Application of Earthquake Early Warning System and Real-time Strong-motion Monitoring System to Earthquake Disaster Mitigation of a High-Rise Building in Tokyo, Japan

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ABSTRACT :

We apply Earthquake Early Warning System (EEWS) and Real-time Strong-motion Monitoring System (RSMS) to reduce earthquake-related damage of the 29-story building of Kogakuin University in the downtown Tokyo, Shinjuku, Japan. EEWS, which is operated by National Research Institute for Earth Science and Disaster Prevention, is the system to provide earthquake information, such as the location and magnitude of an earthquake, the arrival time of the S-wave, and the estimated seismic intensities, before the actual arrivals of S-waves. We estimate the ground motion using EEWS, not only the S-wave, Using EEWS, we estimate not only the arrival time and the amplitude of the S-wave and the surface waves, but also the building response. We apply EEWS to the emergency control systems of the elevators by estimating ground motions at the Shinjuku site and the corresponding building response. To do this, first, we construct a Green's function library to estimate roughly the strong ground motions including the surface waves using the wavenumber integration method for various seismic regions, and a library of the corresponding maximum response values of the building using the modal analysis. To check the accuracy of the library, we compare between the observed record for the 2004 Chuetsu Earthquake and the estimated waves. The results show good agreements with the observations in the first half of the records in the arrival time, the amplitudes. Once an earthquake occurs, the ground motion and the building response are quickly estimated using the proposed method. And, the emergency control systems stop automatically the elevators at the nearest floors to prevent people from trapping. On the other hand, we use RSMS to estimate the building damage during earthquakes, and to reduce secondary damages, such as making an announcement for the building safety to prevent a panic.

KEYWORDS: Earthquake Early Warning System, Real-time Strong-motion Monitoring System, High-rise Building, Surface Wave, Green's function library, Elevator Emergency Control Systems

1. INTRODUCTION

The Shinjuku campus of Kogakuin University is located in the downtown Tokyo, and is a high-rise building of the 29-stories with 149m of height and about 3 sec of the 1st natural period. The campus building needs to prepare for the two types of large earthquakes: one is M7 earthquakes under the Tokyo area, and the other is M8 earthquakes from a rather far subduction zone. The Headquarters for Earthquake Research Promotion estimated about 70% of the occurrence probability of an M7 class earthquake in the southern Kanto area for the next 30 years (Headquarters for Earthquake Research Promotion, [1]). When this type of earthquake occurs, it is estimated disastrous damage in the Tokyo metropolitan area, according to the Central Disaster Prevention Council of Cabinet Office [2]. On the other hand, the occurrence probability of the Tokai earthquake (M8.0) for the next 30 years is estimated at 86% [1]. When the earthquake occurs, the long-period strong ground motions, which are the surface waves excited in the Kanto sedimentary basin, will vigorously shake long-period structures in Tokyo, such as high-rise buildings and oil storage tanks.

In order to reduce earthquake related damage from those earthquakes, we apply EEWS (Early Earthquake Warning System) and RSMS (Real-time Strong-motion Monitoring System) to the elevator control system of the high rise building of Kogakuin University. The Japan Meteorological Agency (JMA) has been distributing the EEWS information to public users since 1st October 2007, which are the estimated seismic intensities and the expected arrival time (JMA, [3]). On the other hand, the National Research Institute for Earth Science and

Disaster Prevention (NIED) also provides the EEWS information for academic users with more detail information than those of JMA, such as the magnitude, depth, location of an earthquake, which we use for estimating the arrival time and amplitudes of the body and surface waves. On the other hand, the building has RSMS for monitoring its response during earthquakes, which is also used to estimate the building damage by computing the story drift angles and the seismic intensities on each floor in real-time.

