CENTRIFUGE TESTS OF IMPULSIVE VERTICAL ACCELERATION GENERATED BY FOUNDATION UPLIFT DURING STRONG SHAKING

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ABSTRACT

Dynamic centrifuge tests were performed using soil-footing-superstructure models to investigate the effects of the roughness of the soil-footing interface on the uplift and the resulting vertical acceleration of the footings during strong shaking. Four footing models, each of which had a smooth or rough surface and was embedded or not embedded in soil, were subjected to strong shaking. The horizontal shearing and the vertical compressive forces on the base of each footing, as well as the earth pressure and the wall friction forces on the active/passive sides of each footing, were elaborately measured with newly developed 2D load cells. It was shown that (1) the collision impulse of the uplifted footing against the ground induced an extremely high vertical acceleration of the structure, which was much larger than could be induced by the vertical movement of the gravitational center of the structure; (2) the vertical acceleration caused by the collision impulse increased with the induced rotation angle of the footing; (3) if the footing was not embedded in the ground, the rotation angle and the resulting vertical acceleration tended to be larger for the rough footing than for the smooth footing, probably because the larger horizontal sliding of the smooth footing was able to reduce the footing rotation; and (4) if the footing was embedded, by contrast, the rotation angle and the resulting vertical acceleration tended to be smaller for the rough footing than for the smooth footing, probably because the larger wall friction that developed on the passive side in the rough footing was able to reduce the footing rotation.

Key words: centrifuge model test, (collision impulse), earthquake, (foundation uplift), shallow foundation, soil and structure interaction, (vertical acceleration) (IGC: E8/E12)

INTRODUCTION

The aspect ratio, the height to width ratio, of a building supported by a shallow foundation, has a significant effect on the response of the building during strong shaking, as it controls the foundation uplift. For example, a number of structures with high aspect ratios survived the ground shaking during the 1960 Chilean earthquake, whereas those with low aspect ratios were severely damaged (Housner, 1963). Housner (1963), in his pioneering study of foundation uplift, suggested that the stability of a tall, slender block subjected to earthquake motion would be much greater than its stability against a constant horizontal force. Subsequently, many researchers have studied the effects of foundation uplift on the seismic response of structures. Based on a numerical analysis, Meek (1975) indicated that uplift leads to a favorable reduction in structural deformation. And, according to shaking table tests and the two-dimensional numerical analysis of a model nine-story building frame, Hueckelbridge and Clough (1978) reported that uplift brings about a general reduction in the applied load. To consider the beneficial effects of foundation uplift in computing the earthquake response of structures, Chopra and Yim (1985) and Yim and Chopra (1985) proposed simplified analyses of the response of structures to foundation uplift.

In the last 20 years, a number of numerical studies have been carried out to evaluate the effects of foundation uplift quantitatively. Psycharis (1991) showed that the effects of foundation uplift on the maximum deformation of superstructures are greatly influenced by the ratio of the period of the structure to the period of the excitation. Wang and Gould (1993) reported that not only the uplift, but also the sliding of a foundation, reduced the response of the structure. From a field performance on buildings affected by the 1995 Hyogo-ken Nanbu Earthquake, Hayashi (1996) indicated that the reduction in damage caused by foundation uplift would have been drastic for buildings with fewer than 15 stories and with foundation widths under 15 m. Gazetas et al. (2010) showed that foundation uplift depends on the static safety factor, which is defined by the ratio of vertical foundation load to ultimate vertical capacity.

To examine the numerical analyses and to investigate the nonlinearity of the soil-structure interaction and the
validity of the numerical studies, various experiments have also been conducted. These include large-scale cyclic loading tests (e.g., Negro et al., 2000), shaking table tests (e.g., Suzuki et al., 1992; Maugeri et al., 2000; Paolucci et al., 2008), and centrifuge tests (e.g., Gajan et al., 2005; Seki, 2008). Previous studies have shown that foundation uplift depends on various conditions, such as the height and the natural period of the superstructure, the foundation size, the structure weight, the soil conditions, the local soil nonlinearity, and the type of input earthquake motion.

