INFLUENCE OF SESIMOMETER FOUNDATION, ADJACENT BUILDING AND SURFACE GROUND CONDITION ON STRONG MOTION RECORDS

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ABSTRACT:

To confirm whether a seismometer placed on a special foundation can accurately record strong ground motion at the surface level, we perform analytical and experimental studies into the influence of seismometer foundations, and on the presence of an adjacent building, on the ground motion recorded by seismometers. For our experiments, we utilize an earthquake observation record produced by a multi-channel array observation system installed in a building. It is determined that the seismometer foundations examined in this study can record horizontal and vertical responses at the free ground surface with good accuracy to about 10 Hz, and that the presence of an adjacent building influenced recording to greater or lesser amounts depending on the distance from the building to the observation site, with influence decreasing as distance from the building increases.

KEYWORDS: Seismometer, Ground motion record, Dynamic Interaction, Thin Layer Method, 3-D FEM

1. INTRODUCTION

A number of strong ground motion observation networks have been rapidly developed and deployed in the period since Japan's 1995 Hyogo-ken Nanbu Earthquake. Normally, a seismometer is placed on a small special foundation at ground level. About 3,000 – 5,000 seismometers have been placed on the ground surface not only to use observation records for the study in the field of earthquake engineering but also to inform people the seismic intensity of each observation station for the disaster mitigation under a large earthquake.

A very important thing is that these seismometers can record the ground motion accurately. It is not mentioned about the seismometer's characteristic but about some observation conditions around them, for example soil condition, the characteristic of the seismometer foundation, etc. The Japan Meteorological Agency (JMA) recommends that a portion of the foundation to be buried beneath the surface to prevent foundation geometrical nonlinearity from occurring during strong ground motions. However, under such circumstances, the response of the foundation itself might have a significant influence on the ground motion record. Furthermore, the response of adjacent buildings might also have major impacts on ground motion records, especially in urban areas.

In this paper, we perform analytical studies into the influence of seismometer foundations and adjacent buildings on the strong ground motion recorded by seismometers, and an analytical examination is conducted into the influence of the dynamic characteristics of various seismometer foundation types on earthquake observation records.

2. INFLUENCE OF SEISMOMETER FOUNDATIONS ON RECORDINGS

2.1. Analysis models of seismometer foundations

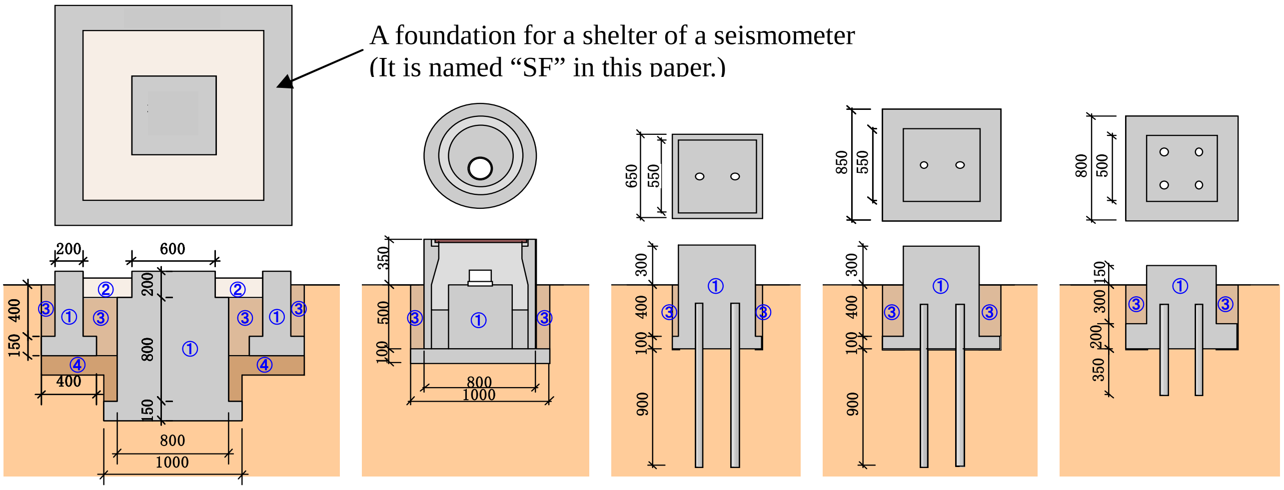
Five seismometers with different foundation types were chosen for examination in this study. They include a