2. EEWS, RSMS AND ELEVATOR EMERGENCY OPERATION CONTROL SYSTEMS OF KOGAKUIN UNIVERSITY

2.2. EEWS and RSMS of Kogakuin University

Figure 1 shows the EEWS between Kogakuin University and NIED; EEW information includes the location of the epicenter of an earthquake, its magnitude, Seismic Intensity Magnitude (Yamamoto *et al.*, [4]) and the observation waves of Hi-Net. Figure 2 shows the elevation plans of the Kogakuin University buildings and the location of the accelemeters of RSMS. The RSMS has been recorded a lot of observation data, such as 2004 Kii Peninsula Offshore Earthquake and 2004 Chuetsu Earthquake. Figure 3 shows the RSMS web pages, the top page outlines the RSMS, the wave page shows the observation record or the real-time data on each channel, and the building response page shows the building response, the seismic intensity and the story drift angle at each floor. When earthquake happens, security officers of the building are possible to check the building damage on real-time by RSMS. Figure 4 shows the location of Kogakuin, a K-Net station [5] and the epicenter of 2004 Chuetsu Earthquake and Figure 5 shows the observed records of RSMS and the K-Net for 2004 Chuetsu Earthquake. The P- and S-waves arrived at Shinjuku at about 37 sec and 59 sec, respectively, after the occurrence of the earthquake. On the other hand, the surface waves arrived at about 93 sec, and shaken the building with the maximum response around at 125 sec. Therefore, we will have enough time for controlling the elevators before the arrival of the surface waves.

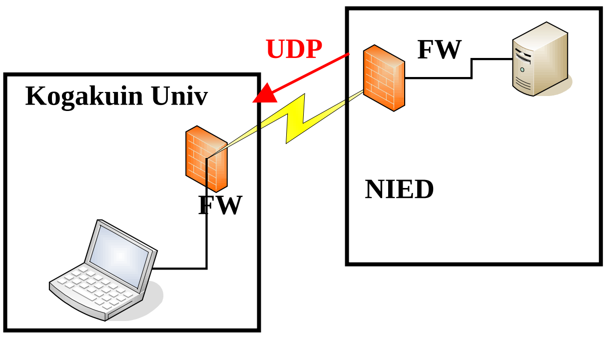


Figure 1 EEWS between Kogakuin University and NIED

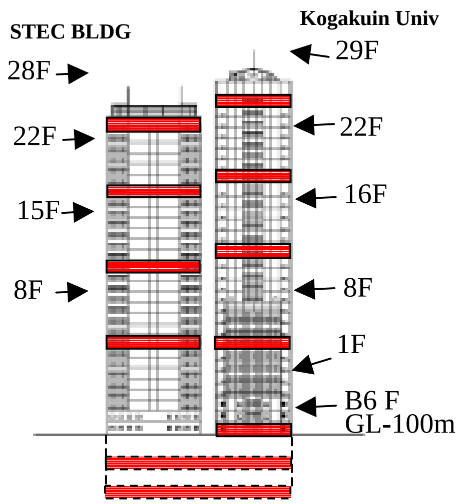
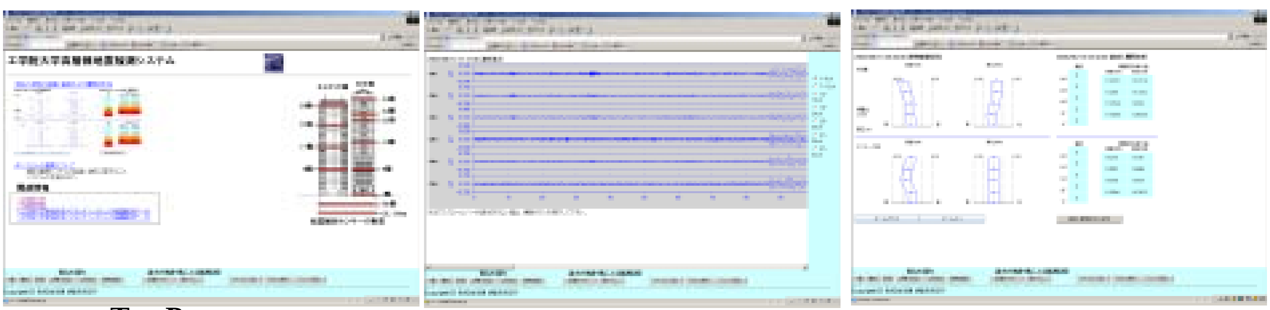