Unlike the above-cited studies, which deal with the positive effects of foundation uplift, Meek (1975) predicted the negative effects of foundation uplift, characterized by collision impulses when the foundation slams into contact repeatedly with the ground. Hucklebridge and Clough (1978) reported that the loading impulses do not significantly affect the story shear or the base-overturning moment. Based on a numerical analysis of reactor buildings subjected to both horizontal and vertical input motions, Muto and Kobayashi (1979) indicated that foundation uplift could induce two types of vertical acceleration, namely, collision impulse by foundation uplift and induced vertical acceleration by the height movement of the gravitational center of the structure. Furthermore, the former could be larger in acceleration amplitude than the latter. Tomura et al. (1988) and Shiomi (2006) also studied the effects of induced vertical acceleration on a nuclear power plant based on numerical analyses. Despite a large number of numerical analyses, few experimental studies are available on the collision impulse generated by foundation uplift.

The objectives of this study are to evaluate the vertical acceleration caused by foundation uplift during strong shaking and to investigate the effects of surface roughness and the embedment of footings on the vertical acceleration. For this purpose, dynamic centrifuge tests on superstructure-footing models with smooth and rough surfaces were performed, in which each footing was either placed on the ground surface or embedded in a sand layer.

**CENTRIFUGE TESTS**

*Test Cases*

Four dynamic centrifuge tests were performed on soil-foundation-superstructure models at a centrifugal acceleration of 40 g using the geotechnical centrifuge at the Disaster Prevention Research Institute, Kyoto University. Table 1 shows all the test cases in which the geological conditions of the foundation, i.e., embedment and roughness, were varied. Each case was labeled with two symbols. The first one indicates whether the footing model was embedded or not (N: No or E: Yes), while the second one defines the roughness of the footing base and the active/passive side walls (R: rough or S: smooth). Figures 1(a) and (b) show the test setup and the instrumentation for the four cases. Each soil-footing-superstructure system was prepared in a laminar shear box with inner dimensions of 450 mm (length) × 150 mm (width) × 200 mm (height). Table 2 summarizes the weights and the dimensions of the footing-superstructure models in the model and the prototype scales. Each footing was modeled with an aluminum alloy of 124 mm (shaking direction) × 64 mm (width) × 52 mm (height). The superstructure modeled with rigid brass of 82 mm (shaking direction) × 58 mm (width) × 50 mm (height) was supported by two plate springs (35 mm height). The weight of the superstructure was 2.0 kg and that of the technical conditions of the foundation, i.e., embedment and roughness, were varied. Each case was labeled with two symbols. The first one indicates whether the footing model was embedded or not (N: No or E: Yes), while the second one defines the roughness of the footing base and the active/passive side walls (R: rough or S: smooth). Figures 1(a) and (b) show the test setup and the instrumentation for the four cases. Each soil-footing-superstructure system was prepared in a laminar shear box with inner dimensions of 450 mm (length) × 150 mm (width) × 200 mm (height). Table 2 summarizes the weights and the dimensions of the footing-superstructure models in the model and the prototype scales. Each footing was modeled with an aluminum alloy of 124 mm (shaking direction) × 64 mm (width) × 52 mm (height). The superstructure modeled with rigid brass of 82 mm (shaking direction) × 58 mm (width) × 50 mm (height) was supported by two plate springs (35 mm height). The weight of the superstructure was 2.0 kg and that of the technical conditions of the foundation, i.e., embedment and roughness, were varied. Each case was labeled with two symbols. The first one indicates whether the footing model was embedded or not (N: No or E: Yes), while the second one defines the roughness of the footing base and the active/passive side walls (R: rough or S: smooth). Figures 1(a) and (b) show the test setup and the instrumentation for the four cases. Each soil-footing-superstructure system was prepared in a laminar shear box with inner dimensions of 450 mm (length) × 150 mm (width) × 200 mm (height). Table 2 summarizes the weights and the dimensions of the footing-superstructure models in the model and the prototype scales. Each footing was modeled with an aluminum alloy of 124 mm (shaking direction) × 64 mm (width) × 52 mm (height). The superstructure modeled with rigid brass of 82 mm (shaking direction) × 58 mm (width) × 50 mm (height) was supported by two plate springs (35 mm height). The weight of the superstructure was 2.0 kg and that of the technical conditions of the foundation, i.e., embedment and roughness, were varied. Each case was labeled with two symbols. The first one indicates whether the footing model was embedded or not (N: No or E: Yes), while the second one defines the roughness of the footing base and the active/passive side walls (R: rough or S: smooth). Figures 1(a) and (b) show the test setup and the instrumentation for the four cases. Each soil-footing-superstructure system was prepared in a laminar shear box with inner dimensions of 450 mm (length) × 150 mm (width) × 200 mm (height). Table 2 summarizes the weights and the dimensions of the footing-superstructure models in the model and the prototype scales. Each footing was modeled with an aluminum alloy of 124 mm (shaking direction) × 64 mm (width) × 52 mm (height). The superstructure modeled with rigid brass of 82 mm (shaking direction) × 58 mm (width) × 50 mm (height) was supported by two plate springs (35 mm height). The weight of the superstructure was 2.0 kg and that of the
footing was 1.0 kg. The natural frequency and the damping constant of the superstructure under the fixed footing conditions were about 105 Hz and 0.5%, respectively. The natural frequency corresponded to a 5- or 6-story building in the prototype scale. Dry sand was air-pluviated to prepare a uniform soil layer with $D_r = 90\%$. Toyoura sand with $D_{50} = 0.21$ mm was used for all the tests. The superstructure-foundation model for each of the four cases was set on the surface of the sand layer when its thickness reached 148 mm. Additional sand was then prepared for Cases ER and ES to embed the foundation to a depth of 50 mm. The total thickness of the sand layer was 148 mm for Cases NR and NS and 198 mm for Cases ER and ES. The static friction coefficient of the footings against Toyoura sand was 0.37 for Cases NS and ES, whereas it was 0.69 for Cases NR and ER in which Toyoura sand was pasted on the footing surfaces.