K-NET seismometer produced by the National Research Institute for Earth Science and Disaster Prevention (NIED) (a), a seismic intensity meter installed by a local government (b) and three SI (means Seismic Intensity proposed by Housner, G. W. (Housner, G. W., 1952)) sensor-mounted foundations developed by a Japanese gas company (c~e), as shown in Figure 1. Around the seismometer (a), there is a foundation of a shelter protecting the seismometer. It is called "SF" in this paper. For the seismometers (c)-(e), four stainless steel piles supporting their foundations are constructed. In this study, the response characteristic of the foundation is compared between under loosening soil conditions surrounding the foundations and firm soil conditions. The circled numbers in the foundation diagrams in Figure 1 correspond to the numbered materials of the loosening soil listed in Table 1. Table 2 shows the soil profile used for this analysis under firm soil conditions.

Here, we compare the impedance and foundation input motions of these foundations, where the foundation weight is assumed to be zero. The dynamic responses of these foundations are also compared. Additionally, by changing the S wave velocity *Vs* of the soil at 0-3 m in Table 2, we examine the influence of soil condition differences on foundation responses. Furthermore, the effects of both the subsurface soil and the foundation supporting piles or "SF" are also examined. Figure 2 shows a coordinate system of our analysis model, to which the hybrid analysis code proposed by Wen et *al.* (Wen et *al.*, 2006) is applied. This code incorporates a combination of the Thin Layer Method (TLM) and the Finite Element Method (FEM). The incident waves utilized are a normal incidence S-wave for the horizontal and/or rotational direction, while a normal incidence P-wave is utilized for the vertical direction. To avoid numeric instability in the analysis that might be caused by the smaller foundation sizes, the scaling law (Iiba et *al.*, 2003) is applied to the examinations.

2.2. Foundation influence results

Figure 3 shows the impedance of each foundation. The upper, middle and lower portions of the figure show the horizontal impedance K_{11}, the vertical impedance K_{33} and the rotational impedance K_{55}, respectively. In this figure, "no SF", "Loosening", "Firm" and "no piles" indicate "not considering the shelter foundation shown in Figure 1", "loosening soil condition", "firm soil condition" and "the case of no piles supporting the foundations (c-e)", respectively. For each foundation, it is recognized that these three directional impedances are smaller under loosening soil conditions than under firm soil conditions. Notably large differences have been noted for rotational impedance K_{55}, which indicates that loosening soil around a foundation has a significant impact on rotational impedance. When Gas type foundations 1, 2, and 3 are compared, we can see that the three directional impedances increase as the bottom area of the foundations become larger. Because the depth and the side area contacting the surrounding soil of foundation are almost same, it appears that the impedances are primarily dependant on the surface area of the foundation bottom. It also appears that the use of support piles has comparatively minor effects on impedances (see graphs of (c) – (e) in Figure 3).


A foundation for a shelter of a seismometer
(It is named "SF" in this paper.)

(a) K-NET (NIED) (b) Local government (c) Gas type 1 (d) Gas type 2 (e) Gas type 3

Figure 1: Seismometer foundations examined in this study

It can thus be seen that the impedance of K-NET foundation of “Firm and no SF” is larger than that of the other four foundations. Furthermore, the decreasing rate of the rotation impedance due to the loosening soil is the highest for the K-NET foundation because the subsurface depth of that foundation is the deepest of the five foundations examined.

Table 1: Parameters of each materials (refer to Figure 1)

material		*Vs* (m/sec)	*ρ* (t/m^3)	*ν*	*E* (N/mm^2)	*h*
①	Concrete		2.4	0.2	21,000	0.03
②	Reclaimed soil (sand)	50	1.7	0.3	11.1	0.05
③	Reclaimed soil (upper part)	60	1.7	0.3	15.9	0.05
④	Reclaimed soil (lower part)	80	1.7	0.3	28.3	0.05

(Circled numbers correspond to numbers in Figure 1, respectively.)

Table 2: Soil Profile

Depth (m)	*Vs* (m/sec)	*ρ* (t/m3)
0-3	163	1.7
3-10	240	1.8
10-18	274	1.8
18-	359	1.9
ν=0.4, h=0.02		

