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Rapid Diagnosis Systems Using Accelerometers in Seismic Damage of Tall Buildings

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Abstract

Installing accelerometers in a building is an effective way to know how the building shakes when an earthquake happens. In this paper, we will introduce an example of an analysis that captures the acceleration reduction effect of the vibration damping device using data observed by the accelerometer at Roppongi Hills Mori Tower in Minato-ku, Tokyo, during the Great East Japan Earthquake on March 11, 2011. Moreover, as the latest effort, from the standpoint of a developer who builds and operates a number of high-rise buildings in Japan, where frequent earthquakes are experienced, a system for real-time processing of accelerometer data was developed to instantly diagnose the degree of damage to high-rise buildings, and the actual system of earthquake damage health monitoring is discussed. This system is currently in operation in twelve high-rise buildings including Roppongi Hills Mori Tower.

Keywords: Damping devices, Structural health monitoring

1. Introduction

Japan is one of the world's most earthquake-prone nations, and has been frequently subjected to earthquake disasters that have caused damage to large cities in recent years. In the Great Hanshin Earthquake of 1995, many buildings with low earthquake resistance and built to old seismic standards collapsed. While building damage due to the 2011 Great East Japan Earthquake was limited, massive damage resulted from a major tsunami in the Tohoku region. Earthquake countermeasures are indispensable in the construction of buildings in Japan. Particularly in large cities with many skyscrapers, it is important to prevent confusion in the event of an earthquake by making early decisions on the damage to a building, and the possibility of its continued use. As a developer and manager of many high-rise buildings within the context of urban redevelopment, Mori Building has been installing accelerometers in skyscrapers to understand earthquake tremors for more than 30 years. In this paper we introduce examples of understanding damping effects using accelerometer data obtained in the 2011 Great East Japan Earthquake. We have developed a system to monitor damage to buildings in real-time by utilizing the lessons learned from the Great East Japan Earthquake, and have introduced this system into 12 high-rise buildings managed and operated by Mori Building. As an example, we introduce the case of Roppongi Hills Mori Tower.

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2. Understanding Accelerometer Measurements and Damping Effects in Roppongi Hills Mori Tower during the Great East Japan Earthquake

2.1. Overview of the Project

Roppongi Hills is located in Minato-ku in central Tokyo, and was completed in 2003 as the largest private redevelopment. It is a composite facility including offices, housing, commercial facilities, museums, and movie theaters (Fig. 1). Even today, more than 10 years after it's opening, the building is crowded with office workers, residents and visitors, making it one of Tokyo's attractions for tourists from domestic and abroad. Designed for earthquake resistance, the building is operated under the slogan of 'A building to escape into, not out of'. It boasts high levels of earthquake resistance, and is well-stocked with emergency equipment. Employees of the developer, Mori Building,



Figure 1. Perspective of Roppongi Hills.