**Earth Pressure, Base Friction, and Soil-structure Response Measurements**

During earthquake shaking, the earth pressure and the sidewall and base friction forces acted on the embedded footings against the structure’s inertia force. Tamura et al. (2007) investigated the earth pressure and the sidewall friction (parallel to the direction of the shaking) acting on the embedded footings, supported by a pile foundation, and reported that the amplitude of the sidewall friction was much less than that of the earth pressure on the passive side in dense sand. This indicates that sidewall friction does not play an important role in the lateral response of shallow foundations. Therefore, this study focuses on the earth pressure and the base friction force for Cases ER and ES. Figure 2 shows the cross section of the foundation for Cases ER and ES, which contacts the sand in the plane parallel to the direction of the shaking with two base plates and two active/passive side plates. Each of these four plates was connected to the main body of the foundation with a newly developed load cell (Tokyo Sokki Kenkyujo Co., Ltd.), as shown in Photo 1, so as to indentify the forces acting on the foundation. Each load cell was designed to measure the normal and the shear forces acting on the attached plates separately. Therefore, the two load cells on the base plates provided horizontal shear and vertical forces, while the remaining two load cells attached to the side walls provided earth pressure and wall friction forces on the active/passive side plates. The base lines of the forces measured by the load cells were set to zero before the start of each centrifuge test.

Each shaking test was run using Rinkai92, i.e., a synthesized ground motion for the Tokyo Bay area, as the input horizontal motion without any vertical motion to the base of the container. The peak acceleration was scaled to about $5 \text{ m/s}^2$ in the prototype scale. In addition to the forces acting on the footings, described in the preceding paragraph, the horizontal and the vertical accelerations of the superstructure, the footings, the soil and the container base, as well as the horizontal and the vertical displacements of the footings were measured (Fig. 1). All data presented herein are of prototype scale and are based on the similitude law for dynamic centrifuge tests (Fuglsang and Ovesen, 1988).