Figure 2 The elevation plan of Kogakuin University and the locations of the accelerometers,



Top Page **Wave Page** **Building Response Page**

Figure3 Real-time Strong motion Monitoring System

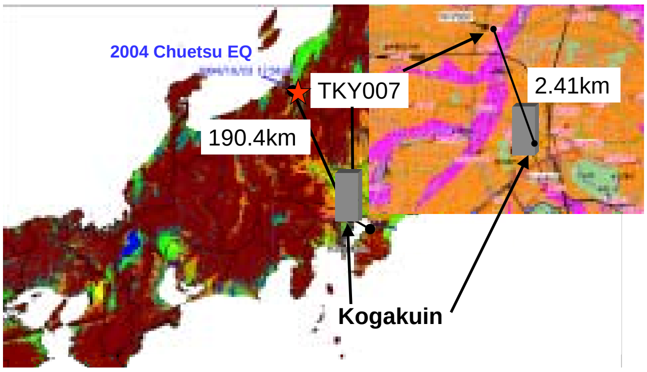


Figure 4 The location of Kogakuin Building, K-net and the seismic source in 2004 Chuetsu EQ

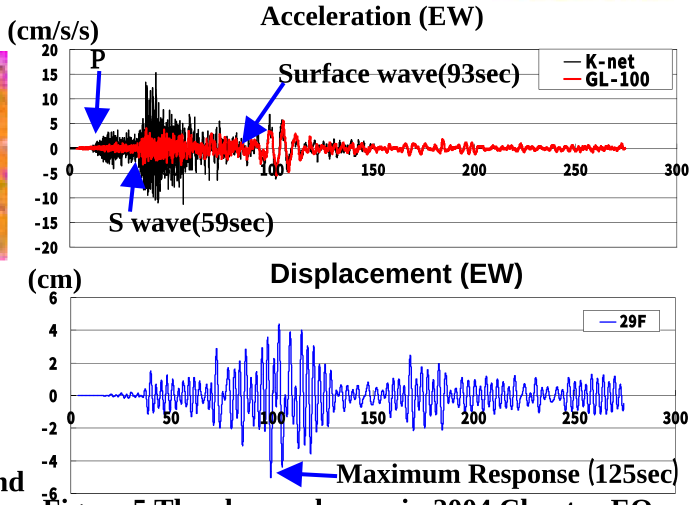


Figure 5 The observed wave in 2004 Chuetsu EQ

2.2. *Elevator Emergency Control System during a Earthquake*

Kogakuin University building has 3 types of elevators. Table 1 shows the locations of the P- and S-wave sensors and their trigger levels for the emergency control during an earthquake. When the P-wave sensors are triggered, the elevators stop by the nearest floors for about 60 sec to 90 sec, and automatically restart their service, if nothing happens afterward. On the other hand, when the S-wave sensors are triggered at the lower levels, the elevators also stop by the nearest floors, but do not restart without confirming the safety by the maintenance company staffs. When the S-wave sensors are triggered at the higher levels, the elevators stop immediately, and thus, the people in the elevators are probably trapped.

Table 1 The P and S sensors, their locations and trigger levels for the emergency operation control systems of elevators of the Kogakuin University

EV type	Lowest trigger level P wave sensor	Low trigger level S Wave sensor	High trigger level S Wave sensor	Others
EVs for the higher and middle floors	No	80gal on penthouse	120gal on penthouse	Seismic Wave Energy sensor
EV for the lower floors	5gal on pit	150gal on 8th floor	No	
EV for Emergency	5gal on pit	40gal on penthouse	80gal on penthouse	

3. ELEVATOR EMERGENCY CONTROL USING EEWS FOR LONG-PERIOD GROUND MOTION

In this study, we propose the elevator emergency control flow using EEW for long-period strong ground motions. As shown in a flow in Figure 6, when the system receives an EEW data (the magnitude, location and depth of an earthquake), it immediately estimates the arrival time of the surface waves and the maximum building response. We estimate the arrival time using an empirical relation, as shown below. To obtain the maximum response, we first prepare database library of long-period ground motions and the corresponding building response, which will be also represented bellow.

