STUDY ON VERTICAL MOTIONS BY ROCKING RESPONSES OF REACTOR BUILDINGS DURING THE 2007 NIIGATAKEN CHUETSU-OKI EARTHQUAKE AT THE KASHIWAZAKI KARIWA NUCLEAR POWER PLANT

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1 ABSTRACT

Earthquake observation records were observed in reactor buildings in Kashiwazaki-Kariwa Nuclear Power Plant Site (KK-NPS) during the Niigata-ken Chuetsu-Oki earthquake (NCO) in 2007. Some studies on the seismic response and simulation analyses were performed to investigate dynamic characteristics of the structures. In particular, it was clarified that the vertical motions of the reactor building of Unit 6 were larger than those of adjacent reactor buildings of Units 5 and 7. This paper discusses the causes of this by earthquake observation records and simulation analyses of the reactor buildings. In general, seismic response of vertical motions is relatively well-simulated using lamped mass model with stick elements which have vertical stiffness and the soil spring between the basemat and support ground. However, vertical motions are influenced by rocking motions with horizontal response in some cases. This paper focus on relationship between the vertical responses and the vertical motions induced by the rocking motions with simulation analyses and observation records during both NCO earthquake and aftershock of NCO. The reasons why the vertical motions of the reactor building of Unit 6 were larger are discussed.

2 INTRODUCTION

In the Niigataken Chuetsu-Oki Earthquake (NCO, hereafter) of July 16, 2007, large ground motions were observed at the Kashiwazaki Kariwa Nuclear Power Plant Site (KK-NPS, hereafter). Analysis of the strong motion records and simulation analysis of nuclear power plant were published about horizontal waves [1] [2].The peak accelerations of horizontal motions of Units 1, 2, 3 and 4 in Arahama side (Southern part of the site) are larger than those of Units 5, 6 and 7 in Ominato side (Northern part of the site). On the contrary, vertical motions were at the same level. On the other hand, it was clarified that the vertical motions of the reactor building of Unit 6 were larger than those of adjacent reactor buildings of Units 5 and 7, focus on Ominato side.

In this paper, we focus on rocking motions of reactor buildings. First we separate the vertical responses and the vertical motions induced by the rocking motions at Units 5 and 6 obtained records in some places from the aftershock. Secondly we separate the vertical responses except vertical motions induced by the rocking motions and the vertical motions induced by the rocking motions during the main shock. Finally, we discussed the reasons why the vertical motions of the reactor building of Unit 6 were larger than Units 5 and 7.

3 OUTLINE OF THE SITE, THE EVENT AND THE OBSERVATION RECORDS

Figure 1 shows the location of the KK-NPS and the epicenter of NCO and the aftershock used for this study. The site is located along the coast of the Sea of Japan in the Niigata Prefecture, Japan, and the distance to the epicenter is about 16km from the site. Figure 2 shows the plan of KK-NPS, including the location of seismic observation points. The site covers an area of 4 square kilometers. There are seven power units in the site, Units 1-4 located in the southern part of the site, Units 5-7 in the northern part of the site. We have been monitoring the ground motion on the base mat of each reactor building and turbine building.

The observed acceleration waveforms on the base mat of Units 5, 6 and 7 during NCO are shown in Figure 3. The maximum acceleration of vertical motions of Unit 6 is larger than those of Units 5 and 7. In addition, it is clear that differences in the observed acceleration waveforms are noticeable in 34 to 36 seconds. Figure 4 shows response spectra of the observation records on the base mat. Response spectra of EW component of Units 5 and 6 at 0.3 sec are larger than those of Unit 7.

