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ABSTRACT

In this study, deformation characteristics of hydraulic-filled cohesionless soils in Korea were investigated using resonant column tests. Seven representative hydraulic-filled soil samples, which mostly classified as SM, SP or SP-SM, were collected along the coastal area in Korea, and the deformational characteristics at small to medium strains (10^{-4} %~0.1 %) were investigated. The predicting equation of small-strain shear modulus, G_{max} was suggested using Hardin model. At strains above elastic threshold, the variations of shear modulus (G) and damping ratio (D) with strain amplitude were investigated at various densities and confining pressures. The normalized modulus reduction curve(G/G_{max}-log γ) was almost independent of density for a given soil but it was affected by confining pressure. The G/G_{max}-log γ curve of hydraulic filled soils moves to the right as confining pressure increases. The representative modulus reduction curves of hydraulic-filled soils in Korea were determined for 5 confining pressure levels using Ramberg-Osgood model and the proposed curve was composed and compared with the well-known modulus reduction curves. The variations in damping ratio with strain amplitude were also determined and the representative damping curves were proposed for 5 confining pressure levels. The proposed modulus reduction and damping ratio curves would be used as a valuable database for the site response analysis during earthquake.

KEYWORDS

Shear modulus, Damping ratio, Modulus reduction curve, Resonant column test, Hydraulic-filled cohesionless soil, Ramberg-Osgood model

INTRODUCTION

As Korean economy is rapidly growing, a number of infrastructure systems are being constructed. Because of the limited land in Korea, most of the projects require large-scale reclamation. When constructed by hydraulic fill underwater, the site is composed of the loose sand deposits, where stability and serviceability of the structures constructed on top, particularly liquefaction susceptibility, are in question.

Deformation characteristics of soil, expressed in terms of shear modulus and material damping, are important parameters in the design of soil-structure systems subjected to cyclic and dynamic loadings. At small strain below about 10^{-4} %, shear modulus and damping ratio are essentially considered to be independent of strain amplitude, and the shear modulus is at its maximum value, G_{max}, and the damping ratio is at its minimum value, D_{min}. For earthquake problems, the strain levels are much higher and the variations in shear modulus and damping ratio with strain amplitude must be taken into account, particularly in the equivalent linear ground response analysis (Schanabel, 1972).

The perceived difference between static and dynamic moduli is also decreasing as the accuracy of static measurements is improving at small strains, and an understanding is growing that strain amplitude is a key variable in predicting soil behavior whether the strain comes from static or dynamic phenomena (Kim and Stokoe, 1994; Tatsuoka and Shibuya, 1991). Therefore, the evaluations of deformational characteristics of hydraulic-filled soils are quite important not only for the site response analysis during earthquake but also for the static analysis of geotechnical structures under working stress conditions.

In this study, deformation characteristics of hydraulic-filled cohesionless soils in Korea were investigated using resonant column tests. Seven representative hydraulic-filled soil samples, which mostly classified as SM, SP or SP-SM, were collected along the coastal area of Korea, and the deformational characteristics at small to medium strains (10^{-4} %~0.1 %) were investigated. At small strains below elastic threshold, the maximum shear modulus (G_{max}) and the minimum damping ratio (D_{min}) were determined on the various types of soils, and the effects of confinement on G_{max} and D_{min} were characterized. The variations in normalized modulus reduction and damping curves of hydraulic-filled cohesionless soils with shear strain amplitude were also investigated at various densities and confining pressures and characterized using Ramberg-Osgood model.

TEST EQUIPMENT

Tests were conducted using a Stokoe type resonant column (RC) apparatus. This equipment is the fixed-free type, with the bottom of the specimen fixed and torsional excitation applied to the top (Kim, 1991). The basic operational principle is to vibrate the cylindrical specimen in a first-mode torsional motion. Once first mode is established, measurements are then combined with equipment characteristics and specimen size to calculate shear modulus, and shearing strain amplitude. Material damping is evaluated from the dynamic soil response using either the free-vibration decay curve or the half-power bandwidth method. The RC equipment is calibrated so that equipment-generated damping can be subtracted from the measurements (Stokoe et. al, 1994).