**CENTRIFUGE TEST RESULTS**

*Soil-structure Responses for Cases NR and NS*

Figures 3 and 4 depict the selected time histories of important values for Cases NR and NS, respectively. These include the vertical acceleration of the footing, the ground surface and the container base, the horizontal acceleration of the superstructure, the top of the footing, the ground surface and the input, the horizontal displacement of the footing base and the ground surface, and the footing rotation. The vertical accelerations of the footing, the ground surface, and the container base were the average of the two values measured on the left and right sides. The measurement of the displacements by a laser displacement sensor was interrupted during the shaking because the footing moved considerably and the laser beam missed the targets. Thus, the displacements were calculated by the double integration of the accelerations, and therefore, correspond to those of the dynamic component. The footing rotation was evaluated as the ratio
of the relative displacement between the vertical displacements on the left and right sides of the footing, which were also calculated by the double integration of the accelerations, to the distance between the two sensors (clockwise rotation = positive).

The peak vertical ground surface acceleration was about 2.8 m/s² in both cases, despite the extremely small values (about 0.8 m/s² in both cases) for the container base. Unlike the horizontal acceleration response described below, the peak vertical acceleration of the footing (6.4 m/s² in Case NR and 3.9 m/s² in Case NS) became larger than those of the ground surface in both cases. In particular, it is significantly larger in Case NR, with much greater amplitude on the positive side than on the negative side.

The peak horizontal accelerations of the ground surface in Cases NR and NS were 8.3 m/s² and 7.9 m/s², respectively. The peak horizontal acceleration of the footing in both cases was about 4.5 m/s², which is apparently smaller than those on the ground surface. This suggests the positive effects of the soil-structure interaction on the horizontal response of the superstructure. The peak horizontal accelerations of the superstructure in Cases NR and NS were 7.2 m/s² and 5.7 m/s², respectively, which are still smaller than those of the ground surface, but are larger than those of the footing. In particular, the peak acceleration of the superstructure was significantly smaller in Case NS than in Case NR, suggesting that a smooth interface of the foundation without embedment could reduce the horizontal response of a superstructure.

The peak horizontal displacement of the footing base became larger than that of the ground surface for both cases. This tendency is significant in Case NS. The footing rotates in spite of the extremely small rotation angle at the shear box base, which is less than 0.008 in radian for all cases. The footing rotation angle was obviously larger in Case NR than in Case NS. This indicates that the sliding of the footing reduces not only the response of the superstructure, but also the amount of uplift. A similar trend has been pointed out by Wang and Gould (1993).

**Soil-structure Responses for Cases ER and ES**

Figures 5 and 6 depict the time histories of the same values as those shown in Figs. 3 and 4, together with those of the horizontal displacement of the soil beneath the footing (1 m in depth from the footing base) for Cases ER and ES, respectively. The peak vertical ground surface acceleration was about 2.8 m/s² in both cases, despite extremely small values on the container base (about 0.3 m/s² in both cases). As in the cases without embedment, the peak vertical accelerations (5.8 m/s² in Case ER and 7.4 m/s² in Case ES) of the footing were apparently larger than those of the ground surface in both cases. In particular, when the foundation was embedded, the effects of the foundation roughness became reversed, i.e., the peak vertical acceleration in Case ES (smooth
foundation) became significantly larger than that in Case ER (rough foundation), with amplitude much greater and more spiky on the positive side than on the negative side.

The peak horizontal ground surface acceleration was 7.1 m/s² in Case ER and 7.5 m/s² in Case ES. The peak horizontal accelerations of the footing for both cases (5.5 m/s² in Case ER and 7.0 m/s² in Case ES) were smaller than those of the ground surface, as is the case in the series without embedment. Unlike the tendency observed in the cases without embedment, however, the peak horizontal accelerations of the superstructure in both cases were similar (8.0 m/s² in Case ER and 8.3 m/s² in Case ES), suggesting that the footing surface roughness would not have a strong effect on the horizontal response of the superstructure when the foundation is embedded. The effects of the foundation surface roughness on the horizontal response of the superstructure have been presented elsewhere (Tamura et al., 2010). The horizontal displacements of the footing were also similar in amplitude for the two cases. However, the footing rotation angle was smaller in Case ER than in Case ES.

