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Study on the Simplified Procedure for Evaluating the Undrained Cycric Strength for Gravelly Soils

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ABSTRACT

A simplified procedure has been proposed for evaluating the undrained cyclic strength of gravelly soils by using penetration resistance or shear wave velocity. This paper describes the results of a study carried out to verify the simplified procedure using new data for different kinds of gravelly soils. In this study, undrained cyclic triaxial tests were conducted on undisturbed sample of gravelly soils obtained by the in-situ freezing sampling method. The undrained cyclic strength increases with increasing Vs □shear wave velocity□ and Nd □large penetration test resistance□and there was a good correlation between the undrained cyclic shear strength and Nd1□normalized large penetration test resistance□.

KEY WORDS: evaluating undrained cyclic strength, gravelly soils, in-situ freezing sampling method, grain size, undisturbed sample, penetration test resistance, shear wave velocity

INTRODUCTION

The undrained cyclic strength of soils is one of the mechanical properties required for evaluating the seismic performance of foundations. A large number of data on the undrained cyclic strength of undisturbed sandy soils have been reported, including relationships between the undrained cyclic strength and N-values obtained from standard penetration tests (SPT) and the shear wave velocity (Vs) on different types of sandy soils (See [1] to [3]). Similar studies have been conducted on gravelly soils ([4] and [5]), though the amount of data on gravelly soils is smaller than that on sandy soils. One of the goals of this study was to re-evaluate with new data on gravelly soils.

In this study, undisturbed samples of gravelly soils were obtained by using the in-situ freezing sampling method. These samples were then tested in a laboratory to determine their undrained cyclic strengths and the data generated from these tests were then examined. Next, the relationships of the undrained cyclic strength with the shear wave velocity (Vs) and the large penetration test resistance (Nd) obtained from field tests were investigated to asses the validity of the simplified procedure that has been proposed for evaluating the undrained cyclic strength of gravelly soils.

SOIL PROFILE OF SAMPLING SITE AND FIELD TESTS

Undisturbed samples of gravelly soils were taken at two sites in Japan using the in-situ freezing sampling method, which is discussed in the subsequent section. Figs. 1 and 2 and Table 1 show the results of field tests conducted at the two sites. At each site, borings were made to identify the soil profile and physical properties of soils were obtained through a standard penetration test (SPT) and PS logging. In addition, a large penetration test (LPT) was conducted on the gravelly soils. The LPT was developed by Kaito, et al. [6] for minimizing the effect of large-sized gravel on the penetration resistance obtained from the SPT. Table 2 lists the specifications of SPT and LPT.

Undisturbed samples were taken from gravelly soils at depths of about 8 meters or below at site A and about 7 meters or below at site B. At each site, undisturbed soil samples were taken at two depths corresponding to soils with different shear wave velocities. At site A, the Vs value in the upper layer was about 520 m/s and 670 m/s in the lower layer while at site B, Vs in the upper layer was about 420 m/s and about 570 m/s in the lower layer.

N and Nd values was measured at every one meter of depth as shown in Figs. 1 and 2. Some of the measured Nd values at site A were extremely large most likely because the penetration of the sampler was hindered as it came in contact with gravels. These extremely large values were excluded and the average Nd values calculated around the sampling depths are listed in Table 1.

An attempt was made using pollen analysis to identify the geological age of the soils, however, it was largely unsuccessful at both sampling sites. Based on the literature, such as geological maps, it was assumed that gravelly soils at site A could have been formed during the Holocene era. As for site B, the pollen analysis of the silty clay accumulated on the top of the gravelly soil layer indicated that that the silty clay could have been formed more than 70,000 years ago. Using this result and making reference to geological maps, it was assumed that the gravelly soil at site B could have been formed during the Pleistocene era.

