

## EFFECTS OF INERTIAL AND KINEMATIC FORCES ON PILE STRESSES IN LARGE SHAKING TABLE TESTS

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### SUMMARY

Effects of inertial and kinematic forces on pile stresses during earthquakes are studied based on large shaking table tests which are conducted with several soil-pile-structure models in either dry or liquefiable sand deposit. The test results show that, if the natural period of the superstructure is less than that of the ground, the inertial and kinematic forces are in phase, increasing the stresses in piles, but that, if the natural period of the structure is greater than that of the ground, they are out of phase, restraining the pile stress from increasing. Pseudo-static analysis is conducted in which the pile stress is determined as the sum of the two stresses caused by the inertial and kinematic effects or the squire root of the sum of the squires of the two, depending on the relation between the natural periods of the ground and superstructure. The estimated pile stresses are in good agreement with the observed ones in all cases.

#### INTRODUCTION

Field investigation and subsequent analyses after recent earthquakes confirmed that not only the inertial effects of their superstructures but also the kinematic induced by 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 [1]). It is therefore required to take both effects into account in designing pile foundations in liquefiable soils; however, little is known 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 in either dry or saturated sand deposit and to discuss how these effects are taken into account in the pseudo-static analysis such as Beamon-Winkler-springs method.

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#### 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. [2][3]). 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 ID consists of three alphabets. The first ID indicates soil condition (D: dry sand and S: saturated liquefiable sand), the second ID indicates whether the foundation has embedment (A: No and B: Yes), and the third ID indicates the natural period of the superstructure relative to that of the ground (S:

shorter than that of the ground and L: larger and shorter than that of the ground before and after liquefaction, 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 of the dry sand deposit were about 80%. 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 was used for all the tests. 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 pile heads were fixed to the foundation having a weight of 20.6 kN that carries a superstructure of 139kN.

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 particular, the accelerometers of piles and the ground were measured at every 50 cm with depth and the bending strains of all piles at every 10-25 cm.

In the tests, an artificial ground motion called Rinkai, as shown in Fig. 3, was used as an input base acceleration to the shaking table. The test results discussed in this paper are those having a peak acceleration of  $2.4 \text{ m/s}^2$ .



#### EFFECT OF INERTIAL AND KINEMATIC FORCES ON PILE STRESS

#### Combination of inertial and kinematic forces in dry sand shaking tests

Figs. 4-7 show acceleration time histories of the ground surface, foundation, and superstructure, as well as bending moment time history at the pile head in DAS, DAL, DBS and DBL. The acceleration responses of the ground surface are similar among the tests, while those of the superstructure and bending moment are quite different. Namely, the response of the superstructure in DAS is twice that of ground surface and the bending moment becomes largest in all the tests. In contrast, the responses of the superstructure in DAL, DBS, and DBL, are almost equal to those of the ground surface and the bending moments are smaller than that in DAS. In particular, an increase in bending moment is very small in DBL, in spite of the similar acceleration response of the superstructure to that in DBS and DAL. These findings suggest that not only the inertial force from the superstructure but also other factors might have affected the bending moment.

To evaluate the change in bending moment with the inertial force, Fig. 8 shows the relation of the two. The inertial force is computed from the accelerations of the superstructure and foundation. It seems that the bending moment increases with increasing inertial force. The trend is more remarkable in the soil-pile-



structure system without a foundation embedment than that with an embedment. Namely, the bending moment in DAS is larger than that in DBS, and that in DAL is larger than that in DBL.

To investigate the effect of embedment on stress in piles, the forces acting on the foundation are modeled as shown in Fig. 9. 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 head computed from the differentiation of the observed bending moment, and F is total inertial force from the superstructure and foundation.

Fig. 10 compares the relations of inertial force with shear force and total earth pressure in DBS and DBL. The shear force is equal to or smaller than the inertial force (Fig. 10(a)(b)). This is probably because that the total earth pressure acts against the inertial force (Fig. 10(c)(d)), which induces the smaller bending moment in DBS and DBL than that in DAS and DAL. In addition, the reduction of shear force induced by the earth pressure is more significant in DBL than in DBS. This is probably because the total earth pressure in DBS is out of phase with the inertial force and becomes very small while that in DBL is in phase with and acts against the inertial force. It is interesting to note that the inertial force is in phase in DBL and out of phase in DBS with ground displacement, as shown in Fig. 11. This confirms that the soil structure interaction does have significant effects on pile stresses.

