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Pile-soil modeling in liquefied sand layer in aseismic design method

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ABSTRACT: To make the rational aseismic design method of pile-superstructure system in a liquefied sand layer, shaking table tests by using shear bin were carried out. A 2-story structure model supported by four piles was set on the saturated sand layer. The obtained bending moment distributions of the pile during liquefaction are compared with the analytical method which is modeled to a beam on an elastic foundation. Dynamic restoring force characteristics between soil and pile are investigated with the excess porewater pressure of the saturated sand layer.

1 INTRODUCTION

Recently, many buildings are constructed or are going to be constructed at the liquefiable soft ground in Japan. The dynamic behavior of such structures with pile foundation is affected by soil-pile interaction in the liquefied sand layer, because the behavior of the soil deposit changes according to the excess porewater generation.

The dynamic behavior of a pile foundation in the liquefied soil has been investigated experimentally. For example, Tatuoka et al. (1978), Kobayashi et al. (1991) and Mori et al. (1990) conducted shaking table tests of structure-pile-ground model. In the design of piles in liquefiable ground, a method based on the Japan Highway Bridge code is frequently used in the aseismic design of a pile-foundation system. In this method, a pile-foundation system is modeled to a beam on an elastic foundation, in which the coefficient of horizontal subgrade reaction is estimated considering the generation of the excess porewater pressure. As for the dynamic response of a pile-superstructure system in liquefiable ground, the use of analytical methods using a beam-winkler spring model are suggested by Kagawa et al. (1981), Mori et al. (1990) and Nomura et al. (1990). However these analytical methods were hardly compared with experimental studies, hence there remains some uncertainty on modeling the soil-pile interaction in liquefied sand layer.

This paper deals with the dynamic behavior of a soil-pile-superstructure system in the liquefied sand layer. Shaking table tests by using shear bin were carried out to obtain it. Bending moment distributions of the pile and dynamic response of a superstructure during liquefaction are investigated in relation with the excess porewater pressure of the saturated sand layer.

2 TEST APPARATUS AND TEST PLAN

Figure 1 shows longitudinal cross-section of the shear bin (4m in length, 2m in width and 2m in height) put on the shaking table. It is composed of 25-frame steps (80mm in height) separated by placing roller bearings between them so as to move without friction in the horizontal direction.

After setting a pile-superstructure model at the center of the shear bin, a saturated sand layer is mode by water-pluviation method by means of a power-bucket. A sand layer is composed of siliceous sand No.6 (D_{50}: 0.254, D_{10}: 0.16, U_c: 1.81). Figure 2 shows the grain size accumulation curve of the used sand. Relative density of the siliceous sand No.6 layer, Dr, is calculated based on the depth of sand layer, the weight of deposited sand and the water content. It varies between 45 and 90%. The unit weight of saturated sand varies between 18.8 and 19.8 kN/m^3. S-wave velocities in the sand layer, Vs, are calculated by the elastic wave exploration test. They are about 70 m/sec. A 2-story structure model supported by four piles is used in the test, which is a scaled model of a middle size R/C building commonly constructed in Japan considering a similarity rule by Yao(1988). The piles are aluminum square pipes (length: 175 cm, Young's Modulus: $0.725 \times 10^4 kN/cm^2$, Cross-Section Area: 2.84 cm^2, 2nd Moment of Inertia: 2.96 cm^4 and Cross-Section: 2.5 x 5.0

