Jour. of the KGS, Vol. 21, No. 7. September 2005, pp. 13~20

Experimental Study on the Effect of Particle Size Distribution of Soil on the Liquefaction Resistance Strength

입도분포가 액상화 저항강도에 미치는 영향에 관한 실험적 연구

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요 지

본 연구에서는 입도분포가 액상화 저항강도 및 동적물성치에 미치는 영향을 실험적으로 검증하였다. 우리나라 준설매립토의 입도분포 조사를 통해 준설매립토의 보편적인 평균입경 4가지와 균등계수 3가지를 선정하였고 평균입경과 균등계수를 각각 달리한 총 12종류의 대표적 준설매립토의 입도분포를 선정, 시료를 제작하였다. 제작된 시료를 이용하여 진동삼축시험을 수행하여 평균입경과 균등계수가 액상화 저항강도에 미치는 영향을 분석하였다. 또한 공진주시험을 수행하여 입도분포가 동적물성치에 미치는 영향도 분석하였다.

Abstract

For experimental study on the effect of particle size distribution on the liquefaction resistance strength, particle size distribution curves of the dredged soil were investigated. In this process, four mean particle sizes and three uniformity coefficients were defined representatively and twelve representative particle size distribution curves which have different mean particle size and uniformity coefficient, were defined and manufactured by using the real dredged river soil. Cyclic triaxial tests and resonant column tests were carried out to analyze the effect of mean particle size and uniformity coefficient on the liquefaction resistance strength and dynamic characteristics.

Keywords : Cyclic triaxial test, Liquefaction resistance strength, Mean particle size, Particle size distribution, Resonant column test, Shear modulus, Uniformity coefficient

1. Introduction

Liquefaction is defined as the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore water pressure and reduced effective stress (Marcurson, 1978). The liquefaction analysis has been performed by many experts in other countries (Ishihara, K., and Yasuda, S., 1975; Castro, G., and Poulos, S. J., 1977; Tokimatsu, K., and Yoshimi, Y., 1983; Ishihara, K., 1993; Youd, T. L. et al., 2001). On the other hand, there was little attention on the liquefaction analysis in Korea. After the Kobe earthquake in Japan in 1995, however, Korean civil engineers recognized that an earthquake is an important factor that should be considered in design and analysis of structures. Consequently, the liquefaction analysis has

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been studied actively since the Kobe earthquake (Shin, Y. S., 1999; Sim, J. W., 2001; Park, S. Y., 2002; Ham, K. W., 2003; Kim, S. I., 2004).

In Korea, reclamation work for structures such as airport and harbor continues to increase due to the narrow territory though it is easy to be damaged by the earthquake. Therefore, it is necessary to take the characteristics of dredged soil into consideration in seismic design and analysis for reclamation site.

In this study, cyclic triaxial tests were performed to discuss the effect of mean particle size and uniformity coefficient on the liquefaction resistance strength for three relative densities. Effect of mean particle size and uniformity coefficient on dynamic characteristics is discussed as well.

2. Representative Particle Size Distribution

Particle size distribution curves of 21 dredged soils used in Korea were investigated and compared with the Jumunjin sand and the grain size distribution chart of soils (Port and Harbour Research Institute, 1997). The investigated result shows that the mean particle size is between 0.09 mm and 2.50 mm, and uniformity coefficient is between 4 and 30 as shown in Fig. 1. It is also found that most particle size distribution curves of the investigated soils fall into the range of 'particularly susceptible to liquefaction' and 'susceptible to liquefaction' area. The procedure to adopt the representative particle size distribution curves is as follows.

The minimum mean particle size of investigated soils was 0.09 mm and the minimum uniformity coefficient was around 4. The particle size distribution curve which has 0.09 mm of mean particle size and 4 of uniformity coefficient, should have the fines content over 35% due to the slope on the graph of percent finer versus grain size. However, It is considered that liquefaction analysis can be omitted in case that soils have a fines content greater than 35% in Korea. Therefore, 0.12 mm was determined for the minimum representative mean particle size from the screening limit. Hence, 1.00 mm, 0.49 mm (the Jumunjin sand), 0.25 mm, and 0.12 mm were taken as representative mean particle sizes because it is concentrated on those points as shown in Fig. 1.