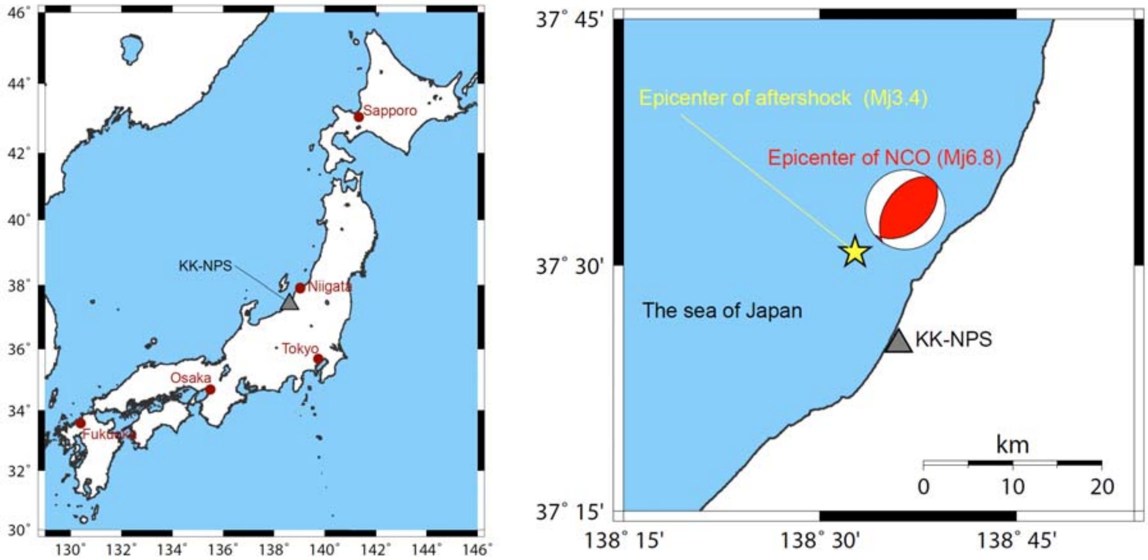


Figure 1. Location of the KK-NPS and the epicenter of NCO and the aftershock used for this study