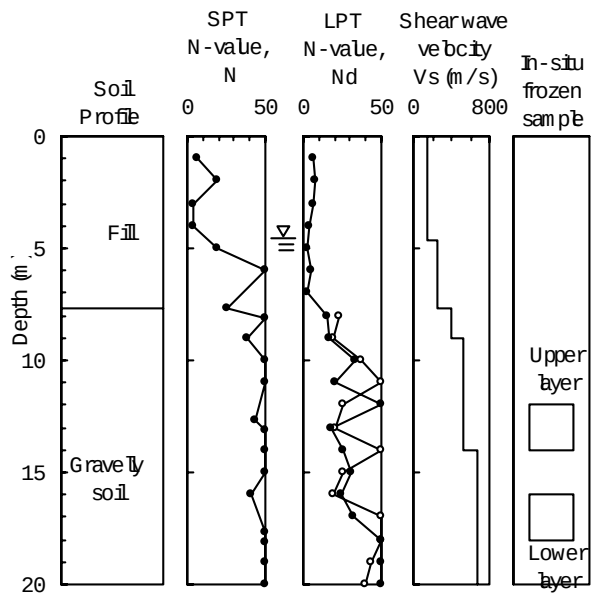


Fig.1 Soil profile of A-site

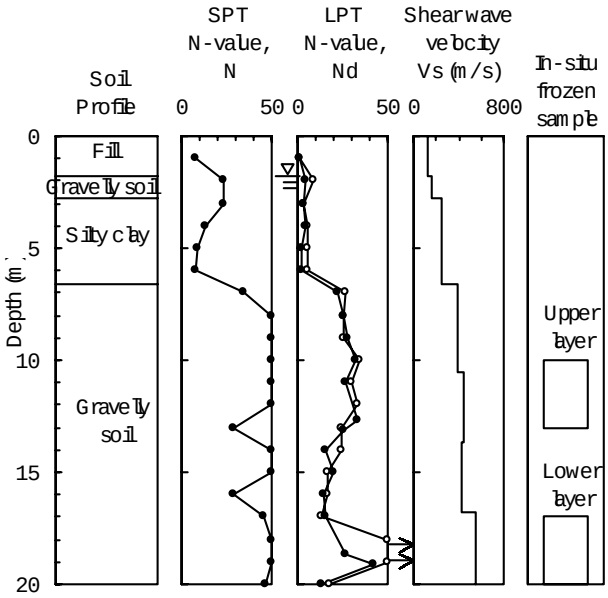


Fig.2 Soil profile of B-site

Table 1 Results of the field tests

	A-site		B-site	
	upper layer	lower layer	upper layer	lower layer
Shear wave velocity (m/sec)	520	670	420	570
Large penetration test resistance, Nd	26	38	30	51

Table 2 Specifications of penetration tests

	Item	SPT	LPT
Hammer	Weight (kg)	63.5	100
	Drop height (cm)	75	150
Rod	Outer Diamater (mm)	40.5	60
Sampler	Outer Diamater (mm)	51	73
	Inner Diamater (mm)	35	50

IN-SITU FREEZING SAMPLING METHOD TO RECOVER HIGH-QUALITY UNDISTURBED SAMPLES

The undrained cyclic strength of soils is evaluated in a laboratory test using soil samples taken from the field. In order to obtain reliable data from these tests, the soil sample should be relatively undisturbed. The in-situ freezing sampling method makes it possible to recover high-quality undisturbed samples of soils with low fines content [7]. In this method, soil is first frozen and then a column of the frozen soil is cored out and specimens for testing are then cut. The procedure of the in-situ freezing sampling method that was followed in this study is outlined below and shown graphically in Fig. 3.

1) A hole having a diameter of about 200 cm was excavated to a depth of eight meters and a steel casing was installed to prevent the borehole walls from collapsing.
2) Five guide pipes whose positions were fixed by two steel plates at both ends, shown in Fig.3, were installed into the bottom of the borehole in order to exactly determine the locations of the freezing pipe and sampling places. A borehole was then drilled with extreme care to a depth slightly lower than the sampling depth and an outer freezing pipe was carefully installed into the borehole.
3) An inner freezing pipe with an open end was then placed into the outer freezing pipe with about a 100 mm clearance from the bottom. Liquid nitrogen was fed into the inner pipe and the soil around the freezing pipe was frozen.
4) After the soil in the target area was completely frozen, samples were recovered from an undisturbed area about one diameter away from the outside of the cylindrical surface of the outer pipe. In order to prevent soils from thawing, core drilling was carried out using chilled mud.
5) The frozen soil column, about 2 m long, was separated at the lower end of the sampler by pulling the double tube core barrel using a boring machine.
6) The frozen soil column was pulled out of the double tube core barrel after the tube had been lifted up to ground level.
7) The frozen soil column, shown in Fig. 4, was then cut to a length of 60 cm at the site using a special diamond saw

for preparing a test specimen for a large-scale triaxial test apparatus. A completed specimen was taken to the laboratory while maintaining its temperature.