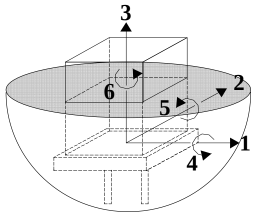
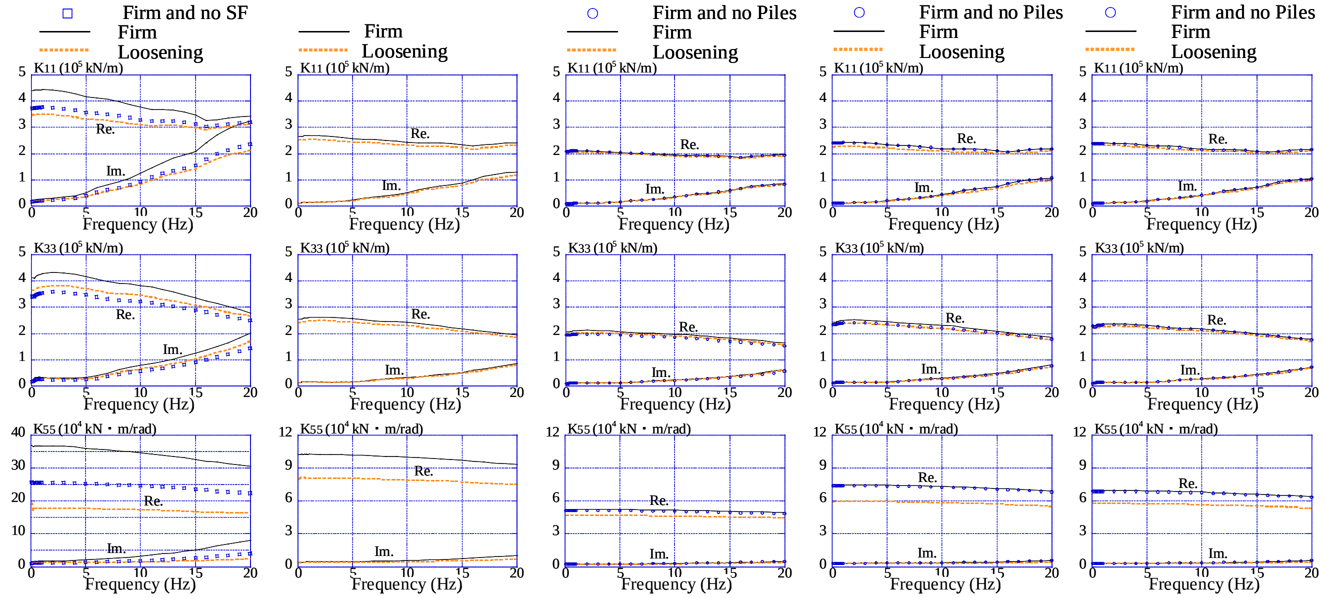
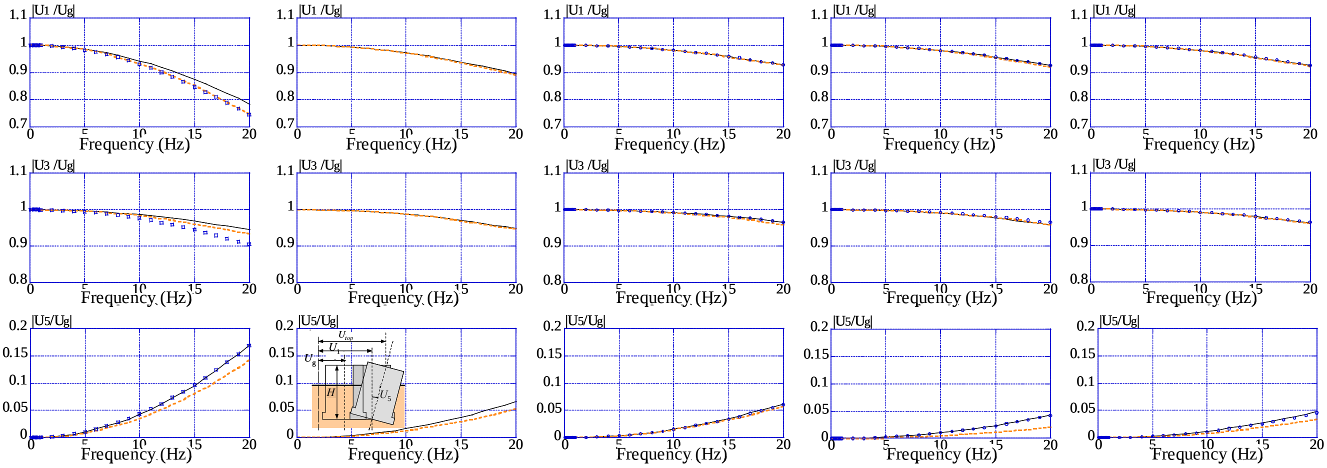