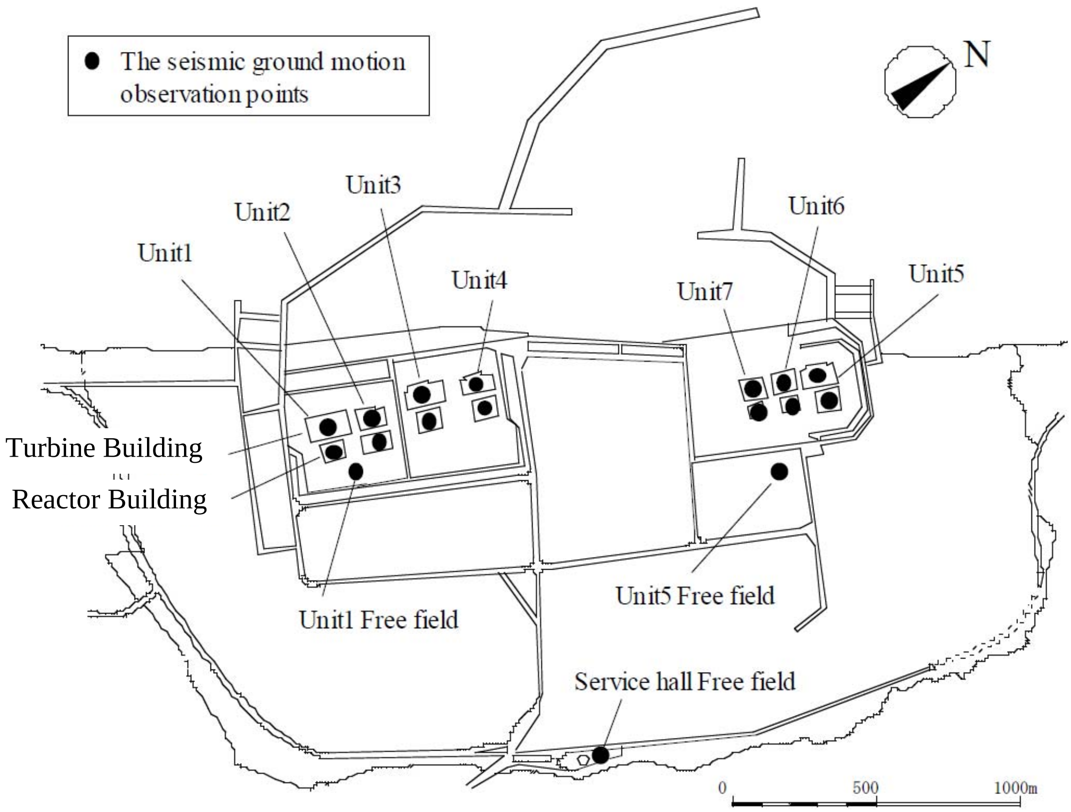


Figure 2. Plan of KK-NPS including the seismic ground motion observation point

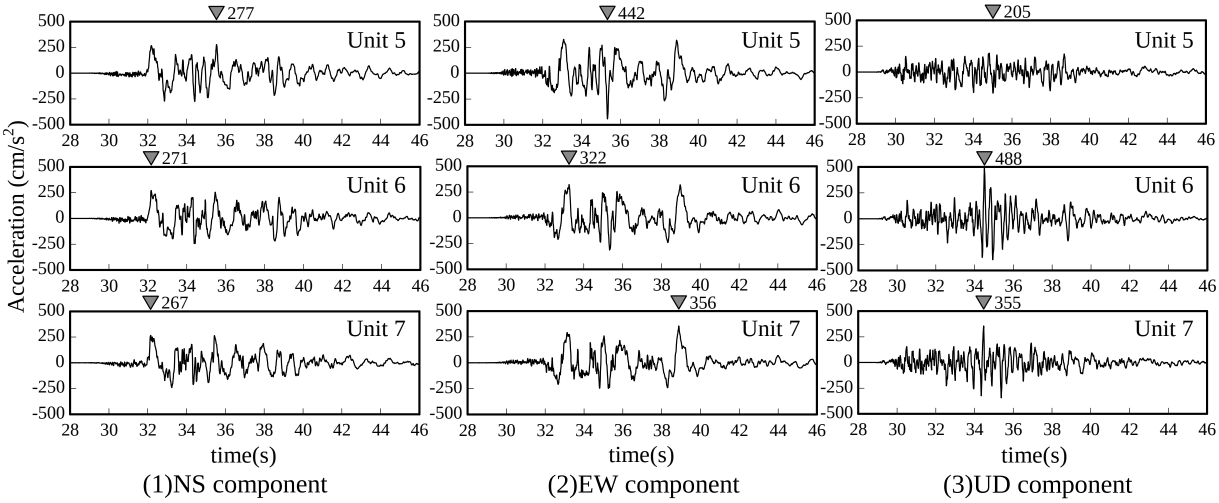


Figure 3. Acceleration waveforms observed on the base mat of each reactor building during NCO

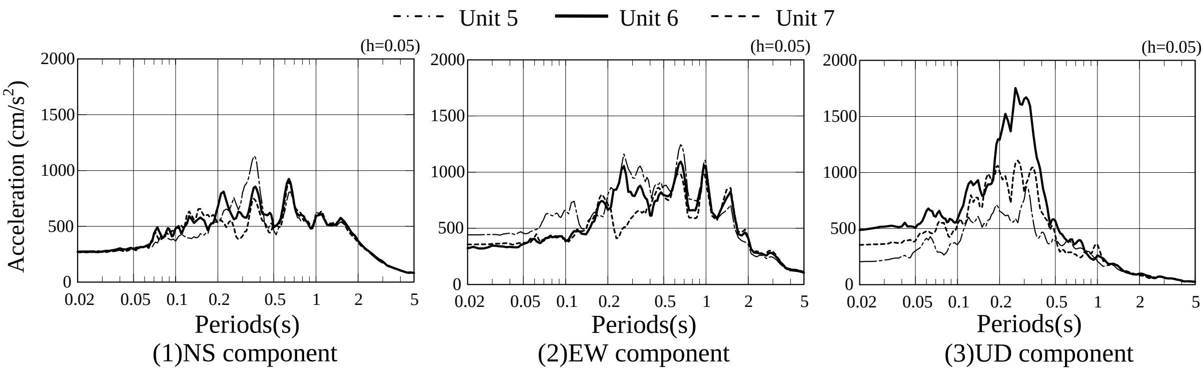


Figure 4. Response spectra observed on the base mat of each reactor building during NCO

4 STUDY ON THE AFTERSHOCK

As shown in Figure 5, there are many seismic observation points on the base mat of Units 5 and 6. Seismic observation points consist of two lines, the basic system of seismometer and the new additional seismometer. The digital data of the main shock waveforms were retrieved by the new additional seismometers but the digital data at the basic system in Units 5 and 6 were lost by overwriting unfortunately. Additionally, there was only new additional seismometer in Unit 7.

The reasons why the vertical motions of Unit 6 were larger are discussed by examining vertical records observed at the base mat of Units 5 and 6 during the aftershock, since many vertical records were observed during aftershocks at the basic system in Units 5 and 6.