**VERTICAL ACCELERATION CAUSED BY FOOTING UPLIFT**

**Footing Responses during Earthquakes**

The centrifuge test results show that high vertical accelerations exceeding 7 m/s² occurred on the footing, in spite of the absence of vertical input motion. To discuss why such high vertical accelerations were induced on the footing, Fig. 7 depicts selected time histories of important values for Case NR for a period of 3 seconds ($T = 22–25$ s) in which the footing rotation has a peak value (Fig. 3(i)). These include the horizontal acceleration of the superstructure, the vertical accelerations on the left and right sides of the footing and their average, the vertical forces acting on the left and right sides of the footing base and their sum, the vertical velocities of the left and right sides of the footing, and the footing rotation.

The horizontal acceleration of the superstructure and the footing rotation (Figs. 7(a) and (e)) have positive peaks at $T = m1$ and $m3$, respectively. The vertical force on the footing base during both instants is almost zero on the left side (the dotted line in Fig. 7(c)), indicating that the footing did uplift on this side. The vertical acceleration on the footing, by contrast, has a large negative peak on the left side (the dotted line in Fig. 7(b)), but with zero or a very small value on the opposite (right) side (the solid gray line in Fig. 7(b)).

The horizontal acceleration of the superstructure and the footing rotation (Figs. 7(a) and (e)) both have a negative peak at $T = m2$. The trends observed at this instant, if horizontally reversed, are basically the same as those observed at $T = m1$ and $m3$. In other words, the vertical force on the footing base is almost zero on the right side,
indicating that the footing did uplift on this side. The vertical acceleration, in contrast, has a large negative peak on the right side, but with zero on the opposite (left) side (Fig. 7(b)). This indicates that the negative vertical acceleration at this instant varies within the foundation. Further examination indicates that the negative peak of the average vertical acceleration (the solid thick line in Fig. 7(b)) would be approximately half of that occurring at the same instant on either side of the foundation.

In spite of the fact that the horizontal acceleration of the superstructure and the footing rotation are almost zero at $T=p_1$, $p_2$, and $p_3$ (Figs. 7(a) and (e), respectively), the vertical accelerations on the footing have large positive peaks (Fig. 7(b)) on both sides. Unlike the instants producing negative peak vertical accelerations, the positive peaks do occur on both sides. The positive peak of the average vertical acceleration (the solid thick line in Fig. 7(b)) would be approximately the same as that occurring anywhere on the foundation.

The velocities were calculated by the integration of the acceleration. The sum of the vertical forces acting on the footing is very similar in waveform to that of the average of the vertical accelerations of the footing, suggesting that the vertical forces measured by the small load cells are reasonably accurate. The vertical solid lines ($T=p_1$, $p_2$, and $p_3$) and the dotted lines ($T=m_1$, $m_2$, and $m_3$) in the figure correspond to the instants when the average vertical acceleration of the footing (the solid thick line in Fig. 7(b)) has a positive peak and a negative peak, respectively. It is interesting to note that the peak average vertical acceleration is significantly greater on the positive side than on the negative side, which was also discussed in a preceding paragraph.

Based on the above findings and discussions, Fig. 8 shows a schematic diagram of the relation among the footing rotation, the superstructure’s inertia force, and the vertical accelerations for a shallow foundation. In Types $A_L$ and $A_R$, the large inertial force acting on the superstructure was able to trigger the uplift of the footing on the side opposite to the direction of the inertia force. This caused downward accelerations varying within the footing. Vertical acceleration is called “induced vertical acceleration”, and it is generated by the movement of the gravitational center of the structure following the uplift of the footing (Muto and Kobayashi, 1979; Tomura et al., 1988; Shiomi, 2006). In Types $B_L$ and $B_R$, without any horizontal inertial force from the superstructure, larger upward accelerations with the same amplitude developed throughout the footing. The vertical acceleration of this type seems to be caused by the collision impulse between the footing and the soil, because it occurs when the footing reattaches to the soil. This is the reason why high vertical accelerations occur during strong shaking on the footing without the presence of the vertical input motion and why the peak average vertical acceleration is significantly greater on the positive side than on the negative side.

