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Experimental study on countermeasures for liquefaction by steel piles with drain

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ABSTRACT: A new countermeasure using steel piles with drain is developed against liquefaction. The piles are composed of pipe piles or sheet piles and steel channels. The channel has holes with mesh to drain pore water in sand layer during earthquakes.

The purposes of this study are to confirm the drain effect of channel in practical use and to clarify lateral resistance of pile under existence of excess pore water pressure and applicabilities to structures.

As the results of shaking table tests, followings are obtained; (1)The steel channel with holes is sufficient to drain pore water. (2)The relationship between modulus ratio of horizontal subgrade reaction and excess pore water pressure ratio is obtained. (3)The piles are useful as countermeasures for liquefaction to prevent the damages of structures effectively.

1 INTRODUCTION

Due to liquefaction of sand layers during earthquakes, the damages of sloped substratum, buried structures, embankments and quay walls appear in the forms of flow sliding, lifting, sinking, etc..

Then, in order to avoid such damages, the steel piles with drain shown in Figure 1 are developed as one of new countermeasures against liquefaction (S.Noda et al. (1990)).

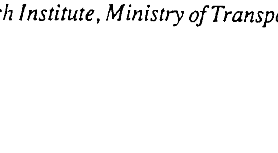


Fig. 1 Examples of Steel Pile with Drain.

As the drain effect, the pile with drain is able to reduce the excess pore water pressure (thereafter referred to as pore pressure) and expect the strength of sand around the pile. Therefore, the lateral resistance of the pile can be expected.

In this paper, authors show the results obtained by the shaking table tests shown in Table 1, in order to get the data for design method of the pile and to confirmthe effects to prevent the damages of structures.

The first shaking table test shown in Table 1 is the drain capacity test of steel piles with drain in practical use, the second is the lateral loading test on model piles, and the last is the damage test of embankment and quaywall.

Table 1 Objects and conditions of shaking table tests

Objects	Drain Conditions	Sand Conditions	Ap*1 (%)	Vibration Conditions(3Hz)	Sand Properties
1.Drain Effect	Drain Channel	Loose{40}*2	5.3	N*3=30	
	Usual Channel	Loose{46}	—	89~165Gal	Gs=2.68
2.Lateral Resistance	Drain Pile	Loose{55}	5.6	N=2,4,6,8,10	D_{50}=0.38mm
	Usual Pile		—	87~155Gal	Uc=3.21
3.Application					
Embankment	Drain Pile	Loose{32}	5.6	N=10,30	
	Usual Pile		—	148~174Gal	
Quay Wall	Drain Pile	Loose{33}	5.6	N=10,30	Gs=2.65
	Without Pile	Back Fill{85}	—	60~175Gal	D_{50}=0.18mm
	Without Pile	Front Ground{85}	—		Uc=1.8

*1. Ap: Area percentage of area of holes to area of the drain surface.
*2. Parenthesized values are relative density of sand. *3. N: Numbers of wave.

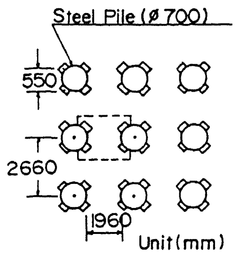


Fig.2 Arrangement of Piles

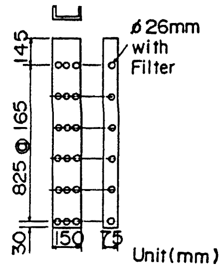
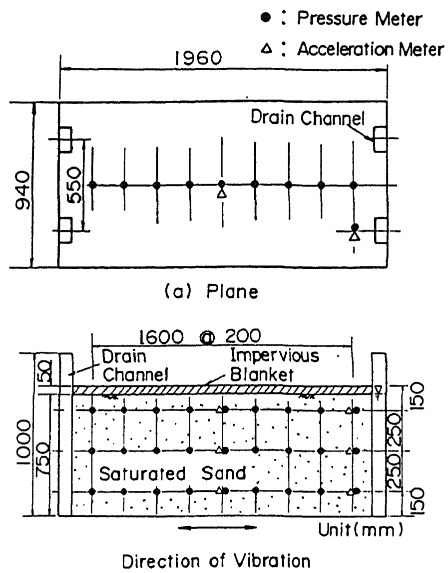


