Liquefaction Countermeasure Using Steel Sheet Pile with Drain Capability

by

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Synopsis

Steel piles with drain capability have been developed as a countermeasure for liquefaction of sand layers. These steel piles have steel channels with a number of holes to drain pore water from the sand layer, and thus are capable of reducing the excess pore water pressure generated by earthquakes. This paper reports on applicability of the sheet pile with drain capability to the liquefaction countermeasures for buried structures and embankments, investigated through model tests using a shaking table. The main results are as follows: (1) Enclosing the buried structure with the sheet piles with drain capability was effective in preventing uplift displacement due to liquefaction. This resulted from preventing the loss of soil strength around the sheet pile walls. (2) Enclosing the embankment with the sheet piles with drain capability was effective in protecting it from the settlement due to liquefaction. The effect of this method is to utilze the sheet pile walls and the soil strength around it to prevent the soil underlying the embankment from spreading out.

1. Introduction

Sand liquefaction, generated by earthquake ground shaking, has been widely recognized since Niigata Earthquake in 1964. In recent years seismic design considering liquefaction has the come to be required in various kinds of standard specifications for design[1),2)]. Some countermeasures for liquefaction have been developed including soil improvement techniques represented by sand compaction, seismic reinforcement using steel piles and pore water pressure reduction techniques represented by gravel drain pile methods[3)].

However, earthquake damage due to liquefaction has been induced in recent earthquakes and Japan still has many places with the potential for disaster due to liquefaction.

Under these circumstances the authors have developed special steel piles which are equipped with drain capability as a liquefaction countermeasure. These steel piles have channels with a number of holes to drain pore water from the sand layer as shown in **Fig. 1** and thus are capable of reducing the excess pore water pressure generated by earthquakes[4)]. The sheet pile developed is called herein SPDC (Sheet Pile with Drain Capability).

This paper reports on the applicability of SPDC to countermeasures for buried structures such as common utility ducts and for soil embankments such as river dikes and road embankments, investigated through model tests using a shaking table.

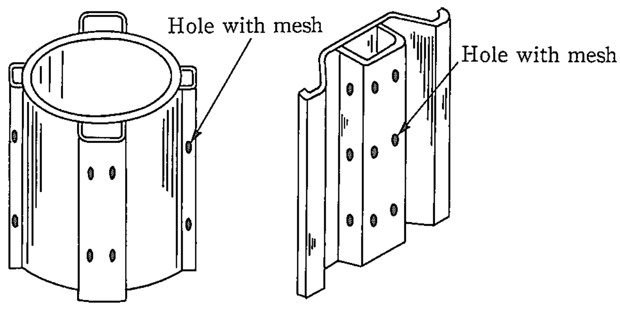


Fig. 1 Examples of steel pile with drain capability

2. Application of SPDC to Countermeasures for Buried Structures

2.1 Outline of Countermeasures for Buried Structures Using SPDC

Buried structures of relatively light weight located in loose saturated sand layers are often damaged due to the uplift displacement by liquefaction generated during earthquakes. This is due to the lateral flow of liquefied sand into the area below the structure where the overburden pressure is lower than in the vicinity.

As a liquefaction countermeasure for such buried structures, the authors have examined enclosing them with the sheet pile with drain capability (SPDC) as shown in **Fig.2.** This method is called herein the cut-off sheet pile method using SPDC. The aim of this method is to prevent the soil around the structures from losing its strength due to liquefaction and to cut off the lateral flow of the surrounding soil into the area below the structure by sheet pile walls driven on both sides of the structure.

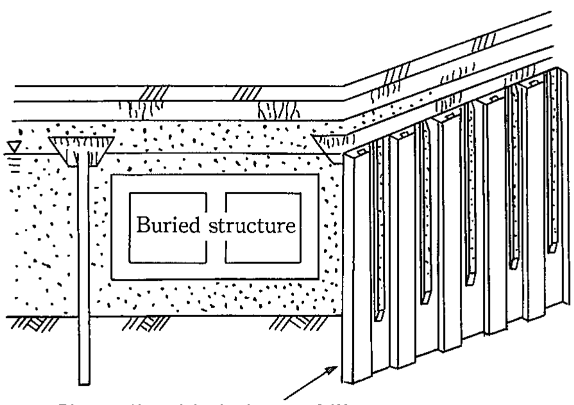


Fig. 2 Liquefaction countermeasure for buried structures using the sheet pile with drain capability

2.2 Shaking Table Tests on the Countermeasures for Buried Structures Using SPDC

The shaking table tests shown in **Table 1** were conducted in order to confirm the effectiveness of SPDC as a countermeasure for buried structures. Three types of model-no-countermeasure, cut-off sheet pile using normal sheet pile, and cut-off sheet pile using SPDC- were applied to these tests, with three different dimensions of liquefiable loose layer thickness prepared for each of the models.