**Impulsive Vertical Acceleration and the Law of Conservation of Momentum**

According to the law of conservation of momentum, if the vertical acceleration in Type B is caused by the collision impulse, then the impulse of the variation in vertical force acting on the footing base should be equal to the momentum of the footing-superstructure, as follows:

$$\int_{t_1}^{t_2} F_l(t)dt = m_f \cdot (v_{fs}(t_1) - v_{fs}(t_2)) + m_s \cdot (v_{sv}(t_1) - v_{sv}(t_2))$$  \hspace{1cm} (1)

where $F_l(t)$ is the variation in vertical force, evaluated by subtracting the weight of the structure from the vertical force acting on the footing base, $t_1$ and $t_2$ are the times when the vertical force acting on the footing base is equal to the weight of the footing-superstructure, the vertical force is greater than the weight in amplitude between $t_1$ and $t_2$, $m_f$ and $m_s$ are the mass of the superstructure and of the footing, respectively, and $v_{fs}(t)$ and $v_{sv}(t)$ are the vertical velocities of the superstructure and the footing’s center of gravity, respectively. Figure 9 shows the relation between the impulse of the vertical force variation


Figure 9. Relation between momentum of footing-superstructure and impulse of vertical force variation acting on footing base for $T = 0-40\text{ s}$ (Case NR)

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**EFFECTS OF FOOTING SURFACE ROUGHNESS ON IMPULSIVE VERTICAL ACCELERATION**

Figure 10 shows the relation of the footing rotation angle and the vertical acceleration, for all the cases, of the left and right sides and their average, which correspond to and are assumed to be at the center of the foundation. When the footing is rotated clockwise (positive angle), the vertical acceleration on the left-side footing is a large negative value, while the accelerations of the other two locations are small values. When the footing is rotated counterclockwise (negative angle), the trends are reversed, but only the vertical acceleration on the right is a large negative value. When the footing rotation is zero, the vertical accelerations at the three locations are large positive values. The positive vertical acceleration caused by the re-contact (the footing rotation is zero) is significantly influenced by the surface roughness and the embedment of the footing. For example, the positive vertical accelerations at re-contact are the greatest in Case ES among the four cases, while they are the smallest in Case NS. Discussed in the following section are the effects of surface roughness and the embedment of the footing on the impulsive vertical acceleration.

**Footing Rotation and Impulsive Vertical Acceleration in Cases NR and NS**

The impulsive vertical acceleration is apparently larger in Case NR than in Case NS, suggesting that it increases with surface roughness for foundations without embedment. Equation (1) and Fig. 9 suggest that the impulsive vertical acceleration depends on the peak vertical velocity of the footing just before re-contact. Figures 11(a) and (b) show the relation between the peak vertical velocity of the re-contact side of the footing (Point B in Fig. 7) and the corresponding impulsive vertical acceleration (Point B in Fig. 7) for each re-contact in Cases NR and NS, respectively. It seems that the impulsive vertical accelerations in both cases increase linearly with the increasing vertical velocity. Since the vertical velocity of the footing is larger in Case NR than in Case NS, the impulsive vertical acceleration is larger in Case NR than in Case NS.

To discuss why the vertical velocity is larger in Case NR than in Case NS, Figs. 12(a) and (b) show the relation between the preceding peak rotation angle (Point C in Fig. 7) and the vertical velocity of the footing just before re-contact (Point A in Fig. 7) in Cases NR and NS, respectively. The vertical velocity of the footing in both cases tends to increase with the increasing footing rotation. The induced rotation angle of the footing is significantly larger in Case NR than in Case NS, and thus, the vertical velocity tends to be larger in Case NR than in Case NS.