3.1. *Development of the Empirical Equation for the Arrival Time of the Surface Wave*

We collect the observation data from 1994 to 2006 and develop the empirical equation for the arrival time of the surface wave. The number of the collected waves is 173, including the 15 waves of the surface wave data. Figure 7 shows the distribution of the epicenters of observation data, and Figure 8 shows plots of the arrival times versus the distances between hypocenters and the Kogakuin site. The P, S, and surface waves correspond to blue lozenges, red boxes, green triangles, respectively. The lines show the average velocities; the P, S-wave and the surface wave are 5.9km/s, 3.5km/s and 2.5km/s, respectively. On the other hand, we also calculate the theoretical velocities of the P, S-wave and the surface wave using the wavenumber integration method (Hisada and Bielak [6]). Tables 2 and 3 show the crustal structure model by NIED and the sedimentary structure model, which consists of the crustal model and the sedimentary layers of the Kanto basin (Yamada and Yamanaka, [7], J-SHIS, [8]). In figure 8, the dotted lines show the theoretical velocities, which are in good approximation in those of the observations.

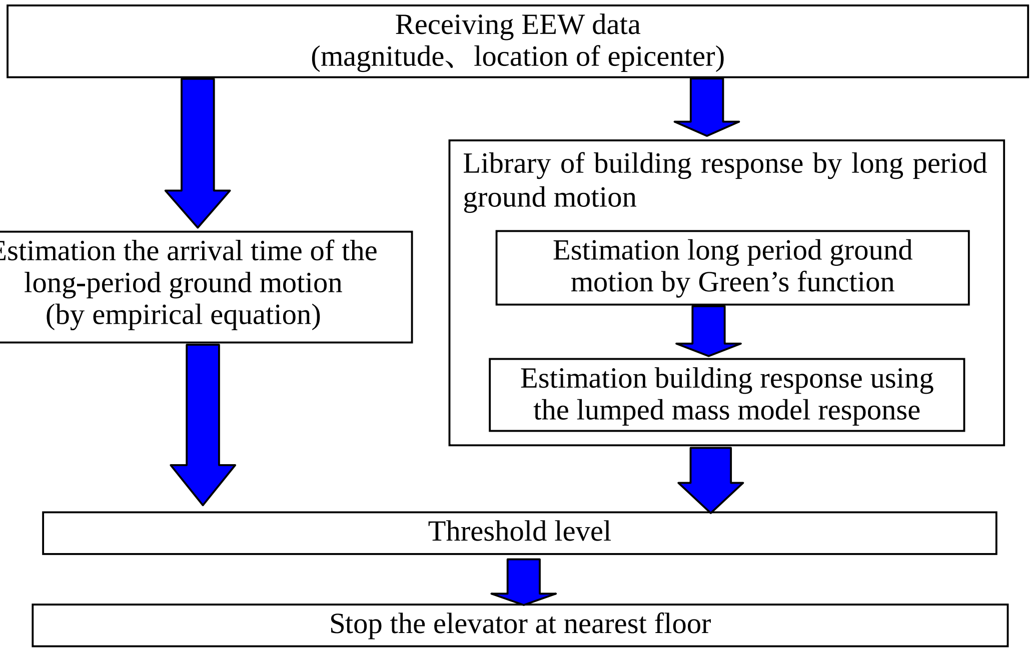


Figure 6 The elevator emergency control flow

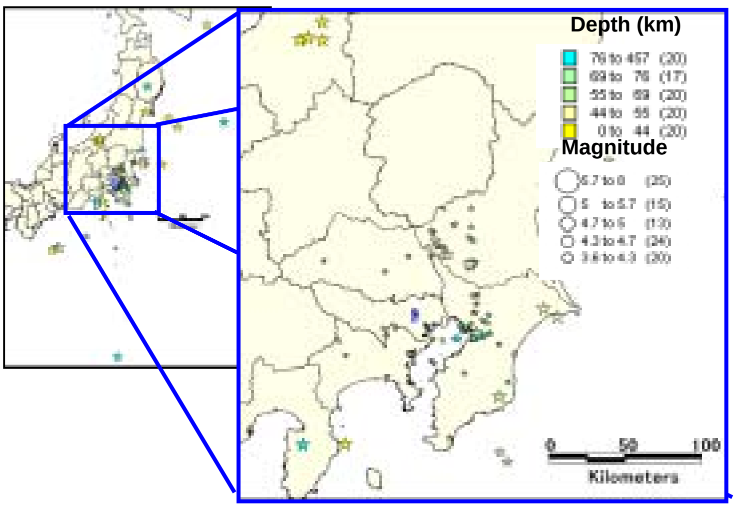


Figure 7 The distribution of the epicenter in the observation data

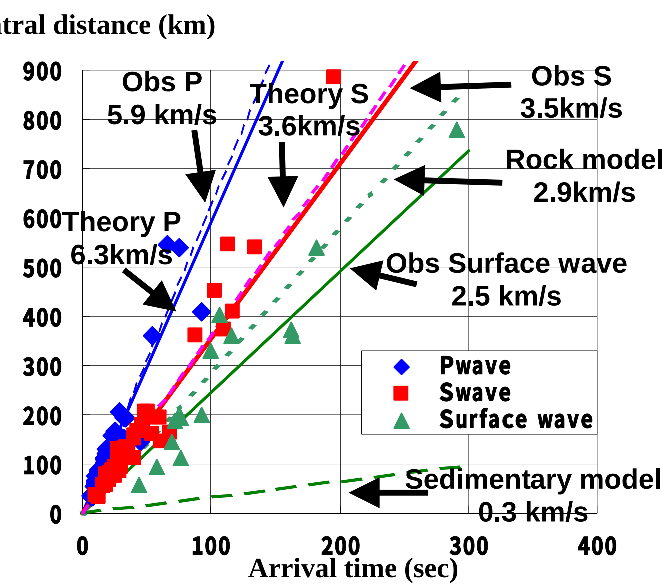


Figure 8 The plot of the arrival time versus the distance between hypocenter and Kogakuin site

Table 2 The structure of Rock model

