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COMBINED EFFECTS OF GROUND DISPLACEMENT AND INERTIAL FORCE ON PILE STRESSES IN CENTRIFUGE MODEL TESTS

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ABSTRACT

To investigate factors influencing soil-pile-structure interaction during earthquakes, centrifuge model tests were conducted on soil-pile-structure systems. In the centrifuge model tests, the natural period of the superstructure, the presence of foundation embedment and mass of superstructure as well as the occurrence of soil liquefaction were varied. Ground motions with different predominant periods were used as an input base motion. The test results show that: 1) When the predominant period of the input motion is shorter than the natural period of ground, the ground displacement is small and pile stresses are controlled only by the inertial force; 2) When the predominant period of the input motion is the same as or longer than the natural period of ground, the ground displacement is large and pile stresses are controlled by combined effects of the inertial force and ground displacement; 3) The combination of the inertial force and ground displacement varies depending on the predominant period of input motion, relations between natural periods of a superstructure and ground, and whether soil liquefaction occurs or not. To examine how the effects of soil-pile-structure interaction are taken into account in the seismic design of pile foundation, pseudo-static analysis was conducted based on the centrifuge model tests. In the analysis, effects of the combination between inertial force and ground displacement were considered. The estimated pile stresses are in good agreement with the observed ones.

Introduction

It has become widely known from field investigations and subsequent analyses after earthquakes that kinematic effects arising from the ground movement as well as inertial effects from superstructure had significant impact on the damage to pile foundations. A great deal of studies concerning the interaction between superstructure and soil has been carried out, based on physical model tests with centrifuge shakers (e.g., Nishimura et al. 1997) or large shaking tables (e.g., Tokimatsu et al. 2005) and numerical analyses (e.g., Nagatsuma et al. 1998). Based on centrifuge shake table tests, Nishimura et al. (1997) reported that the combination of the inertial force and ground displacement varies depending on the relationship between natural periods of

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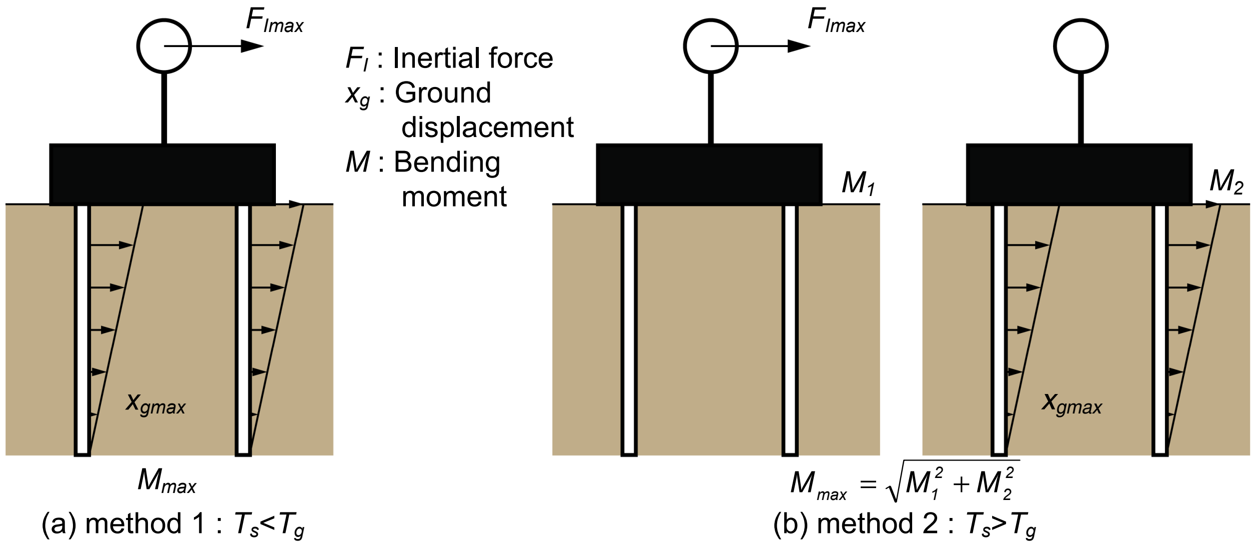

Figure 1. Combination of inertial and kinematic effects on pile stresses

superstructure (T_s) and ground (T_g). Tokimatsu et al. (2005) performed a series of large shake table tests, and reported that in pseudo-static analysis method, pile stress observed in the experiments can be simulated by: (1) applying inertial force and ground displacement simultaneously if T_s is shorter than T_g (Fig. 1 (a)), or (2) applying inertial force and ground displacement separately, and combining the results using square root of sum of squares method, if T_s is greater than T_g (Fig. 1 (b)). Most of them were, however, conducted with limited soil-pile-structure models and seismic waves (e.g., sine wave or white noise). Whether these results still apply when ground conditions and other factors are varied remains unknown.

