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COUNTERMEASURE FOR LIQUEFACTION USING STEEL SHEET PILE WITH DRAIN CAPABILITY

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ABSTRACT

Two types of steel pile with drain capability which are pipe pile and sheet pile type have been developed for the countermeasure against liquefaction of sand layers. In this paper, applicability of the sheet piles among these to the countermeasure for buried structures and embankments was investigated through model tests using a shaking table. Experimental results indicated that to enclose the buried structure with the above-mentioned sheet piles sufficiently prevented it from damage due to the uplift displacement. It was also shown that to enclose the embankment with the above-mentioned sheet piles was effective to prevent it from collapse due to liquefaction of its foundation. These effects of sheet piles with drain capability could be explained as the results of restraining lateral soil flow by sheet pile walls and reducing the bending deformation of the sheet pile on account of retaining the soil strength around it.

KEYWORDS

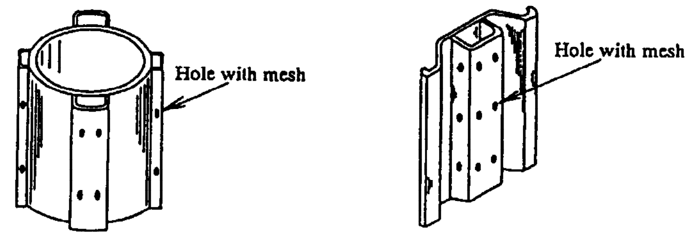
Liquefaction; steel sheet pile; buried structure; embankment; shaking table test;

INTRODUCTION

Sand liquefaction, generated during earthquake ground shaking, often damaged buried structures of relatively light specific weight due to the uplift displacement and embankments due to the settlement. One of the countermeasures against liquefaction for these structures is to enclose them with sheet pile walls, the so-called cut-off sheet pile method (Matsuo et al., 1994).

Authors have developed the steel piles which are equipped with drain capability. These steel piles have channels with a number of holes to drain pore water in sand layer, as shown in Fig.1, and thus are capable of reducing the excess pore water pressure generated by earthquake (Kita et al., 1992). The sheet pile among these is called herein SPDC(Sheet Pile with Drain Capability).

In this paper, applicability of SPDC to the cut-off sheet pile method is investigated through model tests using a shaking table shown in Table 1. These tests are divided into two series. Test series 1 (the upper nine tests) in Table 1 were conducted to investigate the effectiveness of SPDC as a countermeasure for buried structures. Three types of model, which are no-countermeasure, the cut-off sheet pile and the cut-off sheet pile



(a) Pipe pile (b) Sheet pile

Fig.1. Examples of steel pile with drain capability

Table 1. Conditions of shaking table tests

Series	Object	Test No.	Type of countermeasure	Type of sheet pile	Conditions of sand layer H1*(cm)	Dr*(%)	H2*(cm)	Vibration condition	Sand properties
1	Countermeasure for buried structure	1-1	No-countermeasure		55	47.6	35		
		1-2			70	41.5	20	3Hz	
		1-3			90	41.5	0	Sinusoidal	
		1-4	Cut-off sheet pile	1.2mm steel plate	55	47.8	35	30 cycles	
		1-5			70	52.7	20	150gal	
		1-6			90	57.9	0	200gal	G_s=2.678
		1-7	Cut-off sheet pile with SPDC	1.2mm steel plate with resinous drain	55	57.3	35	300gal	
		1-8			70	55.6	20		D_{50}=0.38 mm
		1-9			90	57.6	0		
2	Countermeasure for embankment	2-1	No-countermeasure		40	49.3	35	3Hz	Uc=3.21
		2-2	Cut-off sheet pile	3.2mm steel plate	40	66.3	35	Sinusoidal	
		2-3	Cut-off sheet pile with SPDC	3.2mm steel plate with drain pipe	40	52.7	35 35	30 cycles	
		2-4	Cut-off sheet pile with tie rods	3.2mm steel plate with tie rods	40	53.6	35	150gal	

H 1*: Thickness of loose layer Dr*:Relative density of loose layer H2*:Thickness of dense layer

method with SPDC model, were applied to these tests and then three different dimensions of liquefiable layer thickness were prepared for each type of the models. Test series 2 (the lower five tests) in Table 1 were performed to investigate the remedial effect of the SPDC against the settlement of the embankment. Four types of test model were prepared in this series of tests : no-countermeasure, the cut-off sheet pile method, that with SPDC and that with the restraint by tie rods.