Figure 2: Coordinate system of analysis model



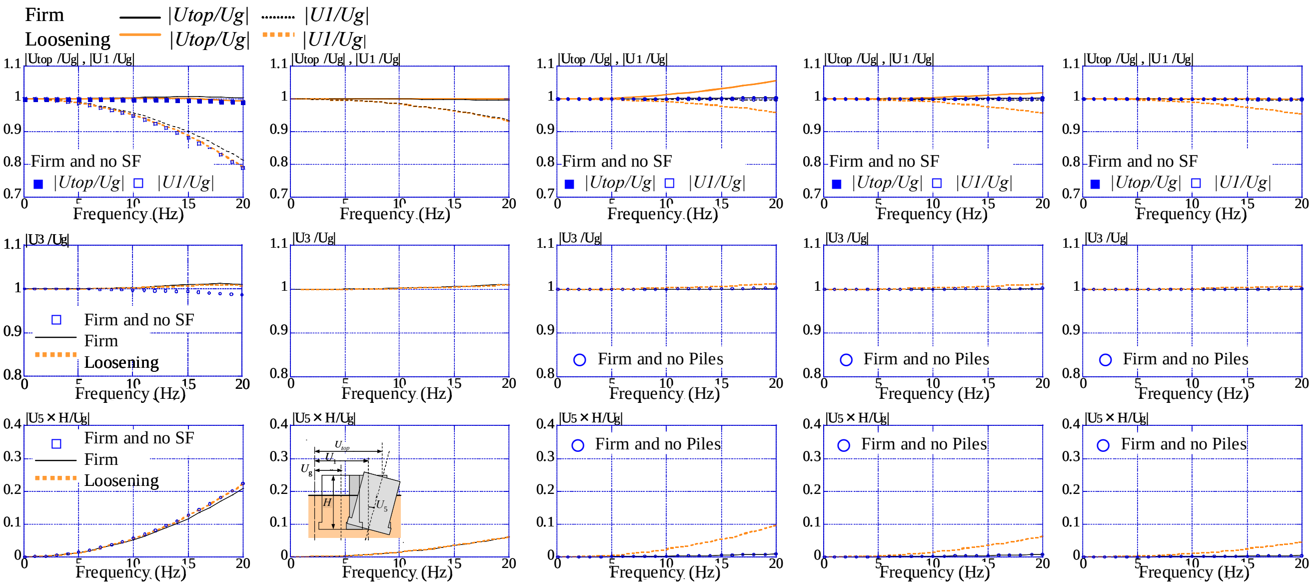
(a) K-NET (NIED) (b) Local government (c) Gas type 1 (d) Gas type 2 (e) Gas type 3

Figure 3: The impedance of each foundation (upper: horizontal, mid: vertical, lower: rotational)



(a) K-NET (NIED) (b) Local government (c) Gas type 1 (d) Gas type 2 (e) Gas type 3

Figure 4: The effective input motion of each foundation (upper: horizontal, mid: vertical, lower: rotational)

