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Cyclic Shear Deformation Characteristics of Soil Considering Geologic Age and Depositional Environment

by

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Abstract

Classification of the cyclic shear deformation characteristics is made for the earthquake response analysis used in risk analysis against earthquakes in wide area. A total of 482 test results are collected in the Tokyo Metropolitan Area, Japan. They contain recent fill and Holocene to Pleistocene-Pliocene deposits, and are classified into 26 categories based on the geologic age and depositional environment as well as soil type. Next, the effect of confining stress and plasticity index for each geologic category are investigated. Strong confining stress dependency is observed in sandy soils and clayey soils with plasticity index less than 30. Plasticity index is also a control parameter of clayey soils. In addition, younger soils show nonlinear behavior at smaller strains than older soils, which indicates geologic age dependency in soils. It is clearly seen in clayey soils, whereas it is not distinct for sandy soils. The geologic age dependency of clayey soils is the same order with the confining stress dependency and plasticity index dependency.

Key words: cyclic shear deformation characteristics, geologic age, depositional environment, risk analysis

1. Introduction

Recently, earthquake response analyses began to be used even in seismic risk analyses in wide area in Japan (e.g., Central Disaster Prevention Council, 2001 and 2003; Saitama Prefecture, 2007; Chiba Prefecture, 2008; Kanagawa Prefecture, 2009). In these analyses modelling of soil profiles and cyclic shear deformation characteristics are of great interest because they affect the result significantly. In the past studies, target area is divided into relevant size grid cell (e.g., 1 km or 250 m) and representative soil profile in each cell is evaluated from the borehole data in the cell; it may be estimated considering the geomorphologic conditions when there is no borehole data in the cell. Thus, many efforts have been made to model the soil profile for the area

On the contrary, modelling of cyclic shear deformation characteristics is very simple. Soils are classified into a few categories such as clayey soils, sandy soils and gravel, and one cyclic shear deformation characteristics is applied for one category because

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data on cyclic shear deformation characteristics are much fewer than borehole data. In this paper, we collected many cyclic shear deformation characteristics test data and classified based on geologic age and the depositional environment as well as soil type. Next, the data are compiled based on confining stress for sandy soils, and both plasticity index and confining stress for clayey soils. The effects on cyclic shear deformation characteristics of these factors are investigated.

2. Collection and classification of cyclic shear deformation characteristics test data

A total of 482 cyclic shear deformation characteristics test results, among which 208 are sandy soils and the rest clayey soils, are collected from 95 sites in the Tokyo Metropolitan Area (Kanto district), Japan as shown in **Table 1**. Test methods are cyclic triaxial test, cyclic torsional test combined with resonant column test using circular solid specimen, and cyclic hollow cylinder torsional test, in order of the numbers. All of the soil samples were taken by tube sampler. Sandy soils are frozen during transportation to avoid disturbance. They are classified into 26 categories based on geologic age, depositional environment and soil type as shown in **Table 2**.

Table 1 Number of sites and data for cyclic shear deformation characteristics test results

Prefecture	Number of sites	Number of samples
Saitama	6	44
Tokyo	34	148
Kanagawa	27	125
Chiba	15	104
Ibaraki	13	61
Total	95	482

