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Rocking Component of Earthquake Induced by Horizontal Motion in Irregular Form Foundation

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SUMMARY

Two horizontal components and a vertical component are usually employed in seismic observations. Therefore, only those components are used as the input ground motions in seismic design code. However, there must be rotational or rocking component together with basic three components in ground motion, because of the existence of Rayleigh wave, phase difference between vertical components at grounds with different stiffness, and no mechanism preventing ground motion from being horizontal for excitations from various directions. Seismographs are generally installed more than several hundred meters apart from each other even in arrayed observations. This distance is too long to identify the existence of rotational or rocking component. And there is no seismograph which can measure this component. Since there has been no information on this component, such component cannot be taken into account in seismic design code. However such component may have an impact on some rigid structures as well as flexible structures. It is indispensable to examine the effects of this component on structural response. In this study, experiments using the model ground excited by a shaking table and simulations of ground motion using FEM are carried out, in which existence of rocking components are examined in earthquake motion generated at various grounds such as the ground with irregular form foundation. Consequently, the experiment and analysis verified existence of rocking motion component. It is shown that the vibration of horizontal direction is the generating factor of rocking motion components in the experiment and that the vibration of vertical direction is the amplifying factor of rocking motion components. Moreover, rocking motion component is large near the border between two different grounds, and depends on the vertical amplitude of vibration and on excitation frequency.

INTRODUCTION

It is remarked that serious damage occurs to the structure built on the irregular form foundation by the earthquake motion. For example, the structure on the irregular form foundation was damaged by Tokachi-Oki earthquake (1968) and Miyagiken-Oki earthquake (1978). The vibration characteristic about irregular form foundation is studied by many researchers[1), 2)].

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In many cases, the soft ground is surrounded by the hard ground. On the surface ground, the response which has phase difference by complicated vibration occurs. If a structure is built on the boundary between hard and soft grounds, it will suffer earthquake motion such as rotational motion component due to phase difference and different amplitudes of vertical ground motions. Such earthquake motion is defined as rocking earthquake motion. Generally the ground is divided into base rock and surface layer. The propagation velocity of wave changes with hardness of the ground. Therefore, refraction and reflection in alluvial layers occur repeatedly at the boundaries of layers. These factors affect the response of ground surface. If the ground motions are observed at arbitrary two points, it will be shown that the responses of the seismic wave are different at these points. Therefore, phase difference and different amplitude are observed in these points. The structure built on such ground will show the action like rotational motion component. The horizontal motion as generated by the rotational motion component is proportional to the height of the structure. Therefore, as the structure is higher, shear force of horizontal component is larger. In this study, rocking earthquake motion generated on the irregular form foundation is verified in experimental and numerical analyses.

2. MEASUREMENT OF ROCKING EARTHQUAKE MOTION USING SHAKING TABLE EXPERIMENT

2.1 Outline of the shaking table experiment

The outline of experiment is shown in Fig.1. The container which is installed on the shaking table is made by steel and acrylic board (length 1.8m×width 0.6m×height 0.8m). A mass of mortar is installed in the container at one side. The inclination angles of the mortar surface are 45 degree and 60 degree, respectively and the height of the mortar is same as the model ground. In order to measure the motion of rocking component, vertical accelerometers are installed on the model ground surface. Accelerometers are set to point *a* (reference point) on the mortar and points *b-j* on the sand ground. Rocking acceleration is defined as the difference of vertical acceleration between point *a* and arbitrary point divided by the distance between these two points. The model ground was vibrated by sinusoidal waves with 3Hz to 9Hz at intervals of 1Hz. The type of shaking direction consists of three cases of vertical direction, horizontal direction, and vertical +horizontal directions. The maximum accelerations are three cases of 100gal, 200gal and 300gal. Time duration is 10s.