Figure 6 shows response spectra of vertical motion on the base mat of Units 5 and 6 during the aftershock used for this study (see Figure.1). Response spectra of vertical motion of Unit6 are larger than those of Unit 5 at 0.3 sec particularly, similarly the main shock. Figure 7 shows the comparison of vertical observation records between the two seismic observation points located symmetrically with respect to the central axis (see Figure 5) of Units 5 and 6. The amplitudes of waveforms are the opposite direction at 32-33 sec. Therefore the vertical motions at 32-33 sec could be induced by the rocking motions (see Figure 8).

We separate the vertical responses except vertical motions induced by the rocking motions (VC, hereafter) and the vertical motions induced by the rocking motions (VR, hereafter) at Units 5 and 6 obtained records in some places from the aftershock. Here, we assumed that observed vertical record was summed VC and VR (see Figure 8). VC are calculated from the following equations:

$$\left.\begin{array}{l} {}_{NS}V_C(t)=(V_1(t)+V_2(t))/2 \\ {}_{EW}V_C\,(t)=(V_3(t)+V_4(t))/2 \end{array}\right\} \quad (1)$$

Where,

${}_{NS}V_C\,(t)$, ${}_{EW}V_C\,(t)$: VC calculated from two seismic observation points(V_1, V_2)) , symmetrical with respect to the central axis (NS or EW)

$V_1(t)$: R64, $V_2(t)$: R68, $V_3(t)$: R67 or V52, $V_4(t)$: R69 or V55

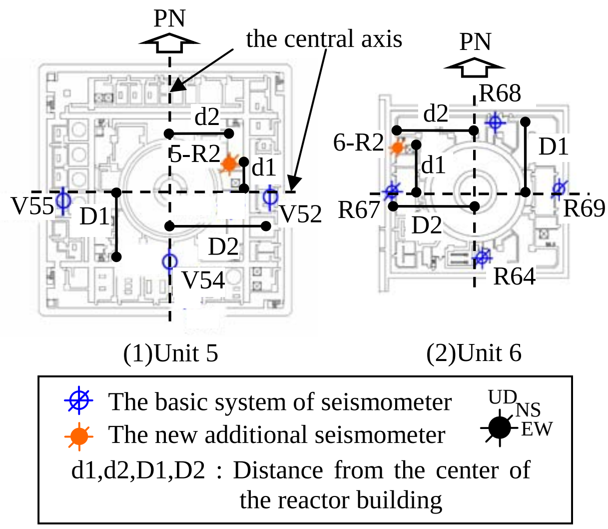


Figure 5. Distribution of seismic observation points at the base mat of Units 5 and 6.

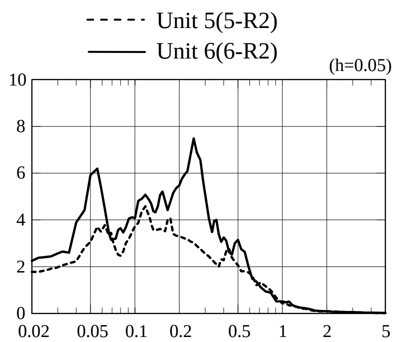


Figure 6. Response spectra of vertical motion on the base mat during the aftershock used for the study.

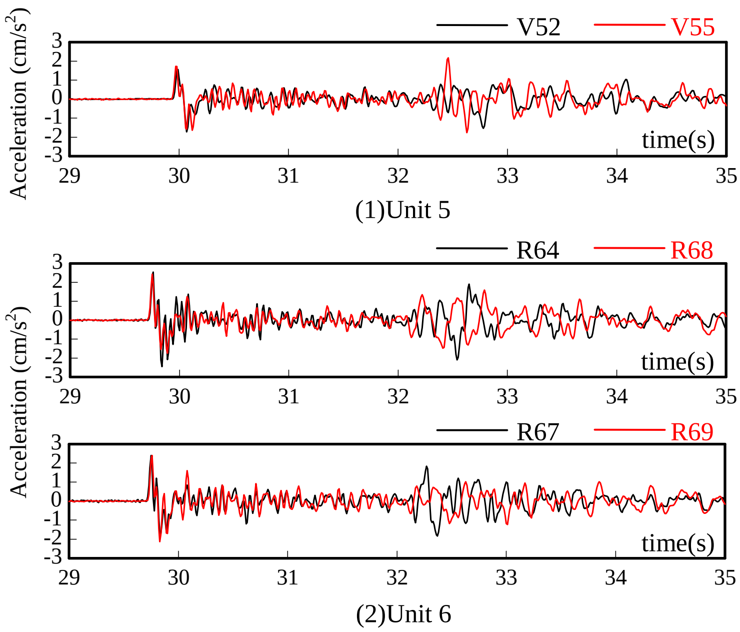


Figure 7. Acceleration waveforms of vertical motion observed on the base mat of each reactor building during the aftershock