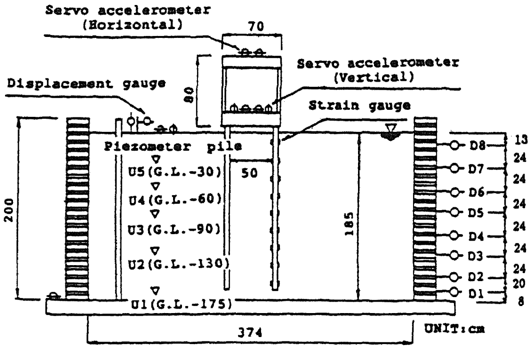


Figure 1. Longitudinal cross-section of shear bin

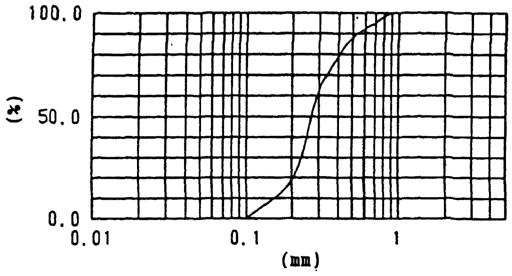


Figure 2. Grain size accumulation curve of the sand

Table 1 Test of plan

TEST No.	Frequency(Hz)	Dr(%)	V_S(m/sec)
TEST-Dr74-2	2	74	69
TEST-Dr83-3	3	83	69
TEST-Dr76-5	5	76	78
TEST-Dr45-7	7	45	70

cm). The weight of the 2-story structure model is 3.2 kN. The measuring instruments in the tests are shown in Figure 1; 6 servo accelerometers on each floor of the structure, 2 servo accelerometers, 2 inductance type displacement gages on the ground, 8 inductance type displacement gages on the side of the shear bin and 5 piezometers were set. In addition, strains gages, earth pressure gages and piezometers are put on a pile connected to a superstructure. Earth pressure gages and piezometers put on a pile fixed on the shear bin. The location of these instruments are shown in Figure 3.

Sinusoidal vibrations are applied in the horizontal direction. The acceleration of the vibrations is increased gradually keeping the frequency constant, which is called sweep up method. Several series of tests were carried out in which the frequency of the external load is different to each other. The same sand deposit is used 4 times in average. It is changed from 1 to 7 Hz. The series of the tests introduced in this paper are shown in Table 1.

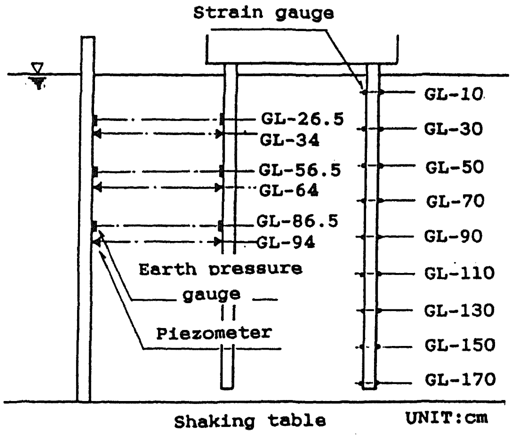


Figure 3. Location of the instruments of the piles

3 TEST RESULT

3.1 Soil layer

Figure 4 shows the vertical distributions of excess porewater pressure ratio, in which the ratio of excess porewater pressure to the initial effective overburden pressure is used in the horizontal axis. The degrees of excess porewater pressure generation are different in each test cases. Excess porewater pressures reach the initial effective overburden pressure, which is in definition of liquefaction level, earlier at the upper layer in TEST-Dr45-7 case, but in TEST-Dr83-3 case excess porewater pressure at the middle layer liquefies earlier.

3.2 Pile-superstructure system

As an example of the test results, Figure 5 shows horizontal displacement, horizontal acceleration, pile bending strains-time histories in TEST-Dr76-5. In Figure 5, displacement gages (D1, D6 and D8), 2 servo accelerometers in the horizontal direction on each floor of the superstructure, 6 strain gages put on a pile at the depth of 10, 90, 130 cm are employed.

The displacement of the soil layer have both residual and cyclic components, which is known because displacements shift to one side as the input acceleration increases. The same tendencies are observed in the other test cases. The deformation of the