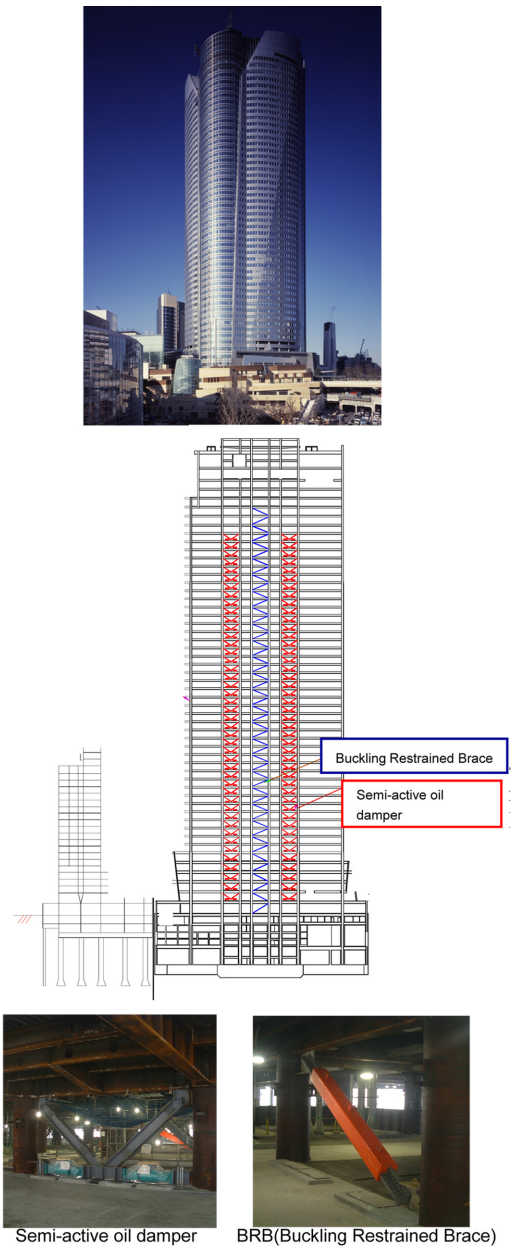


Figure 2. Location and Number of Dampers.

regularly undertake earthquake training in the building.

Two types of Damping devices (semi-active oil dampers, Buckling Restrained Braces with low yield point steel) are installed in Roppongi Hills Mori Tower (the office tower at the center of the facility) to reduce earthquake response (Fig. 2).

2.2. Vibration in Tokyo During the Great East Japan Earthquake

The Great East Japan Earthquake occurred at 2:46 pm on March 11, 2011. The epicenter was located at a depth

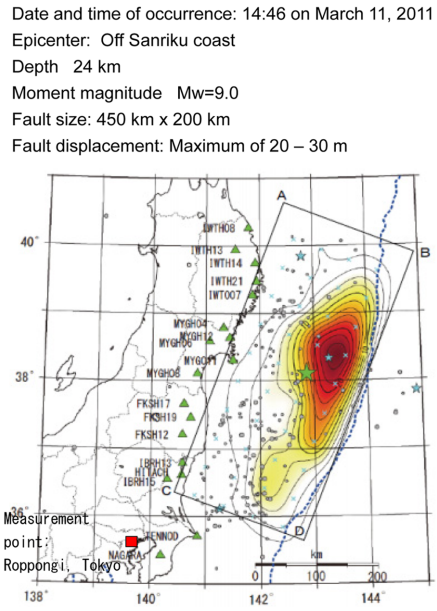
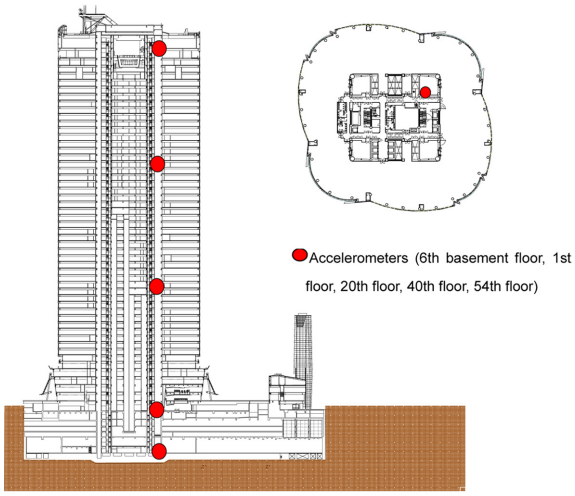


Figure 3. Great East Japan Earthquake - Focal Region and Measurement Points (GIAJ-CDTGP, 2011).

Table 1. Outline of Roppongi Hills Mori Tower

Building outline	Roppongi Hills Mori Tower
Number of floors	54 above ground, 6 underground, 2 penthouse levels
Maximum height	238.05 m
Floor Area	37,9408.63 m^2
Type of structure	Steel structure (columns CFT), underground SRC and RC
Framework	Moment resisting frame structure
Foundations	Raft foundations
Seismic damping	Damped structure (semi-active oil dampers and Buckling Restrained braces with low yield point steel)

of approximately 24 km below the Pacific Ocean at a point approximately 130 km east-south-east of the Ojika Peninsula, and 70 km east of the city of Sendai. A trench-type earthquake along the boundary between the Pacific and North American plates (in the vicinity of the Japan Trench), the focal region covered a wide area of approximately 200 km out into the Pacific Ocean off the coast of Iwate and Ibaraki Prefectures, and approximately 500 km in length (100,000 square kilometers). See Fig. 3. The magnitude indicating the scale of the earthquake was Mw 9.0, the largest in the history of observation in Japan, exceeding Mj 7.9 and Mw 8.2 of the Taisho Kanto Earthquake of 1923. It was the fourth largest earthquake recorded in the world since 1900. Wide-ranging and severe vibration were observed in the Tohoku region. The accelerometer recording the most severe vibration was located at the K-NET Tsukidate - 2933 gal (three-axis synthesis



