Effects of drainage on improving post-cyclic behaviour of non-plastic silt

L'effét du drainage pour ameliorer le comportement aprés-cyclique du non-plastique vase

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ABSTRACT

The effect of drainage history on post-cyclic monotonic undrained shear behavior of non-plastic silt has been investigated using cyclic and subsequent monotonic undrained triaxial tests, following a testing procedure proposed by the authors in which cyclic loading is carried out under stress-controlled conditions and subsequent monotonic loading is conducted under strain-controlled conditions. The results of a battery of tests show that, if the silt did not experience further undrained cyclic loading, the stiffness returned to the original value after once undergoing drainage from full or partial dissipation of excess pore pressures generated during undrained cyclic loading. This characteristic differs greatly from the behavior of cohesive soils, which tend to exhibit stiffness and strength improvement. On the other hand, the post-cyclic undrained strength increased independently of the period at all stages of dissipation of excess pore pressures when drainage was allowed after undrained cyclic loading, depending only on whether liquefaction took place before drainage started. These characteristic features of post-cyclic undrained behavior of non-plastic silt resemble those of cohesive soils including plastic silts and clays, which implies that deformation of silty soil ground during and after earthquakes is more important than ground failure.

RÉSUMÉ

La présente étude rapporte l'observation dans le temps de l'effet d'un drainage sur le comportement d'une zone de cisaillement monodirectionnelle dans un limon solide non-drainé jusque-là ; on a pour cela utilisé des tests triaxiaux portant sur le cycle et sur la zone monodirectionnelle hors drainage. Le résultat de plusieurs séries de tests de ce type montre que, dans le cas d'un limon solide qui a été soumis à un unique drainage occasionnant la dissipation complète ou partielle des pressions interstitielles excessives, la rigidité s'améliore substantiellement moins; mais que la rigidité est alors obtenue à niveau égal si le limon ne passe pas par une phase de non-drainage par la suite du cycle e charge en eau. Voilà qui distingue nettement le comportement des limons de ceux des sols cohésifs, qui ont tendance à voir leur rigidité et leur résistance s'améliorer dans les mêmes conditions. En revanche, une fois le cycle de charge en eau terminé, la résistance d'un sol s'est accrue indépendamment du moment choisi, et ce, à quelque étape que ce soit lors du processus de dissipation des pressions interstitielles excessives, au moment où le drainage est rendu possible après une période, sans drainage, de charge en eau ; cette amélioration de la résistance de la roche dépend du seul facteur suivant : est-ce qu'une liquéfaction a eu lieu avant que le drainage commence ou pas?

Keywords : non-plastic silt, cyclic load history, drainage history

1 INTRODUCTION

Recent studies (Ohtsuka et al., 2004: Yasuhara et al., 2005: Hyde et al, 2007) carried out to elucidate liquefaction mechanisms for silt have revealed marked deformations of the ground which were presumed to be attributable to lateral flow resulting from liquefaction due to application of cyclic loads. Furthermore, it has been confirmed that such deformations persist for a long time because of the lower permeability of silt compared with sand. The excess pore pressures generated by cyclic load are maintained and their dissipation is delayed. Similar to sand and clay (Yasuhara and Hyde, 1997), it is considered that deformations of the silt occur during and after liquefaction. The former is caused by generation of excess pore pressures and the latter is caused by their dissipation. Gravel drains can be used as an effective means for reduction of these deformations. Their effectiveness has already been verified and reported in the authors' earlier studies (Yasuhara et al. 2005).

2 OUTLINE OF EXPERIMENTS

The soil used was non-plastic silt (DL clay) having the grain size distribution presented in Fig. 1. Prescribed cyclic loads were applied under stress control using a triaxial testing machine. Drainage was accomplished by dissipating the excess generated pore pressure. Next, for the specimen that had undergone drainage after cyclic loading, undrained monotonic triaxial testing was carried out under strain control. The effect of the drainage history on shear strength and rigidity of the non-plastic silt after the cyclic history was examined using a series of such tests.