Layer Number	density (t/m3)	Vp(m/s)	Vs(m/s)	Q	Thichness (m)	Data
1	2.3	5450	3179	300	1000	NIED Traveltime Database
2	2.3	5501	3209	300	1000	
3	2.3	5527	3224	300	2500	
4	2.3	5816	3392	400	3000	
5	2.3	6035	3521	500	4000	
6	2.3	6206	3620	600	3000	
7	2.3	6381	3722	600	3000	
8	2.3	6684	3899	1000	5000	
9	2.3	7201	4200	1000	8000	

Table 3 The structure of Sedimentary model

Layer Number	density (t/m3)	Vp(m/s)	Vs(m/s)	Q	Thichness (m)	Data
1	1.85	1840	500	100	400	Yamada･Yamanaka (2003) Japan Seismic Hazard Information Station
2	1.9	1900	750	100	800	
3	2	2200	1350	150	650	
4	2	3863	2287	300	650	
5	2.3	5527	3224	300	2500	NIED Traveltime Database
6	2.3	5816	3392	500	3000	
7	2.3	6035	3521	500	4000	
8	2.3	6206	3620	600	3000	
9	2.3	6381	3722	600	3000	
10	2.3	6684	3899	1000	5000	
11	2.3	7201	4200	1000	8000	
12	2.3	7775	4364	1000	9000	
13	2.3	7804	4380	1000	10000	

3.2. Estimation of the Surface Wave and Building Response using EEWS

Next, we estimate the long-period strong ground motions including the surface waves, and the corresponding building response. We compute the ground motions using the wavenumber integration method [4], and the building response using a lumped mass model. As an example of ground motion simulations, Table 4 shows the source parameters of the 2005 Chuetsu, Niigata, earthquake, from EEWS. The JMA magnitude is estimated from the moment magnitude using the empirical relation by Takemura [9], and the stress drop is the average value of crustal earthquakes in Japan (Turugi *et al.*, [10]). We estimate the ground motion at the Shinjuku site using the Sedimentary structure model shown in Table 3.