Fig.3 Drain Channel



(a) Plane

(b) Cross

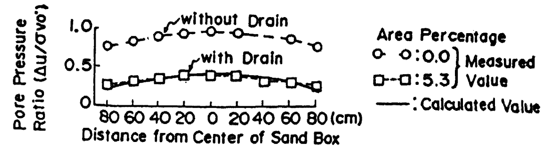
Fig.4 Shaking Table Test on Drain of Channel

2 DRAIN EFFECT OF THE PILE WITH DRAIN

In the past paper, it is confirmed experimentally that the necessary area of holes for drain of pore water is about 5% of surface area of model pile with the diameter of 89mm.

In case of estimating the pore pressure in sand layer around the pile by consolidation equation, it can be also regarded that the coefficient of permeability and the volume compressibility of sand are constant in the range from 0.0 to 0.6 of pore pressure ratio (S.Noda et al. (1990)).

In the following tests, the results mentioned above are introduced to estimate the drain effect of steel channel used as drain of prototype.



(a) Horizontal Distributions of Pore Pressure Ratio (at Depth z=65cm)

(b) Vertical Distributions of Pore Pressure

Fig.5 Horizontal and Vertical Distributions of Pore Pressure (125Gal, 3Hz)

2.1 Outline of test

The plane configuration of pile foundation shown in Figure 2 is assumed to be of practical use. The test is performed on the portion surrounded by broken line.

Figure 3 shows the steel channel for the test and Figure 4 shows the test configuration respectively.

The channel(150x75mm) with holes(ϕ 26mm) used as drain shown in Figure 3 has equivalent diameter of 100mm (assumed to be circular pipe) by setting on side wall of sand box(see Figure 4(a)).

Each side wall of the sand box is corresponding to the surface of two piles surrounded by broken line in Figure 2.

2.2 Results

Figure 5(a) shows the horizontal distributions of pore pressure ratio at depth 65cm from ground surface. Figure 5(b) shows the vertical distributions of pore pressure in sand layer.

The calculated values by consolidation equation are also plotted.

From these figures, it is recognized that the pore pressure ratio of sand layer with drain channel is lower than that without drain, and in case of the drain channel, the calculated values agree with the measured values except at the depth of 45cm.

As the draining of pore water through the channel is caused by pore pressure increasing with the increase of overburden pressure, it should be considered that the drain effect in the test would be similarly expected in the actual sand layer.

3 LATERAL RESISTANCE OF THE PILE

In design of the pile, the relationship be-

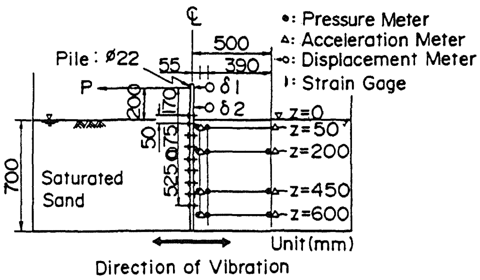


Fig.6 Shaking Table Test on Horizontal Resistance of Pile (3Hz)

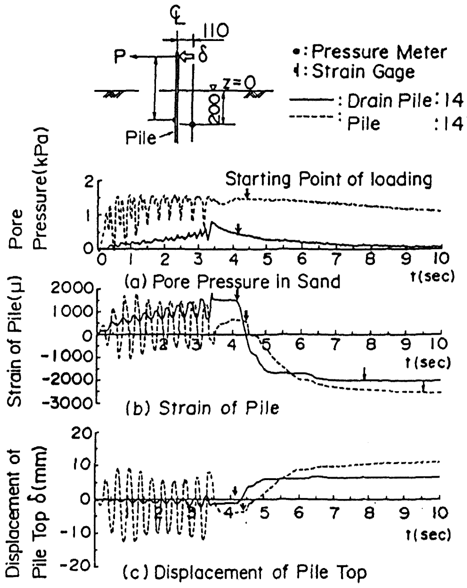


Fig.7 Time Histories of Observed Records (3Hz, 10 Waves)

tween the ratio of vertical subgrade reaction and the pore pressure ratio is already reported(S.Noda et al. (1990)). But the lateral resistance of pile should be estimated as the product of modulus of horizontal subgrade reaction and lateral displacement of pile.

