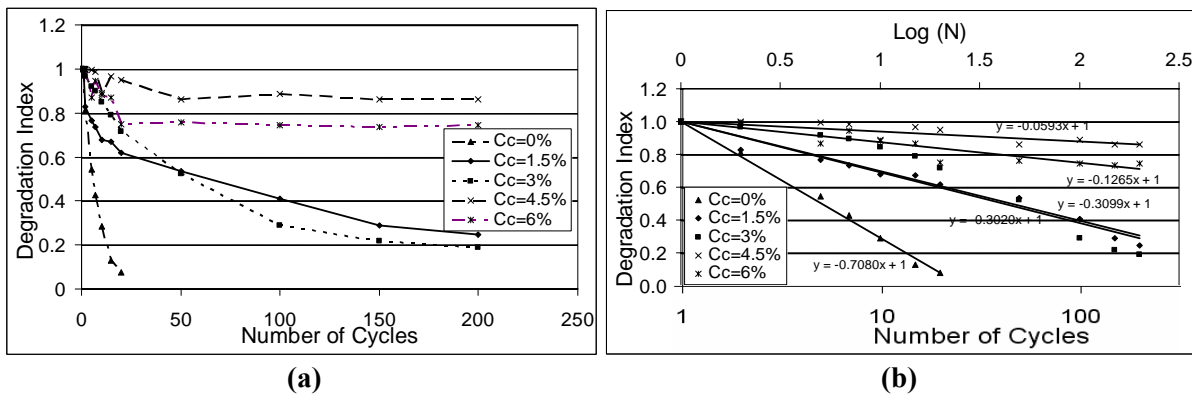


**Figure 11. Variation of  $G$  with strain in logarithmic scale for (a) 0%, 1.5% and 3.0 % cemented samples and (b) 4.5% and 6.0 % cemented samples ( $\sigma_3=100$  kPa and  $\sigma_{d,cyc,DA}=200$  kPa).**

Idriss et al. (1978) proposed a degradation index that was defined as  $\delta = G_N / G_1$  where  $G_N$  is the  $G$  at the  $N^{th}$  cycle and  $G_1$  is that at the first cycle of loading. Variation of degradation index versus the number of cycles (Figure 12-a) has a similar trend to that shown in Figure 11-a; however, the decremental trend of degradation index tends to shift to a constant value after a number of cycles for cemented samples. Yasuhara et al. (1997) defined a degradation index as given in Equation 5 and suggested that the degradation index is a linear function of number of cycles in logarithmic scale.

$$\delta = 1 - \alpha \text{ Log } N \quad (5)$$

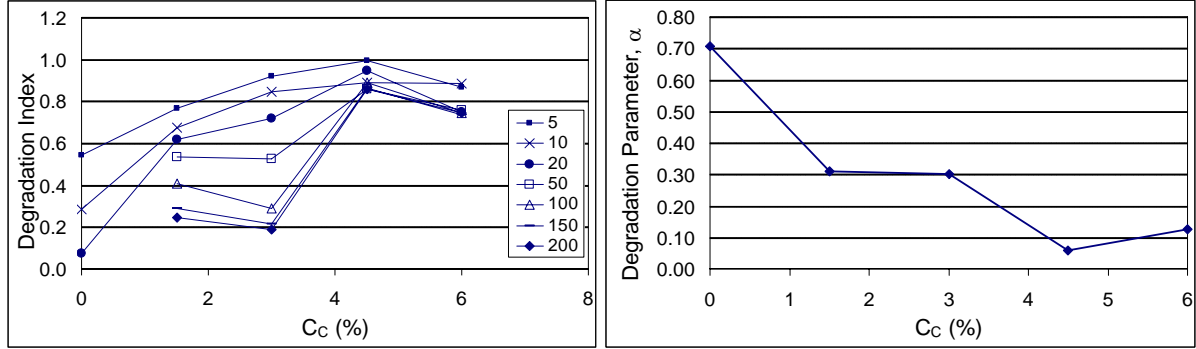
where,  $\alpha$  is degradation parameter. The variation of degradation index with logarithm of the number of cycles for the present study is also shown in Figure 12-b. Based on Figure 12-b, absolute value of parameter  $\alpha$  decreases with increase in cement content.