Table 2 Classification of cyclic shear deformation characteristics test data

Geologic age		Depositional environment	Soil Type	Geologic category	Number of data
Man-made		Fill	Clayey soil	1-Bc	10
			Sandy soil	2-Bs	14
Holocene	Upper	Aeolian	Sandy soil	3-As	2
		Marine	Sandy soil	4-As	15
			Gravel	5-Ag	0
		Brackish-water	Clayey soil	6-Ac	5
			Sandy soil	7-As	20
		Fluvial	Peat	8-Ap	5
			Clayey soil	9-Ac	29
			Sandy soil	10-As	27
			Gravel	11-Ag	0
	Lower	Marine	Clayey soil	12-Ac	107
			Sandy soil	13-As	32
		Fluvial	Gravel	14-Ag	0
Pleistocene	Upper	Marine Brackish-water	Clayey soil	15-Ac	18
			Sandy soil	16-As	4
	Upper	Volcanic ash fall	Loam	17-Lm	14
			Clayey soil	18-Dc	7
			Sandy soil	19-Ds	0
			Gravel	20-Dg	0
	Middle	Volcanic ash fall	Loam	21-Lm	0
			Clayey soil	22-Dc	75
			Sandy soil	23-Ds	93
			Gravel	24-Dg	1
Pliocene-Pleistocene	Lower Pleistocene Upper Pliocene	Marine	Mudstone	25-Dc	4
			Sandy-gravel rock	26-Dsg	0