3.1 Outline of test

In sand box shown in Figure 6, a model pile made of polycarbonate is fixed at the center of the bottom of the box. Diameter of pile is 22mm, and dimensions of sand box are L2mxH1mxB1m.

Just after vibration, the weight of 4.9N is loaded horizontally at the top of the pile or the drain pile under existence of pore pressure.

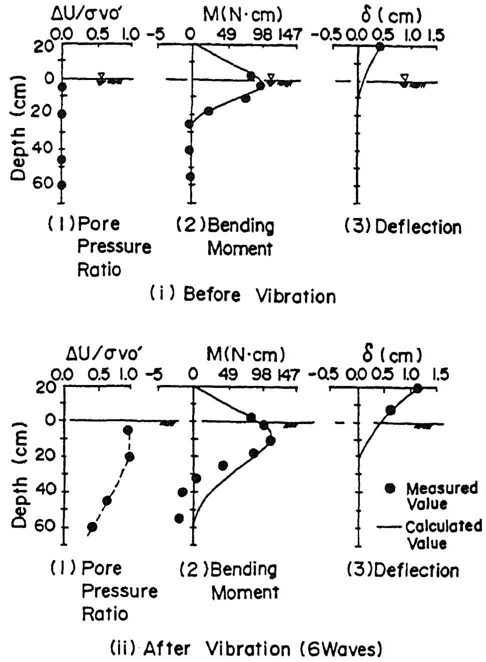


Fig.8 Pore Pressure Distributions, Moment Distributions, Deflections of Pile in Sand Layers

3.2 Results

3.2.1 Time histories of pore pressure, strain of pile and displacement of pile top

The time histories of pore pressure in sand, strain of pile and displacement of pile top are shown in Figure 7.

The arrows shown in Figure 7 indicate the start point of lateral loading. The broken lines are results of pile, and normal lines are those of drain pile.

From these figures, the drain pile restricts the increase of pore pressure and displacement of pile.

These data show that the drain effect is to prevent the decrease of strength of sand around the pile.

3.2.2 Behaviors of pile under lateral loading.

Examples of the behaviors of pile and drain pile under lateral loading are shown in Figure 8 and 9 with vertical distributions of pore pressure respectively.

Black circles are measured values and normal lines are calculated values which are fitted with measured strain of pile by linear elastic subgrade reaction method .

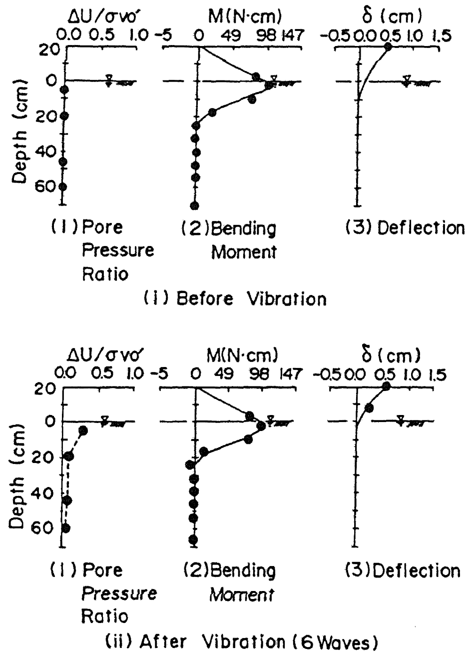


Fig.9 Pore Pressure Distributions, Moment Distributions, Deflections of Drain Pile In Sand Layer