The purpose of this paper is to examine how the effects of soil-pile-structure interaction are taken into account in the seismic design of pile foundation with the ground condition, superstructure and applied seismic waves varied. First, a brief overview of the centrifuge model tests, which this study is based on, is presented. Pseudo-static analysis method is then explained. Finally, the results of analysis are shown along with discussions and conclusions.

Centrifuge Model Tests

To investigate factors influencing soil-pile-structure interaction during earthquakes, centrifuge model tests were conducted on soil-pile-structure systems, using a 1/30 scale model under a centrifugal acceleration of 30g, as illustrated in Fig 2 (Sugimoto, 2008). Scales that appear in the figures and the following article are all in prototype dimensions. Ten different types of models were built, as summarized in Table 1.

The dry soil (Fig. 2 (a)) consisted of a dry Albany silica sand layer (D_{50}=2.677mm, D_r=70%, 13.5m thick), with additional 1.5m-thick embedment, consisting of the same Albany silica sand, at the top. The saturated soil (Fig. 2 (b)) consisted of a saturated Albany silica sand layer (D_{50}=2.677mm, D_r=70%, 9m thick) underlain by a non-liquefied No.4 silica layer (D_{50}=2.651mm, D_r=90%, 4.5m thick), with additional 1.5m-thick embedment, consisting of No.2 silica sand (D_{50}=2.655mm), at the top.

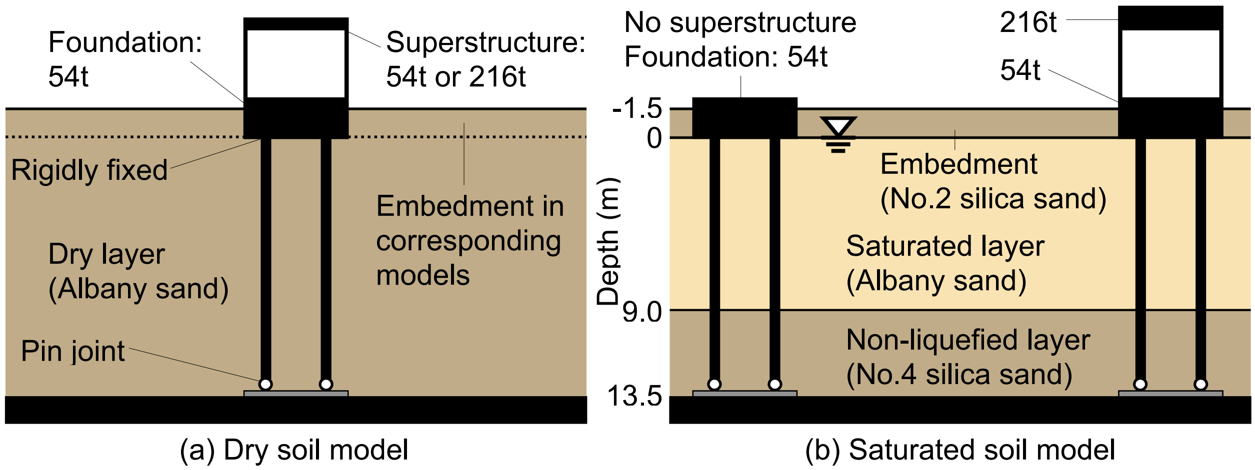

Figure 2. Test models (excerpting portions near piles and foundation)

Table 1. Test series

ID	Soil	Embedment	m_s:m_f	T_s - T_g relation	Input motion
DN1L	Dry	No	1:1	$T_s > T_g$	-S, -L
DN1S	Dry	No	1:1	$T_s < T_g$	-S, -L
DY1L	Dry	Yes	1:1	$T_s > T_g$	-S, -L
DY1S	Dry	Yes	1:1	$T_s < T_g$	-S, -L
DY4L	Dry	Yes	4:1	$T_s > T_g$	-S, -L
DY4S	Dry	Yes	4:1	$T_s < T_g$	-S, -L
SN0N	Saturated	No	0:1	—	-S, -L
SN4S	Saturated	No	4:1	$T_s < T_g$	-S, -L
SY0N	Saturated	Yes	0:1	—	-S, -L
SY4S	Saturated	Yes	4:1	$T_s < T_g$	-S, -L

A 2x2-pile group penetrated the soil, with a nominal spacing of 3.6m center to center in both directions. High stiffness stainless steel pipes, 477mm in diameter and 9mm thick with Young's modulus of 205GN/m^2, were used for the piles. Pile heads were rigidly fixed to the foundation using bolts, while pile tips were connected to the bottom of container with pin joints.