TESTING MATERIALS AND PROCEDURES

Testing Materials

Samples tested in this study were obtained as disturbed samples. They were collected from Taesan, Inchon, Yongjong Island near Inchon, Shinan and Nakdong River where large reclaimed constructions are underway along the coastal area of Korea as shown in Fig 1. They can be considered as the representative hydraulic-filled cohesionless materials in Korea, because the reclamation work seldom occurs in the east coast and the cohesive hydraulic-filled materials are mostly used in the south and southwest coast.

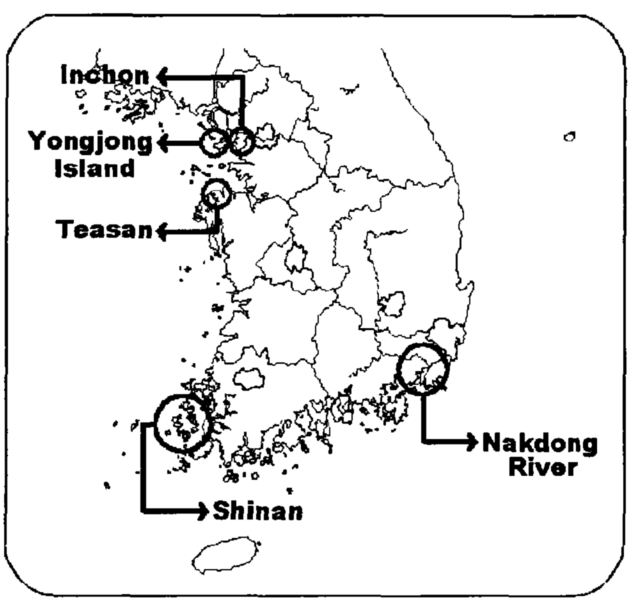

Fig. 1. Location of sites collecting samples

The grain size distributions of tested samples are shown in Fig 2 and the soil properties, such as the grain size corresponding to 50% of the passing by weight (D_{50}) and the percentage of passing #200 sieve, are summarized in Table 1. All samples are non-plastic and classifed as SM, SP or SP-SM by the unified soil classification system (USCS).

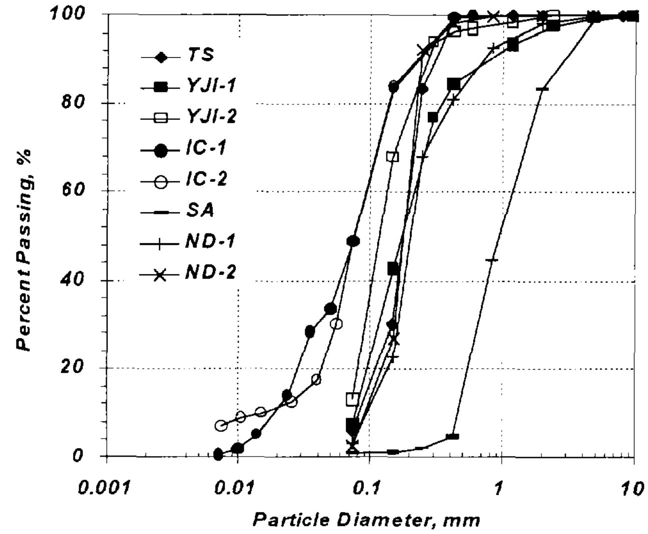

Fig. 2. Grain size distributions of tested samples

Table 1. Properties of tested samples

Location	Sample ID	D_{50}, mm	#200, %	Classif. USCS
Taesan	TS	0.19	5.9	SP-SM
Yongjong Island-1	YJI-1	0.18	7.3	SP-SM
Yongjong Island-2	YJI-2	0.12	13.2	SM
Inchon-1	IC-1	0.08	48.5	SM
Inchon-2	IC-2	0.08	49.0	SM
Shinan	SA	1.01	0.9	SP
Nakdong River-1	ND-1	0.21	3.1	SP
Nakdong River-2	ND-2	0.19	2.7	SP