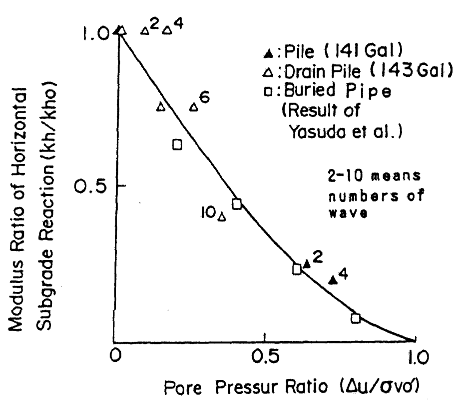


Fig.10 Relationship between Modulus Ratio of Horizontal Subgrade Reaction and Pore Pressure Ratio

These figures show that with the increase of pore pressure, maximum bending moment and displacement of the pile in each test increase and the first point of zero deflection of pile from the ground surface become deeper.

Compared the results of usual pile with those of drain pile, the latter shows less values in bending moment and deflection of pile under the same vibration condition.

3.2.3 Relationship between modulus ratio of horizontal subgrade reaction and pore pressure ratio

Figure 10 shows the relationship between modulus ratio of horizontal subgrade reaction and pore pressure ratio.

Where, modulus ratio of horizontal subgrade reaction is the ratio of the modulus of subgrade reaction under existence of pore pressure to that without pore pressure. And the pore pressure ratio shown in Figure 10 is selected value at the depth of 50mm and the distance of 110mm in front of loading side of pile, considering the pile deflection.

In this figure, white and black triangles are results of drain pile and usual pile respectively. Then, squares are those of lateral buried pipe (S.Yasuda et al. (1989)).

From these results, it is shown that the decrease on modulus ratio of drain pile is less than that of usual pile under the same vibration condition.

Both results of pile and buried lateral pipe under existence of pore pressure show the same relation between the modulus ratio of horizontal subgrade reaction and the pore pressure ratio.

4 APPLICATION TO STRUCTURES

4.1 Embankment

Damages of embankment during earthquakes are observed in the form of flow sliding and sinking due to liquefaction of sand deposit.

In order to confirm the efficiency of drain pile, shaking table tests using drain piles and usual piles are carried out.

4.1.1 Outline of test

Model piles are installed at the top of slope of embankment with several pitch as shown in Figure 11. The pile made of polycarbonate is 89mm in diameter.

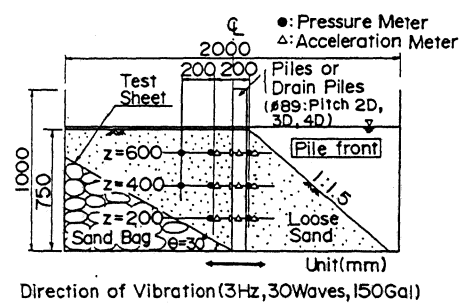


Fig.11 Shaking Table Test for Preventing Deformation of Embankment By Piles

4.1.2 Results

The relationship between flow slide displacement of embankment and pore pressure ratio in front of pile is shown in Figure 12.

From this Figure, it is noted that the flow slide of embankment would not occur under conditions that the drain piles are set with an adequate pitch in loose sand layer and the pore pressure ratio between piles is under the value of 0.5.

4.2 Concrete caisson type quay wall

Compaction works are often applied as countermeasure for deformation of quay wall by liquefaction in Japan. But it is difficult to adopt the compaction works below caisson installed on sand layer.

Considering overburden pressure, liquefaction is hard to occur under caisson, but sand layer in front of caisson is easy to liquefy by earthquakes.

In the tests, three kinds of countermeasures against deformation of quay wall are examined.

4.2.1 Outline of test

Figure 13(a), (b) and (c) show the models of the countermeasures. The first one is the standard type for comparing the others. The second is a countermeasure installing drain piles in sand layer in front of caisson. And the last is another countermeasure in which the compaction works is applied to sand layer in front of caisson. The backfill of these three types are compacted.

The cross section of model caisson is H350 x B400mm. The unit weight of model caisson is the same as prototype concrete caisson. Under the model caisson, the concrete plate with the thickness of 50mm is set in stead of rubble mound.

Model ground is consist of compacted sand layer with the thickness of 300mm at the bottom and the loose sand layer with the thickness of 400mm over that.

Model drain piles with the diameter(D) of 42mm are arranged in single row at the pitch of 5D.