Figure 9 shows the radial and transverse components of the observed records by RSMS and the simulated waves, using a band pass filtered from 0.1 Hz to 1 Hz. Figure 10 shows the corresponding Fourier spectrums. The estimations show good agreements with the observations before 70sec in the waves and less than 4 sec of period. After 70 sec いn duration and 4 sec in period, the simulations underestimate the observations, probably because of the 3D effects of the Kanto sedimentary basin.

Figure 11 shows the observed building response at the top floor and the simulated results using one-mass model, which is equivalent to 1st mode of the building (3 sec of period and 2% of damping). Even though the methodology is very simple, the estimations show in good approximation in the observations, not only in the arrival time, but also in the amplitudes. Since our purpose is to estimate the maximum building response as quickly as possible, the methodology is effectively enough to apply to the emergency control systems of the elevators

Table 4 The point source parameter in 2004 Chuetsu Earthquake

Mjma	Depth(km)	Mo (dyne-cm)	Stress Drop (bar)	fmax (Hz)
6.8	13.2	4.74E+25	30	6

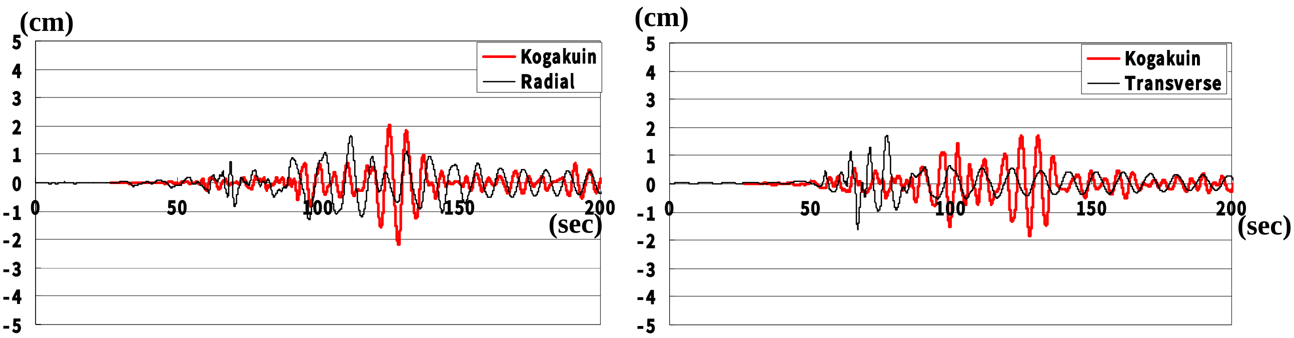


Figure 9 The comparison between the observed wave with the simulation wave in 2004 Chuetsu EQ