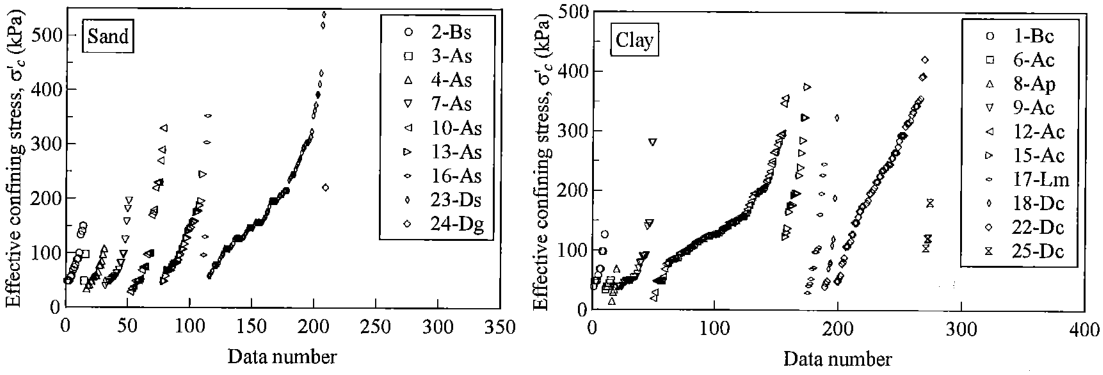


Figure 1 Effective confining stress

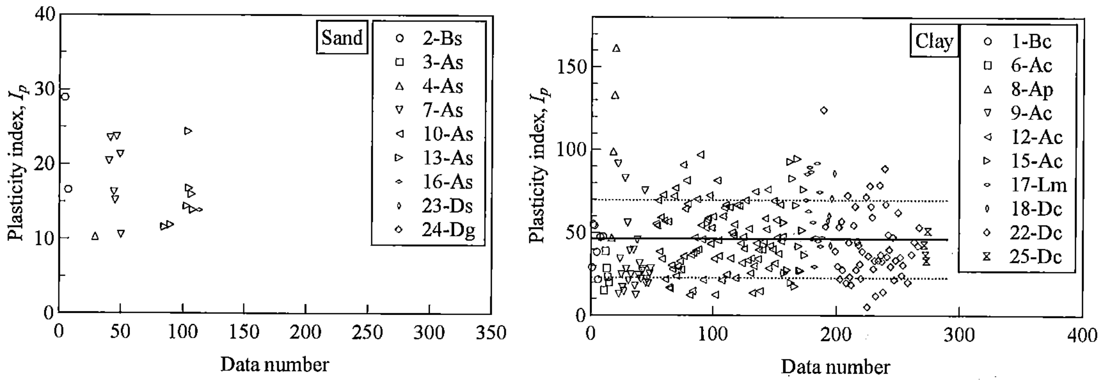


Figure 2 Plasticity index

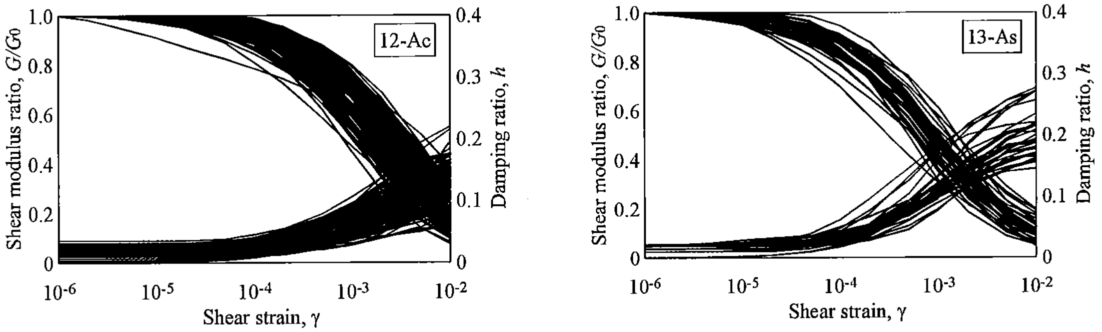
Figure 1 shows confining stress of all test specimens classified based on this classification. Here data number is sequential numbers put on sandy and clayey soils. There is no significant difference between minimum confining stresses for both sandy and clayey soils. On the other hand, maximum confining stresses are smaller for younger soil. This indicates that young deposits do not exist at deep depths.

Figure 2 shows plasticity index I_p for all specimens. Plasticity indices are obtained for 230 specimens among 274 clayey soils and for only 16 specimens among 208 sandy specimens. Plasticity indices of sandy soils are between 10 and 30, but it is noted that this is not a representative value of sandy soils because plasticity index is measured for sand with high plasticity index. Average and standard deviation of clayey soils are 46.0 and 22.4, respectively, which is shown as solid and dotted lines in Figure 2. Maximum plasticity index of clayey soils are less than 100 except peat, and there is no clear characteristic between categories.

3. Controlling factors on cyclic shear deformation characteristics of soils

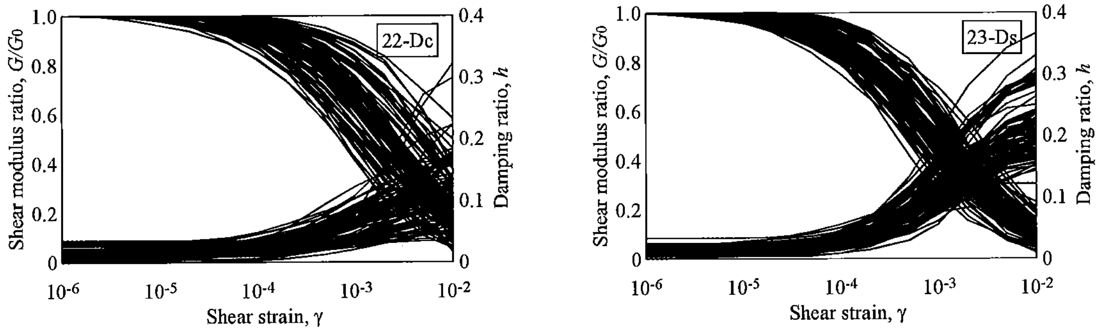
3.1 Effect of soil type, geologic age and depositional environment

Cyclic shear deformation characteristics are expressed as relationships of shear modulus ratio G/G_0 and damping ratio h versus shear strain amplitude γ. **Figures 3** and **4** show comparison between sandy and clayey soils for Holocene and Pleistocene