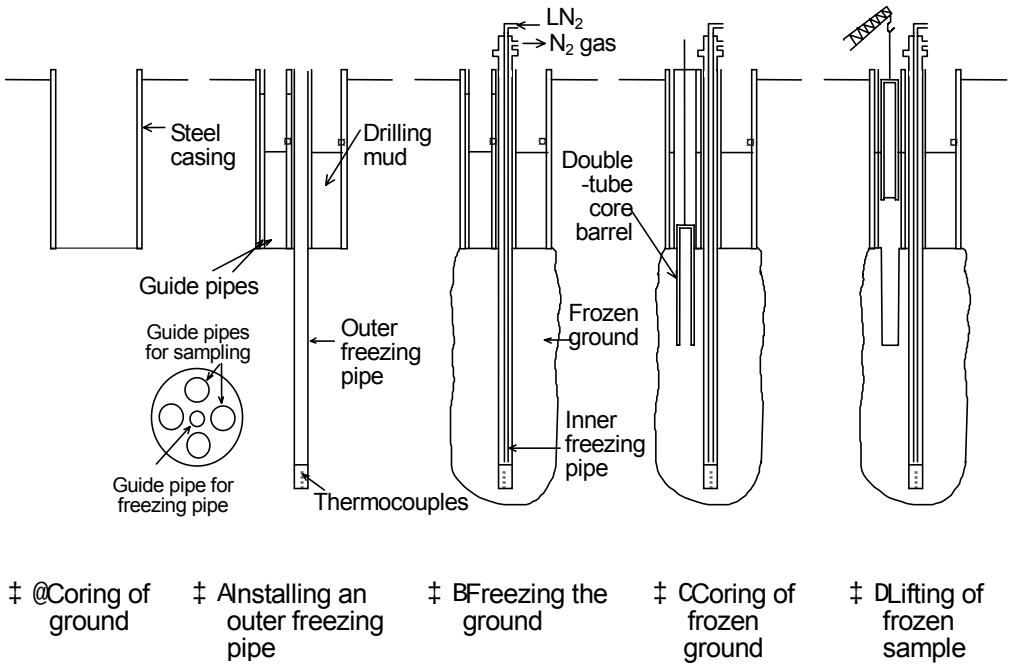


Fig.3 Procedure of in-situ freezing sampling method

(a) A-site

(b) B-site

Fig.4 Frozen gravelly soil column

APPARATUS AND PROCEDURES FOR UNDRAINED CYCLIC SHEAR TESTS

Fig.5 shows a schematic diagram of the test apparatus. A test specimen was placed in the triaxial cell and the axial stress and confining pressure were controlled following the procedure described below. The axial loading in the triaxial cell was applied using oil pressure. The axial stress was obtained by dividing the load measured by a load cell placed in the triaxial cell by the cross-sectional area of the test specimen. The confining pressure was maintained by air pressure and was monitored by a pressure gauge placed in the cell. The procedure followed in the tests is as follows:

1) The frozen test specimen (diameter: 30 cm, height: 60cm) is placed on the pedestal and at the top of the specimen a cap is placed. The specimen is then covered with a rubber membrane and O-rings are used to completely seal off the specimen.

2) The frozen specimen is then allowed to thaw in a drainable state under a confining stress of 19.6 kPa at room temperature.