For uniformity coefficient, it is concentrated around 4 and 10. Therefore, 4.1 and 10.5 were taken as representative uniformity coefficients. In addition, uniformity coefficient of the Jumunjin sand (1.4) was adopted to investigate the effect of uniformity coefficient on the liquefaction resistance strength by comparing with the existing test results of Jumunjin sand.

From the above mentioned, twelve particle size distribution curves were determined with four different mean particle sizes and three uniformity coefficients as shown in Fig. 2.

3. Test Results and Analysis

3.1 Basic Properties of Soils

The maximum and minimum dry unit weight and specific gravity tests were performed for each soil, and

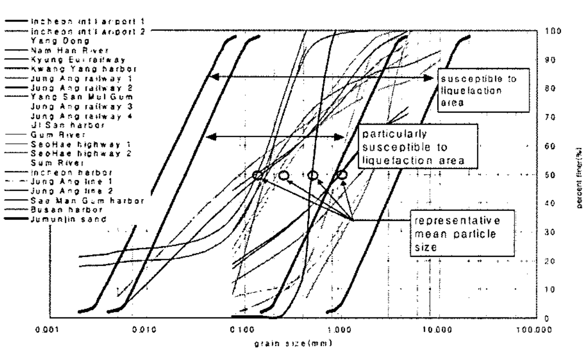


Fig. 1. Particle size distribution curves of dredged soil

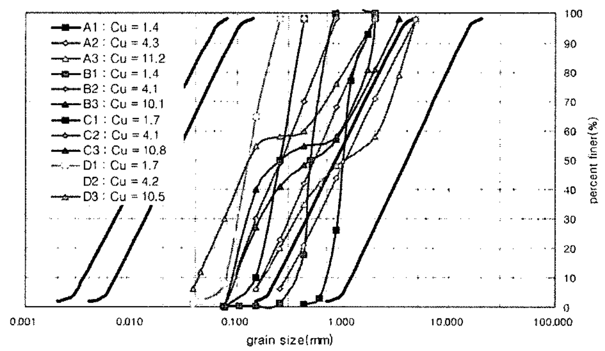


Fig. 2. Representative particle size distribution curves

the results are shown in Fig. 3 and Table 1. As shown in Fig. 3, it is found that maximum and minimum dry unit weights increase with increasing uniformity coefficient.

3.2 Result of Cyclic Triaxial Tests

Cyclic triaxial tests using the sinusoidal loading were carried out under isotropically consolidated condition with an effective confining pressure level equal to 100 kPa and three different relative densities (50, 60 and 70%). Triaxial soil specimens size in this study was 50 mm in diameter and 100 mm in height. All the specimens exhibited the pore water pressure parameter B which equals to 0.97 or greater. The 10 of equivalent number of cycle is adopted to consider the Korean seismic design earthquake magnitude of 6.5 in calculation of the cyclic resistance ratio. The liquefaction resistance strength of twelve representative soils is shown in Table 2. The effect of mean particle size and uniformity coefficient was analyzed and discussed in the following sections.

3.2.1 The Effect of Mean Particle Size on the Liquefaction Resistance Strength

The result of the cyclic triaxial tests is shown in Table 3 and Fig. 4 which shows stress ratio versus mean particle size ralationship. From Fig. 4, it is found that the minimum liquefaction resistance strength of specimens was within the range of 0.5 and 0.6 mm in mean particle size.

It is also found that liquefaction resistance strengths of the soil having 1.00 mm mean particle size were greater than that of other soils having the same uniformity