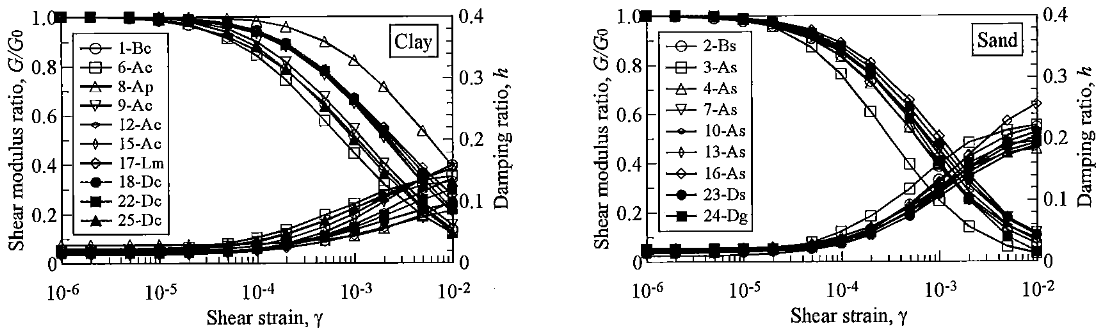
(a) 12-Ac (Lower Holocene marine clay)　(b) 13-As (Lower Holocene marine sandy soil)

Figure 3 Comparison of cyclic shear deformation characteristics between clayey soils and sandy soils for Lower Holocene marine deposits



(a) 22-Dc (Middle Pleistocene cash fall clayey soil)　(b) 23-Ds (Middle Pleistocene cash fall sandy soil)

Figure 4 Comparison of cyclic shear deformation characteristics between clayey soils and sandy soils for Lower Pleistocene volcanic ash fall deposits



(a) Clayey soil　(b) Sandy soil

Figure 5 Average of the cyclic shear deformation characteristics in every category classified by geologic age and depositional environment

deposits, respectively. Sandy soils show larger damping than clayey soils in both ages; the sandy soils become nonlinear easier than the clayey soils. No distinct difference is found in shear modulus ratio, on the other hand, between sandy soils and clayey soils, although clayey soil data contain larger shear modulus ratio at large strains.

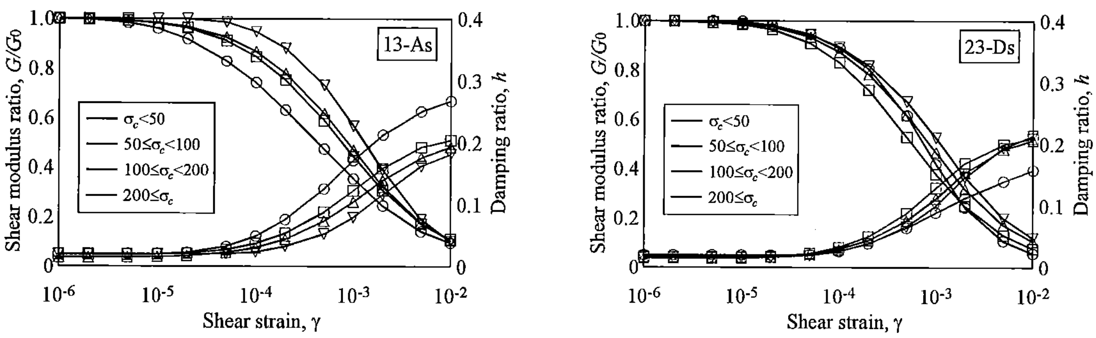
When focusing on difference of geologic age and depositional environment in Figures 3 and 4, no distinct difference could be found between Holocene and Pleistocene soils both for sandy and clayey soils, because the data scatter widely within each geologic age and depositional environment. **Figure 5** (**a**) and (**b**) show the average of the cyclic shear deformation characteristics in every geologic category shown in Table 2 with the exception of 5-Ag, 11-Ag, 14-Ag, 19-Ds, 20-Dg, 21-Lm, and 26-Dsg, as there is no test data. It might be seen from Figure 5 (b) for the sandy soils, younger soils are easier to become nonlinear than the older soils, with the exception of 24-Dg and 3-As. However, the differences depending on geologic age and depositional environment are rather small for sandy soils as seen in Figure 3 (b). In contrast, for the clayey soils in Figure 5 (a), there are distinct differences among the geologic category than that for sandy soils; younger soils are easily to become nonlinear, with the exception of 8-Ap and 25-Dc.

