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VERTICAL ACCELERATION CAUSED BY FOUNDATION UPLIFT DURING STRONG EARTHQUAKE

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ABSTRACT

Dynamic centrifuge tests were performed using soil-footing – superstructure models to investigate the effects of footing uplift on the vertical acceleration of a footing during strong shaking. The horizontal shearing and vertical compressive forces on the base of the footing, as well as the earth pressure and wall friction force on both sides of the footing, were measured carefully using newly developed 2D-load cells. The following conclusions were drawn. (1) The foundation uplift induces vertical acceleration of two types on an embedded footing: "impulsive vertical acceleration" caused by the collision impulse between the foundation and soil and "induced vertical acceleration" caused by the height movement of the gravitational center of structure. (2) The amplitude of the impulsive vertical acceleration, more than 12 m/s^2, is much greater than that of the induced vertical acceleration. (3) When the horizontal superstructure acceleration exceeds about 5 m/s^2, the amplitudes of the impulsive vertical acceleration and the induced vertical acceleration increase dramatically, suggesting that a small earthquake will generate only small vertical acceleration but that an intense earthquake will trigger the foundation uplift and generate extremely high vertical acceleration especially by the collision impulse. (4) The amplitudes of both vertical accelerations increase with the induced rotation angle of the footing.

Keywords: Shallow foundation, Foundation uplift, Vertical acceleration, Centrifuge test, Collision impulse

INTRODUCTION

A slender building supported by a shallow foundation might be uplifted along with rocking during an intense earthquake. Houser (1963), in his pioneering study of the foundation uplift, suggested that the stability of a tall, slender block subjected to earthquake motion is much greater than would be inferred from its stability against a constant horizontal force. Subsequently, many researchers studied the effects of foundation uplift on the seismic response of structures. Based on numerical analyses, Meek (1975) reported that the uplift engenders a favorable reduction in the structural deformation. Based on model nine-story building frame shaking table tests and two-dimensional numerical analyses, Huckelbridge and Clough (1978) reported that the uplift causes a general reduction in the applied loading. To consider the beneficial effects of foundation uplift, Chopra et al. (1985) proposed a simplified analysis of the structure response associated with foundation uplift.

Meek (1975) also predicted negative effects of foundation uplift, as characterized by collision impulses when the foundation slams into renewed contact with the ground. Based on numerical analyses of reactor buildings subjected to both horizontal and vertical input motions, Muto and Kobayashi (1979) reported that

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foundation uplift can induce vertical acceleration of two types: a collision impulse caused by the foundation uplift and induced vertical acceleration caused by the height movement of the gravitational center of the structure. They also reported that the former can have greater acceleration amplitude than the latter. Despite numerous numerical analyses, few experimental studies have examined the collision impulse generated by the foundation uplift.

The objective of this study is to examine the vertical acceleration of those two types caused by foundation uplifting that occurs during strong shaking. A dynamic centrifuge test on a superstructure–footing model was performed, with the footing embedded in the sand layer.

CENTRIFUGE TEST

Test model

A dynamic centrifuge test was conducted using a soil-foundation – superstructure model at 40 × *g* centrifugal acceleration with the geotechnical centrifuge at the Disaster Prevention Research Institute, Kyoto University. Figure 1 shows the test setup and instrumentation. The 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 1 presents the weights and dimensions of the footing–superstructure model in the model and prototype scales. The footing was modeled with 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 35-mm-high plate springs. The superstructure weight was 2.0 kg. That of the footing was 1.0 kg. The natural frequency and damping constant of the superstructure under the fixed footing condition were, respectively, about 105 Hz and 0.5%. 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 the test. The soil model heights were 198 mm; the footing was embedded 50 mm into the dry sand layer. The static friction coefficient between Toyoura sand and the footing surface was 0.37.