Figures 13(a) and (b) show the relation between the preceding peak rotation angle of the footing (Point C in Fig. 7) and the impulsive vertical acceleration (Point B in Fig. 7) for each re-contact in Cases NR and NS, respectively. The impulsive vertical acceleration increases with the increasing rotation angle of the footing. Since the induced maximum rotation angle of the footing is much larger in Case NR than in Case NS, it leads to a larger impulsive vertical acceleration in Case NR.

**Superstructure Responses and Impulsive Vertical Acceleration in Cases NR and NS**

To investigate why the rotation angle of the footing is larger in Case NR than in Case NS, Fig. 14 shows the relation between the peak rotation angle of the footing (Point C in Fig. 7) and the horizontal acceleration of the superstructure at the same instant (Point D in Fig. 7) for the two cases. The peak rotation angle of the footing increases linearly with the increasing horizontal acceleration of the superstructure up to about 5 m/s², and then it increases more rapidly, the trend of which is independent of the cases. The maximum horizontal acceleration of the superstructure in Case NR is about 7 m/s², which is larger than that in Case NS. Therefore, the rotation angle of the footing in Case NR is larger than that in Case NS.

Figures 15(a) and (b) show the relation between the relative displacement and the horizontal base friction in Cases NR and NS, respectively. The horizontal base friction is the sum of the horizontal forces acting on the left sides of the footing base plates. The relative displacement is assumed to be the difference between the footing base plate and the ground surface of the free
field. The friction–displacement loops for the two cases are quite different. The base friction up to about 800 kN in Case NR is induced by a small relative displacement and is mobilized at about 900 kN, accompanied by a relative displacement. The base friction in Case NS, by contrast, is mobilized at a lower value of about 600 kN, but results in a larger relative displacement due to its smoother base surface. Since the base friction that developed in the system without embedment corresponds to the footing-superstructure’s inertia, it is reasonable to consider that the superstructure’s inertia in Case NR becomes greater than that in Case NS.

Figure 16 shows a schematic diagram related to the effects of footing roughness on the footing rotation angle. The rough footing in Case NR (Fig. 16(a)) can bear a larger base friction which leads to a higher inertial force of the superstructure, and thus, a larger rotation angle of the footing. The smooth footing in Case NS (Fig. 16(b)) can bear a smaller base friction which leads to the sliding of the footing, and thus, a smaller inertial force of the superstructure and a smaller rotation angle of the footing. Therefore, the impulsive vertical acceleration becomes...
Fig. 11. Relation between peak vertical velocity of re-contact side of footing and corresponding impulsive vertical acceleration for $T = 0–40$ s (Cases NR and NS)

Fig. 12. Relation between peak footing rotation angle and corresponding vertical footing velocity of re-contact side of footing for $T = 0–40$ s (Cases NR and NS)

Fig. 13. Relation between peak footing rotation angle and corresponding impulsive vertical acceleration for $T = 0–40$ s (Cases NR and NS)

Fig. 14. Relation between peak footing rotation angle and horizontal acceleration of superstructure at the same instance for $T = 0–40$ s (Cases NR and NS)

Fig. 15. Relation between relative displacement and horizontal base friction force for $T = 20–40$ s (Cases NR and NS)

Fig. 16. Effects of footing surface roughness on footing rotation angle

Fig. 17. Relation between peak vertical velocity of re-contact side of footing and corresponding impulsive vertical acceleration for $T = 0–40$ s (Cases ER and ES)

larger in Case NR than in Case NS.

Footing Rotation and Impulsive Vertical Accelerations in Cases ER and ES

As was discussed with reference to Fig. 10 for the embedded footing, the impulsive vertical acceleration in Case ER (rough surface) is smaller than that in Case ES (smooth surface). This indicates that the rough surface of the embedded footing decreases the impulsive vertical acceleration, the trend of which is opposite to that of the footing which is not embedded. To investigate the mechanism of the difference in vertical acceleration, Figs. 17(a) and (b) show the relation between the peak vertical velocity of the re-contact side of the footing and the corresponding impulsive vertical accelerations in Cases ER and ES, respectively. The vertical velocity amplitude is smaller in Case ER than in Case ES. As a result, the im-
Fig. 18. Relation between peak footing rotation angle and corresponding vertical footing velocity of re-contact side of footing for $T=0$–$40$ s (Cases ER and ES).