The mass of the foundation (m_f) was 54t. Two types of superstructures with different masses (m_s), 54t and 216t, were used. The natural period of superstructure (T_s) was varied by using various sheet springs to hold the superstructure. Models without superstructure were also used in corresponding cases.

As the input motion to the shaking table, two seismic waves were selected: (1) Akasaki EW in the 2000 western Tottori prefecture earthquake (short period wave), of which the predominant period is around 0.09s; and (2) JR Takatori NS in the 1995 Kobe earthquake (long period wave), of which the predominant period is around 1.2s. Maximum accelerations were both scaled to 2.0m/s^2. Each model was subjected to the both seismic waves.

Each letter in the model IDs corresponds to each varied factor: soil condition (D: dry; and S: saturated), the presence of foundation embedment (Y: embedded; and N: no embedment), and the mass (0: no superstructure; 1: 54t; and 4: 216t) and natural period (N: no superstructure; L: $T_s>T_g$; and S: $T_s<T_g$) of superstructure. Predominant periods of the input motions are expressed by one letter preceded by a hyphen (S: short period wave; L: long period wave) added to the end of model IDs. Altogether, twenty cases of tests were performed.

The soil-pile-structure system was heavily instrumented with accelerometers, displacement transducers, strain gauges, and, if saturated, pore water pressure transducers. All values used in this study were calculated or obtained from the record of sensors: inertial force (F_I) from record of accelerometers at foundation and superstructure; ground displacement at the pile head (x_g) from record of laser displacement sensor at soil surface; acceleration at soil surface (a_i) from record of accelerometer at soil surface; liquefaction depth from record of pore pressure transducers in soil; observed bending moment from record of strain gauges on piles.

During the tests, the following were observed: (1) In the same model, magnitude of inertial force tends to get larger when long period wave is used; (2) In long period wave cases, magnitude of inertial force is larger in models with larger m_s, as oppose to short period wave cases where magnitude of inertial force is larger in models with smaller m_s; (3) Ground displacement tends to be larger in long period wave cases, regardless of soil and superstructure conditions; (4) Pore pressure ratio doesn't reach 1.0 at all depth in saturated soil subjected to short period waves, while liquefaction occurs in saturated soil subjected to long period waves.

Details on pile stresses observed during the tests will be described in the next chapter.

Pseudo-Static Analysis Method

Pseudo-static analysis is a simplified method for estimating pile stress. The basic equation is given b Eq. 1,

$$EI\frac{d^4x}{dy^4} = k_h B\left(x_g - x\right) \quad (1)$$

where E and I are the Young's modulus and the moment of inertia of pile, x is lateral displacement of pile, y is depth, B is pile's diameter, k_h is modulus of subgrade reaction, x_g is lateral displacement of soil.

Fig. 3 illustrates the pile-foundation model for pseudo-static analysis. Piles and foundation are modeled as beam element with tri-linear moment-curvature (M-φ) relation, as shown in Fig. 4. Soil is modeled as soil spring with modulus of subgrade reaction (k_h). Inertial force from superstructure and foundation, and lateral displacement of soil are applied to calculate pile stress.