Earth pressure, base friction, and soil-structure responses measurements

Figure 2 portrays a detailed cross section of the foundation in the plane parallel to the direction of 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

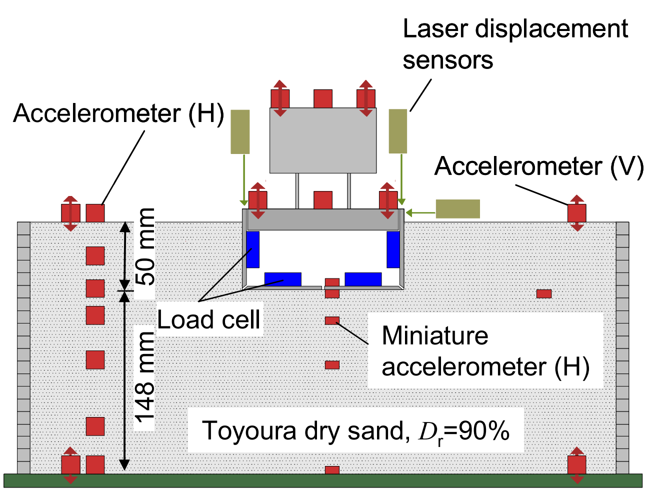


Figure 1. Test model

Table 1. Weights and dimensions of the footing– superstructure model in the model and prototype scale

		Unit	Prototype	Model
Footing	Mass	kg	64,000	1.0
	Length (L×B×H)	m	4.96×2.56×2.08	0.124×0.064×0.052
Structure	Mass	kg	128,000	2.0
	Natural frequency	Hz	3.8	105

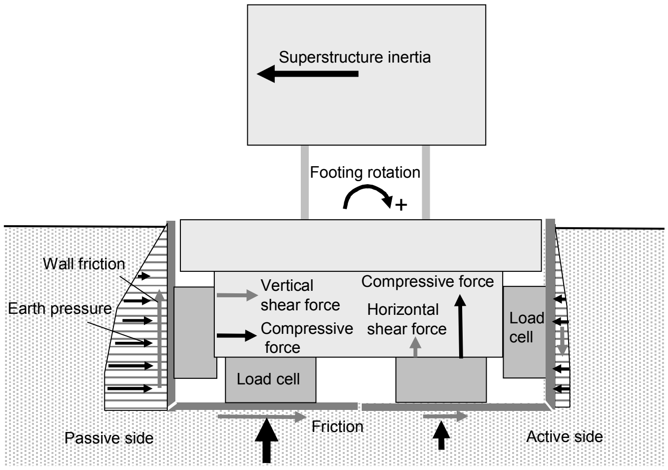
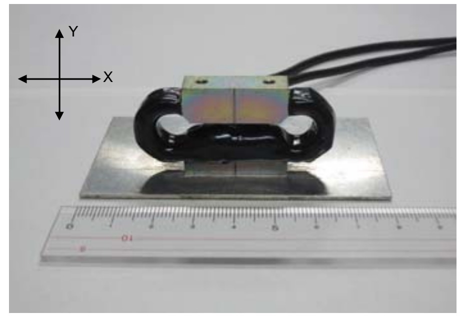


Figure 2. Earth pressure and base friction measurements



Picture 1. Two-directional load cell capable of separate measurements from horizontal and vertical forces

in Photo 1, to identify forces acting on the foundation. Each load cell was designed to measure normal and shear forces acting on the attached plate separately. The two load cells on the base plates therefore provided the horizontal shear and vertical forces. The remaining two attached on the side walls provided the earth pressure and wall friction force on the active and passive side plates. The base lines of the forces measured by the load cells were set to zero before the start of centrifuge test.

The shaking test was run using Rinkai92, i.e., a synthesized ground motion for the Tokyo Bay area, as the input horizontal motion with no vertical motion to the base of the container. The peak acceleration was scaled to about 5 m/s^2 in prototype scale. In addition to forces acting on the footing described in the preceding paragraph, the horizontal and vertical accelerations of superstructure, footing, soil and container base were measured, as well as the horizontal and vertical displacement of the footing (Fig. 1). All data presented herein are of prototype scale.