APPLICATION OF SPDC TO COUNTERMEASURE FOR BURIED STRUCTURES

Test Procedure (Test series 1)

Figure 2 shows the set up of the model tests and instrumentations for measuring the response in liquefiable sand layer of 700mm thickness. All these models were contained in a rigid container of dimensions 2000mm long, 1000mm high, 1000mm wide. Dividing the width of the container into half (500mm wide), a model was set up at each half of a single container so that tests were conducted for two models at one time. Model ground consists of two sand layers as illustrated in Fig.2. The upper one is a liquefiable sand layer. The liquefiable layer was placed by pouring dry sand from a certain height into the water filled in the container. The properties of sand used and relative densities of the upper liquefiable layers in each test are given in Table 1. The average unit weight of the upper layer prepared in these tests was 1.86gf/cm^3. The buried structure model was a rigid box of 500mm long, 250mm high and 400mm wide. Its apparent unit weight was 0.88gf/cm^3. Sheet pile models were steel plates and dimensions of those were 900mm in height, 410mm in width and 1.2mm in thickness. Those with drain capability were equipped with resinous drains on the inner surface of the steel plate, where inside means the area enclosed by sheet piles. Sheet pile models were fixed at the bottom of the container. Each model was excited by 30 cycles of horizontal sinusoidal motion of frequency 3 Hz at the acceleration level either 150, 200, 300gal. One level of input acceleration was applied during one test run and this was repeated for all different levels of acceleration from 150gal to 300gal.

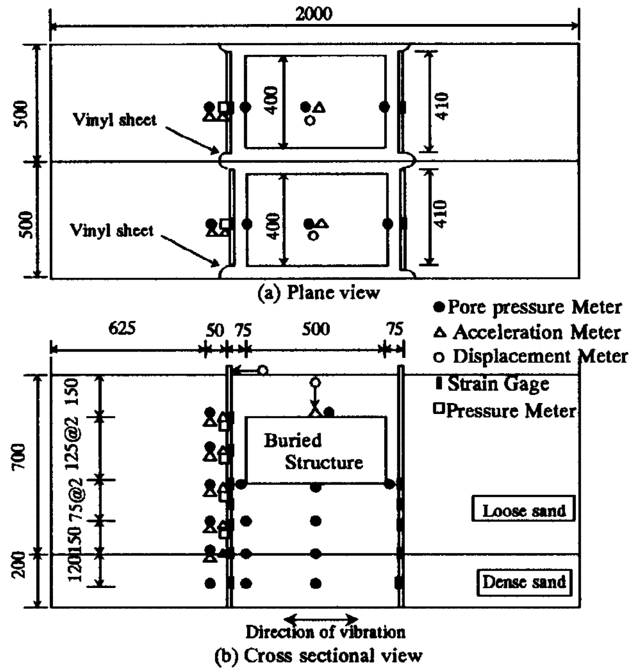
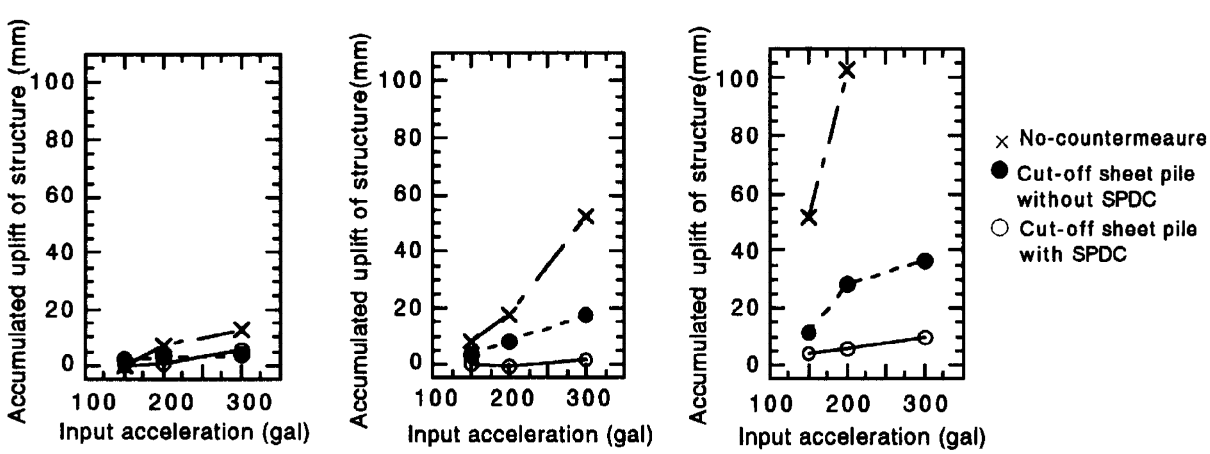