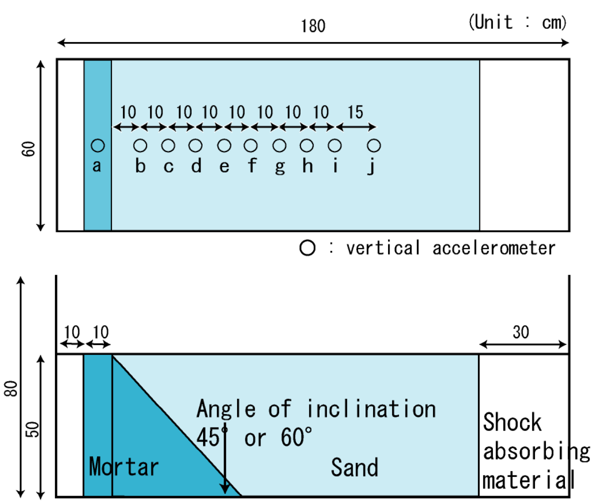

Fig.1 Experimental equipments of shaking table tests

2.2 Experimental results

2.2.1 Effect of inclination angle of the mortar

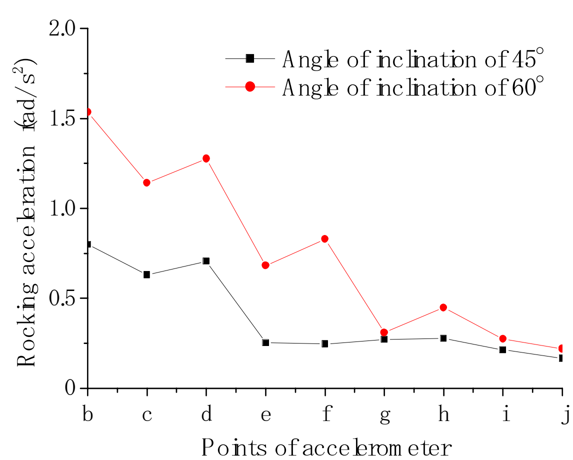

Fig.2 Change of the rocking acceleration by the difference of the inclination angle of the mortar

Fig. 2 shows the change of rocking acceleration by the difference of the inclination angle of the mortar. For example, this figure shows that input frequency is 3Hz, input acceleration is 200gal and shaking direction is horizontal. Natural frequency of sand ground is about 3Hz, that of mortar with the inclination angle of 45 degree is about 7Hz and that of mortar with the inclination angle of 45 degree is about 9Hz, respectively. It is clearly recognized that large rocking vibration occurs near the mortar and at large inclination angle type. In general, the mass of mortar is large, its natural frequency becomes low. Therefore, the natural frequency of mortar and the natural frequency of sand ground approach input frequency. In the case of the mortar with the inclination angle of 45 degree, its mass is larger than the mortar with the inclination angle of 60 degree, and a possibility of resonating with input frequency becomes high. Consequently, the mortar with the inclination angle of 45 degree vibrates greatly. And thickness of sand ground with the inclination angle of 60 degree is larger than that with the inclination angle of 45 degree near the points *b-f*. Then vertical motions of these points are large. Because rocking acceleration is defined as the difference of vertical acceleration between point *a* and arbitrary point divided by the distance between these two points, rocking acceleration between the mortal with the inclination angle of 60 degree is greater than that of the inclination angle of 45 degree. As inclination angle becomes more vertically, horizontal motion generates easily vertical response near mortar. So it is thought that it led to amplification of rocking acceleration.

2.2.2 Effect of excitation direction

Fig. 3 and Fig. 4 show the change of rocking acceleration by the distance from the reference point. Input frequency is 3Hz and shaking direction is vertical and horizontal directions. The mortar with the inclination angle of 45 degree is used. Fig.3 shows that when horizontal acceleration is constant and vertical acceleration changes, rocking acceleration is almost constant at the distance more than 30cm. According to Fig. 4, when horizontal acceleration changes, rocking acceleration also changes. The factor which generates rocking acceleration near the mortar is a horizontal vibration. Rocking vibration is amplified when a vertical vibration is added. And it is clarified that

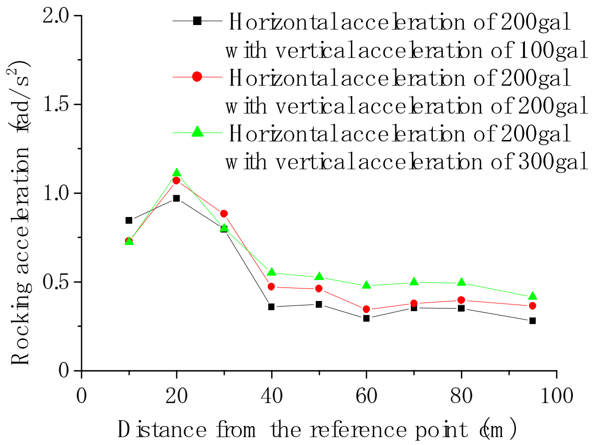

Fig.3 Change of the rocking acceleration by the distance from the reference point (Constant horizontal acceleration)