CENTRIFUGE TEST RESULTS

Horizontal acceleration and footing rotation

Figure 3 depicts the respective time histories of the horizontal acceleration of the input, the ground surface, the top of the footing and superstructure, and the footing rotation. 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 calculated by double integration of the accelerations, to the distance between the two sensors (clockwise rotation = positive). The peak horizontal accelerations of the ground surface and the superstructure are, respectively, 7.5 m/s^2 and 8.3 m/s^2. The amplitude of the horizontal superstructure acceleration tends to be nearly constant for T=20–40 s. However, the amplitude of the footing rotation, generated by the superstructure inertia, tends to change with time. Therefore, the waveform of the footing rotation angle differs greatly from that of the superstructure.

Vertical acceleration

Figure 4 shows the time histories of the vertical acceleration of the container base, the ground surface, and the footing, which are the average of the two values measured on the left and right sides and on the left and right sides of footing. The peak average vertical ground surface acceleration is about 2.8 m/s^2 despite extremely small values on the container base (about 0.3 m/s^2). The peak average vertical acceleration of the footing (7.4 m/s^2) is apparently larger than that of the ground surface. The peak vertical accelerations of

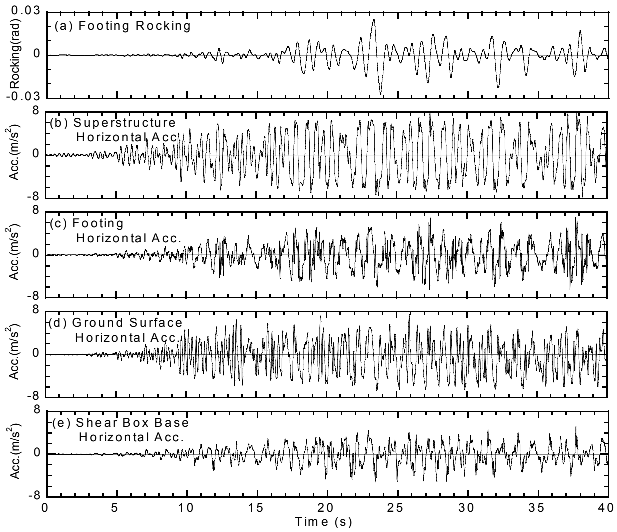


Figure 3. Time histories of horizontal accelerations and footing rotation

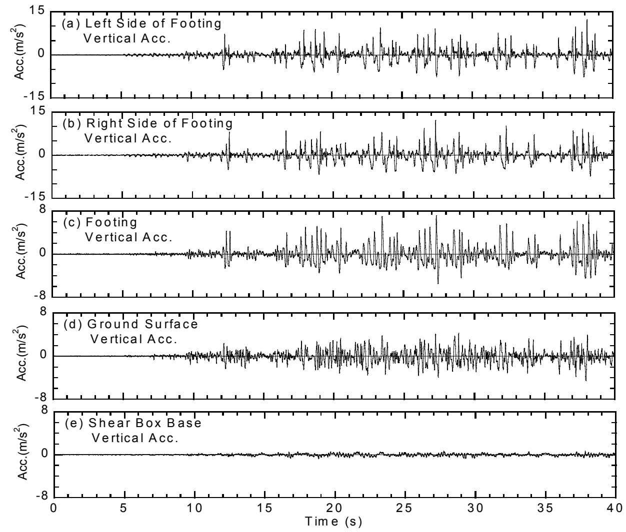


Figure 4. Time histories of vertical accelerations

both sides of the footing were extremely high: greater than 12 m/s^2. It is noteworthy that the positive vertical footing acceleration was spiky and much greater than the negative acceleration.

VERTICAL ACCELERATION CAUSED BY FOOTING UPLIFT

Footing rotation and superstructure acceleration

To investigate the effects of horizontal superstructure inertia on the footing rotation, the relation between the peak rotation angle of the footing and the horizontal acceleration of the superstructure at the same instance is presented in Fig. 5. The peak rotation angle of the footing increases linearly with increasing horizontal acceleration of the superstructure up to about 5 m/s^2. It then increases more rapidly, suggesting a nonlinear soil–structure interaction. Therefore, the waveform of the footing rotation angle differs from that of the horizontal superstructure acceleration, as presented in Figs. 3(a) and 3(b).