3.2 Effect of confining stress and plasticity index

According the previous studies (Zen et al., 1987; Railway Technical Research Institute, 1999), the effects of confining stress σ'_c and plasticity index I_p are dominant both for sandy soils and for clayey soils; they are controlling factors on cyclic shear deformation characteristics of soils. Consequently, data for sandy soils were classified into four groups according to the confining stress, $\sigma'_c<50$, $50\leq\sigma'_c<100$, $100\leq\sigma'_c<200$ and $200\leq\sigma'_c$ (unit: kPa). **Figure 6** shows cyclic shear deformation characteristics with different confining stress for 13-As and 23-Ds, for examples. It can be found that the effect of confining stress is predominant for sandy soils in every category in the Figure 4 (a) and (b) ; the soils with smaller confining stress are easily to become nonlinear.

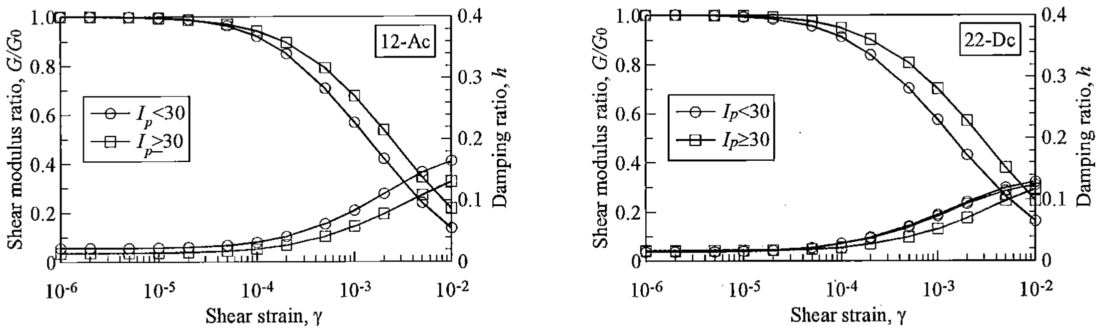
The clayey soils were firstly classified into two groups by plasticity index I_p with less than 30 and with larger than or equal to 30. **Figure 7** shows cyclic deformation characteristics with different plasticity indices for 12-Ac, 22-Dc, as examples. It can be found that the effect of plasticity index is predominant for both Holocene and Pleistocene clayey soils, and nonlinear behavior is more possible as plasticity index is smaller as have been pointed out by previous study.

Then the data shown in Figure 7 (a) and (b) was reclassified into four groups according to the confining stress, $\sigma'_c<50$, $50\leq\sigma'_c<100$, $100\leq\sigma'_c<200$ and $200\leq\sigma'_c$ (unit: kPa), as well as plasticity index. **Figures 8** and **9** show effect of confining stress and plasticity index on cyclic shear deformation characteristics of clayey soils 12-Ac and 22-Ac. Effect of confining stress is seen, but it is less distinct than that for both sandy soils.



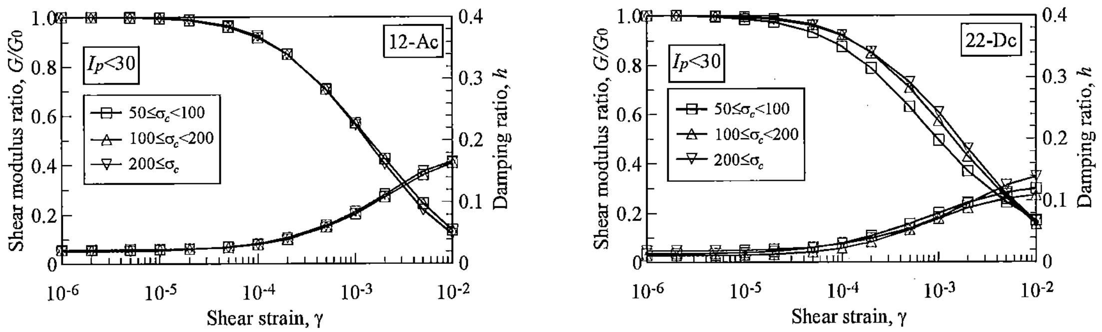
(a) 13-As (Lower Holocene marine sandy soil) (b) 23-Ds (Middle Pleistocene ash fall sand)

