EFFECTS OF DYNAMIC SOIL-STRUCTURE INTERACTION ON PILE STRESS IN LARGE SHAKING TABLE TESTS

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Abstract: Large shaking table tests are conducted to investigate the effects of dynamic soil-pile-structure interaction on pile stresses. A 2x2 pile group founded in either dry or liquefiable sand deposit is shaken with or without a superstructure, whose natural period is either less or greater than that of the ground. The test results show that, if the natural period of the superstructure is less than that of the ground, the kinematic and inertial forces tend to be in phase, increasing the stress in the pile. If the natural period of the superstructure is greater than that of the ground, they tend to be out of phase, restraining the pile stress from increasing. Pseudo-static analysis is conducted to estimate pile stresses in the tests. It is assumed that the pile stress is either the sum of the two stresses caused by the inertial and kinematic effects or the square root of the sum of the squares of the two, depending on the relationship between natural periods of the superstructure and ground. The estimated pile stresses are in good agreement with the observed ones regardless of the occurrence of soil liquefaction.

1. INTRODUCTION

Field investigation and subsequent analyses after recent earthquakes confirmed that not only the inertial effects of superstructures but also the kinematic effects arising from the ground movement had significant impact on the damage to pile foundations, particularly in the areas where soil liquefaction and/or lateral ground spreading occurred (BTL Committee 1998). Little is known, however, concerning the degree of contribution of the two effects.

The object of this paper is to examine the effects of inertial and kinematic components on pile stresses based on the results of large shaking table tests on pile-structure models constructed in either dry or saturated sand deposit and to discuss how these two effects are taken into account in the pseudo-static analysis such as Beam-on-Winkler-springs method.

2. LARGE SHAKING TABLE TESTS

To investigate qualitatively the effects of inertial and kinematic forces, several series of shaking tests were conducted on soil-pile-structure systems using the shaking table facility at the National Research Institute for Earth Science and Disaster Prevention (NIED) (Tamura et al. 2000, 2001). Fig. 1 summarizes the test series in which a pile-structure system was constructed in either dry or saturated liquefiable sand in a large laminated shear box. The dimensions of the shear box were 4.6 or 6.1 m high, 12.0 m wide and 3.5 m long.

Model series IDs starting D and S indicate dry and saturated liquefiable sands, respectively. The soil used for dry sand deposit was Nikko Sand (e_{max} = 0.98, e_{min} = 0.65, D_{50} = 0.42 mm). The relative densities were about 80% for the tests. The soil profile in the liquefaction tests consisted of three layers including a top dry sand layer 0.5 m thick, a liquefiable sand layer 4 m thick and an underlying dense gravelly layer about 1.5 m thick. The sand used was Kasumigaura Sand (e_{max} = 0.961, e_{min} = 0.570, D_{50} = 0.31 mm, F_c = 5.4 %). The cone penetration test was made before each shaking table test to characterize the density profile of the deposit with depth.

A 2x2 steel pile group that supported a foundation of 20.6 kN with a superstructure of 139.3 kN was used. All the piles had a diameter of 16.52 cm with a 0.37 cm wall thickness and their tips were connected to the container base with pin joints. The natural period of the superstructure for series ID containing S at the end was shorter than that of the ground. The natural period for series ID containing L was longer than that of the non-liquefied ground but shorter than that of the liquefied ground.

The soil-pile-structure system was heavily instrumented with accelerometers, displacement transducers, strain gauges, and, if saturated, pore pressure transducers, as shown in Fig. 2. In these tests, an artificial ground motion called Rinkai, produced as an earthquake in Southern Kanto district in Japan was used as an input base acceleration to the shaking table. The test results estimated in this paper are those having a peak input acceleration of 2.4 m/s^2.