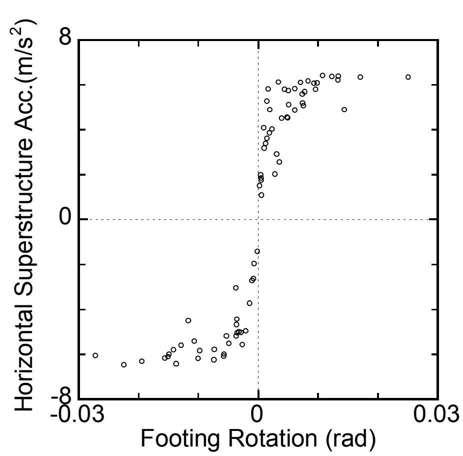


Figure 5. Relation between the peak footing rotation angle and horizontal acceleration of superstructure at the same instance for *T* =0– 40 s

Footing rotation and vertical acceleration on footing

The centrifuge test results show that high vertical acceleration exceeding 12 m/s^2 occurs on the footing in spite of the absence of the horizontal input motion. To discuss why such high vertical acceleration was induced on the footing, Fig. 6 depicts selected time histories of important values for a period of 3 s (*T*=22–25 s) during which the footing rotation has a peak value. These include the horizontal acceleration of the superstructure, vertical accelerations of left and right sides of footing and their average, the vertical shear force acting on active/passive sides (wall friction), the vertical forces acting on the left and right sides of footing base and their sum, and the footing rotation. The vertical solid lines (*T*=p1, p2) and the dotted lines (*T*=m1, m2) in the figure correspond respectively to the instants at which the average vertical acceleration of the footing has a positive peak and negative peak. It is noteworthy that the peak average vertical acceleration is significantly greater on the positive side than on the negative side, as discussed in the following paragraph.

The footing rotation (Fig. 6(e)) has positive peaks at T=m1. The vertical force on the footing base is almost zero on the left side (the blue dotted line in Fig. 6(d)), indicating that the footing was uplifted on this side. The wall friction force on the footing's right side (passive side) has a greater value and acts upward; that on the left side (active side) has a smaller value and acts downward, indicating that the former wall friction reduces the settlement of the footing's right side, but the latter wall friction does not reduce the uplift of the footing's left side. The vertical acceleration on the footing has a large negative peak on the left side (blue dotted line in Fig. 6(b)), but with a very small value on the opposite (right) side (red solid line in Fig. 6(b)).

The horizontal acceleration of the superstructure and the footing rotation (Figs. 6(a) and 6(e)) has a negative peak at T=m2. The trends observed at this instant, if horizontally reversed, are fundamentally the same as those observed at T=m1. That is, 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 was almost zero on the opposite (left) side (Fig. 6(b)), which indicates that the negative vertical acceleration at this instant varies within the foundation. Further examination reveals that the average of the negative peak vertical acceleration (black solid line in Fig. 6(b)) would be approximately half of that occurring at the same instance 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=p1and p2 (Figs. 6(a) and 6(e)), the vertical accelerations on the footing have large positive peaks (Fig. 6(b)) on both sides. Unlike the instants producing negative peak vertical acceleration, positive peaks