2.2.1 Test Procedure

Figure 3 shows the set up of the model tests and instrumentation for measuring the response in a liquefiable sand layer of 700mm thickness. All the models were contained in a rigid container of dimensions 2000mm long, 1000mm high and 1000mm wide. Dividing the width of the container into half (500mm wide), a model was set up in each half of a single container, and tests were conducted for two models at a time. The model ground consists of two sand layers as illustrated in **Fig.3**. The upper one is a liquefiable sand layer. The liquefiable layer was placed by pouring dry sand from a certain height into water in the container. The properties of the sand used and the relative densities of the upper liquefiable layers in each test are given in **Table 1.** The average unit weight of the upper layer in these tests was 1.86gf/cm^3 (18kN/m^3). The buried structure model was a rigid box of 500mm long, 250mm high and

Table 1 Conditions for shaking table tests on the liquefaction countermeasure for the buried structure

Test No.	Type of countermeasure	Sheet pile model	Conditions of sand layer			Vibration	Sand properties
			H1(cm)	Dr(%)	H2(cm)		
1 2 3	No-countermeasure		55 70 90	47.6 41.5 41.5	35 20 0	3Hz Sinusoidal 30 cycles 150gal 200gal 300gal	G_s=2.678 D_{50}=0.38 mm U_c=3.21
4 5 6	Cut-off sheet pile using normal sheet pile	1.2mm steel plate	55 70 90	47.8 52.7 57.9	35 20 0		
7 8 9	Cut-off sheet pile using SPDC	1.2mm steel plates with vertical drain	55 70 90	57.3 55.6 57.6	35 20 0		

H1 : Thickness of loose layer Dr : Relative density of loose layer H2 : Thicknees of dense layer

400mm wide. Its apparent unit weight was 0.88gf/cm^3 (8.6kN/m^3). Sheet pile models were steel plates with dimensions of 900mm in height, 410mm in width and 1.2mm in thickness. Those with drain capability were equipped with vertical drains on the inner surface of the steel plate, where inner means the side enclosed by the sheet piles. The flexural rigidity of the vertical drains was negligible. Sheet pile models were fixed at the bottom of the container. Each model was shaken by 30 cycles of horizontal sinusoidal motion at frequency 3 Hz at the acceleration levels of 150, 200 and 300gal. One level of input acceleration was applied during one test run and this was repeated for each level of acceleration from 150gal to 300gal.

2.2.2 Results and Discussions

(1) Relationship between input acceleration and induced uplift of the buried structure

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

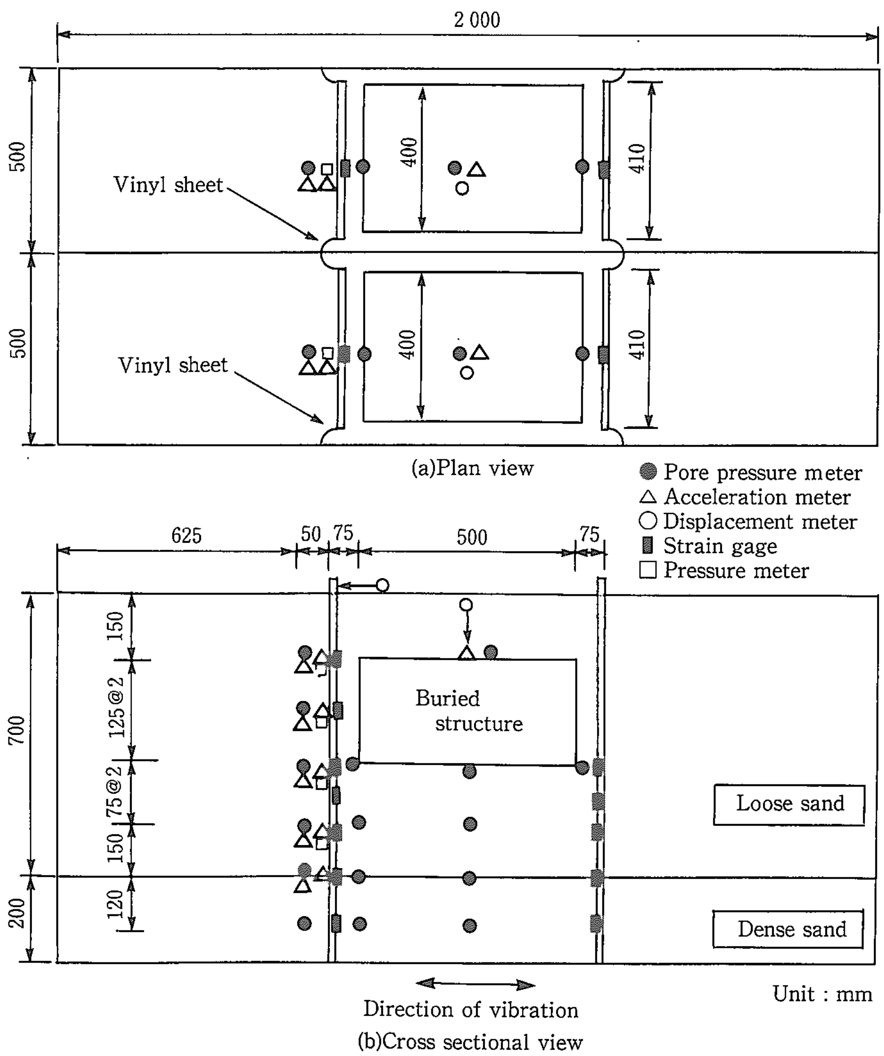


Fig. 3 Model of shaking table tests on the liquefaction countermeasure for the buried structure