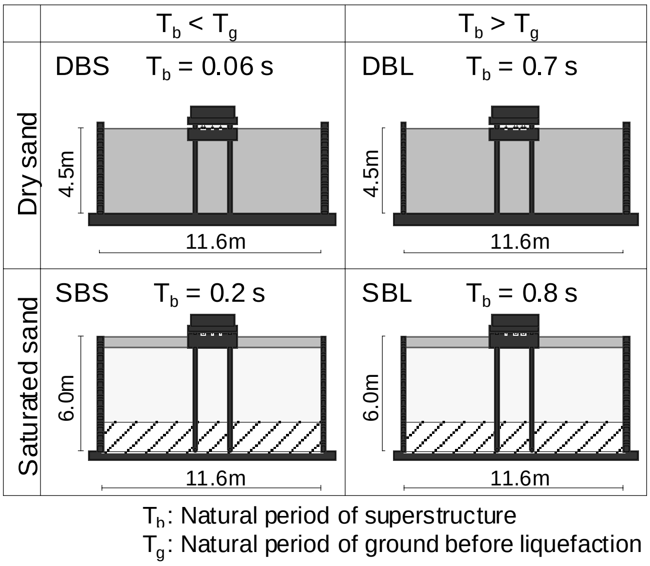


Fig. 1 Model layout

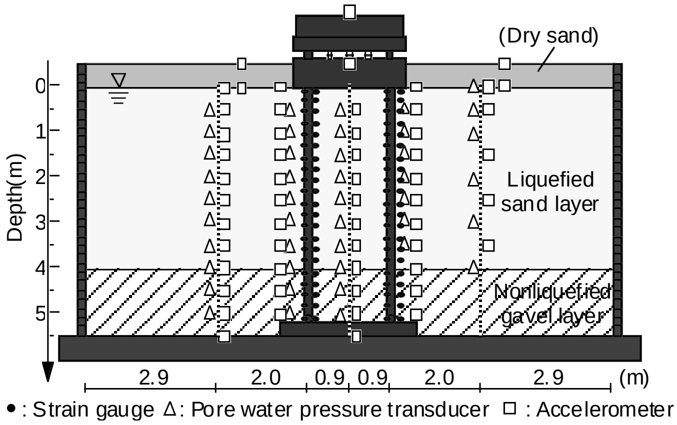


Fig. 2 Soil-pile-structure system

3. EFFECT OF SOIL DISPLACEMENT AND INERTIAL FORCE ON PILE STRESS IN DRY SAND

Fig. 3 shows time histories of acceleration of ground surface, foundation and superstructure, and bending moment at the pile head in DBS and DBL, together with the input base acceleration. In spite of similar acceleration response of the ground and superstructure, the bending moments in two tests are quite different. Namely, the moment in series DBS is almost twice that in series DBL. This suggests that the bending moment is affected not only by the inertial force from the superstructure but also other factors such as the ground displacement of dry sand.

To investigate factors affecting stress in piles, the forces acting on the foundation are modeled as shown in Fig. 4. Neglecting the friction between foundation and soil, the total earth pressure acting on the foundation is defined as:

$$P_E = P_{Ep} - P_{Ea} = Q - F \tag{1}$$

in which P_E is total earth pressure, P_{Ep} and P_{Ea} are earth pressures on the passive and active sides, Q is shear force at the pile heads computed from the differentiation of observed bending moment, and F is total inertial force computed from the accelerations of superstructure and foundation.

Fig. 5 compares the relations of the inertial force with bending moment, shear force, total earth pressure and ground surface displacement in DBS and DBL. The shear force is almost equivalent to the inertial force in series DBS (c), while the former is significantly smaller than the later in series DBL (d). This indicates that most of the inertial force is transmitted to the shear force in pile in series DBS, contributing to the large bending moment; however, this is not the case in series DBL. The difference in transmitted shear stress between the two tests is probably caused by the different actions of earth pressure against the inertial force, as shown in (e)(f). Namely, the earth pressure in DBS is out of phase with the inertial force and does not contribute toward reducing the shear force transmitted to the pile. In series DBL, in contrast, the earth pressure is in phase with and acts against the inertial force, reducing the shear force transmitted to the pile.

It is interesting to note that the inertial force is in phase in DBL and out of phase in DBS with ground displacement ((g)(h)). This indicates that the effects of inertial force and ground displacement become significant at the same time, inducing a large bending moment, in DBS. In contrast, the effects of the two do not become significant at the same time, yielding a small bending moment, in DBL.