Fig. 19. Relation between peak footing rotation angle and corresponding impulsive vertical acceleration for $T=0$–$40$ s (Cases ER and ES).

Fig. 20. Relation between peak footing rotation angle and horizontal acceleration of superstructure at the same instance for $T=0$–$40$ s (Cases ER and ES).

Fig. 21. Relation between footing rotation angle and wall friction acting on active/passive sides for $T=20$–$40$ s (Cases ER and ES).

Fig. 22. Effects of footing surface roughness on footing rotation angle for Cases ER and ES.

The impulsive vertical acceleration is smaller in Case ER than in Case ES.

Figures 18 and 19 show the relation of the preceding peak rotation angle of the footing with the corresponding vertical velocity and the impulsive vertical acceleration of the footing for Cases ER and ES, respectively. The rotation angle of the footing is smaller in Case ER than in Case ES, and thus, the vertical velocity amplitude is smaller in Case ER (Fig. 18). As a result, the impulsive vertical acceleration is smaller in Case ER than in Case ES (Fig. 19), indicating that the impulsive vertical acceleration depends on the rotation angle of the footing regardless of whether the footing is embedded or not.

Figure 20 shows the relation between the preceding peak rotation angle of the footing and the horizontal acceleration of the superstructure at the same instant for Cases ER and ES. The rotation angle of the footing for both cases increases significantly when the horizontal acceleration of the superstructure exceeds about 5 m/s². It is noteworthy that the maximum rotation angle of the footing is smaller in Case ER than in Case ES, although the horizontal acceleration of the superstructure is slightly larger in Case ER than in Case ES. The trend observed here for the embedded footings is quite different from that for the footings which are not embedded (Cases NR and NS).

In order to study the reason why the rough surface of the embedded footing reduced the rotation angle, Figs. 21(a) and (b) show the relation between the rotation angle of the footing and the vertical shearing force acting on the active/passive sides (wall friction) in Cases ER and ES, respectively. When the footing is rotated clockwise in both cases, the wall friction force on the right side (passive side) of the footing has a larger value and acts upwardly, while that on the left side (active side) has a smaller value and acts downwardly. In spite of the small footing rotation angle, the wall friction, particularly on the passive side, is much greater in Case ER than in Case ES.

Figures 22(a) and (b) illustrate the direction of the superstructure’s inertia force and wall friction when the footing is rotated clockwise for Cases ER and ES, respectively. The moment with respect to the center of the footing induced by both wall friction forces is counterclockwise, namely, it is opposite to the footing rotation in-
Dynamic centrifuge tests were performed using soil-footing-superstructure models to investigate the effects of the roughness of the soil-footing interface on the uplift and the resulting vertical acceleration of the footings during strong shaking. Four footing models, each of which had a smooth or rough surface and was embedded or not embedded in soil, were subjected to strong shaking. The horizontal shearing and the vertical compressive forces on the base of the footings, as well as the earth pressure and the wall friction forces on active/passive sides of the footings, were elaborately measured with newly developed 2D load cells. The following conclusions were drawn:

1. The collision impulse of the uplifted footing against the ground induced extremely high vertical acceleration of the structure, which was much larger than could be induced by the vertical movement of the gravitational center of the structure.
2. The vertical acceleration caused by the collision impulse increased with the induced rotation angle of the footing.
3. When the footing was not embedded in the ground, the rotation angle and the resulting vertical acceleration tended to be larger in the rough footing than in the smooth footing, probably because the larger horizontal sliding of the smooth footing was able to reduce the footing rotation.
4. When the footing was embedded, by contrast, the rotation angle and the resulting vertical acceleration tended to be smaller in the rough footing than in the smooth footing, probably because the larger wall friction on the passive side that developed in the rough footing was able to reduce the footing rotation.

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