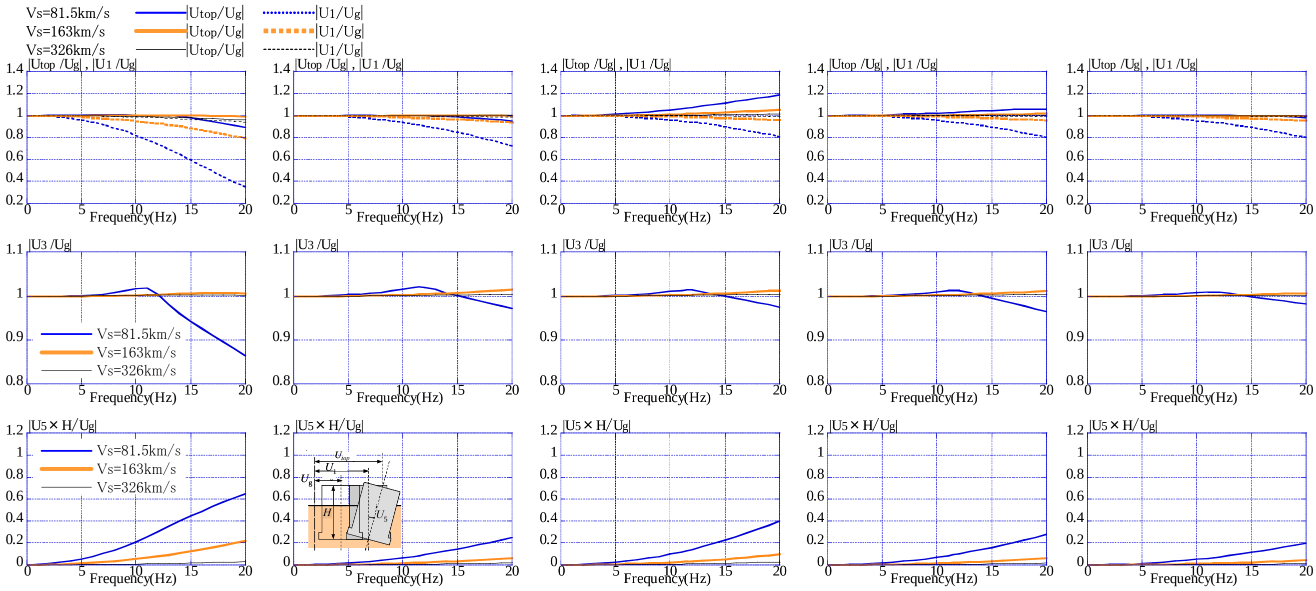


(a) K-NET (NIED) (b) Local government (c) Gas type 1 (d) Gas type 2 (e) Gas type 3

Figure 5: The transfer functions of each seismometer foundation response to the response of the free field (upper: horizontal, mid: vertical, lower: rotational)

The effective input motion of each foundation is shown in Figure 4. The upper, middle and lower portion of the figure shows the horizontal component $|U_1/U_g|$, the vertical component $|U_3/U_g|$, and the rotational component $|U_5/U_g|$, respectively. The horizontal effective input motion decreases in order of Gas types 1~3, the local government and K-NET. This indicates that horizontal effective input motion decreases as the subsurface depth of the foundation increases. As can be seen by Gas types 1, 2 and 3, when the bottom surface area is large, the rotational effective input motion is small. This is because the foundation bottom restricts the excitation of rotational motion. In the case of K-NET foundation, the input motions of “Loosening” are less than that of “Firm” in three directions.

The transfer functions of the responses of each seismometer foundation to that of the free field are shown in Figure 5. The upper, middle and lower portions of this figure show the horizontal response at both the top and bottom of each foundation: $|U_{top}/U_g|$ and $|U_1/U_g|$, the horizontal response at the top of the foundation $|U_5 \times H/U_g|$ stimulated by the rotational response and the vertical response at the top of the foundation $|U_3/U_g|$, respectively. Here, H is the height of the foundation. We confirmed that the phase difference of each transfer function is about five degrees or less. The horizontal responses $|U_{top}/U_g|$, $|U_1/U_g|$ and $|U_5 \times H/U_g|$ will now be examined. In the case of "Firm", even though the input loss effect can be recognized in the responses at the bottom of the foundations in the K-NET foundation and the local government foundation, the responses at the top of the foundations possess the same amplitudes as those of the free field due to horizontal responses stimulated by the rotational responses. As regards to Gas types 1, 2 and 3, it can be understood that the horizontal responses are the same size as those of the free field because the rotational responses, which stimulate the horizontal responses, are very minor. The influence of foundation support piles on the responses is comparatively small in Gas types 1, 2 and 3. We then examined the effect of soil loosening. For the K-NET foundation and the local government foundation, the effects of loose soil around the foundations are comparatively small. However, for Gas types 1, 2 and 3, the horizontal responses of the bottom of the foundations in loosened soil conditions (“Loosening”) decrease by the input loss effect while the rotational responses increase. This shows that the horizontal responses in the high frequency band become larger for Gas types 1, 2 and 3 and indicate that smaller foundation bottom areas, or increased foundation height above ground level, will result in larger horizontal responses due to stimulation by rotational responses. Next, when a vertical response $|U_3/U_g|$ is examined, the difference from the response of the free field is about 5% or less. This allowed us to conclude that the seismometer recordings examined in this study were not significantly affected by loosening soil conditions around their foundations, support piles, or related factors.



(a) K-NET (NIED) (b) Local government (c) Gas type 1 (d) Gas type 2 (e) Gas type 3

Figure 6: The transfer functions of each seismometer foundation response to the response of the free field for each shear velocity at depths of 0-3 m (upper: horizontal, mid: vertical, lower: rotational)

Figure 6 shows the transfer functions of the foundation tops to the free field in a case of "Loosening" under a different soil profile condition at depths of 0-3 m in order to examine the influence of the soil condition on the response of the seismometer foundation. The share velocity Vs, the damping factor h at 0-3 m in depth are assumed to be 81.5 m/s, 0.1 and 326 m/s, 0.02 besides 163 m/s, 0.02 as an initial model. It was confirmed that the phase difference of each transfer function is about five degrees or less, and we can see that the differences in the horizontal and vertical responses between the top foundation and the free field are very small in the frequency band from 0 to 10 Hz for all share velocities.