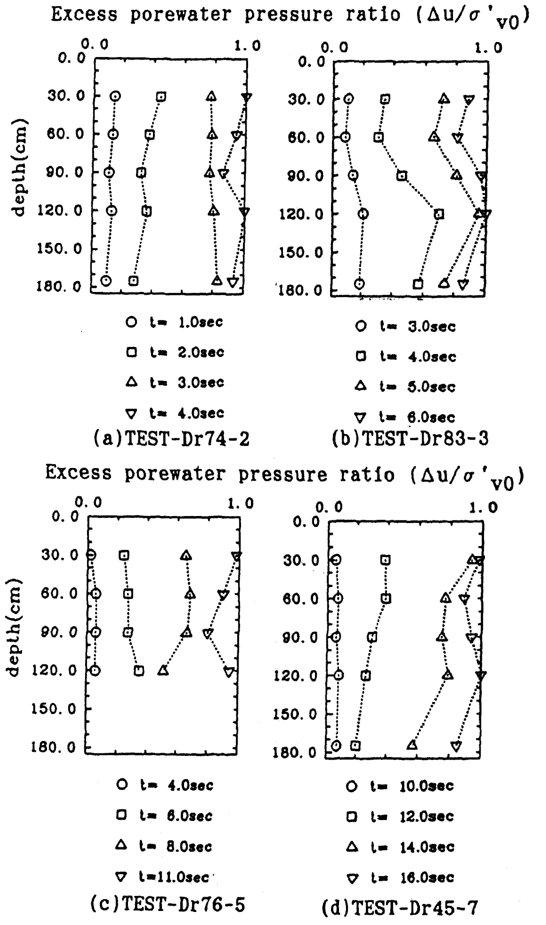


Figure 4. Vertical distributions of excess porewater pressure ratio

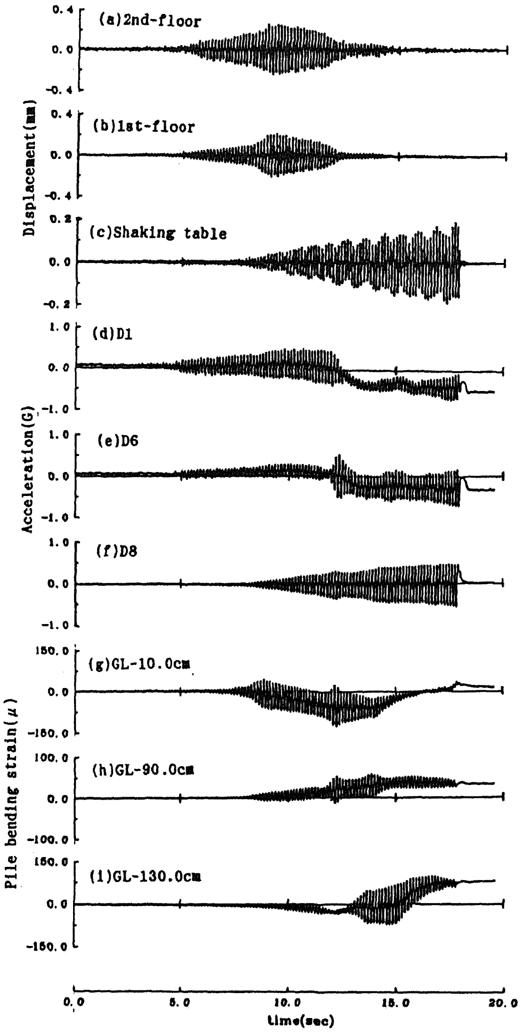


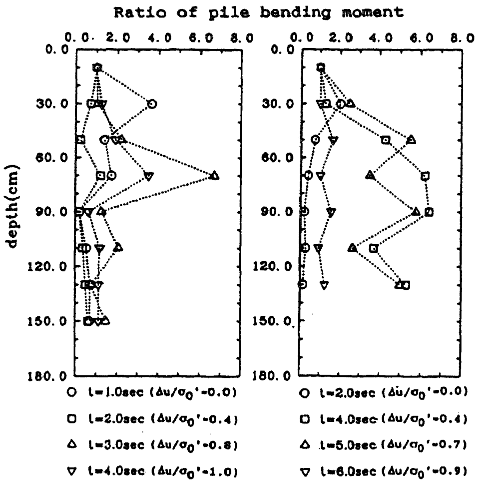
Figure 5. Time histories of horizontal displacements, horizontal accelerations and pile bending strains (TEST-Dr45-7)

pile is similar to that of the soil shown in Figure 5. The acceleration of the superstructure is different from that of soil or pile. To investigate the dynamic behavior of the soil-pile-superstructure system as for only cyclic component, all of the measured data is estimated through the band pass filter of 0.5-20.0 Hz in this paper.