(2) Mechanism of the cut-off sheet pile method with SPDC

It is reported in a 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 the case of SPDC, reducing pore water pressure around the structure[5]. Herein, the relationship between the uplift displacement of the structure and bending deformation of the sheet pile is considered.

Figure 5 shows time histories of sheet pile strain and excess pore water pressure observed at locations of 50mm inside the sheet pile during 150gal shaking in tests No.6, 9. It can be seen that the drain capability of SPDC reduced the excess pore water pressure, particularly with regard to the intermediate component which is defined in **Fig.6**, and then 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.5**. That component of sheet pile strain indicates the deformation of the sheet pile illustrated in **Fig.7**, which contributes to the uplift displacement of the buried structure[6]. Therefore, it is considered that the cut-off sheet pile method using SPDC effectively prevents the uplift displacement of the buried structure.

It is considered that the induced uplift displacement of the buried structure enclosed with in sheet pile walls can be approximately estimated by means of dividing the volume reduction Δv due to sheet pile deformation illustrated in **Fig.6** by the base area of the structure[7]. **Figure** 8 shows a comparison between the uplift displacement observed during each test run in tests No.5-9 and those calculated. The sheet pile strain observed in each test was used in order to evaluate Δv. Uplift displacement values of the structure are reasonably well evaluated by this method. It is, however, found that the uplift displacement values calculated for SPDC tend to overestimate the actual values and those calculated for the normal sheet pile are just the reverse. These results seem to indicate that, in case of the cut-off sheet pile without drain capability, the flow of liquefied soil located between the sheet pile and the structure into the area below the structure may also induce uplift displacement in addition to the bending deformation of the sheet pile. On the other hand, it is considered that SPDC was able to prevent that type of flow because soil strength is retained by the drain capability and a part of Δv is carried away as drained water. This is another reason why SPDC is more effective than the normal sheet pile without drain capability.

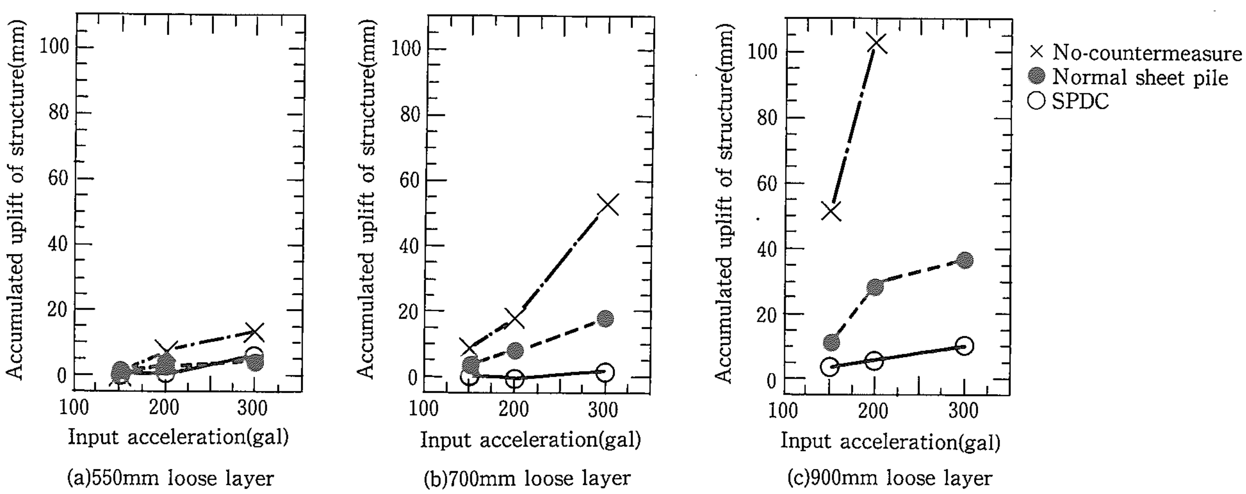


Fig. 4 Relationship between input acceleration and accumulated uplift of the buried structure