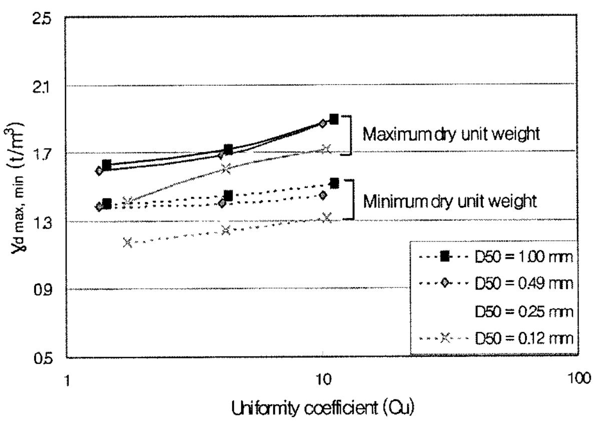


Fig. 3. Maximum and minimum dry unit weights

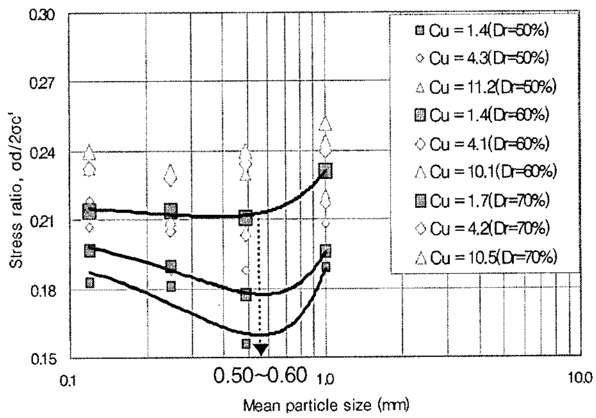


Fig. 4. Minimum liquefaction resistance strength chart according to mean particle size

Table 1. Basic properties of soils

Specimen	D_{50} (mm)	C_u	$\gamma_{d\ min}$ (t/m^3)	$\gamma_{d\ max}$ (t/m^3)
A1	1.00	1.4	1.403	1.630
A2		4.3	1.448	1.720
A3		11.2	1.516	1.895
B1 (the Jumunjin sand)	0.49	1.4	1.390	1.600
B2		4.1	1.400	1.686
B3		10.1	1.450	1.866
C1	0.25	1.7	1.243	1.466
C2		4.1	1.318	1.655
C3		10.8	1.436	1.837
D1 (FC : 8%)	0.12	1.7	1.179	1.412
D2 (FC : 30%)		4.2	1.244	1.602
D3 (FC : 30%)		10.5	1.315	1.721

coefficient and relative density. From the above mentioned results, the grain size distribution chart of soils (Port and Harbour Research Institute, 1997) was proved in part to be reasonable because liquefaction resistance strength of soils in the 'susceptible to liquefaction area (A1, A2, A3)' was greater than that of soils in the 'particularly susceptible to liquefaction area (other soils)'.

In addition, liquefaction resistance strength increased by 35.3% maximum with increasing relative density as shown in Table 3. However, the rate of change in liquefaction resistance strength tended to decrease from 21.1% to 9.5% with increasing relative density.

3.2.2 The Effect of Uniformity Coefficient on the Liquefaction Resistance Strength

The effect of uniformity coefficient on the liquefaction resistance strength is shown in Fig. 5 and Table 4. As shown in each of Figs. 6 (a), (b) and (c), liquefaction resistance strength for well-graded soils was greater than that for poorly-graded soil having the same mean particle size and relative density. This indicates that it is easy for small soil particles to fill up the void of large soil particles in well-graded soils compared to poor-graded soils and that causes small volume change in the drained condition and low excessive water pressure in the undrained

Table 2. Liquefaction resistance strength of soils

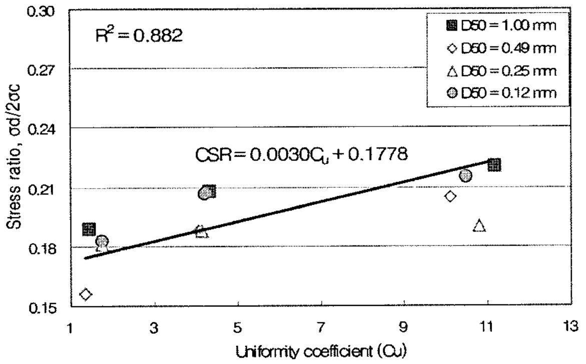
Specimen	D_{50} (mm)	C_u	Liquefaction resistance strength		
			D_r=50%	D_r=60%	D_r=70%
A1	1.00	1.4	0.189	0.196	0.231
A2		4.3	0.208	0.217	0.240
A3		11.2	0.221	0.244	0.252
B1 (the Jumunjin sand)	0.49	1.4	0.156	0.177	0.211
B2		4.1	0.188	0.203	0.234
B3		10.1	0.205	0.230	0.240
C1	0.25	1.7	0.181	0.190	0.214
C2		4.1	0.188	0.205	0.228
C3		10.8	0.190	0.210	0.231
D1 (FC : 8%)	0.12	1.7	0.183	0.197	0.214
D2 (FC : 30%)		4.2	0.207	0.218	0.232
D3 (FC : 30%)		10.5	0.215	0.232	0.240