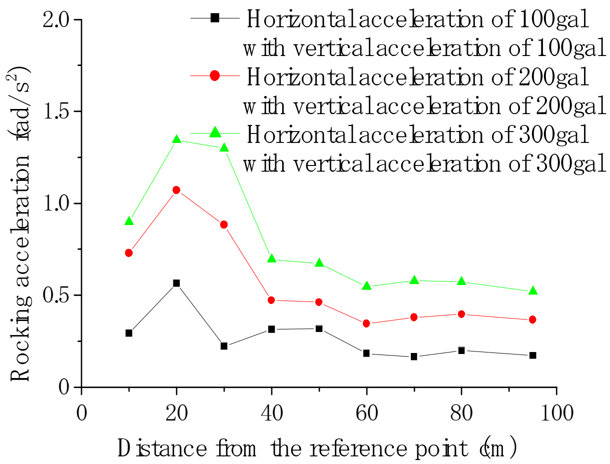

Fig.4 Change of the rocking acceleration by the distance from the reference point (Different horizontal acceleration)

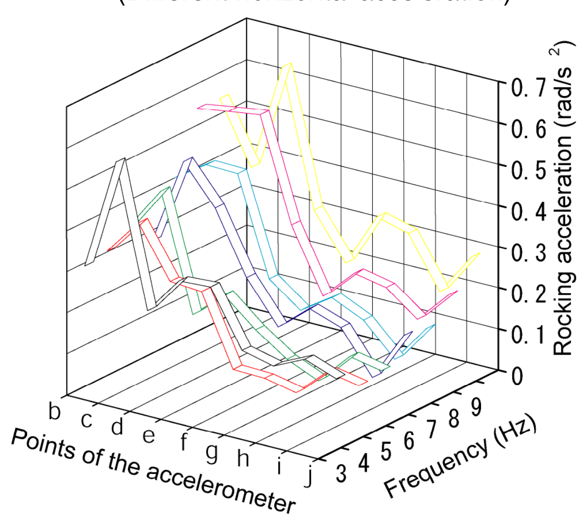

Fig.5 Relationship between excitation frequency and rocking acceleration (vertical and horizontal acceleration :200gal,

the amplification ratio depends on the horizontal acceleration.

2.2.3 Effect of frequency

Fig. 5 shows the relationship between rocking acceleration and input frequency. It is clarified that the vibration mode for each frequency exists on the ground surface. Rocking acceleration is large only near the mortar at low frequency. This reason may be that the distance for two points is related and the vertical vibration amplified by the boundary. And rocking acceleration is large at the ground center in high frequency because the center of the ground is vibrated in primary mode based on reflection of a surface wave. In an earthquake motion, the principal direction of acceleration changes momentarily on tripartite coordinates. Therefore, it is thought that this result has grasped the characteristics of rocking motion more actually.

3. RESPONSE ANALYSIS OF ROCKING EARTHQUAKE MOTION

3.1 Validity of the numerical analysis

The model ground used in the experiment is modeled using finite elements. Comparison with experiment and numerical analysis using FEM is performed. Fig. 6 shows numerical analysis model. Table 1 shows soil parameters used for numerical analysis. The boundary of the side is assumed to be fixed for horizontal direction, and free for vertical direction. The boundary at the bottom is assumed for both horizontal and vertical directions to be fixed. The maximum acceleration of input wave is 100gal and excitation frequency is 3Hz. Time duration is 10s.

Fig. 7 shows a time history of rocking acceleration for experiment and numerical analyses. Low pass filter of 15Hz is applied to these results. The phase of rocking acceleration is mostly in good agreement, however characteristic of amplitude for both results is different. The reasons are follows: Though there are many waves with various frequencies in experiment, they cannot be expressed in numerical analysis. And soil parameters cannot be determined correctly for 2-dimensional FEM analysis. However, it is