Testing Procedures

The testing conditions of samples are summarized in Table 2 whereby e denotes the void ratio and w the water content. The specimens of each sample were reconstituted at e and w of table 2. The specimens of Taesan sample were prepared by the raining method and the other specimens were compacted as five layers by under-compaction method. The raining method uses multiple sieving pluviation apparatus, by which various desired densities of specimen can be provided. The under-compaction method can control the specimen density uniformly by compacting same weight samples with different height at each layer. The specimens of Teasan, Yongjong Island-1 and Yongjong Island-2 had a diameter of 71mm and a height of 150mm, and the other samples had a diameter of 50mm and a height of 100mm.
Each specimen was isotropically consolidated under confining

pressures as quoted in Table 2 by air and then RC tests at each confining pressure were performed in turn as the multi-stage tests. In multi-stage test the sample was first tested up to the highest possible shear strain under a confining pressure. Subsequently the confining pressure was increased to the next confining pressure (higher than the previous confining pressure) and then the resonant column test with various strain amplitudes was performed.

Table 2. Testing conditions of samples

Sample ID	e	w, %	Confining pressure, kPa
TS	0.76	Dry	20, 40, 80
	0.88	Dry	
	1.03	Dry	
YJI-1	0.64	14.7	20, 40, 60, 80, 90
	0.72	14.7	
	0.82	14.7	
YJI -2	0.63	21.2	20, 40, 60, 80, 90, 160, 320
	0.74	18.7	
	0.88	19.0	
	1.10	20.1	
IC-1	0.88	28.0	23, 45, 90
IC-2	0.73	26.0	65, 130, 260
SA	0.79	4.6	45, 90, 180, 360
ND-1	0.94	10.5	25, 50, 100, 200, 400
ND-2	0.84	9.1	50, 100, 200, 400, 550

RESULTS AND INTERPRETATION

Small-Strain Shear Modulus

The parameters affecting the small-strain shear modulus, G_{max}, are presented in terms of the effective isotropic confining pressure, σ_0', the overconsolidation ratio, OCR, soil type, plasticity, void ratio and so on. Based on laboratory test results empirical relations for the small-strain shear modulus have been proposed by many researchers, and among those Hardin(1978) suggested the general equation for the small-strain shear modulus as follows;

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

where
A=dimensionless stiffness coefficient,
$F(e)=0.3+0.7e^2$
OCR=overconsolidation ratio,
k=exponent dependent on PI,
P_a=atmospheric pressure(100 kPa)
n=exponent related to isotropic stress state.

The hydraulic-filled soils in this study are non-plastic, so the effect of OCR in equation 1 is negligible. The log G_{max} F(e) - log σ_0' relations of all tested specimens were shown in Fig. 3. The log G_{max} F(e) - log σ_0' relations were linear and confined in a narrow range, and can be fitted by least-squares regression method and the values of A and n coefficients were obtained. The regression coefficients of A and n for each sample are presented in Table 3, and the representative equation of small-strain shear modulus for all samples was proposed as equation 2;

$$G_{max} = \frac{665}{0.3+0.7e^2} P_a^{0.4} \sigma_0'^{0.6} \qquad (2)$$

Table 3 Values of dimensionless constants A and n

Sample	A	n
Taesan	654	0.68
Yongjong Island-1	562	0.46
Yongjong Island-2	744	0.61
Inchon-1	688	0.51
Inchon-2	667	0.68
Sinan	858	0.58
Nakdong River-1	455	0.60
Nakdong River-2	521	0.58
TOTAL	665	0.60

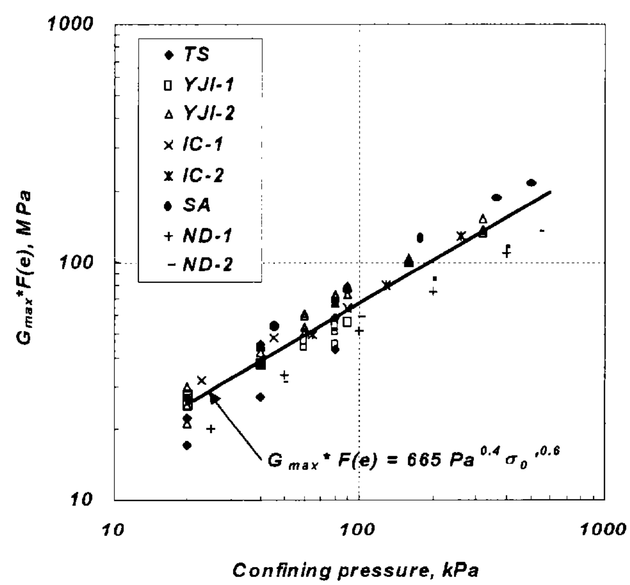

Fig.3. Variation in small-strain shear modulus adjusted by void ratio with confining pressure