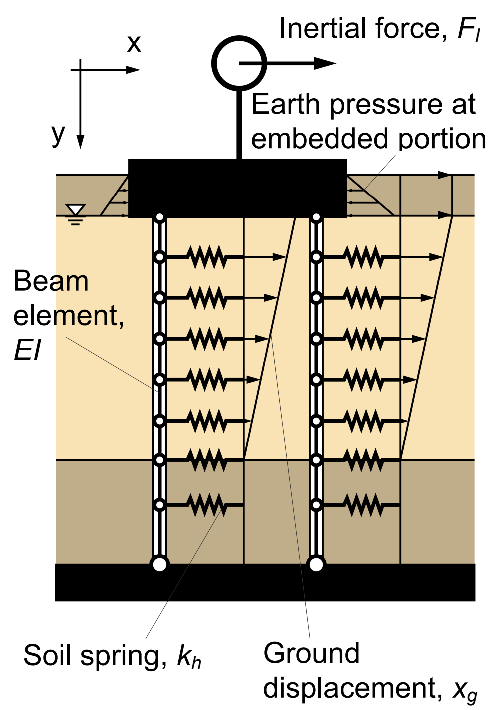

Figure 3. Analysis model

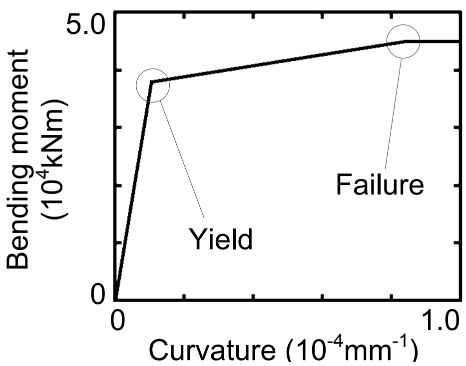

Figure 4. Tri-linear M-φ relation

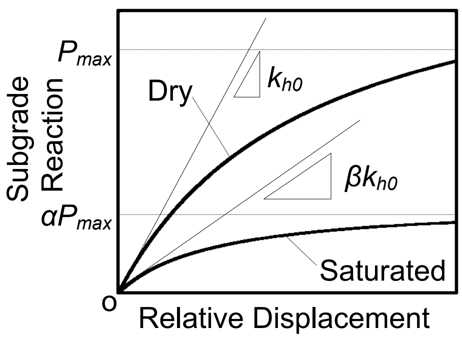

Figure 5. P-x_r relation

Modulus of subgrade reaction (k_h) is obtained from relative density of soil (D_r) and effective overburden pressure (σ_v'). Considering the non-linear characteristic of soil, k_h is reduced according to relative displacement between pile and soil (x_r). Additionally, k_h is reduced in liquefied layer along with maximum subgrade reaction (P_{max}), as shown in Fig. 5. Further details are presented elsewhere (Zhou, 2009).

The earth pressure at the embedded portion, based on the earth pressure theory proposed by Zhang et al. (1998), is given by Eq. 2,

$$P_E = P_{Ep} - P_{Ea} = \frac{1}{2}\gamma H^2 B\left(K_p - K_a\right) \tag{2}$$

where P_E is total earth pressure, P_{Ep} and P_{Ea} are earth pressure on passive and active sides, γ is unit weight of sand, H and B are depth and width of embedment, K_p and K_a are modulus of passive and active earth pressure. Further details are described elsewhere (Zhang, 1998).

Vertical distribution of soil displacement is given in shape of inverted triangle, as described in Fig. 6. Soil displacement is set to zero at depth of pile tip in dry soil (Fig. 6 (a)), or at depth of bottom of the liquefied layer in saturated soil subjected to long period waves (Fig. 6 (b)), or at depth of bottom of the saturated layer in saturated soil subjected to short period waves, in which no liquefaction was observed (Fig. 6 (c)).

In order to confirm the validity of this model, the inertial force and soil displacement, obtained at the instant when the maximum bending moment occurred at pile tops during tests, were applied to calculate pile stresses. Figs. 7 (a)-(j) show distributions of bending moment with depth in selected cases, compared with the observed values. In dry soil cases, observed bending