Table 3. Minimum liquefaction resistance strength according to mean particle size

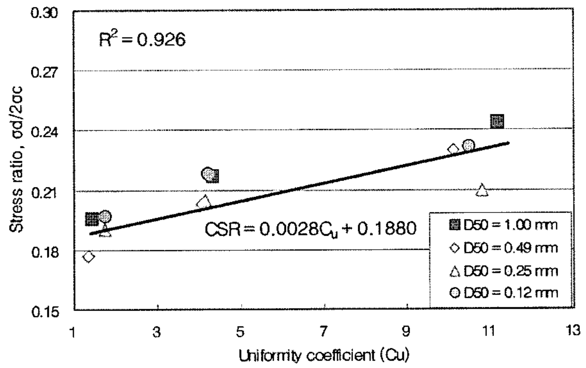
D_{50} (mm)	Minimum liquefaction resistance strength			$(CSR_{max}-CSR_{min})/CSR_{min}$
	D_r=50%	D_r=60%	D_r=70%	
1.00	0.189	0.196	0.231	22.1%
0.49	0.156	0.177	0.211	35.3%
0.25	0.181	0.190	0.214	18.2%
0.12	0.183	0.197	0.214	16.9%
$(CSR_{max}-CSR_{min})/CSR_{min}$	21.1%	11.3%	9.5%	

Table 4. Minimum liquefaction resistance strength

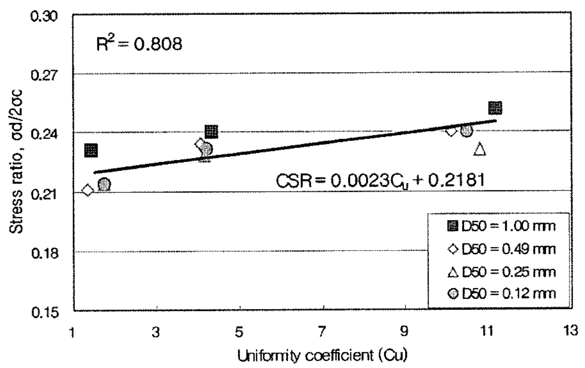
C_u	Minimum liquefaction resistance strength			$(CSR_{max}-CSR_{min})/CSR_{min}$
	D_r=50%	D_r=60%	D_r=70%	
1.4	0.156	0.177	0.211	35.3%
4.1	0.188	0.203	0.228	21.3%
10.5	0.221	0.244	0.252	14.0%
$(CSR_{max}-CSR_{min})/CSR_{min}$	41.7%	37.9%	19.4%	



(a) D_r=50%



(b) D_r=60%



(c) D_r=70%

Fig. 5. Variant of minimum liquefaction resistance strength with increasing uniformity coefficient

condition.

In order to see the effect of uniformity coefficient clearly, Table 4 shows a relationship between uniformity coefficient and minimum liquefaction resistance strength for each relative density. As shown in table 4, the minimum liquefaction resistance strength increases as much as 19.4-41.7% with increasing Cu, while the minimum liquefaction resistance strength decreased as much as 14.0-35.3% with increasing relative density.

3.3 Results of Resonant Column Test

Resonant column tests were performed to investigate the effects of mean particle size and unformity coefficient on the maximum shear modulus, normalized shear modulus and damping ratio. The specimen size was 70 mm in diameter and 140 mm in height. The specimens were created for only about 60% relative density and consolidated by the effective stress of 100 kPa.