Shear Modulus in the Nonlinear Range

The nonlinear behavior can be considered by the variation in normalized shear modulus, G/G_{max}, with the logarithm of shearing strain. In this study, the G/G_{max} at strains above elastic threshold were investigated at various densities and confining pressures. The normalized shear modulus reduction curve (G/G_{max} - log γ) for hydraulic-filled cohesionless soils was almost independent of density for a given soil but it was affected by confining pressure as shown in Fig. 4. The G/G_{max} versus log γ curve of hydraulic filled soils moves to the right as confining pressure increases. The G/G_{max} versus log γ curves of hydraulic filled soils were classifed for 5 confining pressure levels as shown in Fig.4 and the representative curves for each confining pressure level were determined using Ramber-Osgood model.

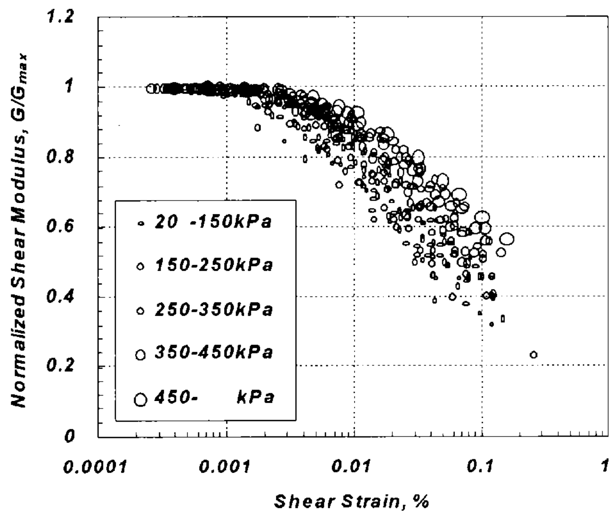

Fig.4. Variation in normalized shear modulus reduction curves with confining pressure

The Remberg-Osgood (R-O) fitting equation can be written as

$$\gamma = G' \cdot \gamma + C(G' \cdot \gamma)^R \tag{3}$$

where $G'=G/G_{max}$=normalized shear modulus and C and R are the R-O parameters. Equation 3 can be rewritten as

$$\gamma \cdot (1 - G') = C \cdot (G' \cdot \gamma)^R \tag{4}$$

By taking the logarithm of both sides, Equation 4 yields

$$\log[\gamma \cdot (1 - G')] = \log C + R \cdot \log(G' \cdot \gamma) \tag{5}$$

Using a least-squares curve fitting, the parameter R is directly determined from the slope, and the parameter C is calculated from the intercept.

The R-O parameters, C and R, were determined for each confining pressure level, and the values are given in Table 4. Using the average of R parameters, which is 2.22, the C parameters were modified. Correlation of C parameters with confining pressure for hydraulic-filled soils was determined using linear regression, and the variation of the general modulus reduction curves with confining pressure is plotted in Fig.5. As shown in the figure, the estimated G/G_{max} curves of Korean hydraulic-filled cohesionless soils exist at the right side of sand curves proposed by Seed et. al. (1986) and Idriss (1990) and the curves move to the right widely as confining pressure increases. The confining pressure is directly related to depth of site and the estimated depths are also included in Table 4. Using the curves in Fig.5, once the small-strain modulus of Korean hydraulic-filled cohesionless soils is obtained from field seismic methods or other methods, it is possible to predict the strain-dependent behavior using the proposed normalized curve at the given confining pressure or at a corresponding depth. Also this result would be used as a valuable database for the site response analysis during earthquake.