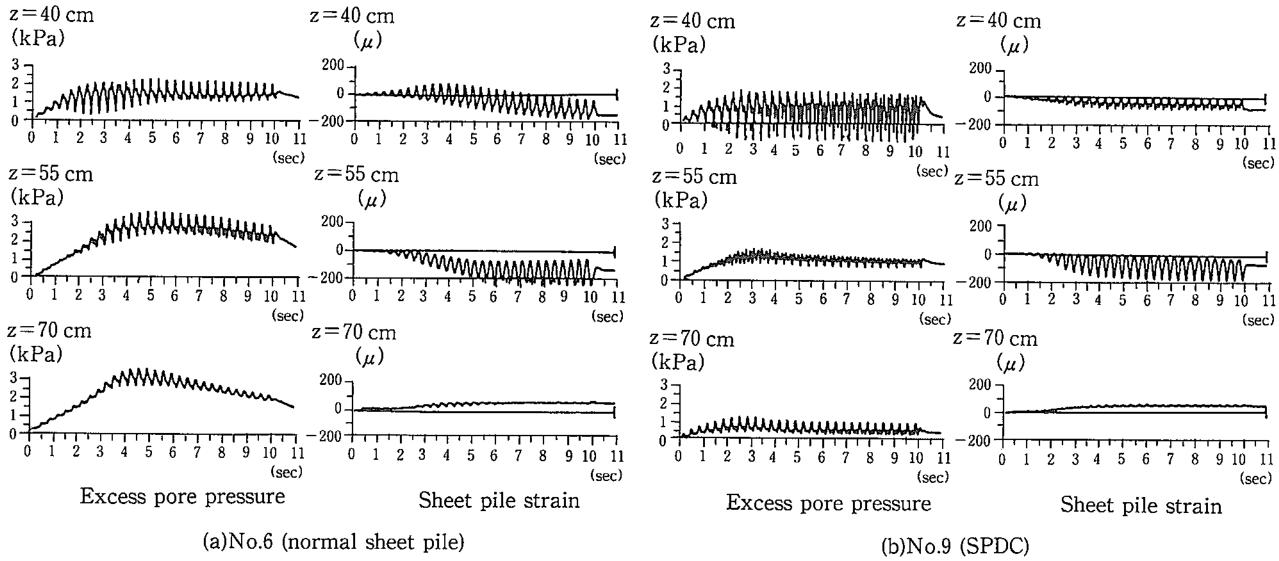


Fig. 5 Observed time histories on excess pore water pressure and sheet pile strain

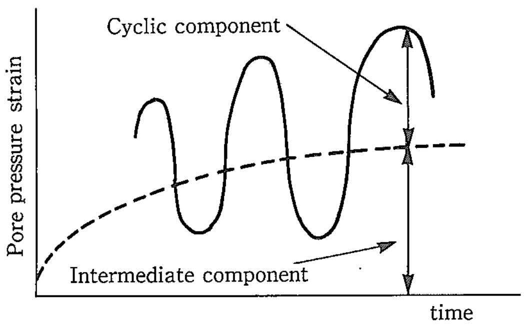


Fig. 6 Cyclic and intermediate component of pore pressure and strain

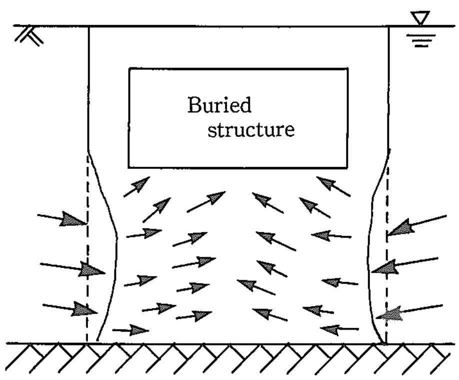


Fig. 7 Illustration on uplift of buried structure

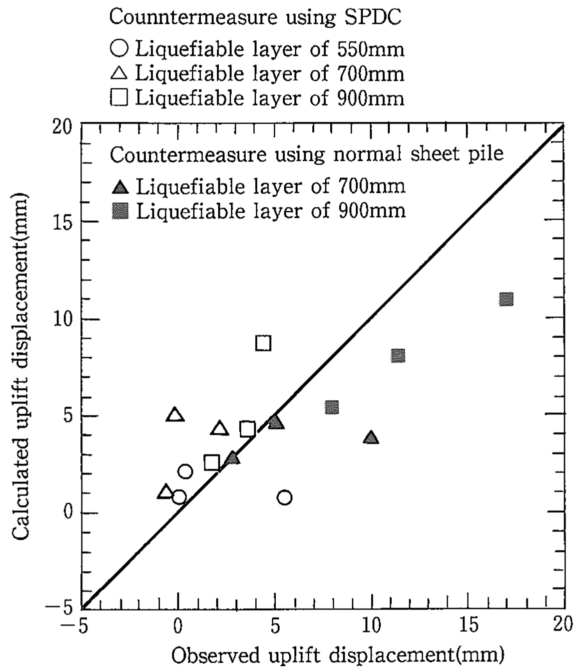


Fig. 8 Comparison between observed and calculated uplift displacement of the buried structure

3. Application of SPDC to Countermeasures for Embankments

3.1 Outline of Countermeasures for Embankments Using SPDC

Soil embankments such as road embankments, river dikes and railway embankments on a loose saturated sand layer are often damaged due to settlement and slope failure because of liquefaction of foundations. This results from spreading out of the liquefied soil underlying the embankment due to the embankment weight.