Hardin (1978) proposed that the maximum shear modulus of soil is generally related to the void ratio and the effective confining stress as shown in Eq. (1). In this study, the maximum shear modulus of specimen was compared with the value estimated by Eq. (1). From Fig. 6, test results and estimated maximum shear modulus showed the same trend to decrease with increasing void ratio despite more or less difference. As shown in Fig. 7, However, it may be said that the maximum shear modulus does not so much depend on uniformity coefficient,

$$G_{max} = A \cdot F(e) \cdot OCR^{k} \cdot P_a^{1-n} \cdot (\sigma_0')^n \qquad (1)$$

where A = coefficient according to soil,

$F(e) = \frac{1}{0.3 + 0.7e^2}$

OCR = overconsolidation ratio

k = coefficient according to plasticity index

P_a = atmospheric pressure

n = the slope of the graph of log G_{max} - log σ_0'

σ_0' = mean effective confining pressure

Fig. 8 shows normalized shear modulus(G/G_{max}) versus shear strain(γ) relationship obtained by resonant column tests. The normalized shear modulus of soil having the same mean particle size tended to decrease with increasing shear strain as shown in each of Figs. 8 (a), (b), (c) and (d). It is also found that the rate of decrease in normalized shear modulus of poorly-graded soil was greater than that of well-graded soil by 0.14 times maximum with increasing shear strain from Fig. 8 (d).

Fig. 9 shows damping ratio versus shear strain relationship obtained by resonant column tests. Damping ratio of soil having the same mean particle size tended to

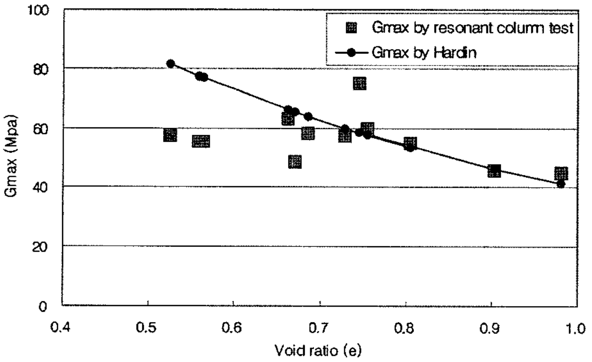


Fig. 6. G_{max} by Hardin and RC test

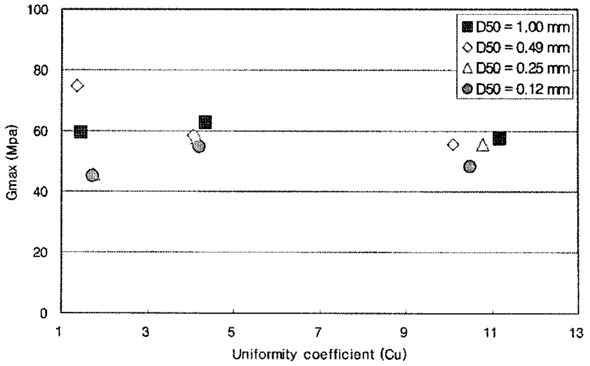
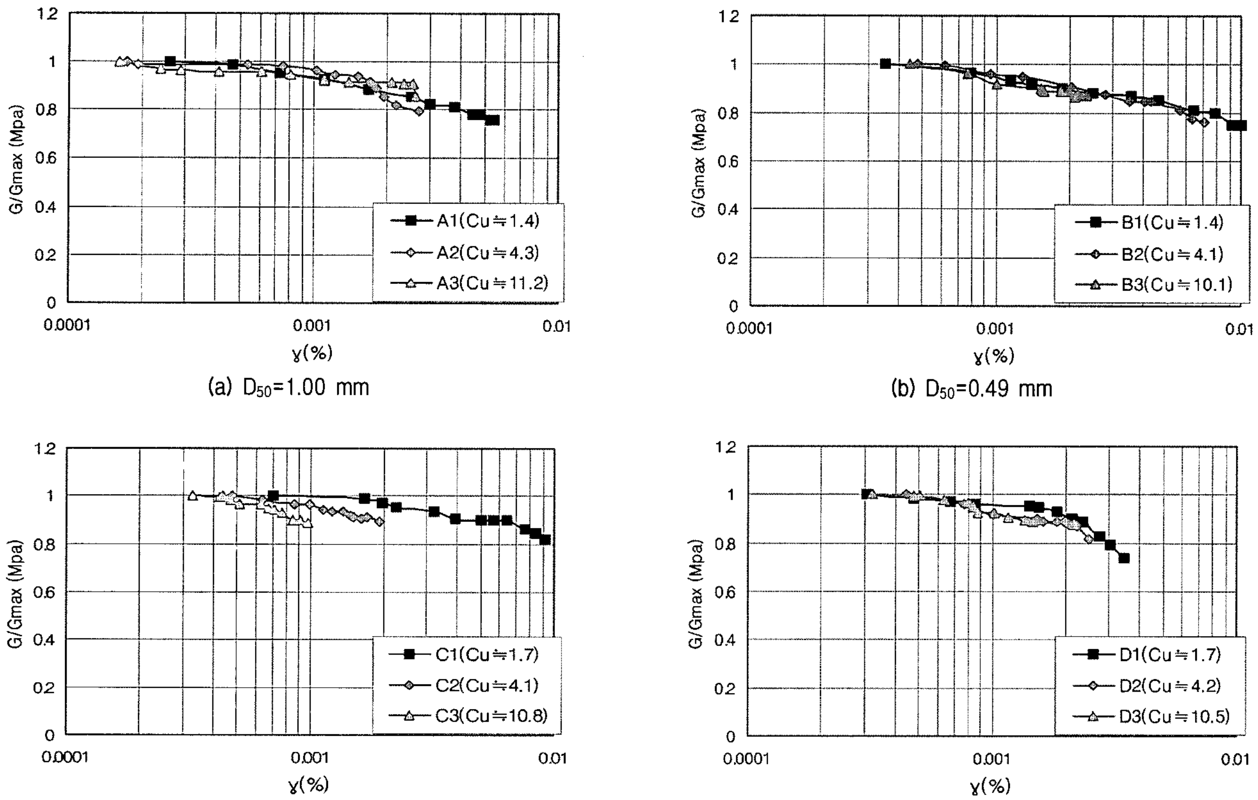