Device Specifications

	Servo-type accelerometer (AS-303T1W1)
Measured component	Horizontal 2 axis, vertical 1 axis , total 3 axis
Measurement range	0 - ±3,000 gal, 0 – 100 Hz
Resolution:	0.005 gal
Oblique view	

Figure 4. Accelerometer Location and Device Specifications.

value).

Large-scale vibration were recorded in the northern part of Miyagi Prefecture (seismic intensity of 7), and between Iwate and Chiba Prefectures (seismic intensity 6-), and widespread liquefaction occurred at landfills in the Kanto region.

In Japan, seismic intensity is generally used as a scale for the strength of earthquakes, and severity of the earthquake is classified in seven steps up to a maximum seismic intensity of 7. Buildings are destroyed at a seismic intensity of between 6 and 7. Vibration of approximately 100 gals on the ground surface occurred even in Tokyo, approximately 350 km from the epicenter, and long-period seismic motion continued for tens of minutes, due to vibration of the entire Kanto Plain. Skyscrapers in Shinjuku were found to have vibrated for more than 10 minutes, with displace exceeding 1 m (one-side). The Tokyo Metropolitan Government office in Shinjuku announced that

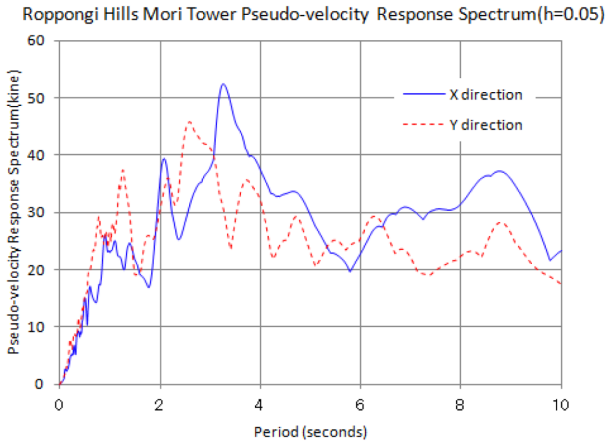


Figure 5. Pseudo-velocity response Spectrum for Roppongi Hills Mori Tower during the Great East Japan Earthquake.

displace of up to 65 cm was observed (ICLGM, 2011).

Furthermore, although a seismic intensity of 3 was observed in Osaka prefecture, several hundred kilometers from the epicenter, resonance of the skyscrapers due to long-period grand motion resulted in an elevator stopping, with passengers trapped inside, and damage to interiors and fire doors.

2.3. Accelerometer Waveform Recorded at Roppongi Hills Mori Tower

Accelerometers were installed in Roppongi Hills Mori Tower on the 6th basement floor, 1st floor, 20th floor, 40th floor, and 54th floor at completion in 2003 (see Fig. 4). The accelerometers are of the servo type (AS-303 W1T1) manufactured by Tokyo Sokushin Co., Ltd. The purpose of the servo accelerometers is to determine the vibration characteristics of the building, to verify whether the damping effect as designed is obtained, and to acquire basic data for structural design of future skyscrapers. Figs. 5 and 6 show the seismic waveforms and pseudo-velocity response spectrum observed at Roppongi Hills on March 11, 2011 during the main shock of the Great East Japan Earthquake. It can be seen that the power equivalent to level 1 earthquake 'rare earthquake ground motion' corresponding to the damage limit generally used for structural design in Japan with a 5% damping pseudo-velocity response spectrum was observed.