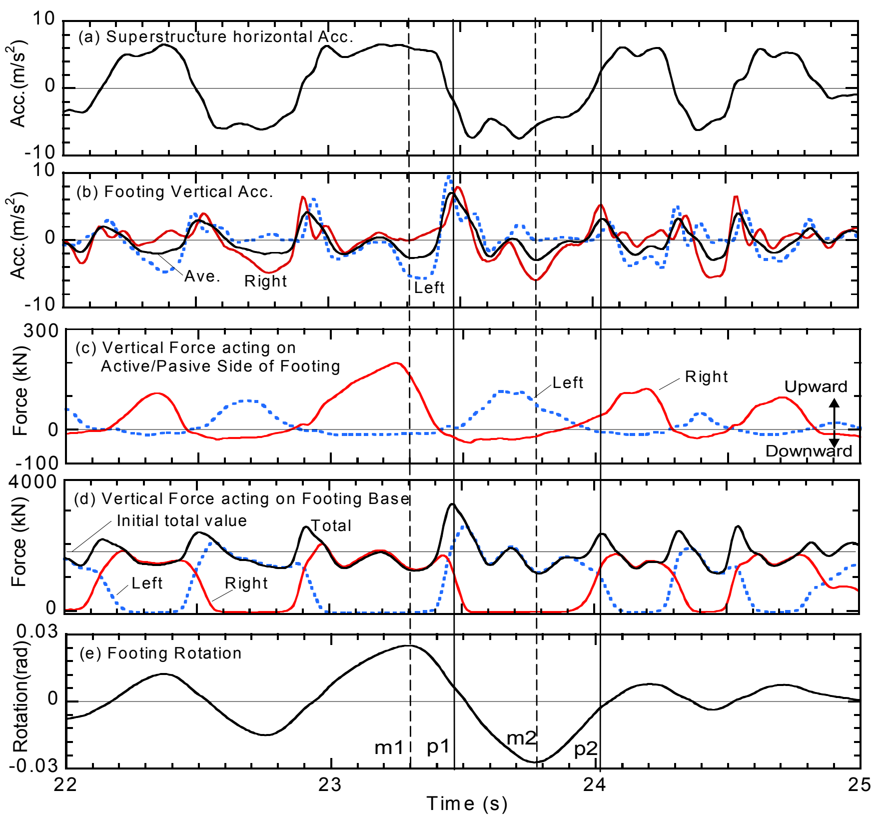


Figure 6. Time histories of footing responses and vertical force acting on the footing base for T=22– 25 s

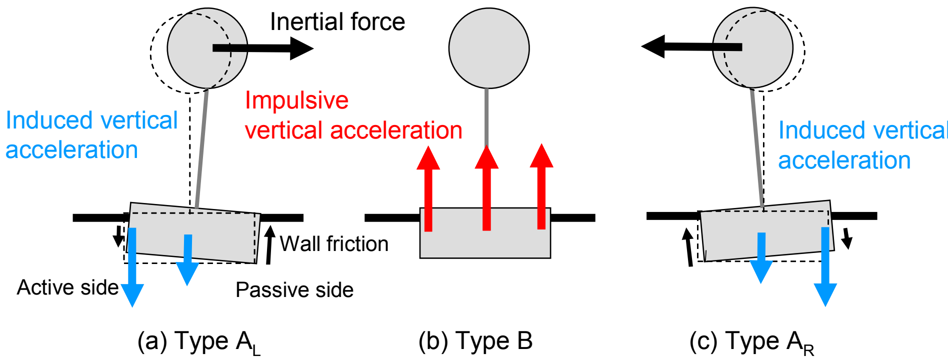


Figure 7. Schematic figure showing footing rotation, superstructure inertia force, and vertical accelerations

do occur on both sides. The average of the positive peak vertical acceleration (black solid line in Fig. 6(b)) would be approximately the same as that occurring anywhere on the foundation. The wall friction forces on the footing's both sides have a small value, probably because an extremely small superstructure inertia causes the earth pressure, which is nearly at rest state.

Based on the findings and discussions presented above, Fig. 7 portrays a schematic diagram showing the relation among the footing rotation, the superstructure inertia force, and the vertical accelerations acting on a shallow foundation. In Types A_L and A_R, a large inertial force acting on the superstructure might trigger an uplifting of the footing on the side opposite to the direction of the inertia force, which could cause varying downward accelerations within the footing. The resultant vertical acceleration is "induced vertical acceleration", the amplitude of which corresponds to the movement of the gravitational center of the structure following the footing uplift (Muto and Kobayashi, 1979). In Type B, with no horizontal inertial force from the superstructure, larger upward accelerations with the same amplitude develop throughout the footing. The vertical acceleration of this type seems to result from the collision impulse between the footing and soil because it occurs when the footing reattaches to the soil. For that reason, high vertical accelerations occur during strong shaking on the footing without the presence of the vertical input motion, which also explains why the peak average vertical acceleration is significantly greater on the positive side than on the negative side.