Table 4. Ramberg-Osgood parameters, R and C, for each sample

Confining Pressure	Estimated depth*	R	C	C_m**
20kPa ~ 150kPa	15 m	2.33	59375	17229
150kPa ~ 250kPa	34 m	2.26	18201	13952
250kPa ~ 350kPa	51 m	2.06	2304	11102
350kPa ~ 450kPa	69 m	2.19	6062	8252
450kPa ~ 550kPa	86 m	2.25	6645	5402

* by assuming e=0.85 , K_0=0.5

** modified C parameter using R of 2.22

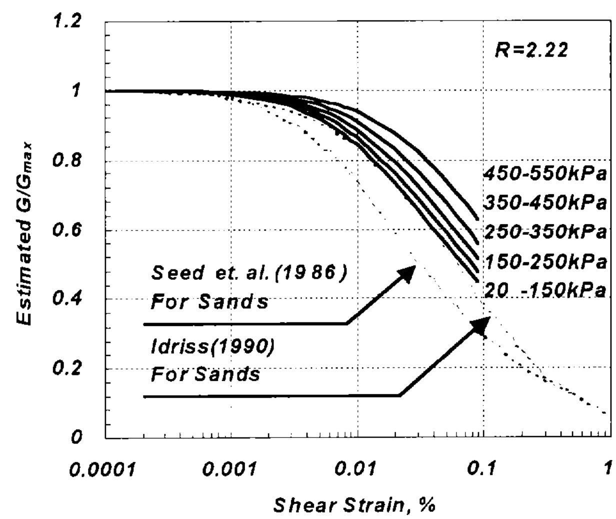

Fig.5. The representative G/G_{max}-log γ curves estimated by Ramberg-Osgood parameters

Small-Strain Damping Ratio

The small-strain damping ratios for hydraulic-filled soils in this study are shown in Fig.6. The small-strain damping ratio decreases with increasing confining pressure but the effect of density is insignificant. The range of small-strain damping ratio varies from 0.1 % to 1.1 %.

The decrease in D_{min} with confining pressure can be expressed in a general form as:

$$D_{min} = BP_a^m \sigma_0'^{-m} \tag{6}$$

The values of B and m are also presented in Fig.6.

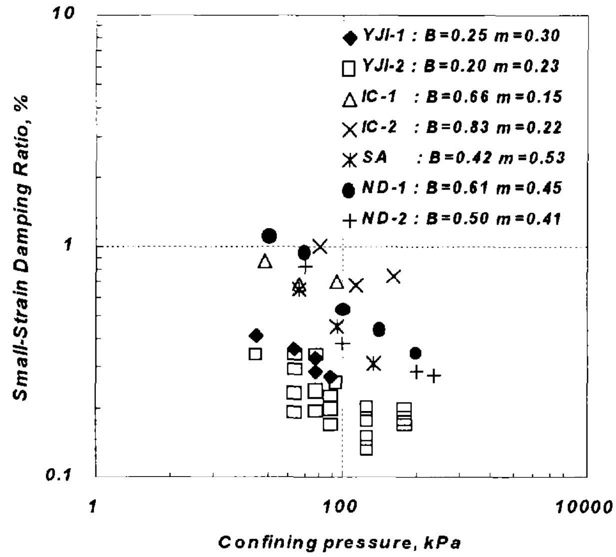

Fig.6. Variation in small-strain damping ratio with effective isotropic confining pressure

Damping Ratio in the Nonlinear Range

The variations in D with log γ as determined in the RC tests are shown in Fig.7. As shear strain increases above the threshold, damping ratio increases significantly. The effect of confining pressure on the D – log γ relationship is described in Fig.7, showing the general trend that damping ratio curve shifts downward as confining pressure increases.

The representative damping ratio curves for 5 confining pressure levels are suggested and presented as solid lines in Fig.7. These damping curves enable to predict the D - log γ relationships for Korean hydraulic-filled cohesionless soils at the given confining pressure or at the corresponding depth.