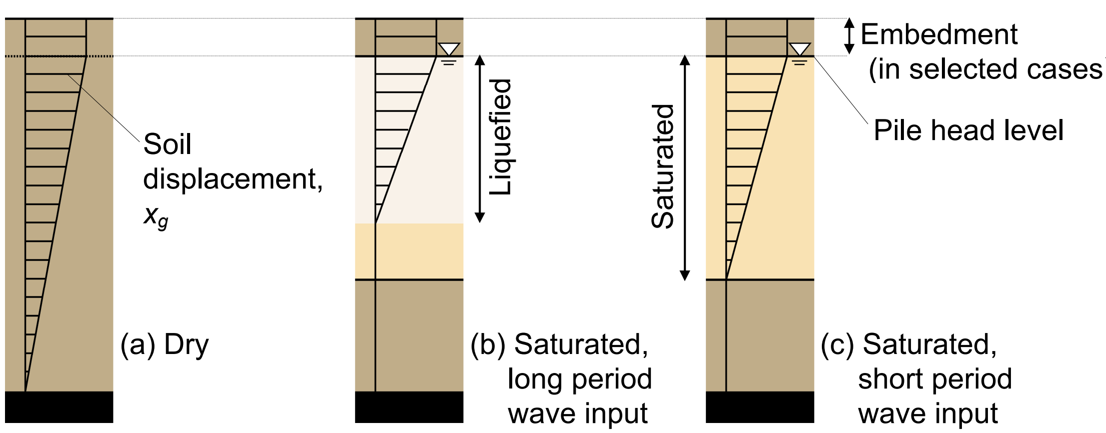

Figure 6. Pattern of distribution of soil displacement

moment gets larger in cases with long period wave input, or no embedment at foundation, or larger mass of superstructure, or T_s shorter than T_g. In saturated soil cases, observed bending moment gets larger in cases with long period wave input, or embedment at foundation, or the presence of superstructure. Bending moment tends to take its peak value at pile head level, except for dry soil cases with long period input where the peak value takes place under ground level. Notably, there is no inflection point in the distribution of bending moment in cases DY1L-L and DY4L-L. Figs. 7 (a)-(j) show that the estimated bending moments can reproduce the observed results with a reasonable degree of accuracy, though bending moment at underground