Impulsive vertical acceleration

To discuss the vertical acceleration of Type B in detail, a free body (mass *m*) falling from a specific height touches the ground at a velocity v_0, and comes to rest. Based on the law of conservation of momentum, the momentum, mv_0 is equal to an impulse as

$$\int_0^{t_f} F(t)dt = m \cdot v_0 \qquad (1)$$

where *F(t)* is the impulsive force when the body contacts the soil and t_f is the interval between the contact and the rest. In fact, *F(t)* can be expressed as follows.

$$F(t) = m \cdot a_v(t) \qquad (2)$$

In that expression, $a_v(t)$ is the impulsive vertical acceleration of the free body. Eqs. (1) and (2) suggest that the impulsive vertical acceleration on the footing caused by the collision impulse depends on the vertical footing velocity immediately before re-attachment.

Figure 8 presents the relation between the peak vertical velocity of the re-contact side of the footing and the corresponding average vertical acceleration (Type B) of the footing. The vertical acceleration increases concomitantly with the vertical velocity, indicating that the vertical acceleration of Type B was actually generated by the collision impulse between the footing and soil, as predicted numerically by Meek (1975) and Muto et al. (1979). The vertical acceleration of Type B will be called "impulsive vertical acceleration".

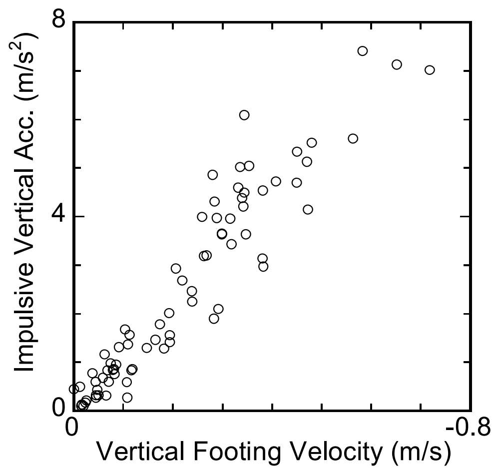


Figure 8. Relation between peak average vertical footing velocity immediately before re-contact and the corresponding average vertical acceleration of footing

IMPULSIVE VERTICAL ACCELERATION AND INDUCED VERTICAL ACCELERATION

Figure 9 shows the relation between the preceding peak footing rotation angle and the peak impulsive vertical acceleration on the footing's left and right sides, in addition to the relation between the footing rotation angle and the peak induced vertical acceleration at the same instance. The peak impulsive acceleration tends to increase concomitantly with increased footing rotation angle and exceeds 12 m/s^2. The peak induced vertical motion also tends to increase concomitantly with increased footing rotation angle but reaches an upper limit of about 8 m/s^2. The peak impulsive vertical acceleration tends to be larger than that of induced vertical acceleration at the same footing rotation angle, indicating that not only the effects of the induced vertical acceleration but also those of the impulsive vertical acceleration on facilities of important structures such as nuclear plants should be investigated.

Figure 10 portrays the relation between the preceding peak horizontal superstructure acceleration and the corresponding peak impulsive vertical acceleration, in addition to the relation between the horizontal superstructure acceleration and the peak induced vertical acceleration at the same instance. When the horizontal superstructure acceleration exceeds about 5 m/s^2, the amplitudes of the impulsive vertical acceleration and the induced vertical acceleration rise dramatically because the superstructure acceleration, whose amplitude is greater than 5 m/s^2, increases the footing rotation angle significantly, as presented in