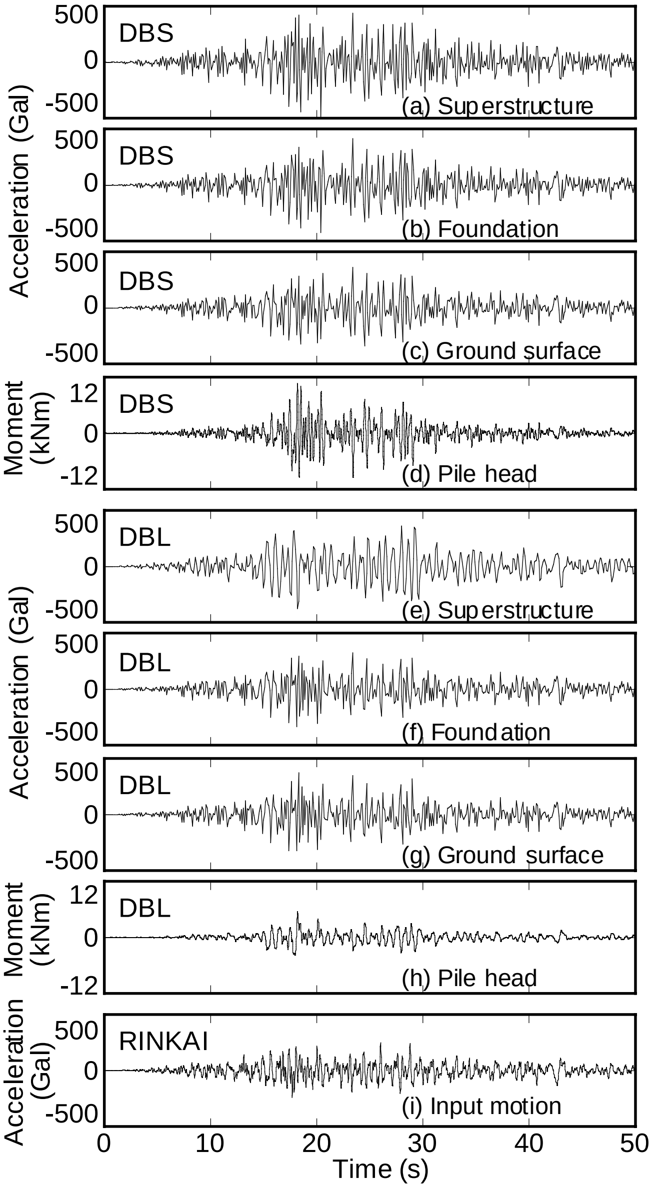


Fig. 3 Time histories in dry sand shaking tests

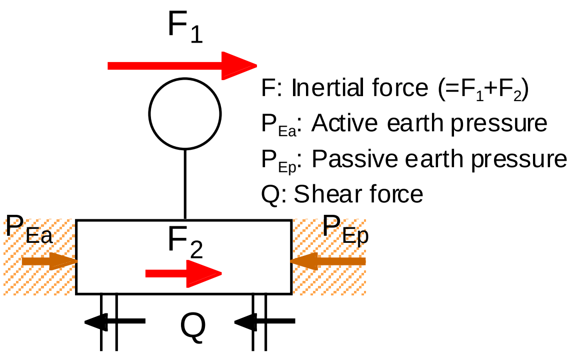


Fig. 4 Forces acting on foundation

4. EFFECTS OF SOIL DISPLACEMENT AND INERTIAL FORCE ON PILE STRESS DURING LIQUEFACTION

To investigate whether the findings in dry sands are valid in liquefiable sands, a similar examination was made for the other test series conducted with saturated sands. Fig. 6 shows the time histories of the accelerations of superstructure and foundation, soil displacement, bending moment at the pile head and pore pressure ratio, for series SBS, and SBL. The pore water pressure ratios in both tests begin to rise in 10 s and approaches 1.0 in about 20 s. After liquefaction, the bending moments in SBL as well as SBS get significantly larger than those before liquefaction. In addition, they are larger than the bending moments in DBS and DBL, shown in Fig. 3. Considering that the acceleration of superstructure decreases and the soil displacement increases with the development of liquefaction, the contribution of inertial and kinematic forces on pile stresses might have changed during liquefaction.