Fig. 7. G_{max} with uniformity coefficient



(a) D_{50}=1.00 mm (b) D_{50}=0.49 mm (c) D_{50}=0.25 mm (d) D_{50}=0.12 mm

Fig. 8. G/G_{max} curves with different mean particle sizes

increase with increasing shear strain as shown in each of Figs. 9 (a), (b), (c) and (d). It is also found that varying uniformity coefficient from 1.4 to 10.5 caused an approximate 167% increase in damping ratio corresponding to 0.001% shear strain as shown in Table 5 and Fig. 9.

4. Conclusions

To investigate the effect of mean particle size and uniformity coefficient on the liquefaction resistance strength and dynamic properties, cyclic triaxial tests under sinusoidal loadings and resonant column tests were performed. The following primary conclusions are obtained as a result of this study:

(1) The liquefaction resistance strength of the soil which has larger uniformity coefficient with the same mean particle size is larger than that of the soil of smaller uniformity coefficient because small soil particles filled up the void of large soil particles. Consequently,

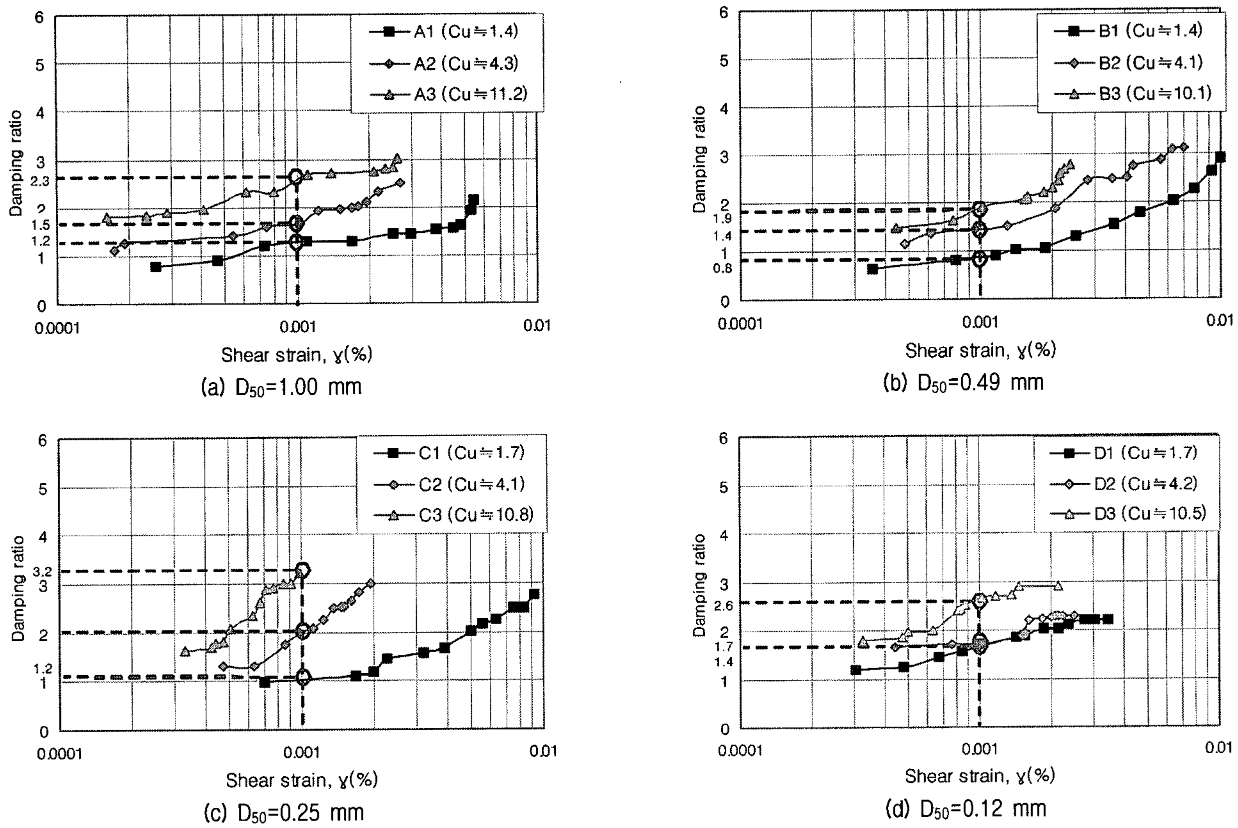


Fig. 9. Damping ratio corresponding to 0.001% shear strain

Table 5. G_{max}, G/G_{max} and damping ratio with different mean particle sizes and uniformity coefficients

Soil	D_{50} (mm)	C_u	G_{max} (Mpa)	G_{max} by Hardin (Mpa)	G/G_{max} at γ_{max}	Maximum difference in G_{max} $(1-G/G_{max})$	Damping ratio corresponding to 0.001% shear strain	Maximum difference in Damping ratio (%)
A1	1.00	1.4	59.75	57.7	0.76	0.10	1.26	89
A2		4.3	62.90	66.4	0.79		1.50	
A3		11.2	57.45	81.5	0.86		2.38	
B1	0.49	1.4	75.00	58.5	0.75	0.12	0.88	118