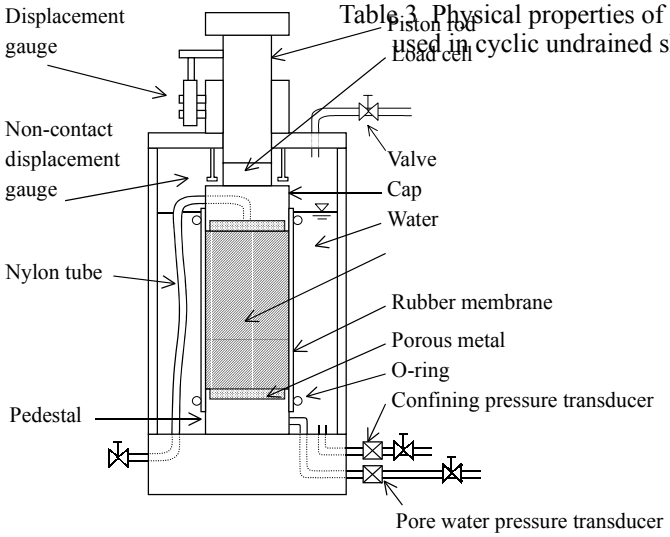
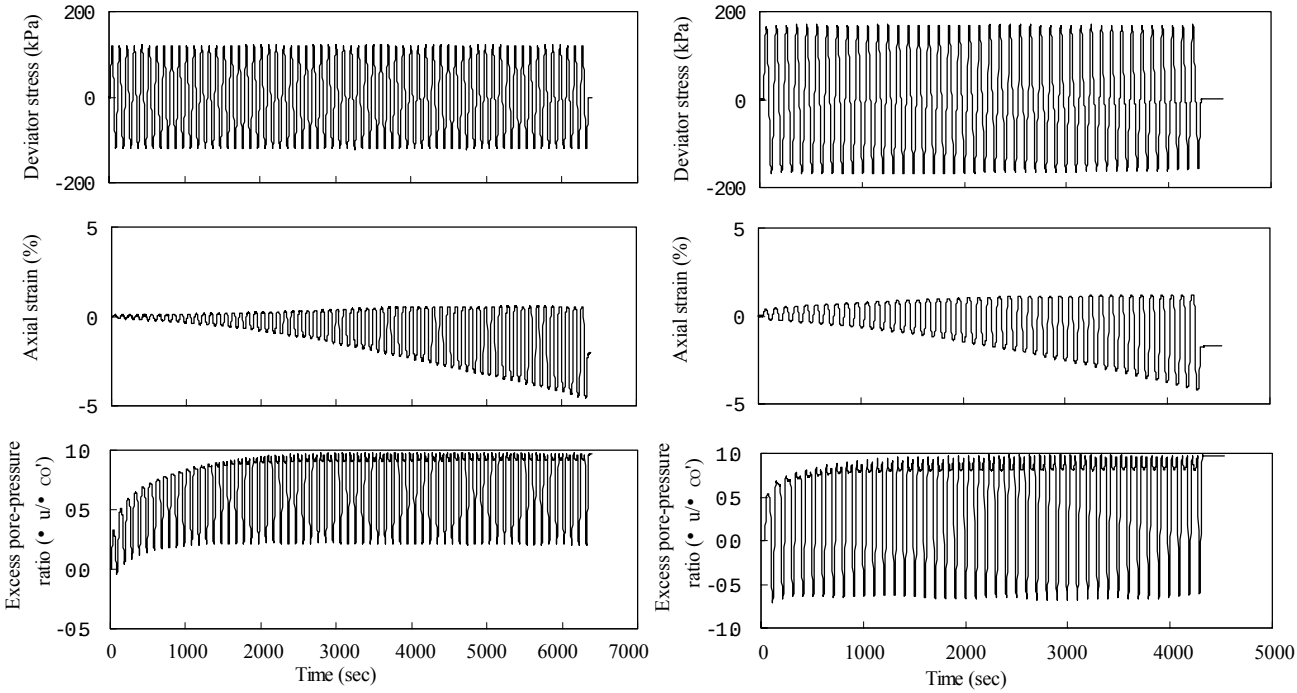


Fig.5 Schematic diagram of the large-scale triaxial test apparatus

Table 3 Physical properties of gravelly soil samples used in cyclic undrained shear test