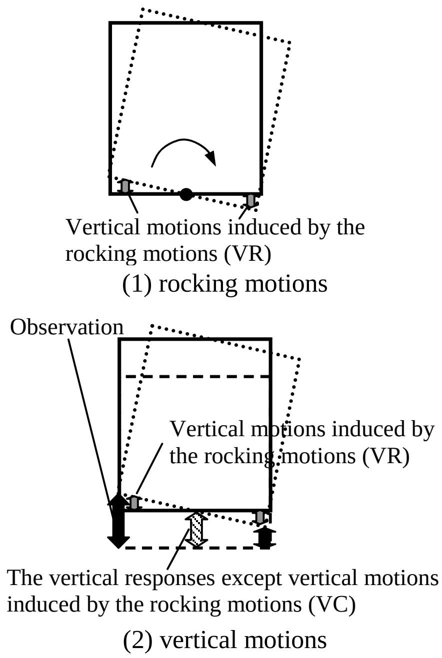


Figure 8. Conception of vertical motions

Figure 9 shows comparison of response spectra between the observed vertical records and VC calculated using equation (1). VC of Units 5 and 6 are less than observed vertical record. We concluded that VC have been estimated accurately because ${}_{NS}V_C\,(t)$ were similar to ${}_{EW}V_C\,(t)$.

Here, observation records of the main shock were retrieved by the new additional seismometers (5R2, 6R2) because the digital data at the basic system were lost. The new additional seismometers are located far away spatially from the central axis (see Figure 5). Therefore vertical records would conclude the rocking motions from NS and EW direction. Thus, we estimated vertical motions at any points on the base mat considering the rocking motions of NS and EW direction. Namely, we tried to estimate the observation record of new additional seismometer (6-R2) from that of basic system of seismometers using equations (2) and (3), assuming that the base mat was rigid.

First, we deducted VC from the observation record of basic system of seismometers on the central axis. Secondly, we tried to estimate VR at the point located new additional seismometer (6-R2) considering the eccentric arm, a distance from the center of base mat to observation points, by equation (2). Finally, we estimated the vertical motions of new additional seismometer (6-R2) using equation (3).

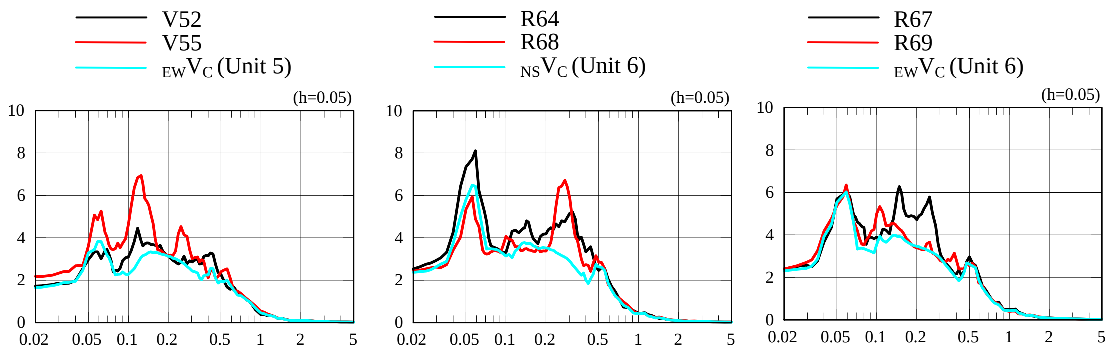
$$\left.\begin{aligned} {}_{NS}V_R(t) &= (VC_{68}(t) - {}_{NS}V_C(t)) \times d1/D1 \\ {}_{EW}V_R(t) &= (VC_{67}(t) - {}_{EW}V_C(t)) \times d2/D2 \end{aligned}\right\} \quad (2)$$

$${}_{6\text{-}R2}V_{cal}\,(t) = {}_{NS}V_C(t) + {}_{NS}V_R(t) + {}_{EW}V_R(t) \qquad (3)$$