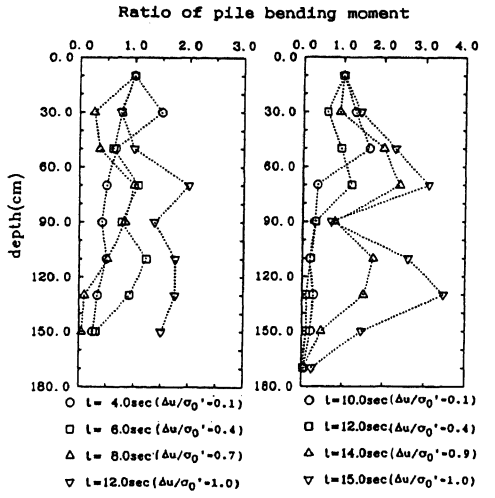
In the bending strain of the pile-time histories shown in Figure 4, the maximum bending moments are found to occur at the different time. Figure 6 shows the bending moment distributions of the pile in TEST-Dr74-2, TEST-Dr83-3, TEST-Dr76-5 and TEST-Dr45-7, in which the ratio of the bending moments at each depth to that at GL-10.0 cm is employed in the horizontal axis. The maximum bending moment occurs at GL-10.0 or -30.0 cm, when the excess porewater ratio were 0.0-0.1. According to the excess porewater generation, large bending moments were observed in the middle of the pile shaft.

4 DISCUSSION

The obtained bending moments of the pile were compared with an analytical results which were derived by modeling the pile to a beam on an elastic foundation in Figure 7. In this method, the coefficient of horizontal subgrade reaction is calculated considering the excess porewater generation and the horizontal force at the pile head is estimated as the inertial force of the superstructure. The force is computed as the sum of the inertial force at two stories, the product of the mass and measured acceleration. Here the initial coefficient of the horizontal subgrade reaction, k_h, before liquefaction is estimated from the following



(a)TEST-Dr74-2 (b)TEST-Dr83-3



(c)TEST-Dr76-5 (d)TEST-Dr45-7

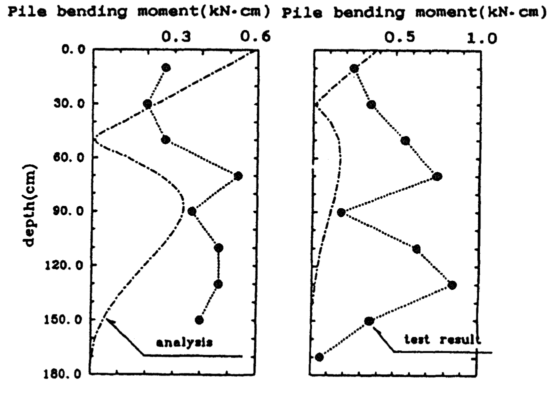
Figure 6. Bending moment distributions of the pile

equations: Equations (1) and (2). The notation K is the horizontal spring constant at the pile head and is calculated from the eigenvalue analysis of the 2 degree of freedom system. In the calculation, the 1st natural frequency of the pile-superstructure system is estimated to be 8.0 Hz in the fourier spectral ratio obtained from S-wave velocity test.

$$K/4 = 4*E*I*\beta^3 \qquad (1)$$

$$\beta = (k_h*B/4*E*I)^{1/4} \qquad (2)$$

The reduced coefficient, α, of horizontal subgrade reaction according to the excess porewater generation is defined by



(a)TEST-Dr76-5 (b)TEST-Dr45-7

Figure 7. Comparison of pile bending moment

$$k_h' = \alpha * k_h \qquad (3)$$

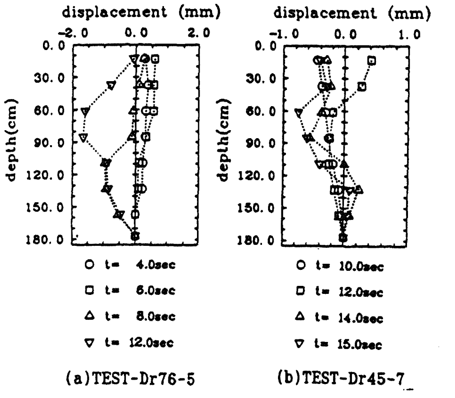
$$\alpha = (\sigma'/\sigma_0')^{1/2} \qquad (4)$$

where σ' denotes the effective stress, and σ_0' denotes the initial effective stress.