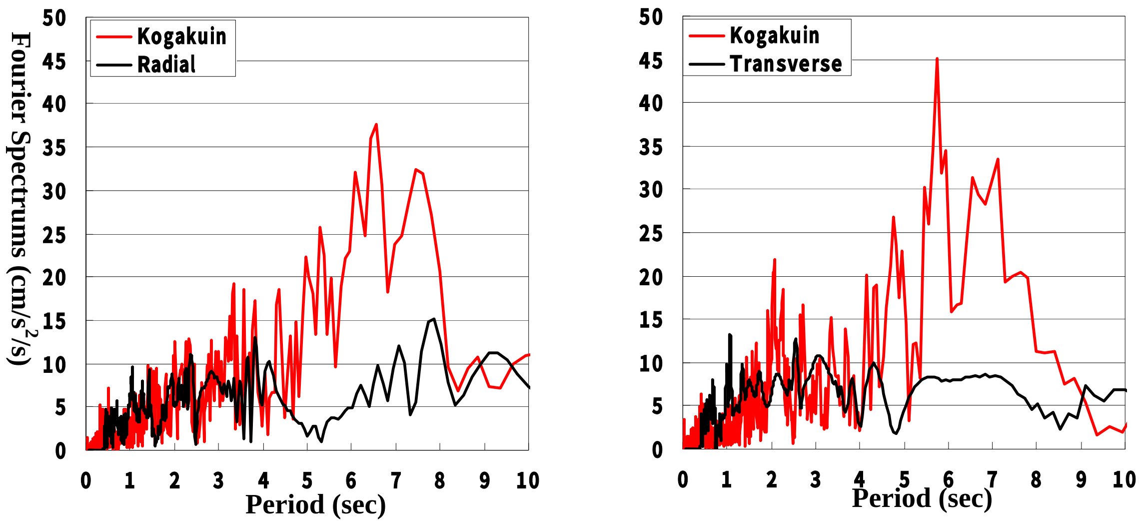


Figure 10 The comparison between the observed Fourier spectrums (red line) with the simulation Fourier spectrums (black line) in 2004 Chuetsu EQ

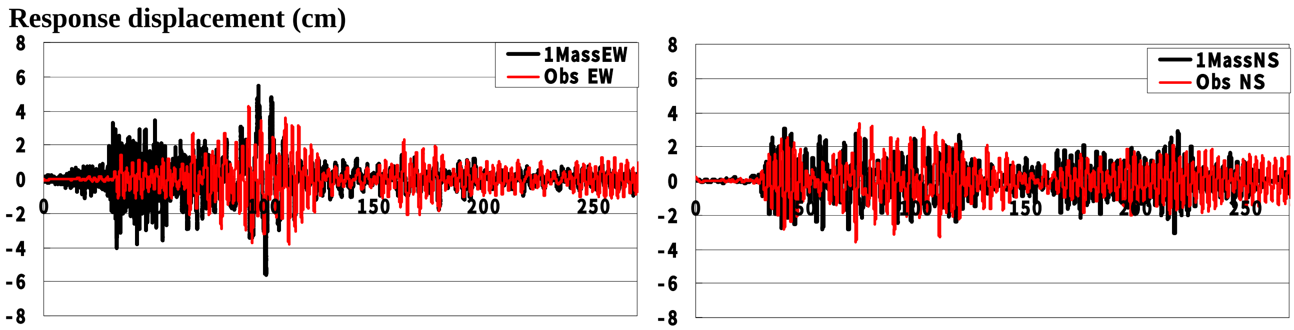


Figure 11 The comparison between the observed displacement with the simulated response displacement in 2004 Chuetsu EQ

3.3. Estimation method of the building response for long-period Ground Motions

For the elevator emergency control during major earthquakes, we develop a database library of the building response, and check the cases for stopping the elevators. Table 5 shows those cases at Kogakuin University.

We estimate the strong ground motion and the building response on these earthquakes using the above method. Figure 12 shows the plot of the observed maximum displacements at the top of building versus the estimated maximum building responses,. The cases for stopping and not stopping the elevators are shown in the red boxes and the blue triangles, respextively. For most of the cases, the elevators stopped when the maximum displacements exceed 2.1 cm. Therefore, the building response is estimated over 2.1 cm, we stop the elevator sbefore arriving the surface wave.