Where:

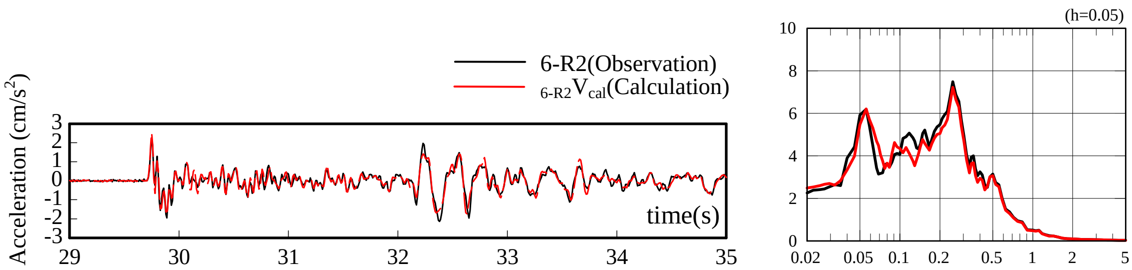
${}_{6\text{-}R2}V_{cal}\,(t)$: Estimated result of the vertical motions of new additional seismometer (6-R2)

Figure 10 shows comparison between observation records and vertical motions estimated from equations (2) and (3). We could obtain satisfactory agreement. We concluded that rocking motions were able to be evaluated accurately assuming that the base mat were rigid.



(1) Unit 5 (EW) (2) Unit 6 (NS) (3) Unit 6 (EW)

Figure 9. Comparison of response spectra between vertical observation records and VC of Units 5 and 6



(1) Acceleration waveforms (2) Response spectra

Figure 10. Comparison between observation record at the new additional seismometer (6-R2) and calculation from observation records at the basic system of seismometers on the base mat of Unit 6

5 STUDY ON THE MAIN SHOCK

Based on analysis of the aftershock, we tried to estimate VC and VR calculated from simulation analysis of horizontal motions during the NCO. First, we estimated angular acceleration on the base mat obtained from the simulation analysis during NCO. Secondly, we estimated VR using equation (4). Finally, we estimated VC using equation (5).

$$\left.\begin{aligned} {}_{NS}V_R(t) &= \ddot{\theta}_{NS}(t)\times L_{NS} \\ {}_{EW}V_R(t) &= \ddot{\theta}_{EW}(t)\times L_{EW} \end{aligned}\right\} \quad (4)$$

where,

$\ddot{\theta}_{NS}(t)$: Angular acceleration obtained from the simulation analysis of NS direction.
$\ddot{\theta}_{EW}(t)$: Angular acceleration obtained from the simulation analysis of EW direction.
L_{NS} : A distance from the center of base mat to the observation point (NS direction).
L_{EW} : A distance from the center of base mat to the observation point (EW direction).

$$V_C(t) = {}_{m\text{-}R2}V_{obs}(t) - {}_{NS}VC(t) - {}_{EW}VC(t) \quad (5)$$

where,

$V_C(t)$: VC each unit.
${}_{m\text{-}R2}V_{obs}(t)$: Observation records each unit.

Figure 11 shows conception of calculation methods. For further details of the simulation analysis, see [3] [4] [5]. Figure 12 shows the transfer function($\ddot{\theta}\cdot L/2E_H$) obtained from simulation analysis. The transfer function of Units 6 and 7 are larger than Unit 5 at 3Hz that is the dominant frequency of the rocking motions. This is because the size of base mat of Units 6 and 7 are smaller than that of Unit 5.

Figure 13 shows comparison of response spectra between vertical observation records and VC estimated using equation (5). Vertical observation records are larger than VC. In particular, it was clarified that the observation record of Unit 6 were influenced by the rocking motion.

3 factors influence rocking motion, input horizontal motion, the transfer function, and a distance from the center of base mat to observation point.

The response spectrum on the base mat of the horizontal motion at 3Hz of Unit 5 is much the same as that of Unit 6 (see Figure 3). However, the transfer function of Unit 6 is larger than that of Unit 5. This is because the size of base mat of Unit 6 is smaller than that of Unit 5 (see Figure 13). In addition, a distance from the center of base mat to observation point of Unit 6 (6-R2) is farther than that of Unit 5 (5-R2). We concluded that VR of Unit 6 are larger than that of Unit 5 because the distance from the center of base mat to observation point is long and transfer function is large.