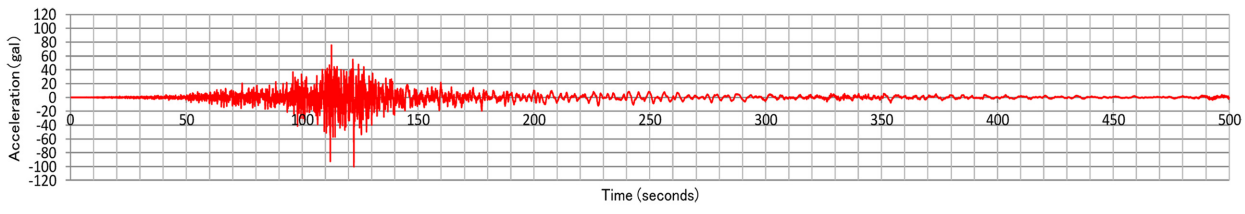


Figure 6. First floor acceleration (Y direction) of Roppongi Hills Mori Tower during Great East Japan.

Table 2. Natural Period and Damping Factor

X direction		20F	40F	54F	Average
Natural Period (sec)	T_1	5.573	5.571	5.575	5.573
	T_2	1.744	1.795	1.740	1.760
	T_3	1.004	0.998	1.005	1.002
	T_4	0.707	0.699	0.699	0.702
	T_5	0.537	-	0.568	0.552
Damping Factor	h_1	0.047	0.040	0.044	0.044
	h_2	0.031	0.011	0.029	0.024
	h_3	0.038	0.038	0.034	0.037
	h_4	0.026	0.041	0.041	0.036
	h_5	0.022	-	0.039	0.030

2.4. Modal Synthesis Analysis of Roppongi Hills Mori Tower

Modal synthesis analysis was conducted on the seismic waveform obtained at Roppongi Hills Mori Tower, and the natural period and damping factor of each mode identified. Results are shown in Table 2. These results were analyzed by supplying data to the Tokyo Institute of Technology Kasai laboratory. Measurements were taken on the 6th basement floor, 1st floor, 20th, 40th, and 54th floors above ground. The 1st floor is the closest to GL and it was set as base point. This building is an high-rise building ,so we extracted 1st to 5th mode. Based on Fig. 7, accuracy of the acceleration with the modal synthesis analysis of the building peak was greatly improved when taking into account the fifth mode in comparison with the third mode. Although the aspect ratio was small, it was found that the higher modes sufficiently affected behavior. Fig. 8 shows the time history of the measured record and modal synthesis analysis at the top of the building. The relative displacements were approximately the same for the primary movement at 120 seconds, and at 250 seconds where the long period grand motion is noticeable. Furthermore, as shown in Fig. 9, the maximum relative displacement and maximum absolute acceleration on each measurement floor are well matched with measured records and modal synthesis analysis. The primary damping factor is approximately 4.7%, and the response is reduced to approximately 0.7 times that of the non-damped case with the damping factor set to 1%. It is considered that the effect of the damping members was sufficient.

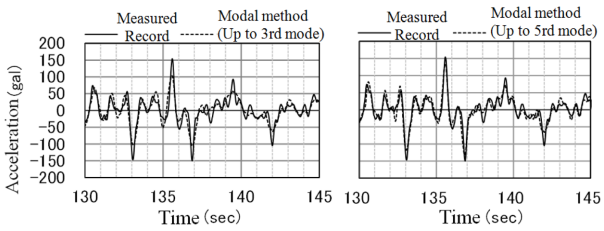


Figure 7. Effects of Higher Modes (top of the building).

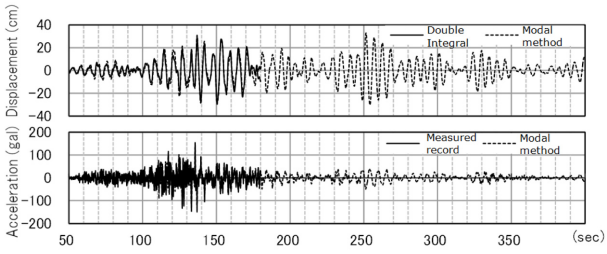


Figure 8. Displacement and Acceleration at the Top of the Building.