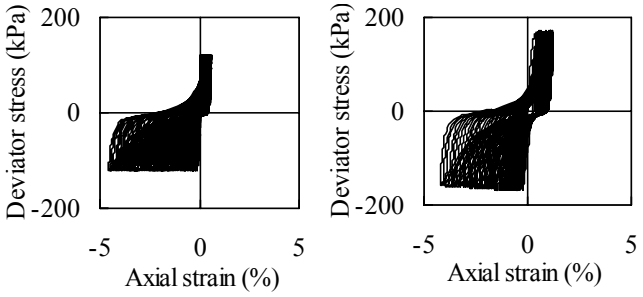
Site	Sample name		50% diamater (mm)	Maximum diamater (mm)	Rock content (%)	Gravel content (%)	Fines content (%)	Dry density (g/cm3)
A	Upper layer	U-1	28.5	106	14.4	68.7	0.6	2.091
		U-2	41.0	150	14.4	68.7	0.6	2.017
		U-3	31.5	300	22.1	61.5	2.1	2.125
		U-4	30.0	300	30.7	55.6	0.8	2.003
		U-5	30.0	150	22.0	63.7	0.6	2.114
	Lower layer	L-1	13.0	150	12.4	67.9	2.2	1.863
		L-2	14.0	150	5.1	71.4	4.5	1.925
		L-3	31.0	150	30.0	54.7	0.1	2.093
		L-4	48.0	150	34.0	50.0	0.8	2.183
B	Upper layer	U-1	23.0	150	6.9	73.2	1.6	2.054
		U-2	21.0	106	6.7	73.3	1.7	2.011
		U-3	13.0	106	7.0	70.1	1.1	2.006
		U-4	11.0	106	0.7	74.2	0.2	2.015
	Lower layer	L-1	9.0	106	2.2	68.0	0.2	2.008
		L-2	7.5	106	1.7	63.8	0.5	2.023
		L-3	6.0	75	0.0	68.7	0.1	2.151
		L-4	9.0	75	0.0	74.4	0.5	2.075



(a) A-site (b) B-site

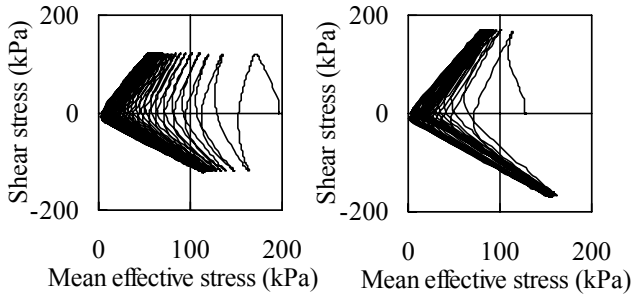
Fig.6 Typical time histories of undrained cyclic shear test

3) After the specimen has completely thawed, it is saturated with the use of CO_2 gas, deaired water and a back pressure of about 196 kPa, until the pore water pressure coefficient B-value reaches 0.95 or higher. After saturation, the specimen is isotropically consolidated at a specified confining pressure, which is equal to the effective vertical stress at the sampling depth.
4) After consolidation, cyclic deviator stresses are applied to the specimen in an undrained condition.
5) After the undrained cyclic shear, the specimen is returned to the drained state.