Figure 6 Effect of confining stress and plasticity index on cyclic shear deformation characteristics for clayey soils



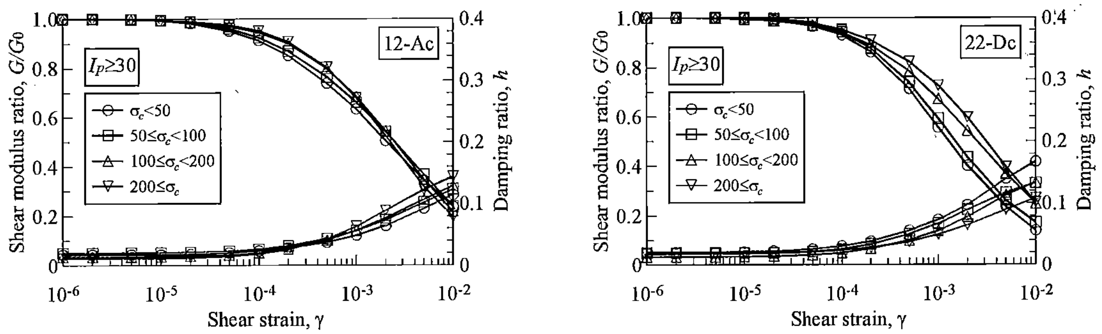
(a) 12-Ac (Lower Holocene marine clayey soil)　(b) 22-Dc (Middle Pleistocene ash fall clayey soil)

Figure 7 Effect of plasticity index on cyclic shear deformation characteristics for clayey soils



(a) 12-Ac (Lower Holocene marine clayey soil)　(b) 22-Dc (Middle Pleistocene ash fall clayey soil)

Figure 8 Effect of confining stress and plasticity index on cyclic shear deformation characteristics for clayey soils with $I_p<30$

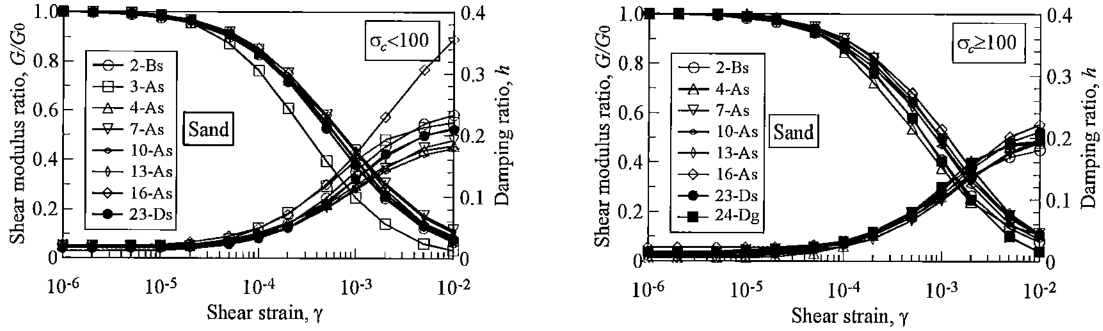


(a) 12-Ac (Lower Holocene marine clayey soil)　(b) 22-Dc (Middle Pleistocene ash fall clayey soil)

Figure 9 Effect of confining stress and plasticity index on cyclic shear deformation characteristics for clayey soils with $I_p \geq 30$