Figs. 7 and 8 compare the relations of the inertial force with bending moment, shear force, total earth pressure and ground displacement for three time segments (0-10, 10-20, and 20-50s) in SBS and SBL. The circle in plates (j)-(l) corresponds to the time at which the bending moment at the pile head is the largest within a time segment of 0.5 s. The bending moments after liquefaction in both cases are larger than those before liquefaction. This is probably because the shear force, which is less than the inertial force before liquefaction, becomes equal to or greater than the inertial force

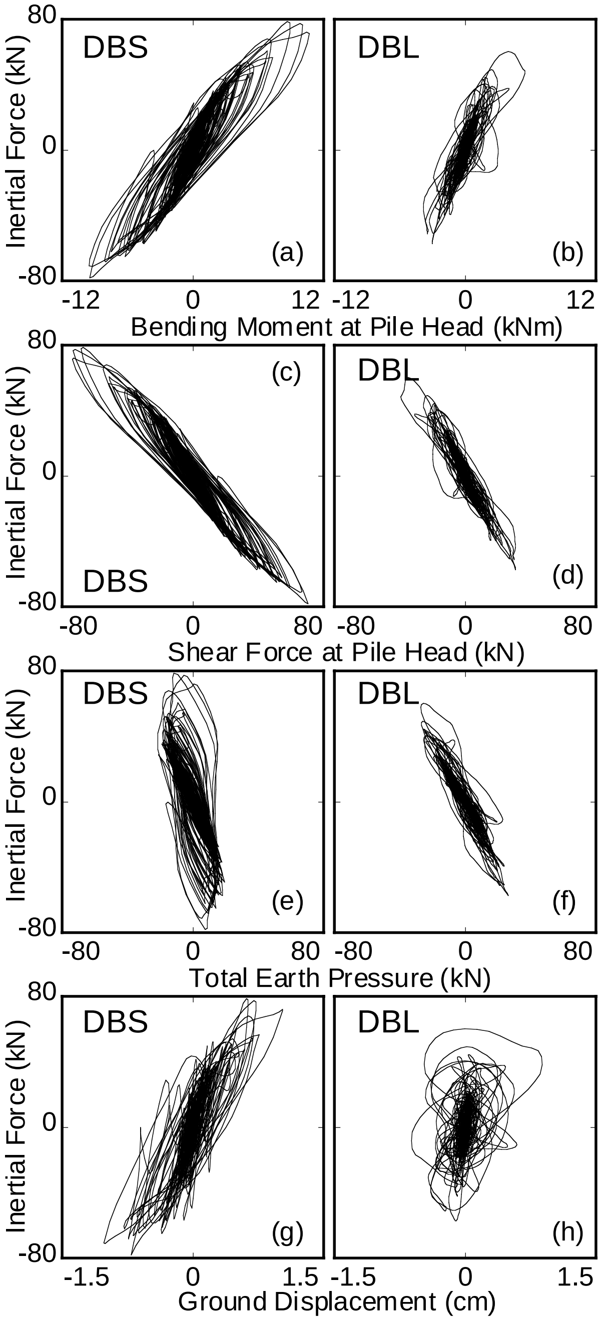


Fig. 5 Relation of inertial force with bending moment, shear force, earth pressure and ground displacement in DBS and DBL