Fig.2. Model of shaking table tests on the cut-off sheet pile method with SPDC for the buried structure

Results and Discussions

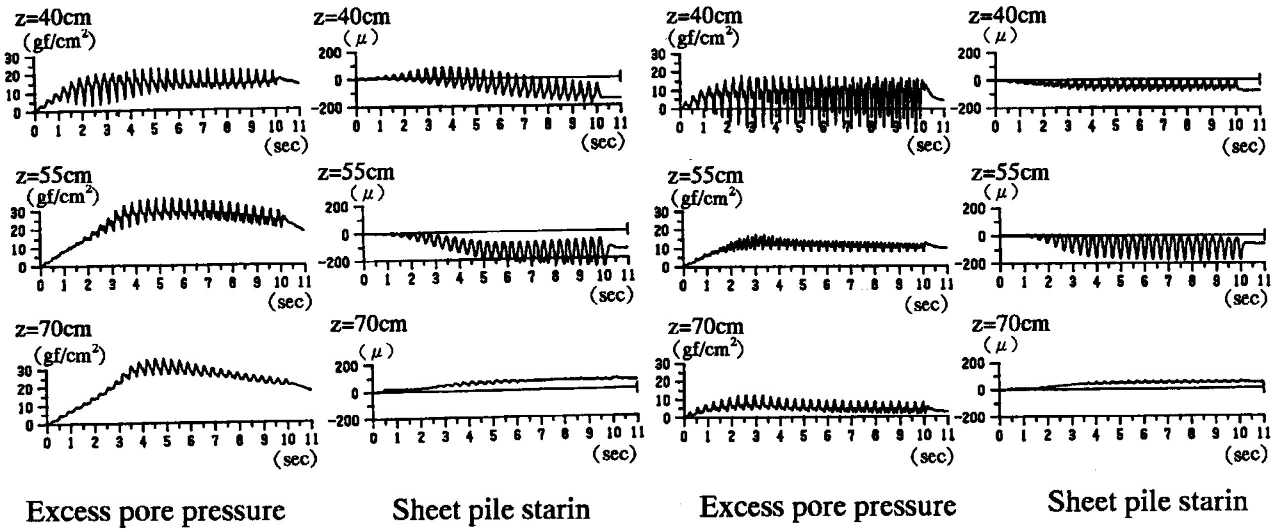
Relationship between input acceleration and induced uplift of the buried structure. Figure 3 shows the variations of the accumulated uplift displacement of the buried structure with input acceleration. Figure 3 (a), (b) and (c) are those for liquefiable layer of 550mm thickness (Test No.1-1,1-4,1-7), 700mm thickness (Test No.1-2,1-5,1-8) and 900mm thickness (Test No.1-3,1-6,1-9) respectively. Effectiveness of the cut-off sheet pile method is confirmed in the results, particularly for the case with SPDC : it can prevent the buried structure from the significant uplift displacement even in liquefiable layer of 900mm thickness and high acceleration level where the considerable uplift was observed in case of the cut-off sheet pile without drain capability.

Mechanism of The Cut-off Sheet Pile Method with SPDC. It is reported in the past paper that the effect of the cut-off sheet pile method results from cutting off lateral flow of liquefied soil into the area below the buried structure and, in case of SPDC, reducing pore water pressure around the structure (Kita et al., 1993). Herein, the relationship between the uplift displacement of the structure and bending deformation of the sheet pile is considered.