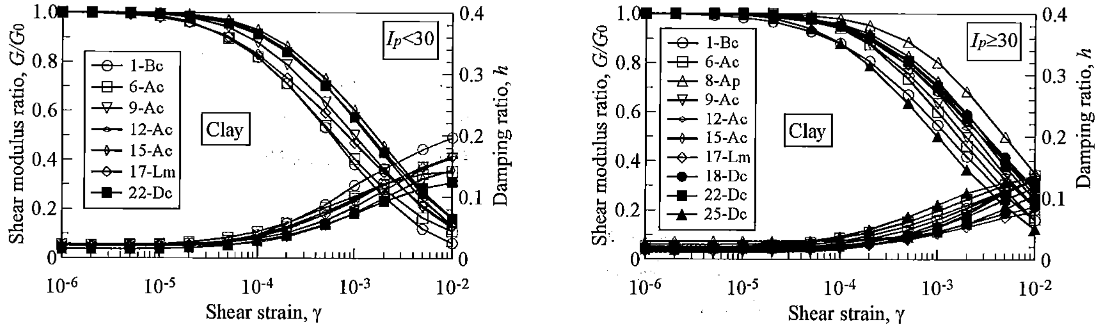
3.3 Predominant factors on cyclic shear deformation characteristics of soils

Discussions are made on the predominant factors that affect cyclic shear deformation characteristics in 3.1 and 3.2, and both confining stress and plasticity index are found to be effective. In this section, the effect of geologic age and depositional environment on cyclic shear deformation characteristics is discussed. In order to see the effect, G/G_0 and h are averaged in every geologic category.



(a) Confining stress σ_c<100 (b) Confining stress $\sigma_c \geq 100$

Figure 10 Effect of geologic age and depositional environment on cyclic shear deformation characteristics for sandy soils classified by confining stress



(a) Plasticity index I_p<30 (b) Plasticity index $I_p \geq 30$

Figure 11 Effect of geologic age and depositional environment on cyclic shear deformation characteristics for clayey soils classified by plasticity index

Figure 10 (**a**) and (**b**) show the effect of the geologic age and depositional environment on cyclic shear deformation characteristics for sandy soils classified by confining stress. No significant effect of the geologic age and depositional environment is found for both confining stress less than 100 kPa and larger than 100 kPa. In the Figure 10 (a), G/G_0 for 3-As and h for 16-As show singular tendency compared with others. This might be because of only a couple of data in each geologic category.

Figure 11 (**a**) and (**b**) show the effect of the geologic age and depositional environment on cyclic shear deformation characteristics for clayey soils classified by plasticity index. It could be found from Figure 11 (a), for clayey soils with plasticity index less than 30, G/G_0 becomes smaller and h becomes larger in the order of younger age. This indicates that younger soils become nonlinear easier than the older soils. The clayey soils with plasticity index larger than 30 shown in Figure 11 (b) shows the same tendency with two exceptions of Holocene peat (8-Ap) and Pliocene-Pleistocene mudstone (25-Dc), whose tendencies were also peculiar same as in Figure 5 (a). As a result, the effect of geologic age and depositional environment is also observed for clayey soils, but its effect is small compared with the one by confining stress and plasticity index.

4. Concluding remarks

Detailed soil classification is carried out for the cyclic shear deformation characteristics of soil considering the geologic age, depositional environment and soil type. They are first classified into 26 geologic categories and the effect of each geologic category as well as confining stress and plasticity index are investigated. Strong confining stress dependency is observed in sandy soils and clayey soils with plasticity index less than 30. Plasticity index is also a control parameter of clayey soils. In addition, young soils show nonlinear behavior at smaller strains than old soils, which indicates geologic age and depositional environment dependency in soils. It is clearly seen in clayey soils, whereas it is not distinct for sandy soils. The geologic age and depositional environment dependency of clayey soils is the same order with the confining stress dependency and plasticity index dependency.

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