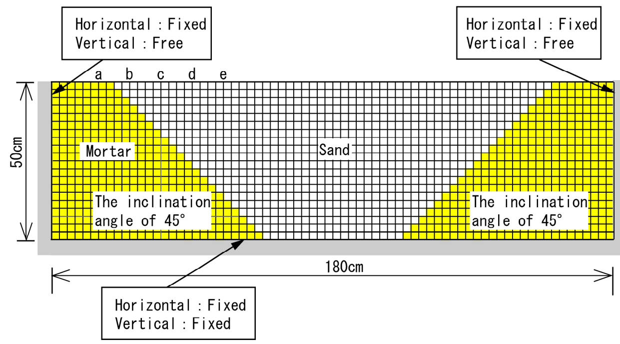

Fig.6 Analytical model

Table1 Parameters

	Mortar block	Sand bed
Unit volume weight γ_t(kN/m^3)	20.68	13.52
Shear wave velocity V_s(m/s)	70	12
Poisson's ratio ν	0.1	0.25

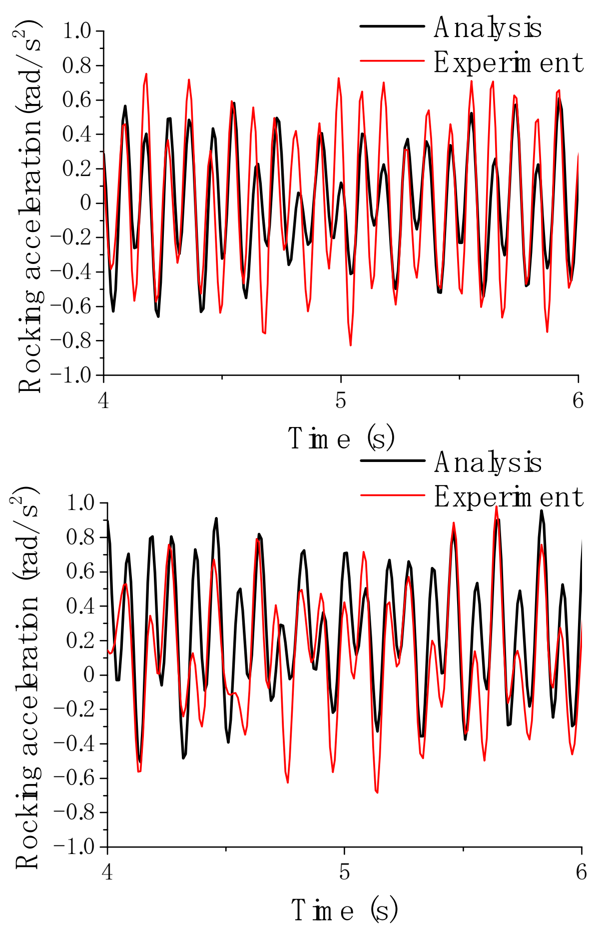

Fig.7 Comparison with experimental and numerical analyses at *b* and *c* points

confirmed that the characteristics of maximum amplitude for both results are mostly in good agreement.

3.2 Response analysis of rocking earthquake motion in model ground

3.2.1 Outline of response analysis

In this study, analytical model composed of ground reclaiming the hollow and the ground of the tertiary layer is used. Fig. 8 shows these analytical models. Table 2 shows soil parameters[2)]. The analytical model is 36m in width and 10m in depth. Two kinds of ground models were modeled by symmetrical 2-dimensional ground with unit element of 50cm × 50cm. Since the shortest wavelength set up by this analysis is about 17m, it is thought that the size of unit element is sufficiently appropriate. The viscous boundary condition in the side of the ground is installed in these models. Input acceleration is sinusoidal wave and analysis is performed by changing amplitude and frequency.