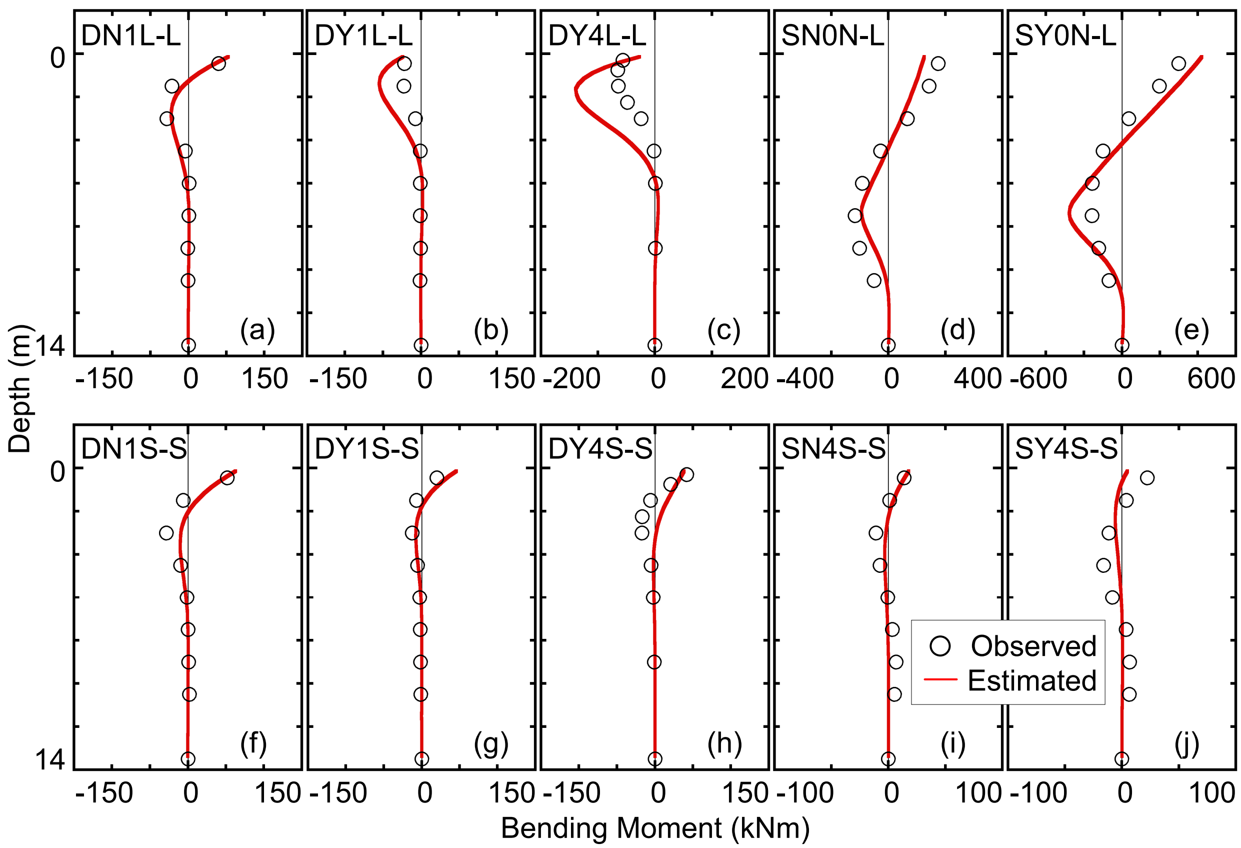

Figure 7. Distribution of observed and estimated bending moment

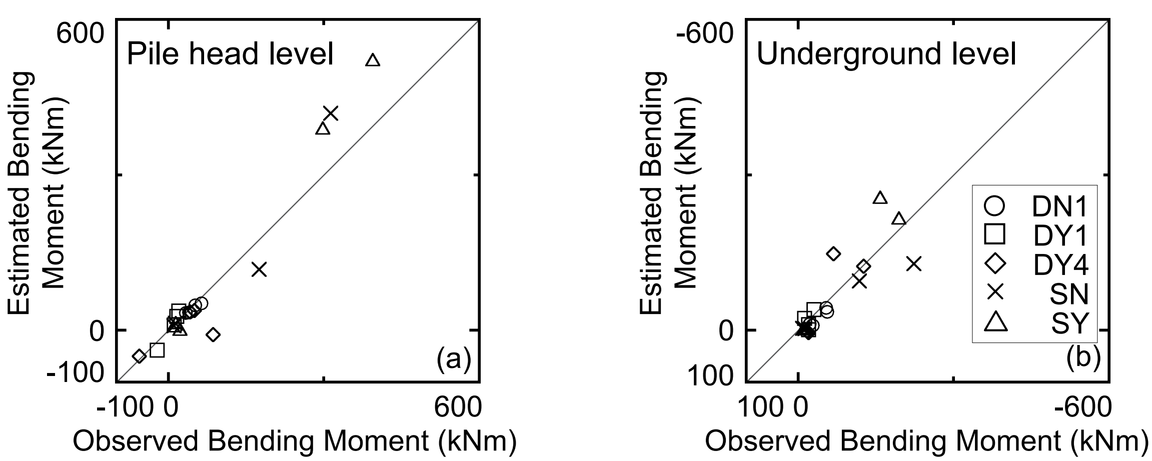

Figure 8. Relation of observed and estimated bending moment

level seems to be overestimated in some cases (e.g., DY1L-L, DY4L-L and SY0N-L).

Fig. 8 compares the observed and estimated bending moment in all cases, at pile head level and the underground level at which bending moment becomes maximum. Estimated results are in fairly good agreement with observed ones, especially at pile head level where bending moment is most likely to take its peak value, which proves the validity of the suggested model.

Effects of Ground Displacement and Inertial Force on Pile Stresses

When applying static analysis to seismic design of pile foundation, the maxima of inertial force and ground displacement are used to estimate pile stresses. In a previous study (Zhou, 2009), maximum inertial force (F_{Imax}) and maximum ground displacement (x_{gmax}), which are obtained from centrifuge tests, were given simultaneously, either in the same or opposite direction, to determine their effects on pile stresses. Fig. 9 compares the estimated and observed bending moment at pile heads. The results have shown that: (1) if T_s is shorter than T_g, observed and estimated pile stresses are in better agreement when F_{Imax} and x_{gmax} are given in the opposite direction (Fig. 9 (a)); and (2) if T_s is greater than T_g, observed and estimated pile stresses are in better agreement when F_{Imax} and x_{gmax} are given in the same direction (Fig. 9 (b),(c)). In addition, the ground displacement is small in the short period wave case and the inertial force of superstructure plays a dominant role in controlling pile stress. The ground displacement gets relatively large in the long period case, the trend of which is more significant in the saturated case, and plays a dominant role in controlling pile stress.

Other than applying inertial force and ground displacement simultaneously on piles, there are various ways to apply them. To further study the effects of inertial and kinematic forces on pile stresses, in this study, the inertial force and ground displacement are simultaneously or separately considered, depending on the T_s relative to T_g (see Fig. 1). Namely, pile stresses in cases in which T_s is greater than T_g are estimated by method 2 (Fig. 1 (b)), while those in all other cases in which T_s is shorter than T_g are estimated by method 1 (Fig. 1 (a)).