B2		4.1	58.32	64.0	0.76		1.41	
B3		10.1	55.45	77.7	0.87		1.92	
C1	0.25	1.7	45.66	46.2	0.82	0.07	1.20	167
C2		4.1	57.52	60.0	0.88		2.00	
C3		10.8	55.57	77.0	0.89		3.20	
D1	0.12	1.7	45.15	41.4	0.74	0.14	1.40	86
D2		4.2	54.87	53.5	0.82		1.75	
D3		10.5	48.46	65.5	0.88		2.60	

it caused small volume change in the drained condition and low excessive water pressure in the undrained condition.

(2) The minimum liquefaction resistance strength of specimen is within the range of 0.5 mm and 0.6 mm in mean particle size. The liquefaction resistance strength according to the change of mean particle size increased with the same relative density as much as 21.1%. The liquefaction resistance strength according to the change of uniformity coefficient increased with the same relative density as much as 41.7%. However, the effect of mean particle size and uniformity

coefficient decreased as relative density increased.

(3) It is proved that the grain size distribution chart of soils (Port and Harbour Research Institute, 1997) is reasonable because liquefaction resistance strength of soils in the 'susceptible to liquefaction area' was larger than that of soils in the 'particularly susceptible to liquefaction area'.

(4) In the case of the same mean particle size, the rate of decrease in shear modulus and damping ratio on the basis of shear strain of 0.001% increased as the uniformity coefficient increased.

Acknowledgement

This research was performed under Grant No. R11-1997-045-13003-0 from Korea Earthquake Engineering Research Center (KEERC).

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(received on Mar. 8, 2005, accepted on Aug. 26, 2005)