One of the liquefaction countermeasures for embankments is the method illustrated in **Fig.9**[8]. In this method steel sheet piles are driven into the ground at the toes of the embankment slopes and the top of the sheet piles are connected by steel tie rods. Steel tie rods are installed in order to protect the sheet pile walls from bending deformation induced by the lateral flow of liquefied soil. It is, however, difficult to apply this method to river dikes because of possibility of water leakage along the tie rods. It is also difficult to install tie rods in existing embankments. In such cases, the cut-off sheet pile method using SPDC without tie rods shown in **Fig.10** is proposed herein as the countermeasure for embankments.

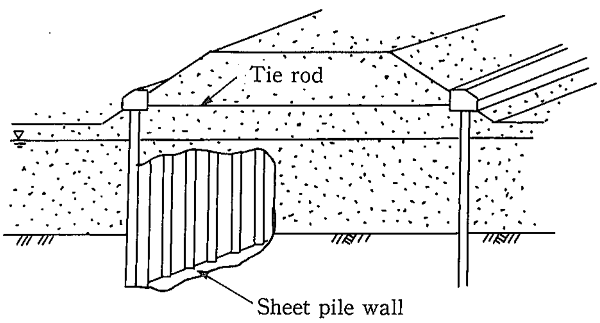


Fig. 9 Liquefaction countermeasure for embankments using sheet pile walls and tie rods

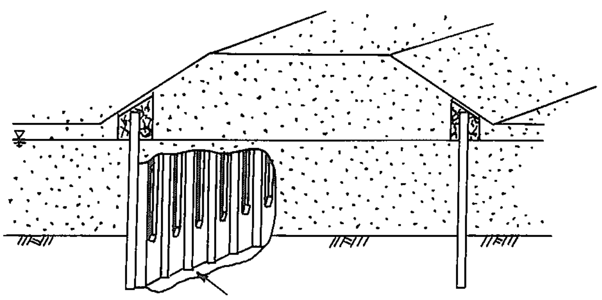


Fig. 10 Liquefaction countermeasure for embankments using sheet pile with drain capability

3.2 Shaking Table Tests on the Countermeasures for Embankments Using SPDC

Shaking table tests shown in Table 2 were performed to investigate applicability of SPDC to the liquefaction countermeasures for embankments. In these tests, four types of test model were prepared: no-countermeasure, the cut-off sheet pile method without tie rods using normal sheet piles, the cut-off sheet pile method without tie rods using SPDC and the cut-off sheet pile method with tie rods using normal sheet piles.

3.2.1 Test Procedure

Figure 11 shows the set up for the model tests and the locations of gages. The conditions for the tests can be found in **Table 2.** The 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, and its unit weight was approximately 1.6gf/cm^3 (15.7kN/m^3). The vinyl sheet underlaid the embankment to cut off permeation of pore water from the saturated liquefiable layer. Sheet pile models were steel plates with dimensions of 780mm in height, 410mm in width and 3.2mm in thickness. Those with drain capability were equipped with vertical drain pipes (15mm dia.) on both the surfaces of the steel plate, which did not contribute to the flexural rigidity of the steel plate. The drain pipes on the inside of the cut-off enclosure were connected to vinyl piles of 5mm in diameter in order to carry drained water away from the embankment, so that the drain capability inside the enclosure was less than that outside. Tie rods used in test No. 4 were steel rods with a diameter of 3mm and were not prestressed. Each model was excited by 30 cycles of horizontal sinusoidal motion at a rate of 3Hz. The amplitude of input acceleration was about 200gal.