Figs. 10 (a)-(j) compare observed and estimated distribution of absolute values of bending moment with depth in selected cases. The observed values are those at which the maximum bending moment at the pile head occurs. In most cases, especially those subjected to

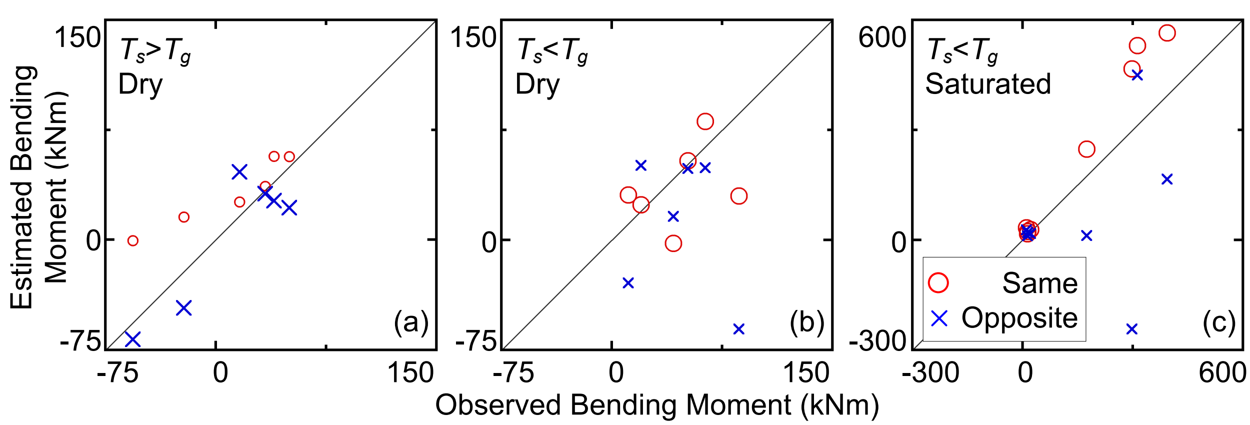

Figure 9. Relation of observed and estimated bending moment at pile heads

long period waves, bending moment tend to be overestimated. This might be due to the fact that, in most cases, the maximum values of F_I and x_g are larger than those observed at the instance when bending moment at pile heads actually became the maxima. However, on the whole, the estimated and observed values are in fairly good agreement.

Fig. 11 compares absolute values of the observed and estimated bending moment in all cases, at the pile head level and the underground level at which bending moment takes its peak value. The estimated results are in fairly good agreement with observed ones, although they