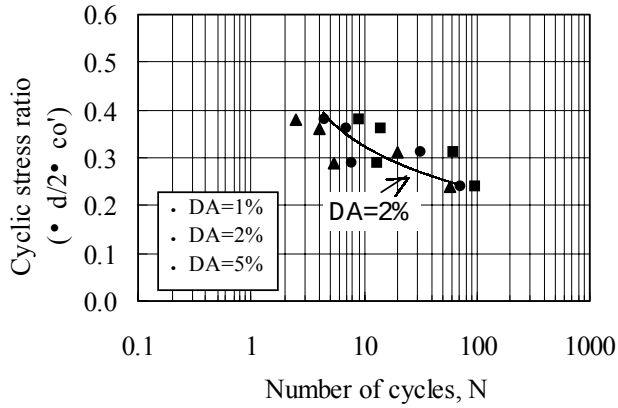
(a) A-site (b) B-site

Fig.7 Typical stress-strain relationship

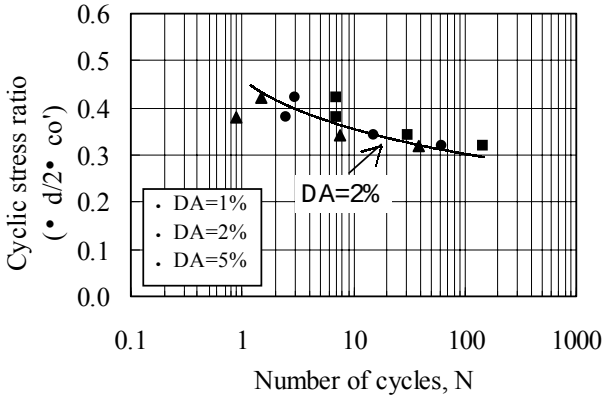


(a) A-site (b) B-site

Fig.8 Typical stress path

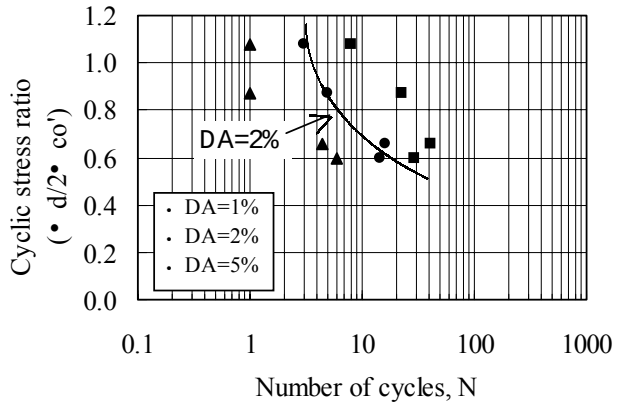


(a) upper layer

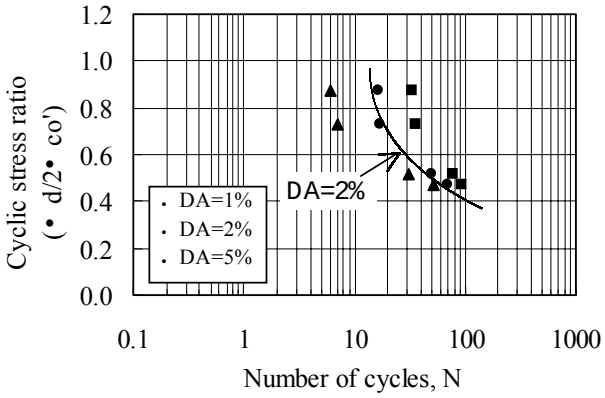


(b)lower layer

Fig.9 Undrained cyclic strength test results for A-site



(a) upper layer



(b)lower layer

Fig.10 Undrained cyclic strength test results for B-site

TEST RESULTS

Table 3 shows the physical properties of the test specimens. It is clear from Table 3 that the samples from site A have a larger grain size with a higher rock content than those from site B. Fig. 6 shows typical time histories of deviator stress, axial strain, and excess pore-water pressure ratio for samples. The amplitude of deviator stress was controlled steadily throughout the test as can be seen in Fig. 6. Fig. 7 shows the relation between deviator stress and axial strain and Fig. 8 shows the relation between shear stress and mean effective stress. As seen in Fig. 7 the axial strain progressed gradually on the extension side.

The correlation between the cyclic stress ratios required to cause a double amplitude axial strain (DA) of 1 %, 2 %, and 5 % and the cycles of stress application for samples from site A are shown in Figs. 9 (a) and (b) for the upper and lower sampled layers. Similarly, Figs. 10 (a) and (b) show the test results for samples from site B. In this study, the cyclic stress ratio, when the strain (DA) of 2 % occurs at the number of stress application cycles of 15, is defined as the

undrained cyclic strength. Using this definition, the undrained cyclic strength at site A obtained from Figs. 9 (a) and (b) was 0.30 in the upper layer, and 0.34 in the lower layer. Similarly, the undrained cyclic strength at site B obtained from