The size of base mat and location of observation point of Unit 6 are much the same as that of Unit 7. However, the response spectrum on the base mat of the horizontal motion at 3Hz of Unit 6 is larger than that of Unit 7 (See Figure 3). We concluded that VR of Unit 6 were larger than that of Unit 7 because the horizontal motion on the base mat at 3Hz that is the dominant frequency of the rocking motions. VC of Unit 6 were much the same as that of Units 5 and 7 (see Figure 13). We concluded that the cause of the differences among 3 Units, Units 5, 6 and 7 of vertical observation records during NCO was the rocking motions.

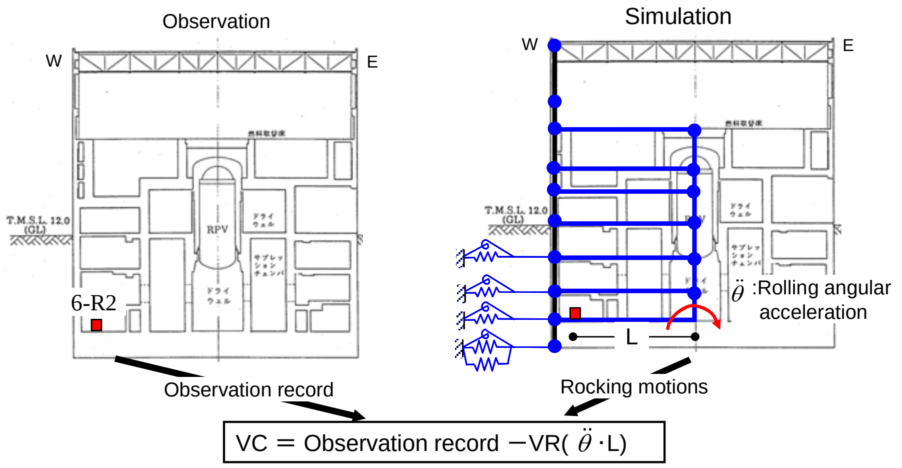
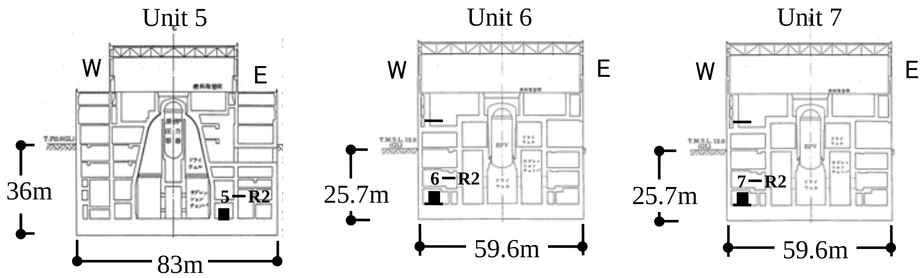
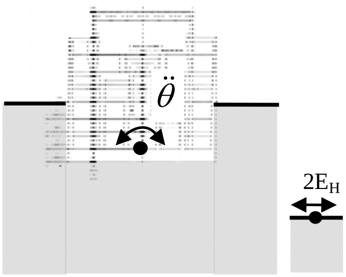


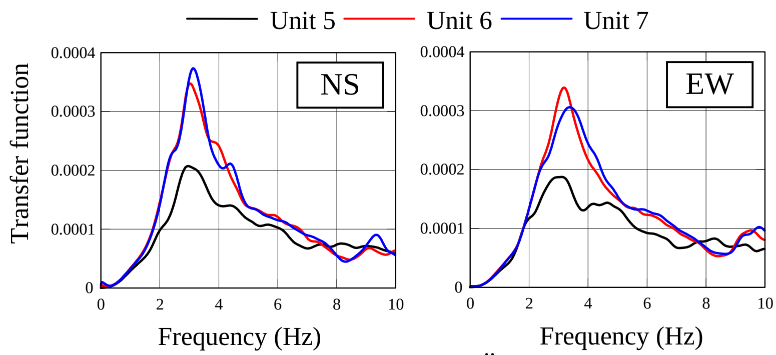
Figure 11. Conception of calculation methods