Table 5 The case of the elevator stopped by the long-period ground motion

EQ	Hypocenter Distance (km)	Logitude	Latitude	Depth	M_{JMA}	Elavator Status
1998/4/9 Fukushima Offshore	184	141.0	36.9	90km	5.4	
1999/5/22 West Kanagawa	53	139.2	35.5	23km	4.4	
2000/7/15 Near Niijima & Kozushima	146	139.3	34.4	10km	5.9	
2003/7/26 East Miyagi	330	141.2	38.4	10km	6.2	
2003/9/26 Tokachi Offshore	695	144.1	41.8	42km	8.0	
2003/10/31 Miyagi Offshore	359	142.7	37.8	30km	6.8	
2004/9/5 Kii Peninsula (19o'clock)	411	136.8	33.0	38km	6.9	
2004/9/5 Kii Peninsula (23o'clock)	425	137.1	33.1	44km	7.4	Lowest trigger
2004/10/23 Chuetsu (17o'clock)	194	138.9	37.3	13km	6.8	Lowest trigger
2004/10/23 Chuetsu (18o'clock)	193	138.9	37.3	14km	6.5	
2004/10/27 Chuetsu	189	139.0	37.3	12km	6.1	
2004/11/8 Chuetsu	200	139.0	37.4	Shallow	5.9	
2005/8/16 Miyagi Offshore	358	142.3	38.2	42km	7.2	Lowest trigger
2005/11/15 Miyagi Offshore	540	144.9	38.0	45km	7.2	
2006/4/21 East Shizuoka	95	139.2	34.9	7km	5.8	
2008/5/8 Ibaraki Offshore	181	141.6	36.2	35km	7.0	Low trigger

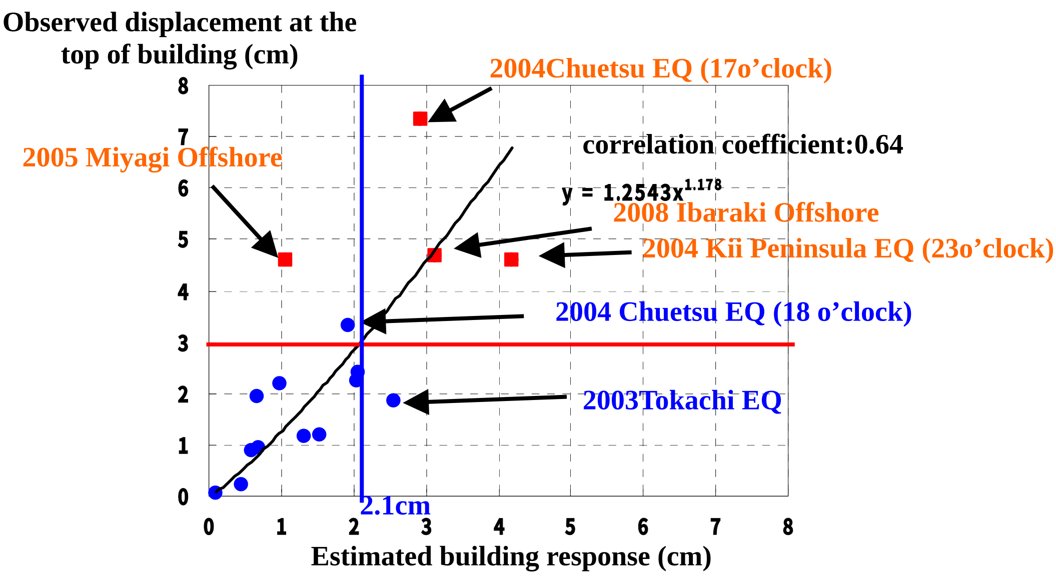


Figure 12 The plot of the observed displacement at the top of building versus the estimated building response

4. CONCLUSIONS

We applied EEWS and RSMS to the emergency operation control systems of the elevators of the high-rise campus building in downtown Tokyo, considering long-period strong motions. Once an earthquake occurs, the maximum building response can be quickly computed using the source data of EEWS and the database libraries, which are estimated by computing the surface waves in the Kanto basin, and by using a lumped mass model of the building. If the response is estimated over a certain threshold value, the EEWS server sends a signal to the emergency control systems of elevators as the lowest trigger level for stopping them at the nearest floors. In addition, we are planning to apply EEWS and RSMS to the announcement system to prevent a panic by providing the accurate information about the building's safety; this is important because the high-rise building will continue to shake vigorously for several minutes by the surface waves, especially for M8-class earthquakes.

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