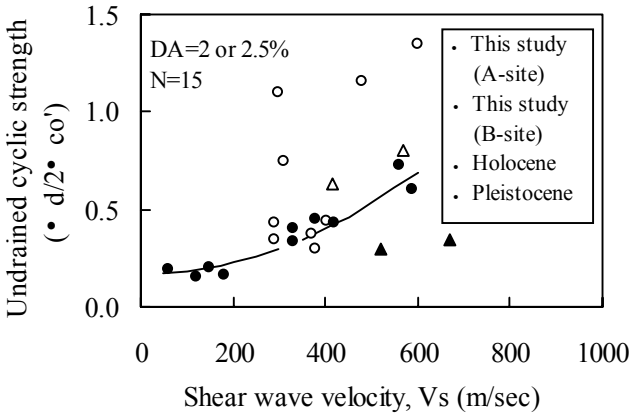


Fig.11 Relationship between shear wave velocity and undrained cyclic strength

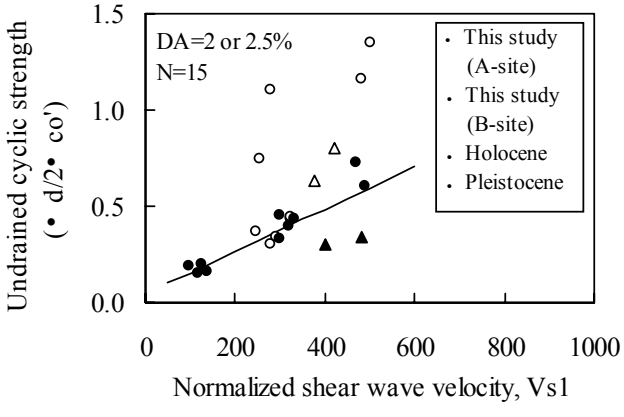


Fig.12 Relationship between normalized shear wave velocity and undrained cyclic strength

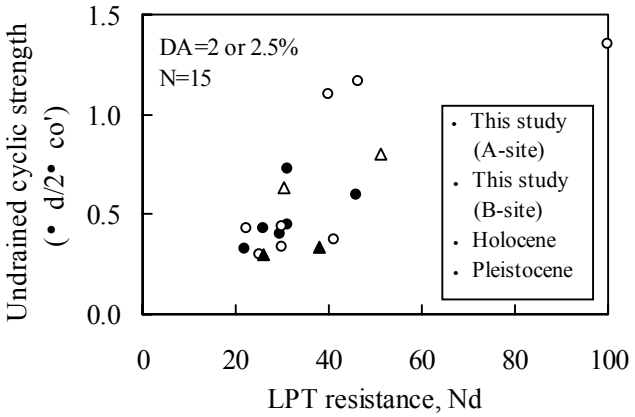


Fig.13 Relationship between LPT resistance and undrained cyclic strength

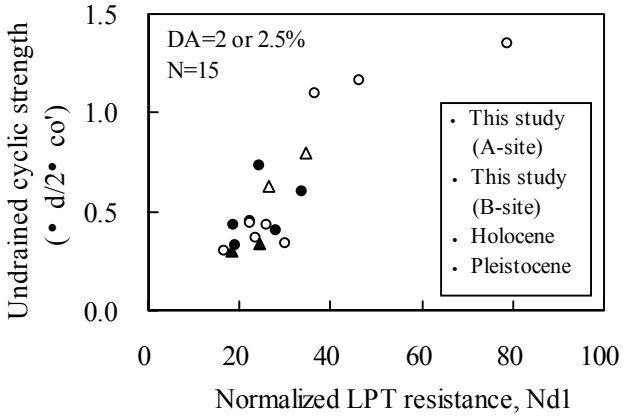


Fig14 Relationship between normalized LPT resistance and undrained cyclic strength

Figs. 10 (a) and (b) was 0.63 in the upper and 0.80 in the lower layers, showing a considerably larger value than the undrained cyclic strength at site A.

As shown in Fig. 1 and Fig. 2, it is clear that the Vs values at A-site were slightly larger both in the upper and lower layers than at B-site. It is assumed, in general, that the larger the Vs value is, the harder the soil is, with an increase in the undrained cyclic strength. However, in fact, the undrained cyclic strength obtained at B-site, where the Vs value was smaller, showed a larger value. One of the causes for this trend is that large particles contained in gravelly soils may have affected the measured values of in-situ Vs.