**Figure 12. Variation of degradation index with the number of cycles (a) normal scale, (b) semi-logarithmic scale.**

Variation of degradation index with cement content is also shown in Figure 13-a, which indicates an

increasing trend of degradation index with increase in cement for almost all numbers of cycles up to 4.5% cement content. However a slight decrease in degradation index can be observed for samples with 6% cement content. Variation of degradation parameter ( $\alpha$ ) with cement content is also shown in Figure 13 that generally represents a decreasing trend of ( $\alpha$ ) with cement content. However, a slight increase of ( $\alpha$ ) with cement content more than 4.5% lime is also visible in this figure. Such behaviour implies that the brittleness of cemented soil rises with cement content up to a certain cement value and then decreases.



**Figure 13. (a) Variation of degradation index with cement content, (b) Variation of  $\alpha$  with cement content ( $\sigma_3=100$  kPa and  $\sigma_{d,cyc,DA}=200$  kPa).**

## CONCLUSIONS

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

- Dynamic shear modulus of tested limy cemented gravely sands increases with increase in cement content up to 4.5% lime and decreases for 6% lime.
- Damping ratio does not show a clear trend with change in cement content. However a minimum value of damping ratio could be seen about 3.0 to 4.5 % cement.
- Shear modulus rises continuously with increase in confining pressures in the range of 100 to 700 kPa. On the other hand, performed tests show a downward trend for damping ratio versus confining pressure.
- In contrast to shear modulus, damping ratio does not vary so much with the number of cycles.
- Comparing different definitions of shear modulus, compression and extension modules are the highest and the lowest modulus, respectively. Average and secant modules are approximately equal in the performed tests.
- Degradation index has a decreasing linear relation to the number of cycles in semi-logarithmic scale for cemented samples.
- Brittleness increases with cement content up to a certain value of cement value and then gradually decreases.

## ACKNOWLEDGEMENTS

All cyclic triaxial tests conducted in the Advanced Geotechnical Engineering Laboratory of Civil Engineering Department at Sharif University of Technology that is acknowledged. Also the financial support of Vice Presidency in Research of the Sharif University of Technology is acknowledged.

## REFERENCES

- Acar, Y. B., El-Tahir, A. E., "Low strain dynamic properties of artificially cemented sand", *Journal of Geotechnical Engineering Division, ASCE*, Vol. 112, No. 11, 1001-1015, 1986.
- Cai, Y. Q., and Liang, X., "Dynamic properties of composite cemented clay", *Journal of Zhejiang University Science*, Vol. 5, No. 3, 309-316, 2004.
- Haeri, S.M., Yasrebi, S. and Asghari, E., "Effects of cementation on the shear strength parameters of Tehran alluvium using large direct shear test", *Proceedings 9<sup>th</sup> IAEG Congress, Durban, South Africa*, PP. 519-525, 2002.
- Haeri, S. M., Hamidi, A., "The effect of gypsum cementation on mechanical behaviour of cemented gravely sands", *Geotechnical Testing Journal*, Vol. 28, No. 4, 380-390, 2005.
- Haeri, S. M., Hosseini, S. M., Toll, D. G. and Yasrebi, S. S., "Experimental study of the behavior of a cemented gravely sand," *Geotechnical and Geological Engineering Journal*, Vol. 23, No. 5, 537-560, 2005.
- Idriss, I.M., Dobry, R. & Singh, R.D., "Nonlinear behaviour of soft clays during cyclic loading," *Journal of Geotechnical Engineering, ASCE*, 104 (GT12), 1427-1447, 1978.
- Kramer, S.L., *Geotechnical earthquake engineering*, Prentice Hall, 1996.
- Poulos, H. G., A review of the behaviour and engineering properties of carbonate soils, *Research Report No. R381, School of Civil and Mining Engineering, University of Sydney, Australia*, 1980.
- Ribay-Delfosse, E., Maigre-Djeran, I., Cabrillac, R., and Gouvenot, D., "Shear modulus and damping ratio of grouted sand," *Soil Dynamic and Earthquake Engineering*, Vol. 24, 461-471, 2004.
- Sharma, S. S., and Fahey, M., "Degradation of stiffness of cemented calcareous soil in cyclic triaxial tests," *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 129, No. 7, 619-629, 2003.
- Yasuhara, Y., Hyde, A.F.L., Toyota, N. & Murakami, S., "Cyclic stiffness of plastic silt with an initial drained shear stress," *Géotechnique Symposium on Pre-failure Deformation Behaviour of Geomaterials*, Jardine, R. J. Davies, M. C. R., Hight, D. W., Smith, A. K. & Stallebrass, S. E. (eds), 373-382, 1997.