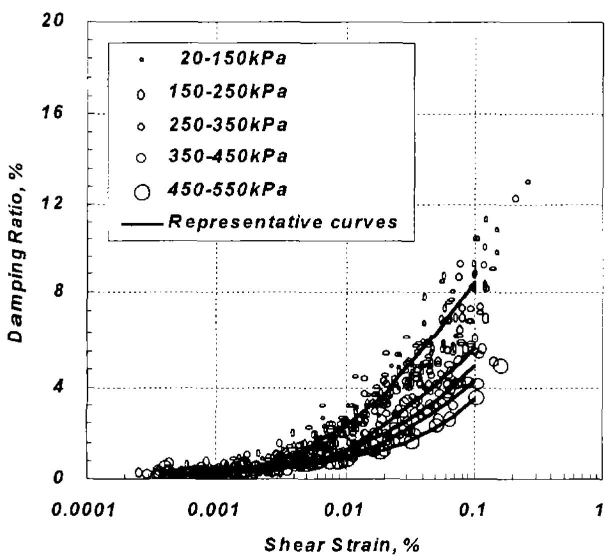

Fig.7. Variation in damping ratio with logarithmic shear strain

Using the R-O parameters, R and C, determined by fitting modulus-strain data, damping ratio can be computed by assuming Masing behavior as follows(Kim, 1991):

$$D = \frac{2(R-1)}{\pi(R+1)}(1-G') \tag{7}$$

Damping ratios were calculated using the values of R and C in Table 4. Calculated damping ratios at small strain (below 0.001%) are zero according to the Masing criteria. However, the experimental data clearly show that material damping exists even at very small strains as shown in Fig.6 and Fig.7. To account for small-strain damping, the damping ratio computed by the R-O-M model was modified by adding the measured value of D_{min} to it. Damping ratios calculated with the R-O-M model are plotted together and compared with the representative curves based on measured damping ratios in Fig.8. Obviously, calculated damping ratios do not match with experimental data. At higher strains computed damping ratio increases rapidly with increasing strain amplitude and computed damping ratios exceed the measured ones. Using Ramberg-Osgood model with Masing criteria, can overpredict the damping ratios at high strain amplitudes and it is recommended to use the experimental representative damping curves suggested in Fig.7.

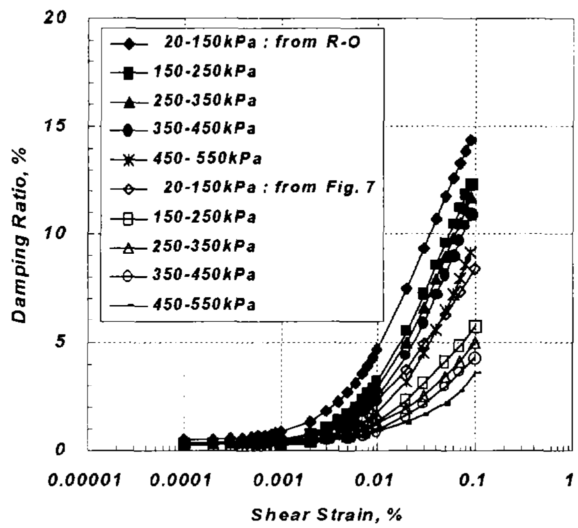

Fig.8.Cmparison between damping curves estimated using Ramberg-Osgood-Masing model and measured ones

CONCLUSIONS

Deformation characteristics, expressed in shear modulus and damping ratio were investigated for Korean hydraulic-filled cohesionless soils at small to medium strains (10^{-4}%~10^{-1}%) using resonant column tests. Small-strain shear modulus, G_{max} increases and small-strain damping ratio, D_{min} decreases as confining pressure increase. The predicting equation of G_{max} on Korean hydraulic-filled soils was suggested using Hardin model. The normalized modulus reduction curves (G/G_{max}-log γ) were almost independent of density for a given soil but it was affected by confining pressure. The G/G_{max}-log γ curve of hydraulic filled soils moves to the right as confining pressure increases. The representative modulus reduction curves of hydraulic-filled cohesionless soils for 5 confining pressure levels were suggested using Ramberg-Osgood model. The variations in damping ratio with strain amplitude were also independent of density for a given soil but affected by confining pressure. The representative damping curves based on measured data were proposed for 5 confining pressure levels. Damping ratios calculated by Ramberg-Osgood-Masing model overpredict the measured data at strain amplitudes above 10^{-2}%. At higher strains calculated damping values are larger than measure data. So the representative damping curves based on measured data were recommended.

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