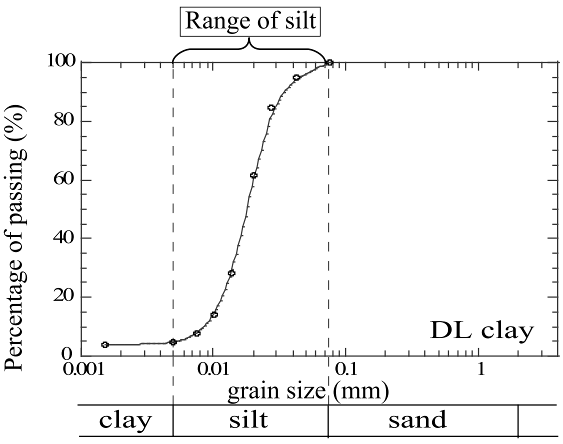

Figure 1. Grain size distribution curve

2.1 *Experimental conditions*

The DL clay was moistened to the optimum moisture content (w_{opt} = 20.8%) and subsequently compacted onto a pedestal in

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eight layers. In all cyclic triaxial tests, isotropic consolidation was allowed for 1 hr at 98 kPa. The frequency used in the subsequent cyclic loading was 0.1 Hz. The loading rate for monotonic shearing after the excess pore pressure caused by cyclic loading had dissipated was set to 0.05%/min. Experimental conditions after the triaxial tests are presented in Table 1. In Table 1(a), monotonic shearing data is presented for tests without allowing drainage after the excess pore pressure ratio *u*/*p*' during cyclic loading was maintained for six states within the range of 0.000–1.000. Liquefaction did not occur in cyclic shearing in this series of tests. The void ratio at consolidation prior to shearing was 0.872–0.937. Table 1(b) presents experimental conditions for a series in which liquefaction did not occur and the excess pore pressure caused by cyclic loading was dissipated. The status of void ratio reduction by drainage is well understood also here. In particular, marked changes that occurred after liquefaction are well demonstrated. Here, excess pore pressure ratios of five kinds were selected from 0.000 to 1.000, including those with liquefaction. Table 1(c) shows experimental conditions in which the drainage was closed in the middle of the drainage process after liquefaction. Monotonic shearing was performed immediately. The table shows that, compared to the case in which the loading was interrupted and drainage was allowed before liquefaction during undrained cyclic loading, the pore pressure ratio in this series (L-series), decreased and the specimen was made more compact.

Regarding the excess pore pressure ratio, seven values in the middle of drainage process were selected arbitrarily and monotonic shearing was carried out in that state.

Table 1 Test conditions of post-cyclic monotonic loading

(a) Post-cyclic without drainage (C-series)

Specimen No.	Cyclic stress ratio	Excess pore pressure ratio	Void ratio e
			Post-compression
S1	-	0.000	0.937
C1	0.102	0.261	0.896
C2	0.102	0.402	0.905
C3	0.099	0.530	0.924
C4	0.113	0.730	0.872
C5	0.107	1.000	0.918

(b) Post-cyclic with drainage (Cd-series)

Specimen No.	Cyclic stress ratio	Excess pore pressure ratio	Void ratio e
			Post-compression
L1	0.102	1.000	0.742
Cd1	0.109	0.220	0.846
Cd2	0.124	0.469	0.890
Cd3	0.101	0.610	0.872
Cd4	0.110	0.710	0.843

(c) Post-cyclic with drainage after liquefaction (L-series)

	Cyclic stress ratio	Excess pore pressure ratio	Void ratio e
			Post-drainage
L1	0.102	0.000	0.742
L2	0.103	0.285	0.790
L3	0.102	0.368	0.760
L4	0.101	0.623	0.773
L5	0.102	0.700	0.798
L6	0.100	0.895	0.782

2.2 *Experimental methodology*

The state paths presented in Fig. 2 were used for triaxial tests relating to deterioration of strength and stiffness attributable to the cyclic loading history preceding liquefaction. First, in the C-series, undrained cyclic triaxial loading of arbitrary magnitude was applied to the isotropically consolidated specimens to generate excess pore pressure. Subsequently, the cyclic loading was terminated and an undrained monotonic triaxial compression test was carried out. Then, in the Cd-series, to verify the effects of drainage history on monotonic shearing behaviour, excess pore pressure was generated by cyclic loading until liquefaction occurred, even if only partial. It was then left for a while until fluctuations of excess pore pressure had stabilized. Excess pore pressure caused by cyclic loading was then dissipated by opening a drainage valve and changes in axial strain and volume change were recorded. The valve was closed when excess pore pressure had completely dissipated, thereby obtaining the undrained state again. Monotonic compression tests were then carried out. Finally, in the L-series, the specimen was liquefied and excess pore pressure was dissipated by drainage. The valve was closed, terminating the drainage, at an arbitrary excess pore pressure. The strength and the stiffness during the drainage process after liquefaction are obtained if a monotonic shearing test is carried out in this state. In Fig. 2, ○ denotes a state in which monotonic shearing occurs. These experiments identify the effects of drainage history on monotonic shearing behavior of the specimen subject to a drainage history before and after liquefaction.