(a) 550mm loose layer (b) 700mm loose layer (c) 900mm loose layer

Fig.3. Relationship between input acceleration and accumulated uplift of the buried structure



(a) No.1-6 test (Cut-off sheet pile without SPDC)   (b) No.1-9 test (Cut-off sheet pile with SPDC)

Fig.4. Observed time histories of excess pore water pressure inside of cut-off enclosure and sheet pile strain (No.1-6 and No.1-9 test)

Figure 4 shows time histories on sheet pile strain and excess pore water pressure observed at the locations of 50mm inside from the sheet pile during 150gal shaking in No.1-6, 1-9 test. It can be seen that the drain capability of SPDC reduced the excess pore water pressure, particularly with regard to the intermediate component of it, which is defined in Fig.5, and prevented soil in the vicinity from softening due to liquefaction. This effect results in reducing the intermediate component of the sheet pile strain as recognized in Fig.4. That component of sheet pile strain indicates the deformation of the sheet pile illustrated in Fig.6, which contributes to the uplift displacement of the buried structure(Tanaka et al., 1995). Therefore it is considered that the cut-off sheet pile method with SPDC effectively prevented the uplift displacement of the buried structure.

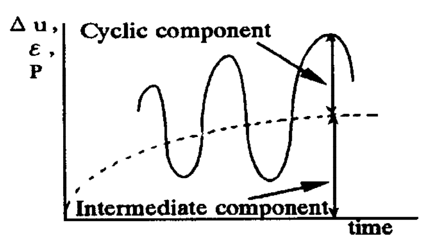


Fig.5. Cyclic and intermediate component of pore pressure and strain

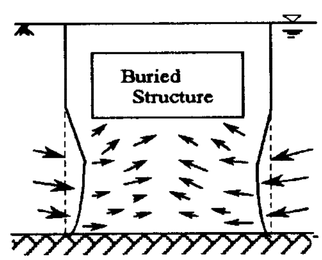


Fig.6. Illustration on uplift of buried structure

It is expected that the induced uplift displacement of the buried structure enclosed with sheet pile walls is approximately estimated by means of dividing the volume variation Δv due to sheet pile deformation illustrated in Fig.6 by the base area of the structure (Yoshimi et al. 1991). Figure 7 shows a comparison between the uplift displacement observed during each test run in No.1-5~1-9 tests and those calculated. The sheet pile strain observed in each test was used to evaluate Δv. Uplift displacement values are reasonably evaluated by this method. However, it is found that the uplift displacement values calculated for SPDC tend to overestimate experimental values and those for the ordinary sheet pile without drain capability are just the reverse. These results seem to indicate that the flow of liquefied soil between the sheet pile and the structure into the area below the structure may also induce the uplift displacement in case of the ordinary sheet pile, which can not sufficiently prevent liquefaction. On the other hand, SPDC can prevent that type of flow because of holding soil strength by drain capability and carry away a part of Δv as drained water. Then that is also one of the reason why SPDC is more effective than the ordinary sheet pile without drain capability.

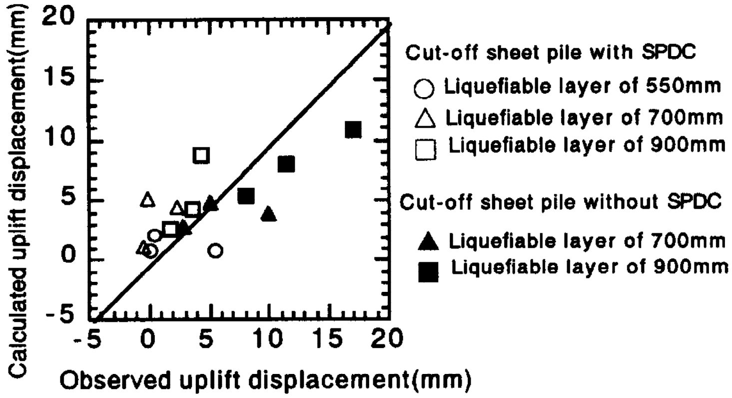


Fig.7. Comparison between observed and calculated uplift displacement of the buried structure

APPLICATION OF SPDC TO COUNTERMEASURE FOR EMBANKMENT

Test Procedure (Test series 2)