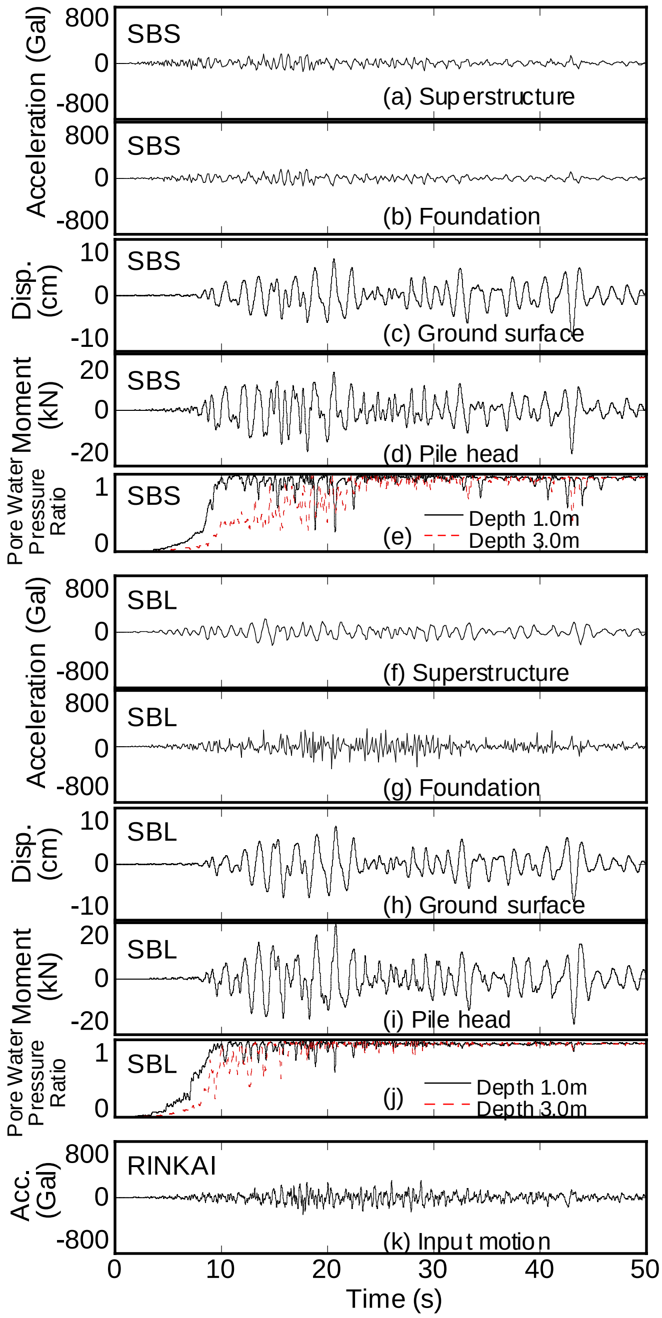


Fig. 6 Time histories in SBS and SBL

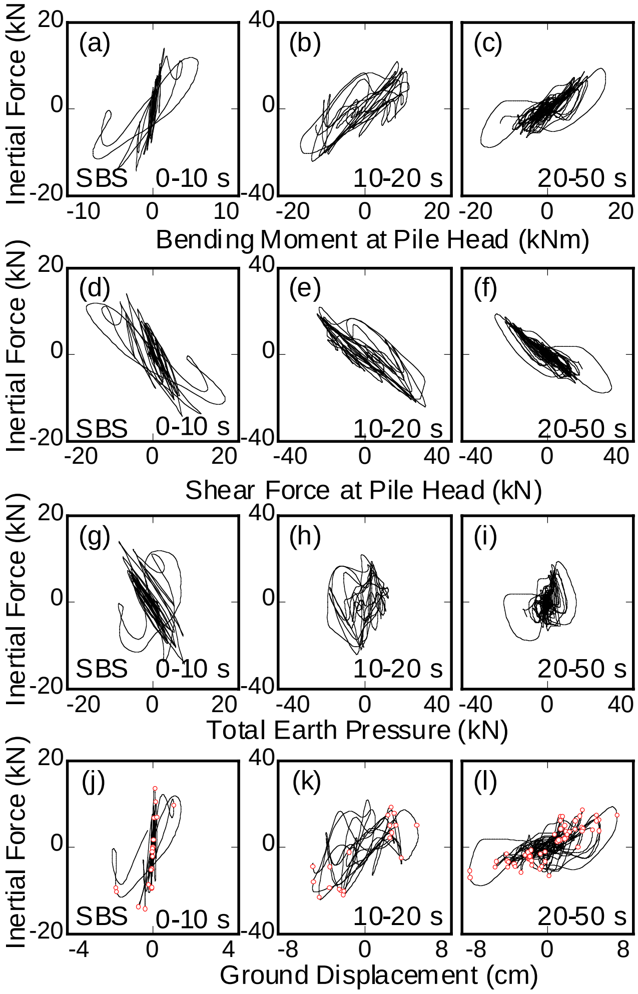


Fig. 7 Relation of inertial force with bending moment, shear force, earth pressure and ground displacement in SBS