DISCUSSION ON SIMPLYFIED PROCEDURE FOR EVALUATING THE UNDRAINED CYCLIC STRENGTH

The relation between the undrained cyclic strength of various gravelly soils and the field test results is reviewed using the new data obtained from the tests reported here as well as published data. Hatanaka et al. [4] reported the relationship between the undrained cyclic strength of soil taken by an in-situ freezing sampling method and the in-situ measured Vs. Fig. 11 shows the data reported by Hatanaka et al. as well as data obtained from the tests in this study. In the earlier data, the undrained cyclic strength obtained at DA = 2% and DA = 2.5% are mixed up. Though the data shows a wide variation, there is a clear trend for the undrained cyclic strength to increase with increasing Vs.

The shear velocity, Vs, of soils is affected with the confining stress. The Vs shown in Fig. 11 were measured at different depths and therefore the Vs values were obtained under varying conditions of confining stress. For the sake of being consistent, the Vs value, which is normalized to the value under the same confining stress using Eq. (1), as in the previous study [4], is defined as Vs1.

$$Vs1=Vs/(\sigma_{\square}'/98)^{\square 3/8\square} \quad \square 1\square$$

where,$\sigma_{\square}'$□Effective loading pressure□kPa□

Fig. 12 shows the relation between Vs1 and the undrained cyclic strength. Figs. 11 and 12 also present the curve

approximating the relation between the undrained cyclic strength and Vs as well as Vs1 reported by Hatanaka et al. [4]. The data from site B matched well with the curve proposed by Hatanaka et al., whereas the data from site A were smaller. A possible explanation for this difference in behavior between the data from sites A and B is that gravels with a larger grain size contained in soils from site A may have affected the Vs measured in-situ.

Fig. 13 shows the relation between large penetration resistance (Nd) obtained from field tests and the undrained cyclic strength. In a manner similar to Vs, the Nd value, which is normalized to the value under the same condition of confining stress using Eq. (2), is defined as Nd1 [5]. Fig. 14 shows the relation between Nd1 and the undrained cyclic strength.

$$Nd1=Nd/(\sigma_{\square}'/98)^{\square 1/2\square} \quad \square 2\square$$

It is clear from Figs. 13 and 14 which show the published data [5], [8], and [9] as well as the new data obtained from this study that the undrained cyclic strength tends to increase with increasing Nd and Nd1. The trend shown by the new data obtained from the tests conducted on samples from both sites A and B is similar to the trend seen in the previously published data. Thus, it is assumed that gravels had relatively small effects on the measured Nd in the soils examined in this study. The smaller scatter in the data in Fig. 14 than that in Fig. 13 suggests that the undrained cyclic strength is correlated better with Nd1 than Nd.

The estimation of the undrained cyclic strength of gravelly soils from laboratory tests is a long and laborious process so there is a need for a simplified method for evaluating the undrained cyclic strength based on Vs and Nd both of which are obtained relatively easily from field tests. The results of this study clearly indicate that the undrained cyclic strength of gravelly soils is correlated with Vs and Nd. Examining the various relationships plotted in Figs. 11 to 14, the scatter is seen to be less for Nd than for Vs and Nd1 had the least scatter. Thus it is possible to evaluate the undrained cyclic strength of gravelly soils more easily and more accurately based on Nd1. One thing to note, however, is that gravels in soils may affect the measured Vs and Nd and a comprehensive evaluation of the measured Vs and Nd is required when using these to estimate the undrained cyclic strength..

CONCLUSIONS

In this study, undisturbed samples were taken from two sites in Japan with gravelly soils using an in-situ freezing sampling method. The undisturbed samples were used as specimens in laboratory tests for evaluating their undrained cyclic strengths. Then, using new data obtained from this study as well as those previously published, the relationships of the undrained cyclic strength with the shear wave velocity (Vs) and the large penetration test resistance (Nd) obtained from field tests were examined. The following conclusions were made:

1. The undrained cyclic strength obtained at B-site, where the Vs value was smaller, showed a larger value. One of the causes for this trend is that large particles contained in gravelly soils may have affected the measured values of in-situ Vs.
2. The undrained cyclic strength increases with increasing Vs1 and Nd1. A good correlation was seen between the undrained cyclic shear strength and Nd1. The correlation is the best with Nd1 and this suggests that the undrained shear strength of gravelly soils can be estimated based on Nd1.

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