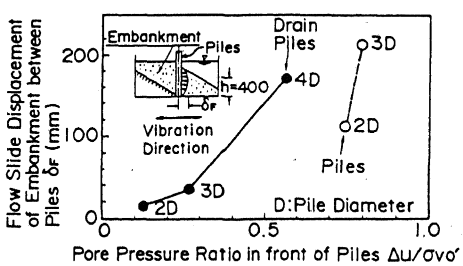


Fig.12 Flow Slide Displacement versus Pore Pressure Ratio

4.2.2 Results

Figure 14 shows the time histories on pore pressure at lower measuring point(z=300mm: see Figure 13) located in front of caisson.

From this figure, the drain pile type and sand compaction type are very effective to restrict the increase of pore pressure under the acceleration of 175Gal.

Next, the relationships between settlement of caisson and acceleration of shaking table is shown in Figure 15.

From these figures, it is confirmed that the settlement of caisson increases with the increase of acceleration. But the settlement in case of drain pile type is the same as that in case of sand compaction type.

It is considered that the effect of restricting deformation by the pile with drain on quay wall depends on the rigidity and the drain effect of the pile.

5 CONCLUSIONS

As one of the countermeasures for liquefaction, the new method using steel piles with drain has been developed.

In order to establish the design method of the piles with drain, the shaking table

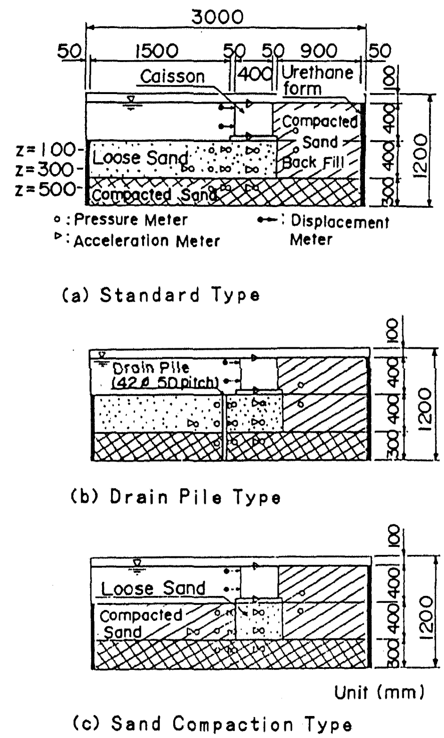


Fig.13 Shaking Table Test of Quay Wall with Countermeasure against Liquefaction

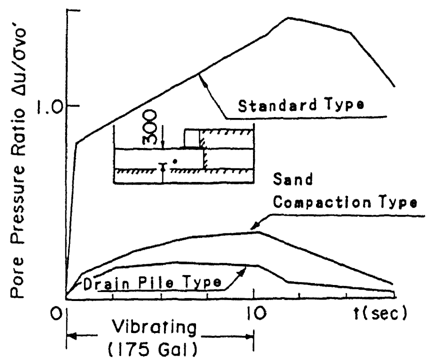


Fig.14 Time Histories of Pore Pressure

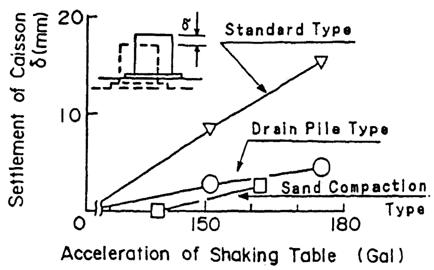


Fig.15 Quay Wall Settlement Versus Acceleration of Shaking Table

tests have been carried out on models. Following results are obtained.

1) The steel channel with holes is sufficient to drain pore water.

2) The pile with drain installed in liquefied sand deposit prevents the increase of bending moment and displacement of pile under lateral loading .

3) The relationship between modulus ratio of horizontal subgrade reaction and pore pressure ratio is obtained.

4) The flow slide of embankment does not occur if the pore pressure ratio between the piles is under the value of 0.5.

5) The piles with drain are effective to avoid the settlement of quay wall.

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