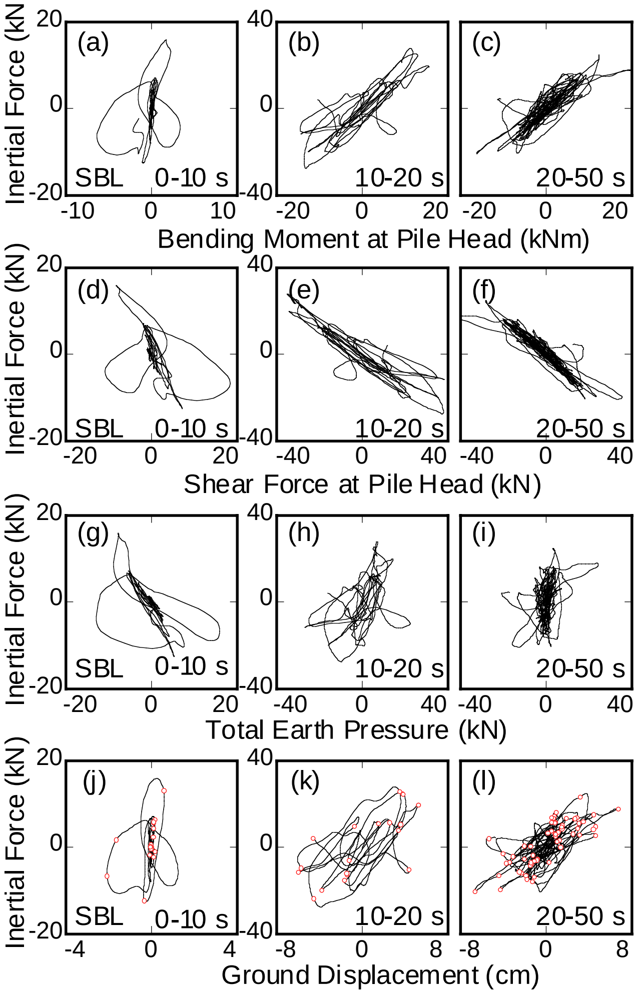


Fig. 8 Relation of inertial force with bending moment, shear force, earth pressure and ground displacement in SBL

after liquefaction, as shown in (d)-(f). The drastic change in shear stress transfer to the pile with the development of liquefaction might have been induced by the change in action of earth pressure against the inertial force, as shown in (g)-(i). Namely, the earth pressure that acts against the inertial force before liquefaction and reduces the shear force transmitted to the pile acts with the inertial force after liquefaction, increasing the shear force to the pile.

It is interesting to note that the inertial force and ground displacement after liquefaction are in phase in both SBS and SBL, as shown in (j)-(l). This is because the natural period of the liquefied soil is always grater than that of the superstructure. It is conceivable therefore under such a condition that the effects of soil displacement and inertial force are in phase, increasing the bending moment in piles. The trend is consistent with that observed in dry sand.

5. PSEUDO-STATIC ANALYSIS

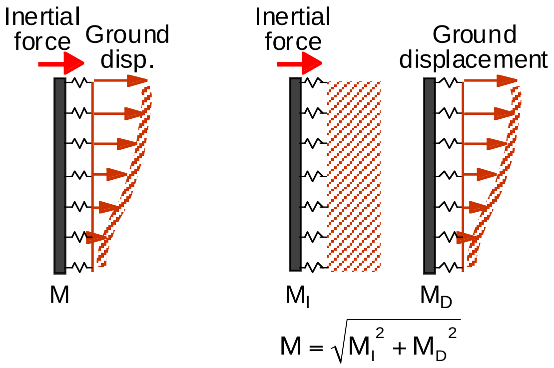
5.1 Contribution of inertial and kinematic components

Seismic design of foundations may be made based on either dynamic response or pseudo-static analyses. In this study, a pseudo-static analysis based on Beam-on-Winkler-springs method is conducted to examine its effectiveness in estimating pile stresses in the shaking table tests. Simplified pseudo-static design methods using p-y curves for pile foundations (Architecture Institute of Japan 2001, Nishimura 1978, and Tokimatsu & Asaka 1998) are based on the following equation:

$$EI\frac{d^4y}{dz^4} = -k_h B_p\left(y - y_g\right) \tag{2}$$

in which E and I are Young's modulus and moment of inertia of pile, y and y_g are horizontal displacement of pile and ground, z is depth, k_h is coefficient of horizontal subgrade reaction, and B_p is pile diameter.