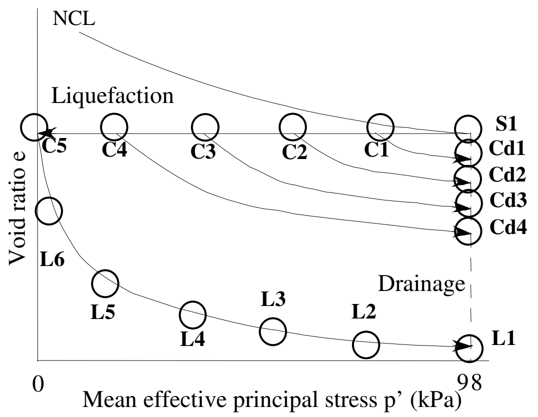

Figure 2. State paths during and after undrained loading

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 *Monotonic shearing behaviour after cyclic loading history*

Figures 3 and 4 respectively portray relationships between the deviator stress and axial strain for the C-series, where excess pore pressure caused by cyclic loading was not dissipated, and the Cd-series where it was. Figure 3 corresponds to S1, C1–C5 in Fig. 2 without a drainage history; Fig. 4 corresponds to S1, Cd1–Cd4 in Fig. 2, with a drainage history. It is apparent from Fig. 3 that the greater the pore pressure caused by cyclic loading, the greater the reduction in peak deviator stress. After yielding, the residual strength is low and similar for all samples. Meanwhile, Fig. 4 shows that the greater the excess pore pressure created during cyclic loading, the greater the peak the deviator stress caused by effects of the drainage history. Furthermore, similar to the peak strength, the greater the excess pore pressure u/p'_c, the greater the residual strength. However, there is a marked softening tendency after yielding in both cases.

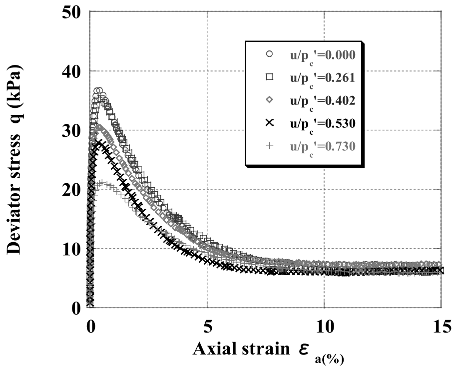

Figure 3. Result of monotonic shear test before liquefaction without drainage (C-series)

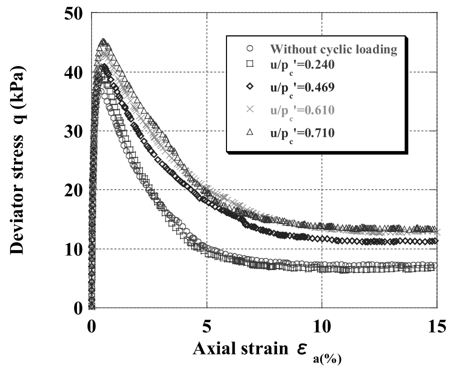

Figure 4. Post-cyclic stress-strain without subsequent drainage (Cd-series)

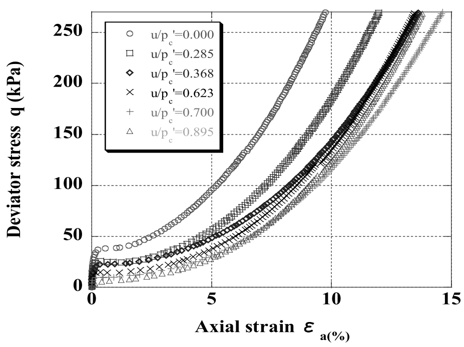

Figure 5. Post-cyclic stress-strain with subsequent drainage (L-series)

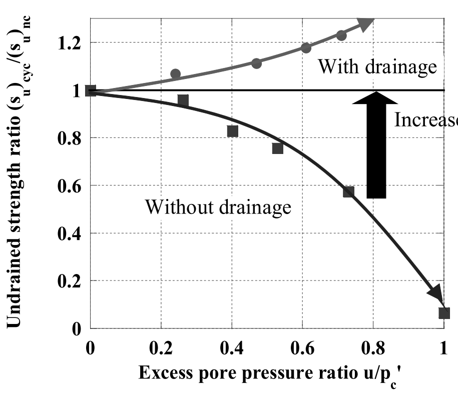

Figure 6. Post-cyclic undrained strength ratio with and without drainage (C-series and Cd-series)