The instantaneous displacement in soil layer in TEST-Dr76-5 and TEST-Dr45-7 are shown in Figure 8. It can be seen that the analytical results based on elastic foundation differ from the measured results and the maximum bending moments of the pile calculated from the analytical method are underestimated. It is considered that the bending moments of the pile are affected by the large deformation of soil layer caused by excess porewater generation.

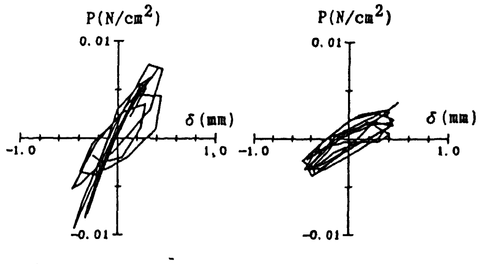
Some analytical methods using a beam-winkler spring model are suggested as the dynamic response analysis of a soil-pile system in a liquefiable soil. Very few studies as for the spring modeling between soil and pile in a liquefied soil have investigated in these analysis procedure. Figure 10 shows the relationship between the horizontal subgrade reaction P and the relative displacement δ. Here P is computed by subtracting the measured earth pressures of the pile at each depth from the excess porewater pressures (U1-U5) at the same depth of the each earth pressure gage. δ is computed by subtracting the displacement at the side of shear bin from the pile displacement at each depth, which is calculated from the horizontal displacement on the 1st floor of the structure and the pile bending moments.

It is clearly observed in Figure 9 that the stiffness becomes low and the hysteresis damping becomes large in accordance with the generation of the excess porewater pressure and shear strain of soil layer. The tendency is similar to that of the dynamic force

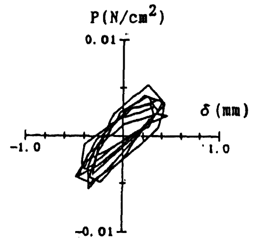


(a)TEST-Dr76-5 (b)TEST-Dr45-7

Figure 8. Vertical distributions of horizontal displacement of shear bin



(a)t=12.0-13.0 sec (b)t=14.0-15.0 sec



(c)t=15.0-16.0 sec

Figure 9. The Relationship between the horizontal subgrade reaction and the relative displacement (GL-56.5 cm)

restoring force characteristics at the pile top.

To obtain the dynamic behavior of a superstructure in a liquefied sand layer, the acceleration amplification ratio is computed by dividing the acceleration amplitude at the base of shear bin from that of the 2nd floor of the structure. Figure 10 shows change of the acceleration amplification ratio versus exciting time relationships. It is observed that the acceleration response of a superstructure in a saturated sand layer changes according to the generation of excess porewater pressure and shear strain. This is a reason why the secant modulus and the damping ratio, which were obtained from the dynamic restoring force characteristics at the pile top, change according to the generation of excess porewater pressure (see Kobayashi et al.(1991)).

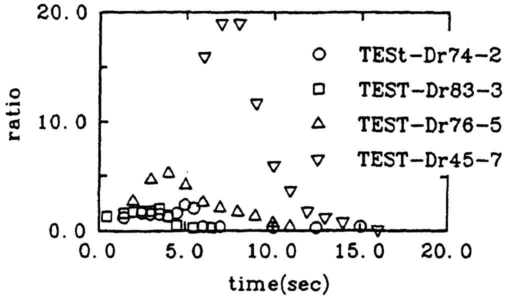


Figure 10. Acceleration amplification ratio-time histories

5 CONCLUSIONS

The behavior of a soil-pile-superstructure system is investigated from the shaking table tests using large scale bin. It is observed that the large bending moments of the pile in a liquefied sand layer are generated in the middle of the soil. The bending moment distribution of the pile changes due to the generation of ground displacement and excess porewater pressure.

It is observed that the relationship between the horizontal subgrade reaction and the relative displacement changes remarkably due to the generation of excess porewater pressure and shear strain. As excess porewater pressure ratio reaches to about 1.0, a large damping effect appears in the hysteresis loop. It is recognized that the natural frequency of a soil-pile-superstructure system changes to the lower frequency from the obtained acceleration amplification ratios of a superstructure. The transient resonance phenomena on the process of liquefaction sometimes produce the maximum acceleration response. It is important in the aseismic design in a liquefied sand layer to make clear the dynamic response of a superstructure.

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