When the natural period of the ground is longer than that of the superstructure, the pile stress can be estimated assuming that both soil displacement and inertial force are in phase and act on the pile at the same time (Method 1 in Fig. 9). When the natural period of the ground is smaller than that of the superstructure, the pile stress can be given by square root of the sum of the squares of the two values estimated, assuming that the soil displacement and inertial force are out of phase and act on the pile separately (Method 2 in Fig. 9).



(a) Method 1 (b) Method 2

Fig. 9 Combination between inertial and kinematic forces

5.2 p-y curve

To estimate pile stresses, k_h in p-y curve (Eq. (2)) is defined as (Tokimatsu et al. 2002):

$$k_h = k_{h1}\frac{2\beta}{1+\left|y_r/y_1\right|} \tag{3}$$

in which y_r is relative displacement between ground and pile ($= y$-y_g), y_1 is reference value of y_r, β is scaling factor for liquefied soil, and k_{h1} is reference value of k_h and can be estimated by (Architecture Institute of Japan 2001, and Japan Road Association 1997):

$$k_{h1} = 80E_0B_0^{-0.75} \tag{4}$$

$$E_0 = 0.7N \tag{5}$$

in which E_0 (MN/m^2) is modulus of deformation, N is SPT N-value, and B_0 is pile diameter in cm.

5.3 Earth pressure acting on foundation

Based on the studies (Zhang et al. 1998 and Tokimatsu et al. 2003) on earth pressure acting on the foundation, the total earth pressure P_E defined in Fig. 4 may be given as:

$$P_E = P_{Ep} - P_{Ea} = \frac{1}{2}\gamma H^2 B(K_{Ep} - K_{Ea}) \tag{6}$$

in which γ is unit weight of soil, H and B are height and width of foundation, and K_{Ea} and K_{Ep} are the coefficients of active and passive earth pressures and may be expressed by the following equations:

$$K_{Ea} = \frac{2\cos^2(\phi - i)}{\cos^2(\phi - i)(1+R) + \cos i\cos(\delta_{mob} + i)(1-R)I_{E.1}} \tag{7}$$

$$K_{Ep} = 1 + \frac{1}{2}(R-1)\left[\frac{\cos^2(\phi - i)}{\cos i\cos(\delta_{mob} + i)I_{E.2}} - 1\right] \tag{8}$$

$$\begin{pmatrix} I_{E\cdot 1} \\ I_{E\cdot 2} \end{pmatrix} = \left[1 \pm \sqrt{\frac{\sin(\phi + \delta_{mob})\sin(\phi - i)}{\cos(\delta_{mob} + i)}}\right]^2 \tag{9}$$

$$\tan i = k_i \qquad (10)$$

$$R = \max\left[-1, -\left(\frac{|\Delta_r|}{\Delta_a}\right)^{0.5}\right] \qquad \text{(Active Side)} \qquad (11)$$

$$R = \min\left[3, 3\left(\frac{|\Delta_r|}{\Delta_p}\right)^{0.5}\right] \qquad \text{(Passive Side)} \qquad (12)$$

$$\delta_{mob} = \frac{1}{2}(1 - R)\delta_a \qquad \text{(Active Side)} \qquad (13)$$

$$\delta_{mob} = \frac{1}{2}(R - 1)\delta_p \qquad \text{(Passive Side)} \qquad (14)$$

in which ϕ is internal friction angle of sand, i is angle of seismic coefficient in the horizontal direction (k_i), R is lateral strain constraint and is smaller than or equal to 0 in active side and larger than or equal to 0 in passive side, Δ_r is relative displacement between soil and foundation, δ is friction angle of the surface of the foundation, δ_a and δ_p are friction angles of sand at the active and passive states, and Δ_a and Δ_p are reference relative displacements at active and passive states, expressed as:

$$\Delta_a = aH \qquad (15)$$

$$\Delta_p = bH \qquad (16)$$

in which a is equal to 0.001-0.005, and b is equal to 0.05-0.1.