Figure 8 shows the set up of the model tests and the locations of gages in test series 2 (No.2-1~2-4 test). The conditions of the tests can be found in Table 1. Model ground underlying the embankment consists of two sand layers; the upper liquefiable layer of 400mm thickness and the lower compacted layer of 350mm thickness. These sand layers were prepared in the same manner as explained in the previous section. The embankment was formed of same sand as its unit weight was approximately 1.6gf/cm^3. The vinyl sheet underlaid the embankment to cut off permeation of pore water in the saturated liquefiable layer. Sheet pile models were steel plates and dimensions of those were 780mm in height, 410mm in width and 3.2mm in thickness. Those with drain capability were equipped with the vertical drain pipes(ϕ 15mm) on both the surfaces of the steel plate which did not contribute to the flexual rigidity of the steel plate. The drain pipe with the inside of cut-off enclosure were connected to the vinyl pile of 5mm in diameter in order to carry drained water away from the embankment, so that drain capability inside of enclosure was less than that outside. Tie rods used in No.2-4 test were steel rods with a diameter of 3mm and not prestressed. Each model was excited by 30 cycles of horizontal sinusoidal motion at the rate of 3Hz. The amplitude of input acceleration was about 200gal.

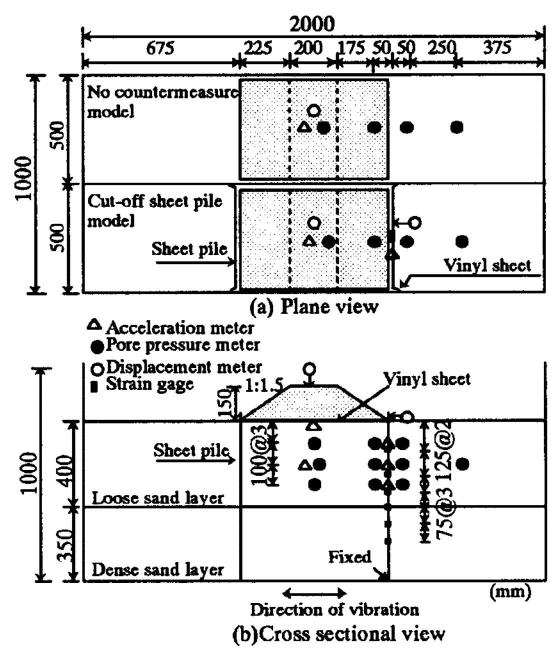
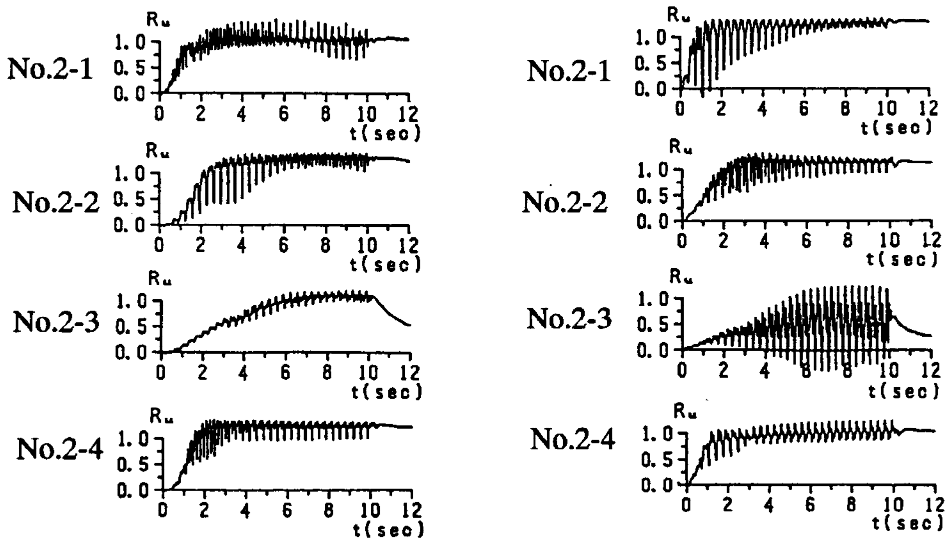


Fig.8. Model of shaking table tests on the cut-off sheet pile method with SPDC for the embankment

Results and Discussions

Observed Time Histories on Excess Pore Water Pressure. Figure 9 shows the time histories on the excess pore water pressure observed during No.2-1~2-4 test. This includes those observed at the depth of 200mm below the center of the embankment and at the depth of 200mm of 50mm outside from the sheet pile. The vertical axis was shown in the form of the excess pore water pressure ratio $Ru = \Delta u / \sigma_{vo}'$. It is observed that the sand layer outside of cut-off enclosure was liquefied in 2~3sec except No.2-3 test. In No.2-3 test performed for the SPDC model, the excess pore water pressure ratio R_u did not reach 1.0 to reduce pore water pressure by drain capability. The sand layer inside of cut-off enclosure was also liquefied in 2~3sec due to insufficiency of overburden pressure from the embankment. Even in the SPDC (No.2-3 test), inside soil was liquefied in 5~6sec since drain capability inside of cut-off enclosure was less than that outside.