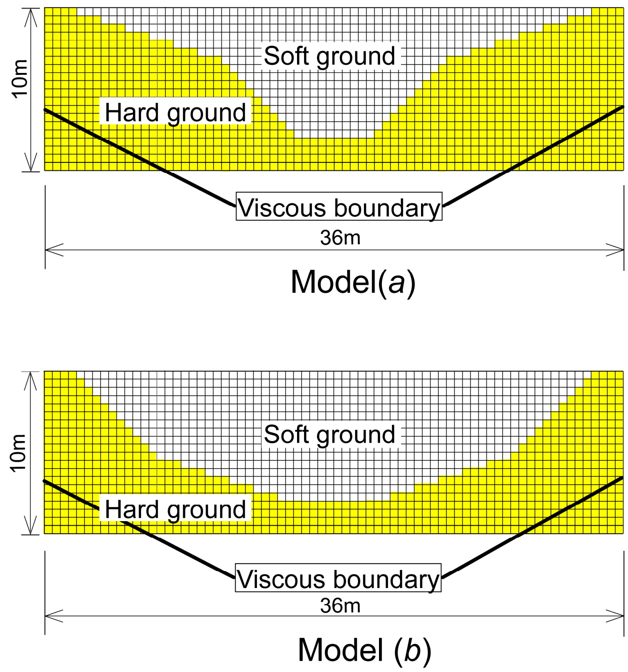

Fig.8 Analytical models

Table2 Parameters

	hard ground	soft ground
Shear wave velocity *Vs* (m/s)	400	120
Unit volume weight γ_t (kN/m^3)	17.64	
Poisson's ratio v	0.4	
Standard distortion γ_r	4.2×10^{-4}	
Attenuation constant in the infinite maximum distortion	0.4	

3.2.2 Effect of phase difference

Fig. 9 shows the time history waves of the vertical response acceleration at points of 12m right and left from the center of the ground in model (*a*). Input frequency is 3.0Hz and the maximum horizontal acceleration is 100gal. On the ground surface, the phases at the two points are reversed. Existence of rocking component that generates inclination in the ground surface has been checked by numerical analysis.

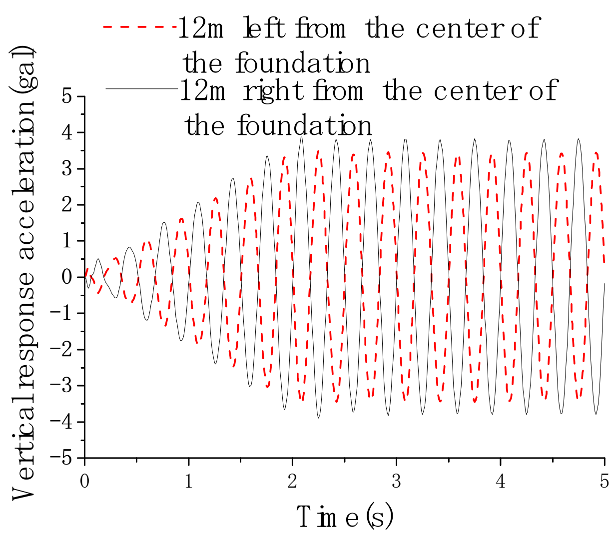

Fig.9 Time history of response acceleration for model (*a*)

3.2.3 Effect of frequency

Fig. 10 shows the relationship between the maximum rocking acceleration and frequency changing from 3Hz to 6Hz at intervals of 1Hz. The maximum input acceleration of horizontal component is 200gal. Rocking acceleration does not depend on frequency but it is amplified near the center of the ground on model (*a*). In model (*b*), the peak of rocking acceleration exists in the position near the reference point. As the inclination angle of the boundary becomes more vertical, horizontal motion generates vertical response more easily. Therefore, it is thought that the vertical boundary makes rocking acceleration amplify. Rocking acceleration is amplified on the boundary near the ground surface on model (*b*). It is clarified that the amplification characteristics of rocking acceleration are not influenced by the change in frequency but are influenced by the geographical feature.

3.2.4 Effect of input acceleration

Fig. 11 shows the relationship between rocking acceleration and input acceleration changing from 100gal to 300gal at intervals of 100gal. Input frequency of model (*a*) is 7.0Hz and model (*b*) is 5.5Hz. As compared model (*a*) with model (*b*), rocking acceleration of model (*b*) shows larger than model (*a*). This is because of the depth from the ground surface to the boundary and the inclination angle of the boundary.

4. CONCLUSIONS

This study dealt with the generating factor and the characteristics of rocking earthquake motion in the irregular form foundation by the shaking table experiment and numerical analyses. The conclusions of this study are summarized below.