3. INFLUENCE OF AN ADJACENT BUILDING ON RECORDS

3.1. Outline of the building examined in this study and its multi-channel array observation system

A multi-channel array observation system was installed in a school building of Nagoya University. As shown in Figure 7, two seismometers were placed on the ground surface adjacent to the building and others were placed on various floors or on the building's support piles. The seismometer installed on the ground surface 5 m away from the building was named "G5" and the seismometer installed 14 m away was named "G14". The building profile is shown in Table 3 and the soil profile around the building is shown in Table 4. An analytical examination of this building was performed to determine the influence that an adjacent building has on earthquake observation recordings at the soil surface level, and the results were compared with observed records. Our original hybrid analysis code was also applied to the analysis, and it is assumed that the effect of the seismometer foundation on the observation records is very small based on result above mentioned. In our analysis, the building is replaced with the equivalent single-lumped mass and spring model. The parameters of that model are outlined in our previous research (Sakakibara et *al.* 2007). The examination is performed using the strong motion record obtained in the 2004 earthquake offshore of the Kii peninsula, Japan.

3.2. The influence of the adjacent building based on observation records

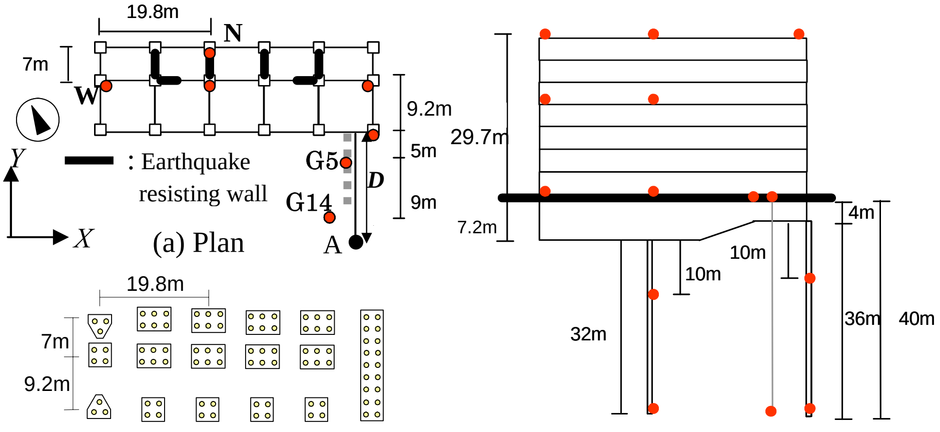
Figure 8 shows transfer functions in X and Y directions (see Figure 7(a)) calculated from the observed records and our analysis model. Each figure includes three types of transfer functions. The first is the transfer function (RF/G14) as a soil-building system, which is a ratio of the response at the roof level (RF) to that at the free field (G14). The second is the transfer function (RF/1F) as a fixed-base system except for the rocking component,

Table 3: Building Profile

Total Floor Area	6,000m^2
Stories	0-7-1
Height	29.7m
Structure Type	PCa
Foundation Type	PHC Pile

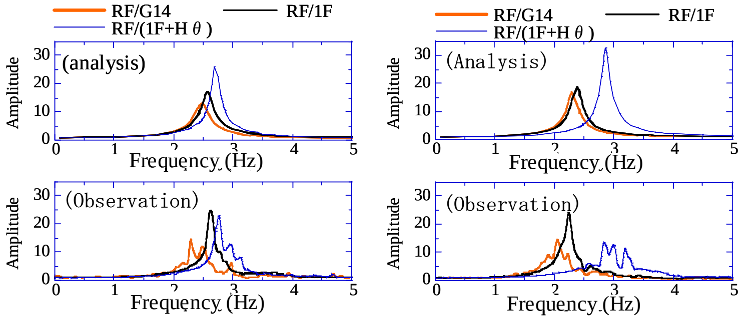
Table 4: Soil Profile

Depth (m)	V_s (m/sec)	ρ (t/m3)	h
0-5.3	330	1.9	0.03
5.3-9.6	220	1.9	0.05
9.6-15	250	1.9	0.04
15-28.3	250	1.8	0.04
28.3-35.5	320	1.8	0.03
35.5-	400	1.9	0.03



(a) Plan (b) Foundation Plan (c) Elevation

Figure 7: Schematic view of the building and observation stations (red circled)