To examine the contribution of the inertial and kinematic forces on pile stresses, Fig. 12 shows Fourier spectra of the input motion and accelerations of the ground surface, foundation and superstructure in the four tests. The Fourier spectrum of the superstructure in DAS and DBS has a peak at the same period as that of the ground surface acceleration, while that in DAL and DBL has a spectral peak greater than that of the ground or the foundation. It is conceivable therefore that,



Fig. 10 Relation of inertial force with shear force or earth pressure in dry sand

if the natural period of superstructure is shorter than that of the ground, the effects of ground displacement and inertial force tend to be in phase, inducing the large pile stress. In contrast, if the natural period of superstructure is longer than that of the ground, they are out of phase, suppressing the increase in pile stress.

# Combination of inertial and kinematic forces in saturated liquefiable sand shaking tests

To investigate whether the findings in dry sands are valid in liquefiable sands, similar examination was made for the other series conducted with saturated sands. Figs. 13 and 14 show the time histories of the accelerations of superstructure and ground surface, bending moment at the pile head and pore pressure ratio, in 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. The bending moments in both tests after liquefaction are quite large, despite the small acceleration responses of superstructure and ground surface.

Fig. 15 shows the relationship between inertial force and bending moment for three time segments (0-10, 10-20, and 20-50s) in SBS and SBL. The bending moments during liquefaction in both tests are larger than those in DBS and DBL (Fig. 8(c)(d)), in spite of their significantly smaller inertial force as



Fig. 12 Fourier spectrum in dry sand

a result of the development of liquefaction. This suggests that the combined effects of inertial and kinematic forces on pile stresses might have changed during liquefaction.

Figs. 16 and 17 show the relations of inertial force with shear force and total earth pressure in SBS and



SBL. The shear force before liquefaction in both tests is less than the inertial force, and the shear force transmitted to the pile head is significantly reduced in SBL than in SBS. This is very similar to the trend in dry sand. In constant, the shear force after liquefaction is equal to or greater than the inertial force in both SBS and SBL. This trend is different from that in dry sand. The drastic change in shear stress transfer to the pile with the development of liquefaction is induced by the change in action of earth pressure against the inertial force, as shown in Fig. 17. Namely, the earth pressure acts against the inertial force before liquefaction, reducing the shear force transmitted to the pile, and acts with the inertial force after liquefaction, increasing the shear force to the pile, as shown in Fig. 18.

Fig. 19 shows the relation between inertial force and ground displacements for the two tests. It is interesting to note that the inertial force and ground displacement after liquefaction are in phase in both SBS and SBL. The circle in plates corresponds to the time at which the bending moment at the pile head is the largest within a time segment of 0.5 The maximum bending moment after s. when liquefaction occurs both soil displacement and inertial force get large. 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.

#### **PSEUDO-STATIC ANALYSIS**

# Combination between inertial and kinematic component

Seismic design of foundations may be made based on either dynamic response or pseudostatic 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 (Architectural Institute of Japan [4], Japan Road Associate [5], Nishimura [6], and Tokimatsu & Asaka [7]) are based on the following equation:

$$EI\frac{d^4y}{dz^4} = -k_h B(y - y_g)$$
(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* 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. 20). 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. 20).

#### p-y curve

The relation between subgrade reaction, p and relative displacement,  $y_r (= y-y_g)$  is defined by the coefficient of subgrade reaction,  $k_h$ :

$$p = k_h B y_r \tag{3}$$

in which  $k_h$  is given by Tokimatsu et al. [8]:

$$k_h = k_{hl} \frac{2\beta}{1 + \left| y_r / y_l \right|} \tag{4}$$

in which  $\beta$  is scaling factor for liquefied soil,  $y_1$  is reference value of  $y_n$  and  $k_{h1}$  is reference value of  $k_h$  and can be estimated by Architectural Institute of Japan [4]:

$$k_{hl} = 80E_0 B_0^{-0.75} \tag{5}$$

$$E_0 = 0.7N \tag{6}$$

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

#### Earth pressure acting on foundation

To model the earth pressure acting on the foundation based on the study by Zhang et al. [9], the total earth pressure  $P_E$  is defined from Fig. 9 as (Tokimatsu et al. [10]):