3.2 *Monotonic shearing behaviour after liquefaction*

Figure 5 shows the relationship between stress and strain under monotonic shearing (L-series) for specimens subjected to a drainage history after liquefaction. This test was performed to observe the manner in which shearing behaviour was affected by a difference in drainage history. Values of excess pore pressure correspond to L1– L6, as presented in Fig. 2. Comparison with Fig. 4 indicates the effects of the drainage history: In the C-series, in which liquefaction is not allowed, yielding occurs after the peak strength and a marked softening tendency is shown. In the L-series, a definite yield point is not recognized, even after the peak strength is apparent. Instead, hardening behaviour was observed.

3.3 *Effects of drainage history on non-drainage strength*

The monotonic shearing strength was obtained from the relationship between deviator stress and axial strain, as shown in Figs. 3 and 4, and divided by the monotonic shearing strength for the no cyclic history case. The results obtained are depicted in Fig. 6 in terms of the strength ratio. Figure 6 clarifies that the greater the excess pore pressure generated by cyclic loading, the greater is the reduction in non-drainage strength. This feature resembles that of clay. However, if drainage is allowed from this state, compared to the case with no cyclic history, the strength will increase markedly as the excess pore pressure to be dissipated increases. In the L-series the strength after liquefaction cannot be expressed as a strength ratio because a definite peak was not apparent in the stress–strain curves presented in Fig. 5. However, it is known from Fig. 5 that the specimen, if subjected to a drainage history, does not yield but rather hardens. It is then capable of withstanding a larger deviator stress and the strength increases dramatically.

3.4 *Effects of drainage history on recovery of rigidity*

The secant modulus of deformation was obtained from the deviator stress–strain relationship at an axial strain of 0.1%. In addition, the secant modulus of deformation ratio was selected as an index to represent the rigidity. Figure 7 shows results for the modulus of the deformation ratio for where drainage was allowed after cyclic loading (Cd1–Cd4 of the Cd-series) and where it was not allowed (S1, C1–C5 of the C-series). Figure 7 shows the tendency for the rigidity to decrease as the excess pore pressure, caused by cyclic loading, increases. It is almost impossible to resist deformation after reaching liquefaction. Meanwhile, although the rigidity recovers from this state if subjected to a drainage history, recovery is only back to the modulus of deformation of the specimen not subjected to a cyclic history. As described above, although strength recovers markedly, recovery of rigidity is unsatisfactory, even if subjected to drainage after cyclic loading.

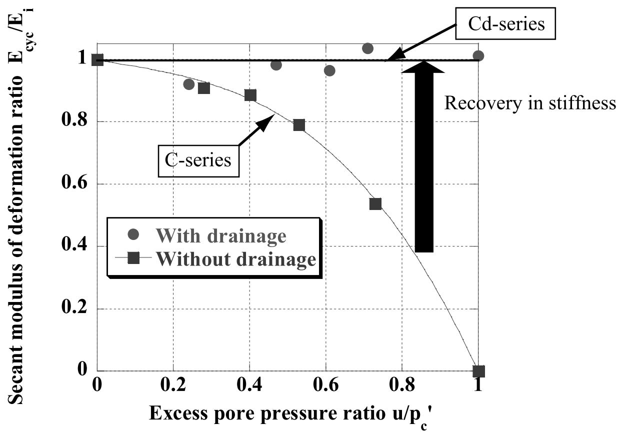

Figure 7. Post-cyclic rigidity reduction and recovery (C-series and Cd-series)

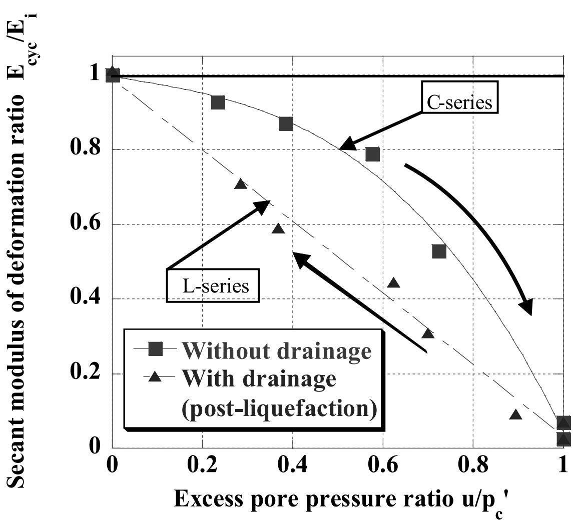

Figure 8. Post-liquefaction rigidity reduction and Post-liquefaction recovery (C-series and L-series)