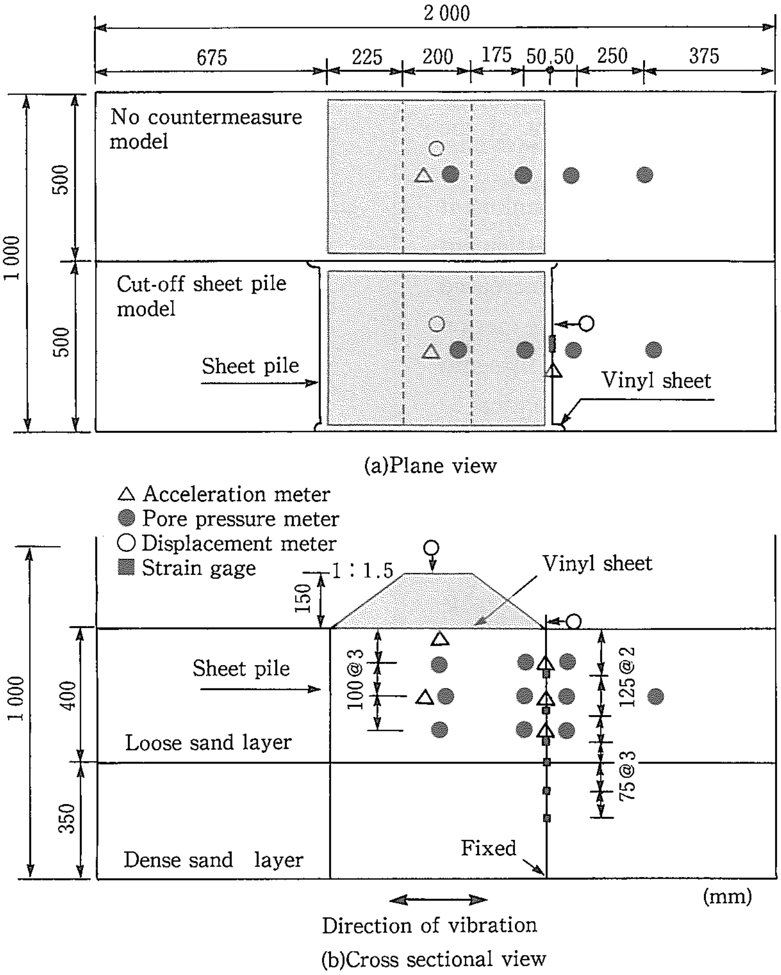


Fig. 11 Model of shaking table tests on liquefaction countermeasures for embankments

Table 2 Conditions for shaking table tests on the liquefaction countermeasure for embankments

Test No.	Type of countermeasure	Sheet pile model	Conditions of sand layer			Vibration	Sand properties
			H1(cm)	Dr(%)	H2(cm)		
1	No-countermeasure		40	49.3	35	3Hz Sinusoidal 30 cycles 150gal	Gs=2.678 D_{50}=0.38 mm Uc=3.21
2	Normal sheet pile without tie rods	3.2mm steel plate	40	66.3	35		
3	SPDC without tie rods	3.2mm steel plate with vertical drain	40	52.7	35 35		
4	Normal sheet pile with tie rods	3.2mm steel plate	40	53.6	35		

H1 : Thickness of loose layer Dr : Relative density of loose layer H2 : Thicknees of dense layer

3.2.2 Results and Discussion

(1) Observed time histories for excess pore water pressure

Figure 12 shows the time histories for excess pore water pressure observed during tests No.1-4. This includes those observed at a depth of 200mm below the center of the embankment and at a depth of 200mm, 50mm outside the sheet pile. The vertical axis shows the excess pore water pressure ratio Ru= $\Delta u/\sigma_{vo}'$. It is observed that the sand layer outside of enclosure was liquefied in 2-3 sec except for No.3. In No.3, for the SPDC model, the excess pore water pressure ratio R_u did not reach 1.0, as pore water pressure was reduced by the drain capability. The sand layer inside the enclosure was also liquefied in 2-3 sec due to insufficiency of overburden pressure from the embankment. Even with SPDC (No.3), the inside soil was liquefied in 5-6 sec since the drain capability inside the enclosure was less than that outside.

(2) Observed time histories for settlement of the embankment

The time histories for settlement of the embankment are shown in **Fig.13**. It can be seen that the settlement of the embankment in tests No.1, 2 and 4 increased substantially after the fifth cycle of the table motion and that in No.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.12**. This indicates that the drain capability of SPDC was effective in preventing the settlement of the embankment. It is, however, recognized that, after 22 cycles of table motion, the induced settlement in No.3 (SPDC) was greater than that in No.4 (tie rods). This indicates that restraint of the sheet pile displacement by tie rods held its effectiveness even with liquefaction of the sand layer underlying the embankment.

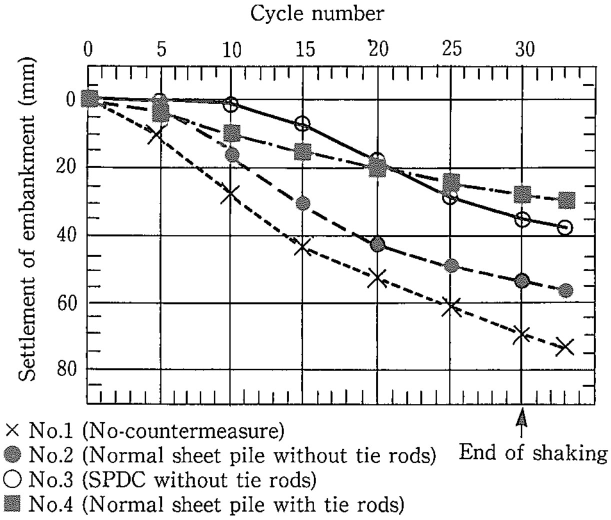


Fig. 13 Observed time histories on the settlement of the embankment

(3) Residual deformation of embankment

Figure 14 illustrates the residual deformation of the embankments after each test. It seems that the embankments sank into the liquefied layer, largely retaining their shape, and without sliding failure of the slope. This is due to liquefaction of the whole area under the embankment. It can be seen in **Fig. 14(a)** that settlement of the embankment without reinforcement was very prominent and soil surrounding the embankment was elevated by lateral flow of