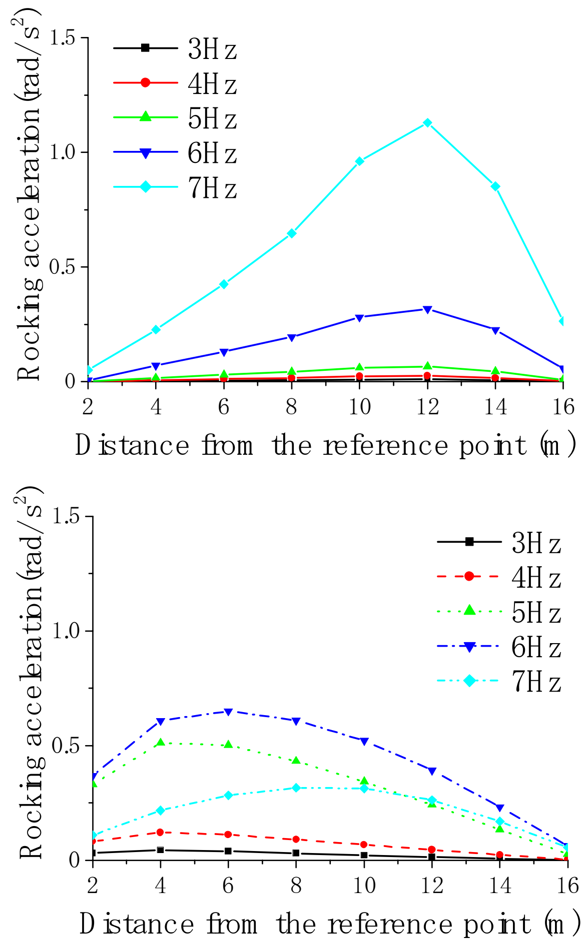

Fig.10 Relationship between input frequency and rocking acceleration
(top : model (*a*), bottom : model (*b*))

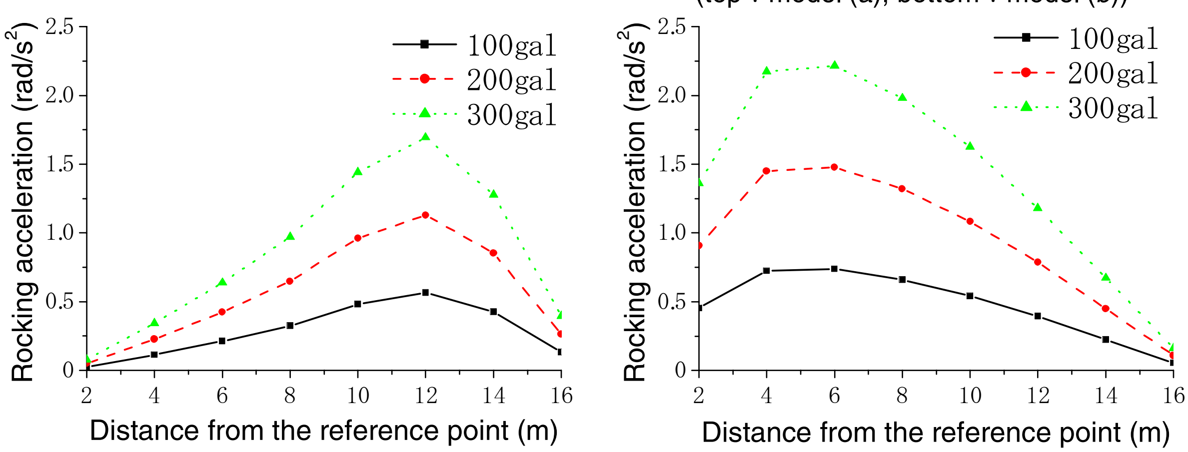

Fig.11 Relationship between input acceleration and rocking acceleration
(left : model (*a*), right : model (*b*))

In the shaking table experiment, the characteristics of rocking earthquake motion in the irregular form foundation were observed. As an inclination angle becomes more vertically, horizontal motion generates easily vertical response near the mortar. So this led to amplification of rocking acceleration. The factor which generates rocking acceleration near the mortar is horizontal vibration. Rocking vibration is amplified when vertical vibration is added. And it is clarified that the amplification ratio depends on the horizontal acceleration.

In the FEM analysis, it is clarified that the amplification characteristics of rocking acceleration are not influenced by the change in frequency but are influenced by the geographical feature. The amplification characteristics of rocking acceleration occur because of the depth from the ground surface to the boundary and the inclination angle of the boundary.

However, it is not enough to examine only rocking acceleration if the response of a structure is the subject of a study. It is necessary to consider rocking velocity and rocking displacement. If the ground supporting the tall structure is inclined by the rocking motion, it is expected that excessive load is generated in the lower part because response acceleration is generated in the top part. Therefore in analyzing structural motion, the damaging factor to structure must be cleared by using the rocking component as well as horizontal and vertical components as input motion.

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