Below the center of the embankment | 50mm outside of the sheet pile

Fig.9. Observed time histories on excess pore water pressure

Observed Time Histories on Settlement of The Embankment. The time histories on the settlement of the embankment are shown in Fig.10. It can be seen that the settlement of the embankment in No.2-1, 2-2 and 2-4 test remarkably increased after the fifth cycle of the table motion and that in No.2-3 (SPDC) increased after the fifteenth cycle. These cycle numbers were almost identical to those in which the excess pore water pressure ratio in each test reached 1.0 as shown in Fig.9. This indicates that drain capability of SPDC was effective to prevent the settlement of the embankment. It is, however, recognized that, after 22 cycles of table motion, the induced settlement in No.2-3 (SPDC) was more than that in No.2-4. This indicates that restraint of the sheet pile displacement by tie rods kept its effectiveness even in liquefaction of sand layer underlying the embankment.

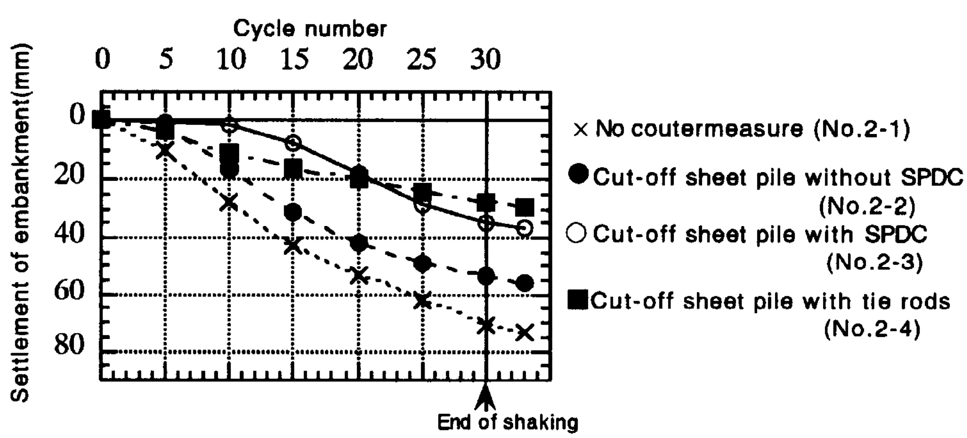


Fig.10. Observed time histories on the settlement of the embankment

Residual Deformation of Embankment. Figure 11 illustrated the residual deformation of the embankments induced in each test. It seems that the embankments sank into liquefied layer with those forms almost held and without sliding failure of slope. This is due to liquefaction in the whole area right under the embankments. It is recognized in Fig.11(a) that the settlement of the embankment without reinforcement stood out remarkably and soil surrounding the embankment was elevated by lateral flow of liquefied soil underlying the embankment due to its weight. In Fig.11(b), (c) and (d), the elevation of surrounding soil is not shown due to cutting off lateral flow of liquefied soil by sheet pile walls and the settlement of embankment was reduced in comparison with that in case of no-countermeasure. Particularly remedial effects of the cut-off sheet pile with drain capability and with tie rods are remarkable as shown in Fig.11(c) and (d).