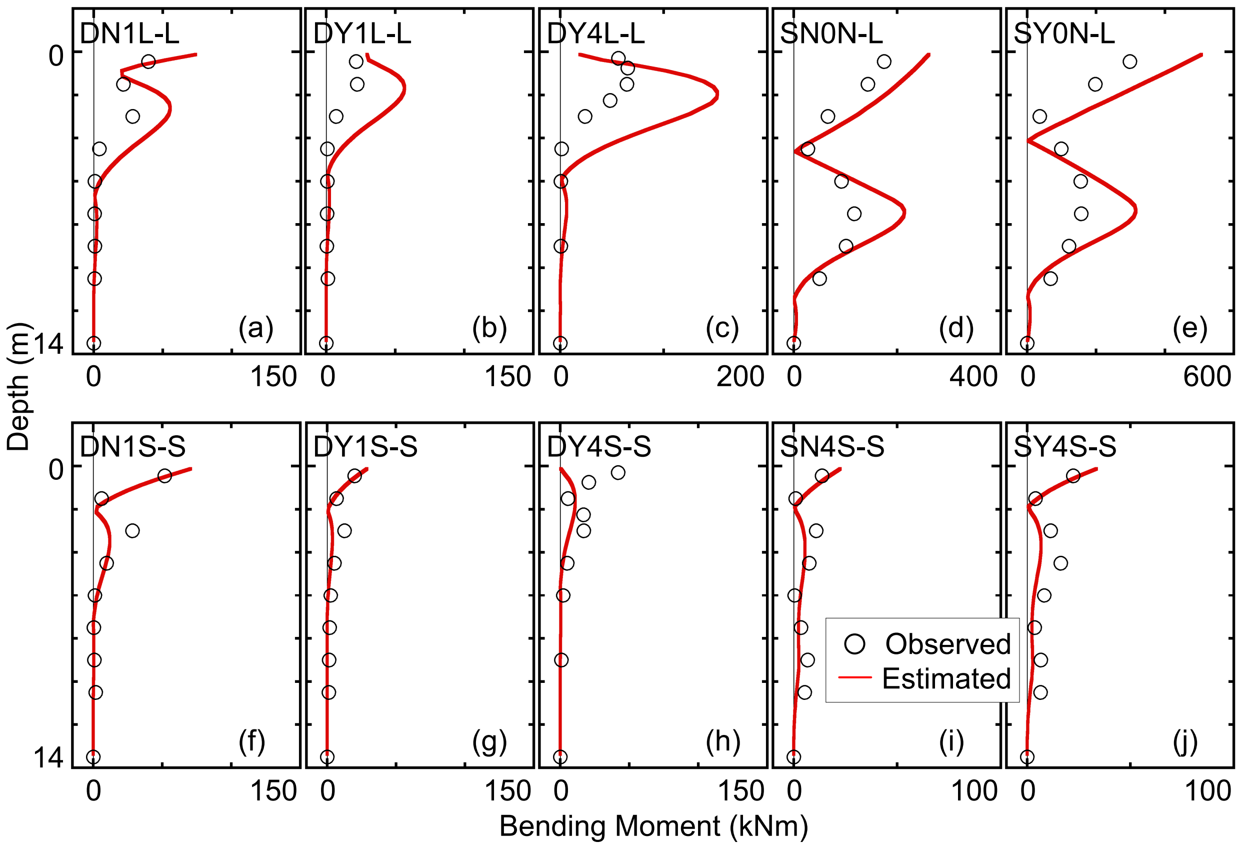

Figure 10. Distribution of observed and estimated bending moment

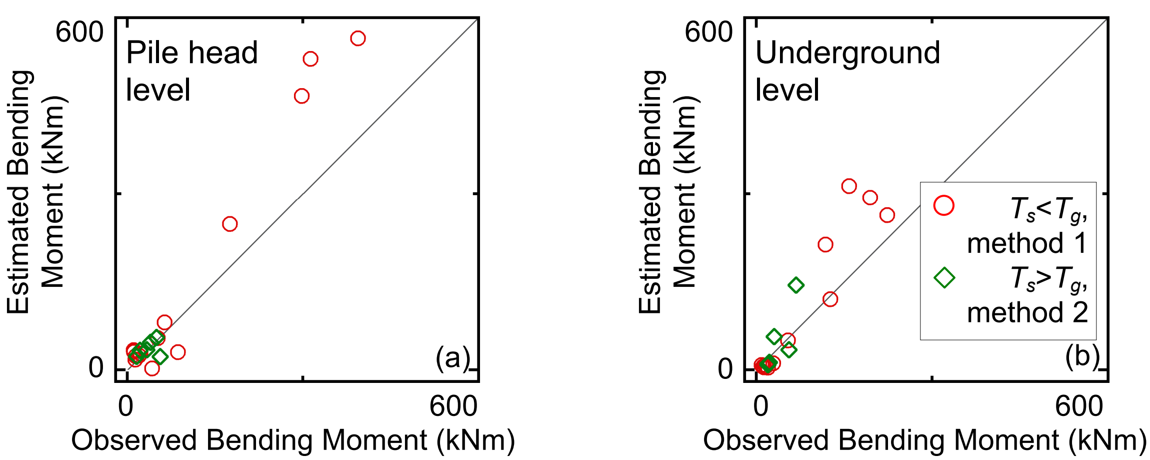

Figure 11. Relation of observed and estimated bending moment

seem to be slightly overestimated. Overall, the results indicate that the pseudo-static analysis together with the consideration of the effects of ground displacement is promising for estimating pile stress.

Discussions and Conclusions

The effects of inertial and kinematic forces on pile stresses have been studied based on centrifuge model tests on pile-structure models. A pseudo-static analysis has been conducted to estimate pile stress in the tests. The results and analysis have shown the following:

(1) Relation between the natural period of superstructure (T_s) and that of soil (T_g) has to be taken into account in seismic design of piles using pseudo-static analysis.

(2) If T_s is shorter than T_g, the maximum bending moment can be estimated by applying inertial force and ground displacement simultaneously. If T_s is greater than T_g, the maximum bending moment can be estimated by applying inertial force and ground displacement separately, and combining the results using square root of sum of squares method.

(3) The pile stresses from the pseudo-static analysis are in good agreement with the observed values, regardless of the soil condition, mass of superstructure, the relation of natural periods between the superstructure and ground, the presence of foundation embedment, and input motion. This suggests that the pseudo-static analysis is promising for estimating pile stress with a reasonable degree of accuracy.

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