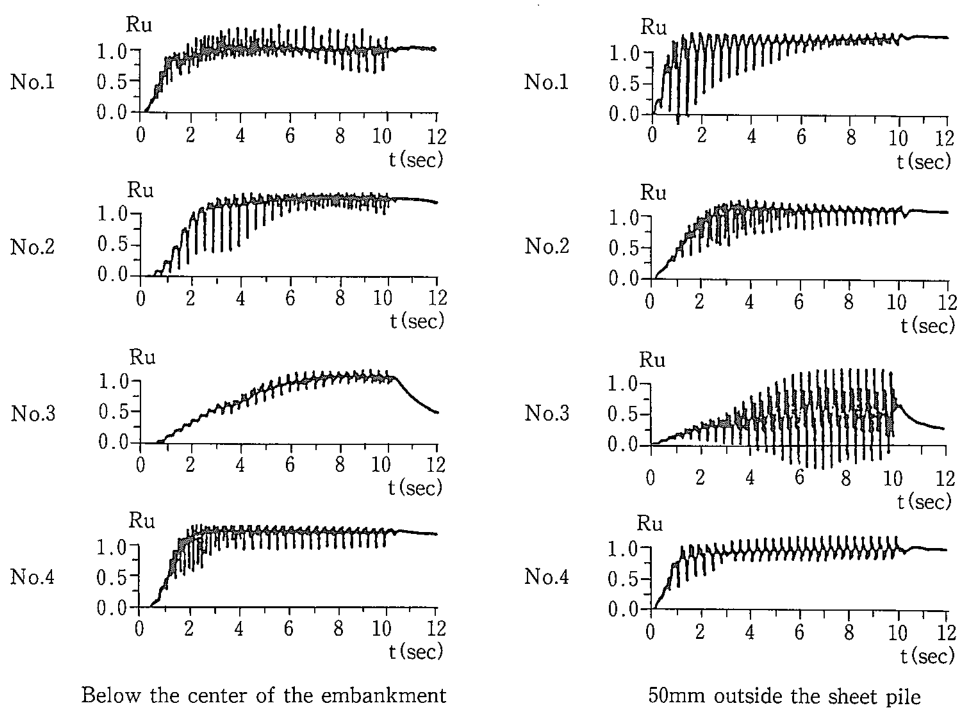
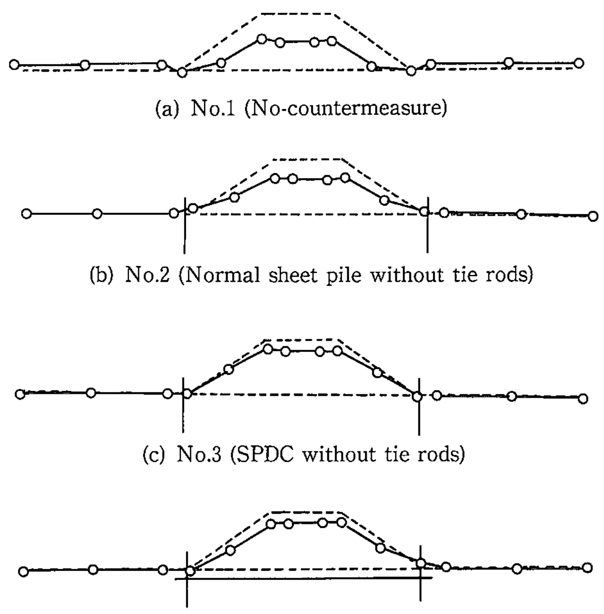


Fig. 12 Observed time histories on excess pore water pressure



(a) No.1 (No-countermeasure)

(b) No.2 (Normal sheet pile without tie rods)

(c) No.3 (SPDC without tie rods)

(d) No.4 (Normal sheet pile with tie rods)

Fig. 14 Residual deformation of the embankment

liquefied soil underlying the embankment. In **Fig. 14(b), (c)** and **(d)**, the elevation of surrounding soil is not seen due to the lateral flow of liquefied soil being cut off by the sheet pile walls, and the settlement of embankment was reduced in comparison with that in test No.1 (no-countermeasure). The remedial effects of the cut-off sheet pile method with drain capability and with tie rods are particularly remarkable as shown in **Fig.14(c)** and **(d)**.