(a) Unit size and distribution of seismic observation points that digital data of the main shock waveforms were retrieved



(b) Simulation model



(c) Transfer function($\ddot{\theta}$ ･$L/2E_H$)

Figure 12. Transfer function ,VR to the horizontal motions on the free surface of the base stratum ($\ddot{\theta}$ ･$L/2E_H$)

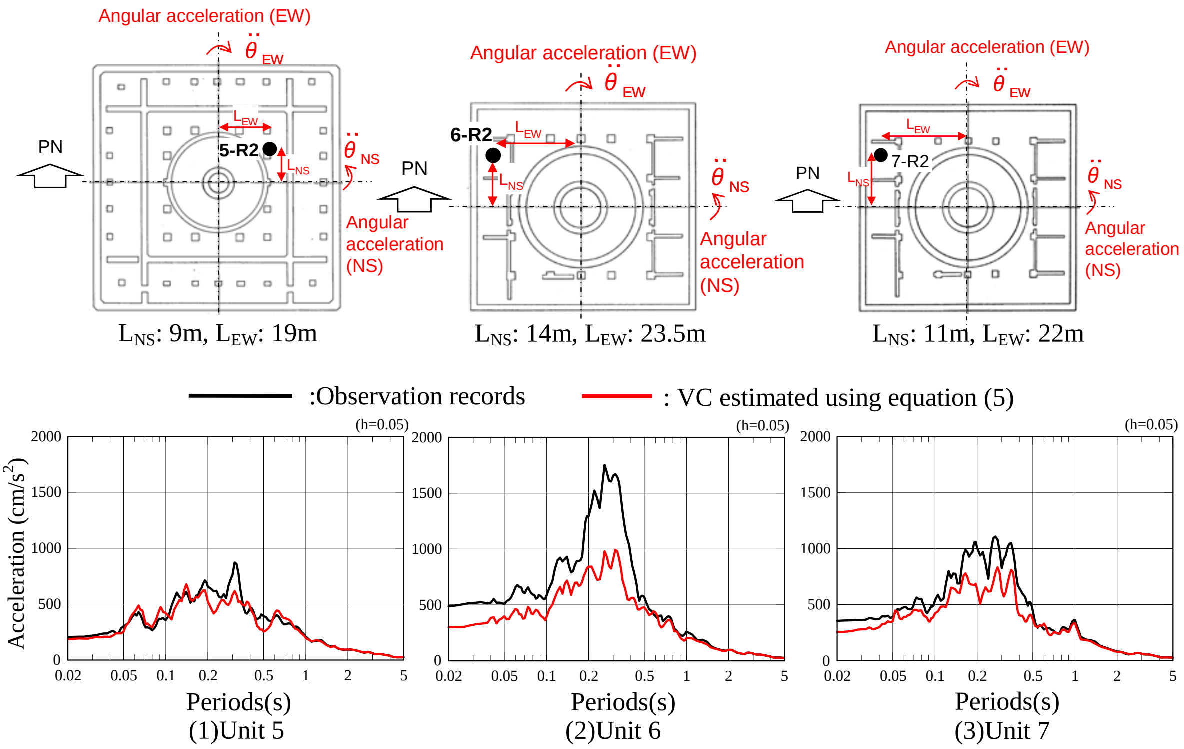


Figure 13. Comparison of response spectra between vertical observation records and VC estimated using eq.(5)

6 CONCLUSION

The vertical motions of the reactor building of Unit 6 were larger than those of adjacent reactor buildings of Units 5 and 7 during NCO. In this paper, we focused on relationship between the vertical responses and the vertical motions induced by the rocking motions with simulation analyses and observation records during both NCO and the aftershock of NCO. The reasons why the vertical motions of the reactor building of Unit 6 were larger are discussed.

We concluded that rocking motions were able to be evaluated accurately assuming that the base mat is rigid from the study on aftershock. We estimated that VC of Unit 6 during the main shock are similar to that of Units 5 and 7 during NCO. We concluded that the reasons why the vertical motions of the reactor building of Unit 6 were larger are rocking motions. We should notice that influence of rocking motions on the simulation analysis if observation point is located far away spatially from the center of base mat. It is important that distribution of seismic observation points concluded influence of rocking motions, for example, two seismic observation points symmetrical with respect to the central axis of unit.

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