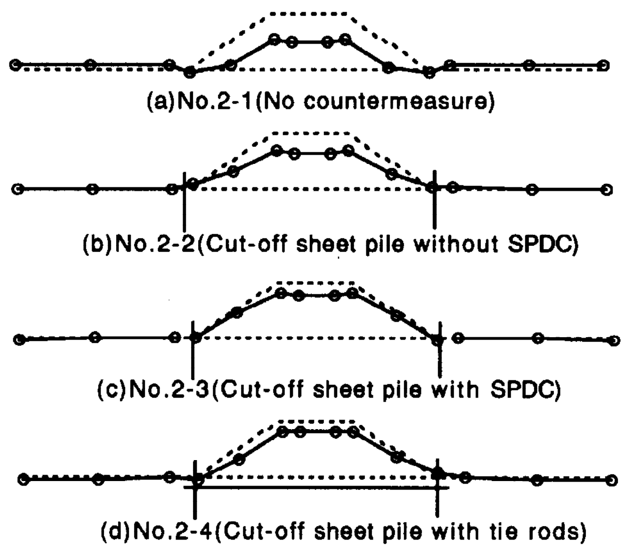


Fig.11. Residual deformation of the embankment

Mechanism of The Cut-off Sheet Pile Method, That with SPDC and That with tie rods. The vertical distributions on residual bending strain and deformation of the sheet pile are shown in Fig.12 (a) and (b) respectively. Residual deformation in Fig. (b) was calculated from residual strain shown in Fig. (a). The sheet pile deformation for No.2-3 test (cut-off sheet pile method with SPDC) is reduced on account of drain capability of SPDC in comparison with that for No.2-2 test (normal cut-off sheet pile method). It is also found that restraint by tie rods sufficiently prevented the sheet pile from bending deformation. The remedial effects result from prevention of lateral flow of liquefied soil due to the flexural rigidity of the sheet pile, in case of the normal cut-off sheet pile, the flexural rigidity of the sheet pile and retaining soil strength by drain capability, in the cut-off sheet pile method with SPDC, and the flexural rigidity of the sheet pile and restraint of sheet pile deformation by tie rods, in the cut-off sheet pile with tie rods, respectively.

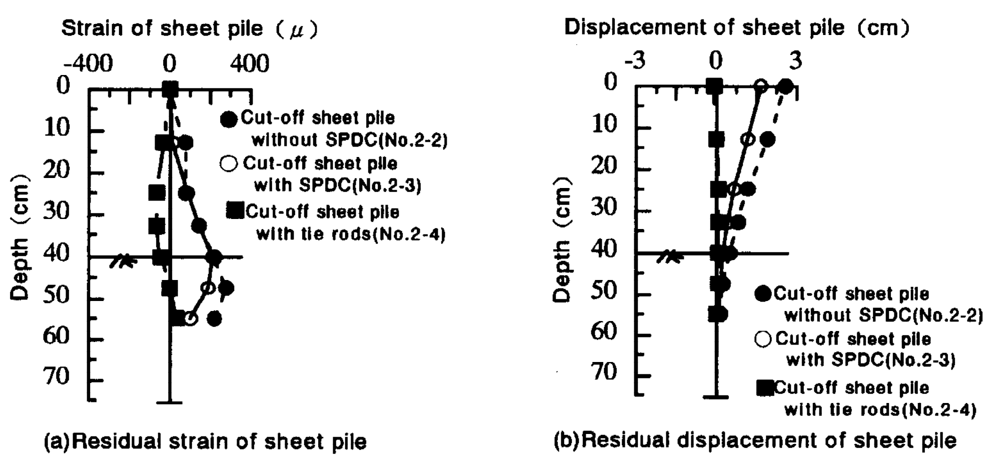


Fig.12. Vertical distributions on residual bending strain and deformation of the sheet pile

CONCLUSION

As one of the countermeasures for liquefaction, a new method using the steel sheet pile with drain capability has been developed. In this paper, shaking table tests were performed to investigate the effectiveness of that method. The main results are as follows.

(1)To enclose the buried structure with the sheet piles equipped with drain capability sufficiently prevented it from damage due to the uplift displacement even for the case with thick liquefiable layer in which the significant uplift were observed for the cut-off sheet pile without drain capability.

(2)Uplift displacement of buried structure enclosed with sheet pile walls was mainly induced by the bending deformation of the sheet pile walls and the folw of liquefied soil between the structure and the sheet pile walls into the area below the structure. The sheet piles with drain capability were able to reduce both of them on account of retaining the soil strength in the vicinity. This is the reason why the sheet pile with drain capability was effective as a countermeasure for uplift displacement of the buried structure.

(3)To enclose the embankment with the sheet piles equipped with drain capability was effective to prevent it from the settlement due to liquefaction. Expected effect of this method is to prevent the soil underlying the embankment from spreading out due to the embankment weight and to reduce the bending deformation of the sheet pile on account of retaining the soil strength around it.

(4)One of the reliable countermeasures for settlement of the embankment due to liquefaction was to enclose it with sheet pile walls and to connect the top of them with tie rods. The restraint of sheet pile deformation by tie rods resulted in preventing the soil underlying the embankment from lateral flow and keep its effectiveness even in liquefaction of sand layer underlying the embankment.

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