(4) Residual deformation of sheet pile

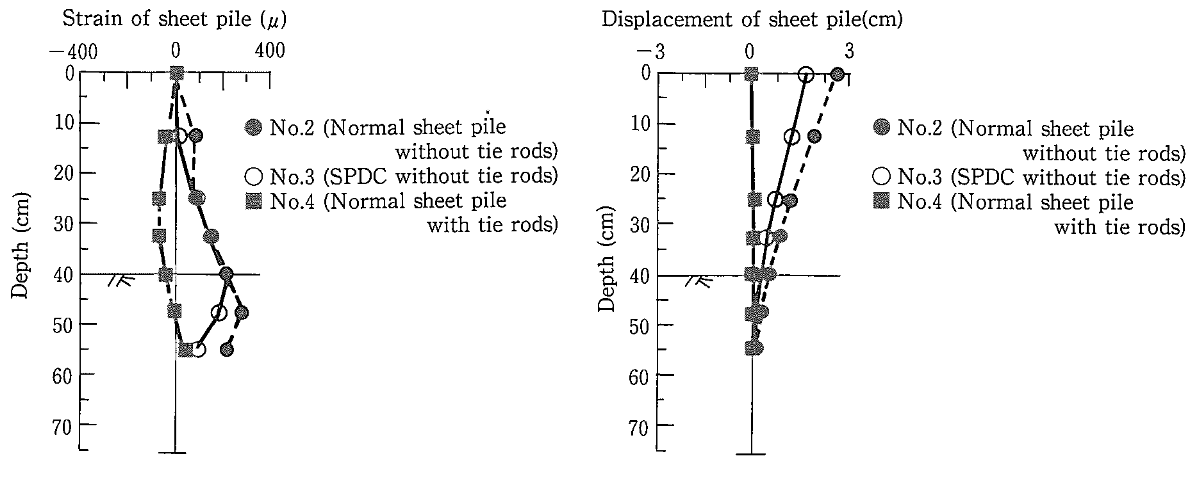
The vertical distributions of residual bending strain and deformation of the sheet pile are shown in **Fig.15(a)** and **(b)**. Residual deformation in **Fig.15(b)** was calculated from residual strain shown in **Fig. 15(a)**. The sheet pile deformation for test No.3 was less than that for test No.2. This is due to soil strength around the sheet pile walls being retaind by the drain capability of SPDC. In fact, the sheet pile strain was never observed while the preventive effect against liquefaction was substantially effective during the first 5 seconds. It is also found that restraint by tie rods sufficiently prevented the bending deformation of sheet pile even after soil liquefaction.

It is concluded that remedial effects result from prevention of lateral flow of liquefied soil by the flexural rigidity of the sheet pile in the case of the normal sheet pile without tie rods, by the flexural rigidity of the sheet pile and the soil strength around it in the case of SPDC without tie rods and the flexural rigidity of the sheet pile and restraint of sheet pile deformation in the case of normal sheet pile with tie rods.

4. Conclusion

As one of the countermeasures for liquefaction, a new method using steel sheet piles with drain capability has been developed. In this paper, applicability of such special sheet piles to liquefaction countermeasures for buried structures and embankments was investigated through model tests using a shaking table. The main results were as follows:

(1) Enclosing a buried structure with the steel sheet piles equipped with drain capability sufficiently prevented its uplift displacement even for the case with a thick liquefiable layer in which significant



(a) Residual strain of sheet pile

(b) Residual displacement of sheet pile

Fig. 15 Vertical distributions on residing bending strain and deformation of the sheet pile uplift was observed with normal sheet piles.

(2) Uplift displacement of the buried structure enclosed with sheet pile walls was mainly induced by the bending deformation of the sheet pile walls and the flow 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 these phenomena 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) Enclosing an embankment with the sheet piles equipped with drain capability was effective in protecting it from settlement due to liquefaction. In this method, the soil underlying the embankment is prevented from spreading out by the sheet pile walls and the soil strength around it .

(4) One of the reliable countermeasures for settlement of an embankment due to liquefaction was to enclose it with sheet pile walls and to connect their tops with tie rods. The restraint of sheet pile deformation by tie rods prevented the soil underlying the embankment from undergoing lateral flow and retained its effectiveness even with liquefaction of sand layer underlying the embankment.

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References

1) Japan Road Association: Specifications for Highway Bridges Part V:Seismic Design, 1990
2) Japan Road Association: Design Manual for Common Utility Ducts, 1986
3) N. Suematsu, Y. Yoshimi and Y. Sasaki: Tsuchi-to-Kiso, **Vol.30** (1982), No.4, pp.71-79
4) H. Kita, T. Iida, M. Nishitani and S. Noda: Experimental study on countermeasures for liquefaction by steel piles with drain, Proc. 10th WCEE, **Vol. 2** (1992), pp.1701-1706
5) H. Kita and M. Nishitani: Proc. 48th annual conference of JSCE, **Vol. 3** (1993), pp.206-207
6) H. Tanaka, H. Kita, T. Iida and Y. Saimura: Countermeasure against liquefaction for buried structures using sheet pile with drain capability, Proceedings of First International Conference on Earthquake Geotechnical Engineering, **Vol. 1** (1995), pp.999-1004
7) Y. Yoshimi, K. Tamaoki, N. Mori and T. Kondo: Stabilization of liquefiable sand deposits using cut-off walls, Proceedings of Symposium on Remediation for Liquefaction (1991), pp.263-268
8) O. Matsuo, Y. Koga, J.Koseki and S. Washida: Study on cut-off sheet pile method as a countermeasure against liquefaction of embankment foundation, Proc. 4th US.-Japan Workshop on Soil Liquefaction (1994), pp.203-222