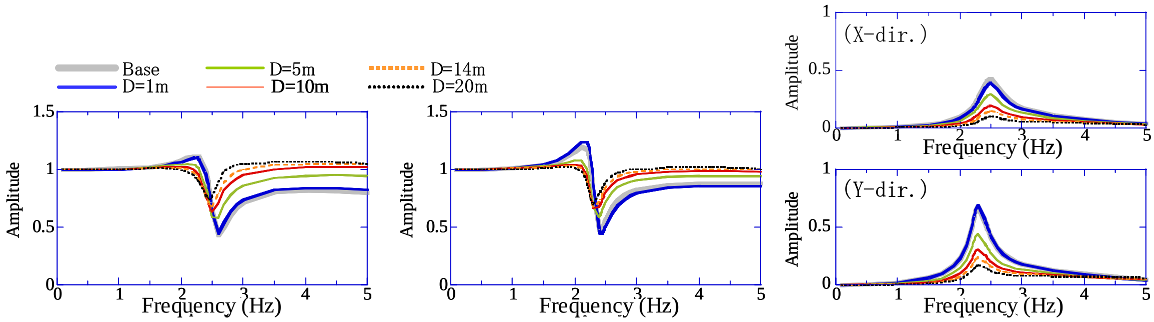


(a) X-direction (b) Y-direction

Figure 8: Comparison of the transfer functions of the building

Table 7: Comparison of the sway and rocking ratio at the predominant frequency of the transfer function (RF/1F) between the analysis model and the observed records

	X-dir.		Y-dir.	
	Sway	Rocking	Sway	Rocking
Analysis model	8%	7%	7%	22%
Observed record	11%	8%	11%	29%



(a) X-direction (b) Y-direction (c) Vertical direction

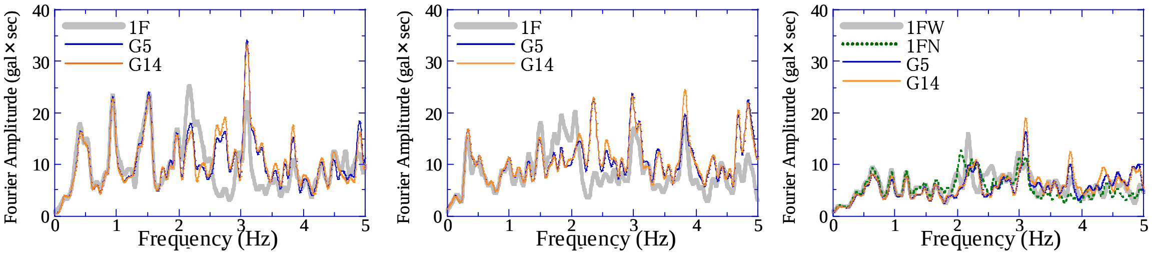
Figure 9: Transfer functions at point A to the horizontal response of the free field by the analysis model

which is a ratio of the response at roof level (RF) to the sway component of the first floor (1F). The third is the transfer function (RF/ (1F+$H\theta$)) as a fixed-base system, which is a ratio of the response at roof level (RF) to the sway and rocking components of the first floor (1F+$H\theta$), where H is equivalent to building height and θ is the rotation angle of the building foundation. Table 7 indicates the sway and rocking ratio at the predominant frequency of the transfer function (RF/1F) about an analytical model and the observed records. It was determined that the frequency characteristic of the analytical model showed good correspondence with that of the observed records, even though slight differences were observed in the amplitude characteristics of both and the sway and rocking rate of the analytical model are somewhat smaller than that of the observed records shown in Table7. These results indicate that the analytical model is appropriate for making approximate observations.

Figure 9 shows the transfer functions for the two horizontal directions and the vertical direction at point A (see Figure 7(a)) to the horizontal response of the free field obtained by the analysis model based on the condition that the building and the building foundation exist. In this figure, D refers to the distance of point A from the building, which is measured at 1 m, 5 m, 10 m, 14 m, and 20 m. The vertical response of the point A consists of the rocking vibration component stimulated by the normal incidence S-wave in the horizontal direction of the building. It was found that the building's vibration characteristic has an affect on the ground response in the vicinity of the building's natural frequency in three directions and that the influence declines as the distance D lengthens. In two horizontal directions, the dynamic characteristic in the vicinity of the natural frequency of the building is changed by the inertial interaction. In the frequency band higher than the natural frequency of the building, it is found that the amplitude of each transfer function decreases due to the kinematic interaction. The influence distance of the kinematic interaction in the Y-direction is longer than that in the X-direction. As for the vertical direction, the vertical response of the soil surface around the building is stimulated by the rocking vibration of the building foundation, which is very strong in the Y-direction.