6. ESTIMATION OF PILE STRESSES IN SHAKIG TABLE TESTS BASED ON PSUEDO-STATIC ANALYSIS

To demonstrate the effectiveness of the pseudo-static analysis, the bending moment distributions of the shaking table tests with dry and saturated sands are simulated by the method. The pile stresses in DBS, SBS, and SBL are estimated by method 1 as the natural period of the ground is longer than that of the superstructure while those in DBL is estimated by method 2 as the natural period of the ground is shorter than that of the superstructure. It is assumed that the soil displacement at the ground surface and the inertial force are the maximum values observed in the tests. In this analysis, the N-values in the deposit were estimated by CPT-values measured prior to the shaking table test. It is assumed that β is 0.1, y_1 in Eq. (3) is 1.0 % of pile diameter (Japan Road Association 1997), ϕ is 30 degrees, δ_a and δ_p are 15 degrees, and Δ_a and Δ_p are 0.5 % and 5 % for the height of the foundation.

Fig. 10 compares the observed and computed moment distributions of the four tests. The com-

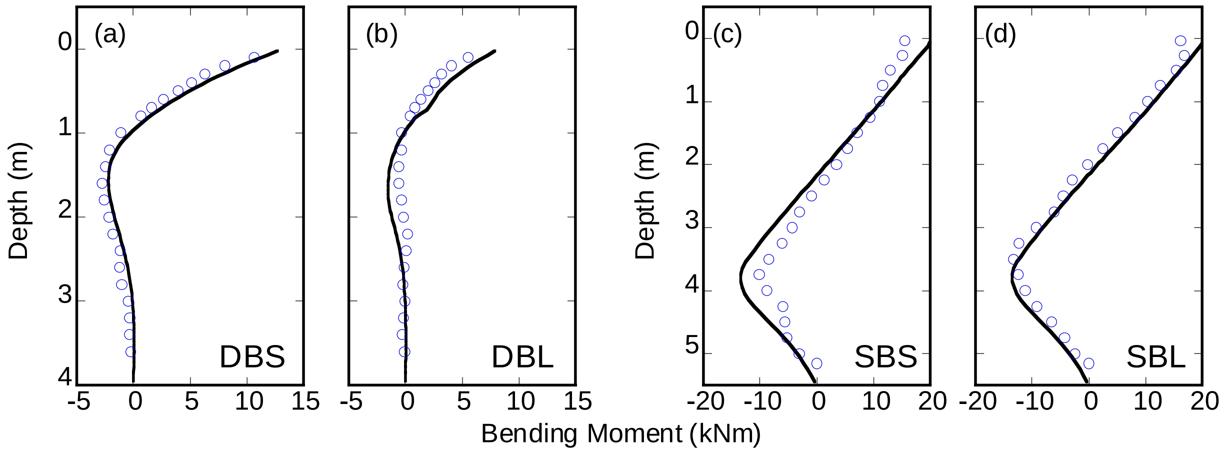


Fig. 10 Distribution of observed and estimated bending moments

puted moment distributions agree reasonably well with the observed ones, indicating that the pseudo-static analysis together with the consideration of effects of ground displacement is promising to estimate pile stress.

7. CONCLUSIONS

The large shaking table tests were conducted to estimate the effects of dynamic soil-pile-structure interaction on pile stress in both dry and saturated sands. The results and analysis have shown the following:

1) If the natural period of the structure is less than that of the ground, the kinematic force tends to be in phase with the inertial force, increasing the stress in piles. The maximum pile stress occurs when both inertial force and ground displacement become maxima at the same time and act in the same direction.
2) If the natural period of the structure is greater than that of the ground, the kinematic force tends to be out of phase with the inertial force, restraining the pile stress from increasing. The maximum pile stress tends to occur when both inertial force and ground displacement do not become maxima at the same time.
3) Above findings are valid for liquefiable sand as well as dry sand. During liquefaction, the kinematic effect becomes significant due to large ground displacement, increasing pile stress.
4) The pseudo-static analysis has been proposed, in which the combination of the inertial and kinematic effects is taken into account. The estimated bending moments are in good agreement with the observed values both in dry and saturated liquefied sands. This suggests that the pseudo-static analysis is promising to estimate pile stress with a reasonable degree of accuracy.

Acknowledgments

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