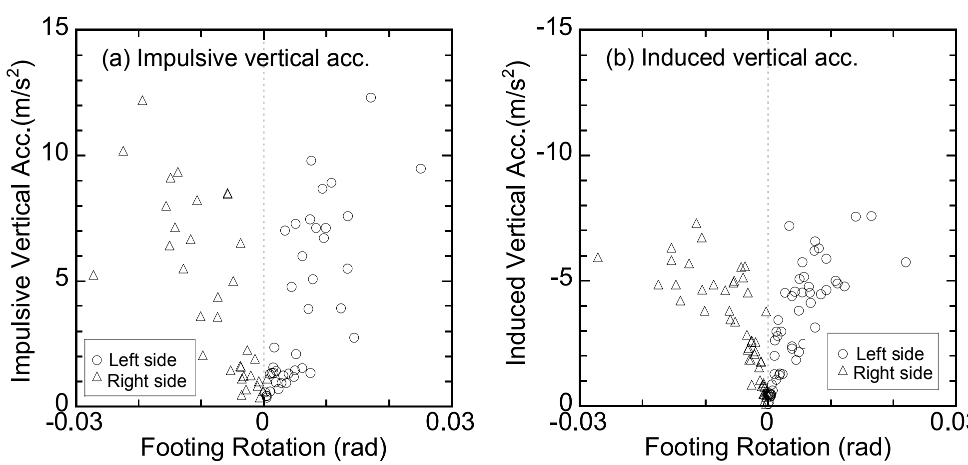


Figure 9. Relation between the preceding peak footing rotation angle and the peak impulsive vertical acceleration, and the relation between the footing rotation angle and the peak-induced vertical acceleration at the same instance

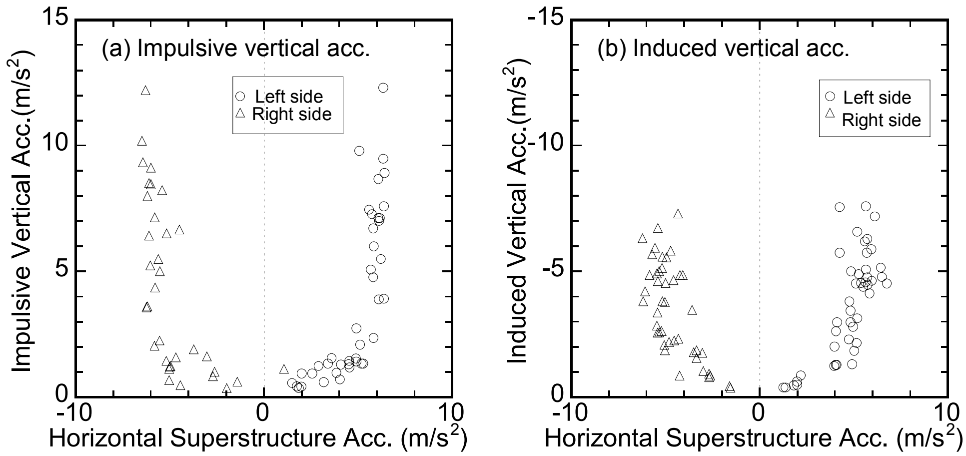


Figure 10. Relation between preceding peak horizontal superstructure acceleration and peak impulsive vertical acceleration, and the relation between peak horizontal superstructure acceleration and peak induced vertical acceleration at the same instance

Fig. 5. The explanation above suggests that a small earthquake will generate only slight vertical acceleration, but that an intense earthquake will trigger the foundation uplift and generate extremely high vertical acceleration, especially because of the collision impulse.

CONCLUSION

Dynamic centrifuge tests were performed using soil-footing – superstructure models to investigate the effects of the footing uplift on the vertical acceleration of the footing during strong shaking. The horizontal shearing and vertical compressive forces on the base of the footing, in addition to the earth pressure and wall friction force on both sides of the footing, were measured carefully using newly developed 2D-load cells. The following conclusions were drawn.

(1) The foundation uplift induces vertical acceleration of two types on an embedded footing: “impulsive vertical acceleration” caused by the collision impulse between the foundation and soil and “induced vertical acceleration” caused by the height movement of the gravitational center of the structure.
(2) The amplitude of the impulsive vertical acceleration, more than 12 m/s^2, is much greater than that of the induced vertical acceleration.
(3) When the horizontal superstructure acceleration becomes greater than about 5 m/s^2, the amplitudes of the impulsive vertical acceleration and the induced vertical acceleration rise dramatically, suggesting that a small earthquake will generate only small vertical accelerations but that an intense earthquake will trigger the foundation uplift and generate extremely high vertical acceleration, especially by the collision impulse.
(4) The amplitudes of both vertical accelerations increase with the induced rotation angle of the footing.

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