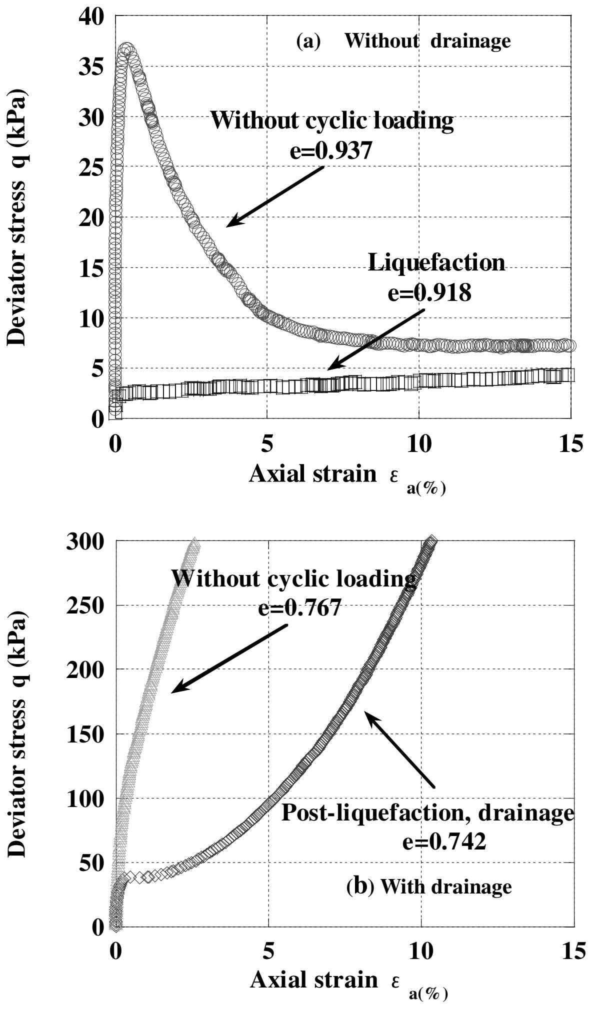

Figure 9. Monotonic shear behavior of post-liquefaction with and without drainage history

Figure 8 shows a comparison of the modulus of deformation ratio for specimens (C1–C5) not subjected to a drainage history after cyclic loading and specimens (L1–L6) subjected to a drainage history after liquefaction. The probability of recovery of rigidity because of dissipation of excess pore pressure after liquefaction is small compared to the reduction in rigidity for a case in which drainage is not allowed after cyclic loading. For example, a comparison of cases for which the excess pore pressure ratio is 0.5 reveals that reduction in the rigidity for the case of shearing without allowing drainage after cyclic loading is approximately 80%, while recovery of the rigidity of the specimen in which drainage was allowed after liquefaction is approximately 50%, which means that recovery even to the initial state is not possible. Consequently, the material remains in a deteriorated state. To investigate this finding in detail, monotonic shearing tests were performed for specimens of the following four types: (1) Without cyclic history (S1); (2) At liquefaction (S1); (3) Drainage was allowed after liquefaction and excess pore pressure thoroughly dissipated (L1); and (4) Specimens not subjected to cyclic history, but close to the void ratio (S1*). The relationships between the deviator stress and strain are shown in Fig. 9. It can be seen from Fig. 9(a) that shear strength is lost completely if drainage is not allowed after liquefaction. It is seen in Fig. 9(b) that the shear strength increased markedly if drainage is allowed. Giving contrasting tendencies of deterioration and recovery of the rigidity.

4 CONCLUSIONS

1) The shearing resistance of silt specimens subject to a drainage history increases by dissipating excess pore pressure caused by the undrained cyclic loading, irrespective of the presence or absence of liquefaction. The greater the dissipation of the excess pore pressure, the more marked is the strength is increased. In particular, the strength of specimens subjected to drainage after reaching liquefaction increased drastically.

2) In contrast, if the drainage is allowed after cyclic loading, although the rigidity shows a tendency to recover, it recovers only to the rigidity of the specimen in the initial state without cyclic history. Furthermore, if once liquefied, the recovery of the rigidity is extremely difficult. This tendency is entirely different from that of strength recovery.

3) Results described in 1) and 2) suggest that liquefied silt ground is in a vulnerable state and will be deformed easily by a subsequent earthquake.

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