$$P_{E} = P_{Ep} - P_{Ea} = \frac{1}{2} \gamma H^{2} B(K_{Ep} - K_{Ea})$$
(7)



in which  $\gamma$  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 given by the following equations [9]:

$$K_{Ea} = \frac{2\cos^2(\phi - i)}{\cos^2(\phi - i)(1 + R) + \cos i \cos(\delta_{mob} + i)(1 - R)I_{E.1}}$$
(8)

$$K_{Ep} = 1 + \frac{1}{2} (R - 1) \left[ \frac{\cos^2(\phi - i)}{\cos i \cos(\delta_{mob} + i) I_{E,2}} - 1 \right]$$
(9)

$$\binom{I_{E\cdot 1}}{I_{E\cdot 2}} = \left[1 \pm \sqrt{\frac{\sin(\phi + \delta_{mob})\sin(\phi - i)}{\cos(\delta_{mob} + i)}}\right]$$

$$(10)$$

$$\tan i = k_i \tag{11}$$

$$R = \max\left[-1, \left\lfloor\frac{|F_r|}{\Delta_a}\right]\right]$$
 (Active Side) (12)

$$R = \min \left[ 3.3 \left( \frac{|\Delta_{r}|}{\Delta_{p}} \right)^{0.5} \right]$$
 (Passive Side) (13)

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

$$\delta_{mob} = \frac{1}{2}(R-1)\delta_p \qquad (Passive Side) \qquad (15)$$

in which  $\phi$  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,  $\Delta_r$  is relative displacement between soil and foundation,  $\delta$  is friction angle of the surface of the foundation,  $\delta_a$  and  $\delta_p$  are friction angles of sand at the active and passive states, and  $\Delta_a$  and  $\Delta_p$  are reference relative displacements at active and passive states, expressed as:

$$\Delta_a = aH \tag{16}$$

$$\Delta_p = bH \tag{17}$$

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

#### ESTIMATION OF PILE STRESSES IN SHAKING TABLE TESTS BASED ON PSUEDO-STATIC ANALYSIS

To demonstrate the effectiveness of the pseudo-static analysis, the pile stress distributions of shaking table tests that were conducted with dry and saturated sands (DAS, DAL, DBS, DBL, SBS, and SBL) are simulated. Fig. 21 shows the soil-pile-structure model used in the analysis, in which either inertial force or ground displacement or both are considered, depending on the natural period of the superstructure relative to that of the ground (see Fig. 20). Namely, the pile stresses in DAS, DBS, SBS and SBL where the natural period of superstructure is less than that of ground are estimated with Method 1, while those in other tests are estimated with Method 2.

It is assumed that the soil displacement, having the maximum observed ground displacement at the surface and decreases linearly with depth to zero at either the bottom of the dry sand layer or of the liquefiable sand layer. The inertial force of the superstructure is estimated from the response analysis of a one-degree-of-freedom system subjected to the observed ground motion. The N-values in the deposit were estimated by CPT-values measured prior to the shaking table test. It is assumed that  $\beta$  is 0.1,  $y_1$  in Eq. (3) is 1.0 % of pile diameter (Tokimatsu et al. [8]),  $\phi$  is 30 degrees,  $\delta_a$  and  $\delta_p$  are 15 degrees, and that

 $\Delta_a$  and  $\Delta_p$  are 0.5 % and 5 % for the height of the foundation.

Figs. 22 and 23 compare the observed and estimated bending moment and shear force distributions of all the tests. The estimated moment and shear force 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.



#### CONCLUSIONS

The large shaking table tests were conducted to estimate the effects of dynamic soil-pile-structure interaction 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 tends to occur when both inertial force and ground displacement take maxima 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 either inertial force or ground displacement take maxima with the other being very



Fig. 23 Distribution of shear force

small or when both inertial force and ground displacement do not become maxima at the same time.

- 3) The earth pressure in dry sand tends to act against the inertial force, while that in saturated liquefied sand tends to act with the inertial force. This is because the ground displacement becomes large with the development of liquefaction.
- 4) Based on the above findings, the pseudo-static analysis has been proposed, in which both inertial and kinematic effects are taken into account. The estimated pile stresses 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.

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