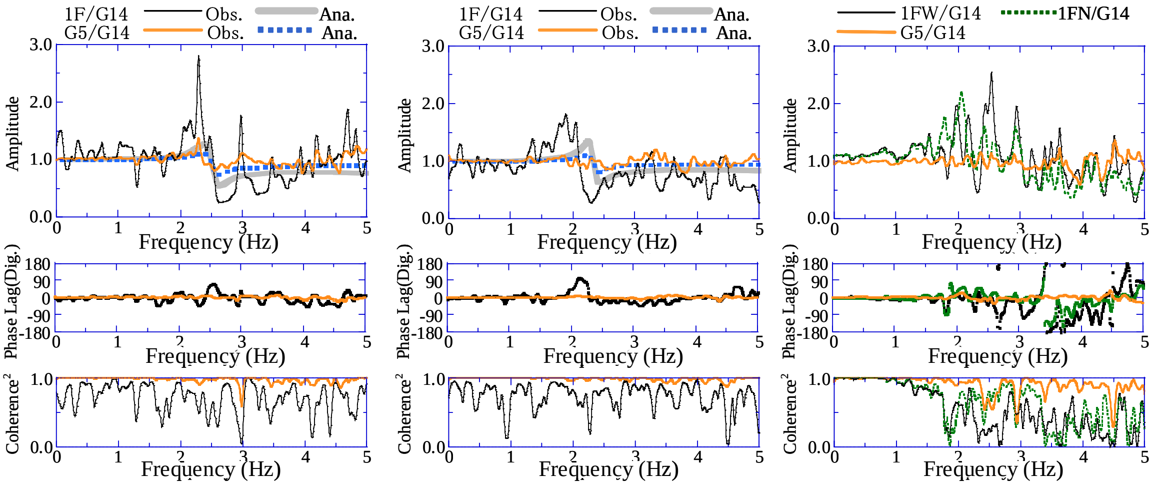
Fourier acceleration spectra are depicted in Figure 10 and the transfer functions of (1F/G14) and (GL5/GL14) are shown Figure 11. These were calculated from the seismic ground motion observed at the first floor of the building and at G5 and G14 as shown in Figure 7. In Figure 11, the results using analytical model are also shown. Looking at Figure 10, it can be seen that the spectra at three points are in good agreement in the lower frequency area than about 1.5 Hz. However, in the frequency area higher than 1.5 Hz, differences in the spectra recorded at G5 and G14 appears. Some peaks, which do not appear in the spectrum at the first floor, are found in G5 and G14.

With regards to the transfer functions in three directions obtained from the observed record shown in Figure 11,



(a) X-direction (b) Y-direction (c) Vertical direction

Figure 10: Fourier acceleration spectra of the records observed by some stations



(a) X-direction (b) Y-direction (c) Vertical direction

Figure 11: Comparison of transfer functions of (1F/G14) and (GL5/GL14) between the analysis model and the observed records

the tendency observed for G5/G14 in the vicinity of the natural frequency of the building was found to be similar to that of 1F/G14, and exhibit high coherence. It appears that G5, which is nearer the building than G14, vibrates in the same manner as the foundation because the building vibration influences G5 more strongly. On the other hand, no distinctive differences in the transfer functions between G5 and G14 in the Y-direction and vertical direction were observed. When the transfer functions obtained by the analysis of two horizontal directions of Figure 11 are observed, we find that the tendencies of 1F/G14 and G5/G14 correspond to those of the observed records in the X-direction. The fluctuation of the transfer function in the Y-direction is smaller than that in the X-direction. If we consider the tendency corresponding to the result of Figure 10 (b), it appears that the difference in the response of the two points, G5 and G14, is small because the influence of the building vibration extends a significant distance. Furthermore, the same tendency was found in the vertical response stimulated by the rocking vibration of the building.

Thus, the influence of an adjacent building on an earthquake observation record has been confirmed by means of the above examinations and the examined phenomenon is also suitable for calculation by analysis model.

4.CONCLUSION

The influence of a seismometer foundation type and an adjacent building on the earthquake observation record was examined. The obtained findings are shown below:

(1) The five seismometer foundation types examined in this study were confirmed to be capable of recording the horizontal and vertical responses of the free field with accuracy up to about 10 Hz regardless of the soil conditions surrounding them.
(2) In the high frequency band of 10 Hz or more, the influence of the soil-foundation interaction might become excessive.
(3) Through examinations conducted on a school building at Nagoya University, it was confirmed that the presence of an adjacent building influenced observed records, and that the influence decreased as the distance away from the building increased.
(4) The distance an influence travels will differ depending on the vibration component of the building.

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