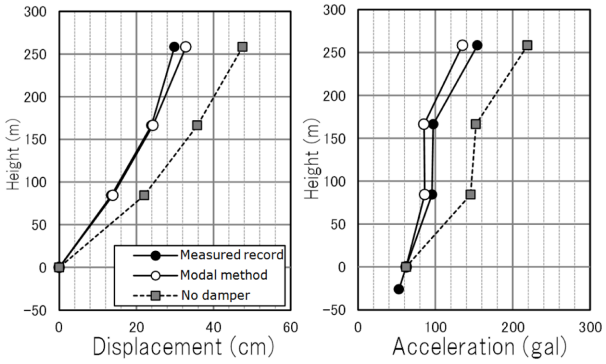


Figure 9. Displacement and Acceleration at the Top of the Building.

Considering that the damping factor of a general steel frame buildings is 1 to 2%, the data shows very high damping factor values. This is considered to be due to the damping effect of the damping devices, and since the load

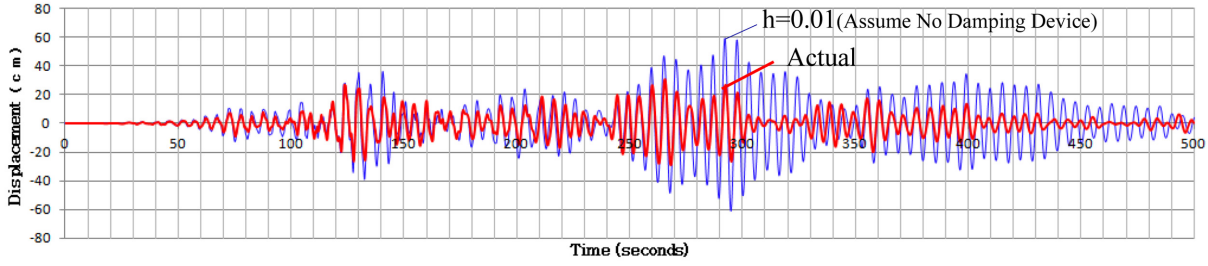


Figure 10. Comparison of Deformation with Deformation of Peak and 1% Damping (Y direction).

in the buckling restrained braces was below the yield load, it is considered that the semi-active oil dampers worked effectively. The displacement at the top at this time was 32.9 cm one-sided shaking width. Fig. 10 shows the analysis of the displacement at the top with a damping factor of 1% assuming the actual displacement at the top of Roppongi Hills Mori Tower and no damping devices. According to the graph waveform, both the maximum value and the post-shock are suppressed well. When there are no damping devices, it can be seen that the displacement is approximately twice the measured amount. Use of the data from the accelerometer in this way makes it possible to evaluate the earthquake resistance of the building (Kasai et al., 2013).

3. Development of a System for Assessment of the Degree of Damage Based on Lessons Learned From the Great East Japan Earthquake

3.1. Development of the Damage Assessment System

During the Great East Japan Earthquake, the intensity of the vibration was beyond the experience of building workers, and a number of inquires were received by the Security Control Center asking whether they should remain in the building or take refuge outside. There were also workers who evacuated to the ground in a hurry via the evacuation staircase.

Since it is a building with high level earthquake resistance, an announcement was made that it was safe if they stayed inside the building. Tens of thousands of people exiting the building simultaneously may result in secondary disasters due to extreme overcrowding if they were out of the building all at once.

Foreign-affiliated companies also asked for objective explanatory materials on safety in the case of continued use of the buildings. As a lesson learned from this disaster, the operator of high-rise building with tens of thousands of workers concluded that merely improving the earthquake resistance of the building is insufficient, and that is necessary to determine to what extent the level of earthquake for which the building was designed approximated the actual earthquake, and based on objective indicators, determine whether safety is adequate, to prevent confusion in the initial stages of the disaster. On this basis, Mori Building developed the e-Daps system to instantaneously diagnose the safety of buildings using accelerometers that were already installed. Fig. 11 shows the screen configuration. When the ground surface acceleration exceeds 0.6 gal, it is determined that an earthquake has occurred, and the system is brought into operation. The safety of the building in terms of the severity of the disaster is evaluated according to whether the story drift angle is within the elastic range set at the design stage, or if exceeded, by how much. Damage to the framework and the possibility of fixtures in the room falling are displayed in real time on the graph (5) in Fig. 11 in terms of the ratio of the elastic limit displacement and whether the acceleration threshold value has been exceeded.

3.2. Method of assessing acceleration and story drift angle on each floor

Since accelerometers are not installed on each floor of the building, as described above, the intermediate floors

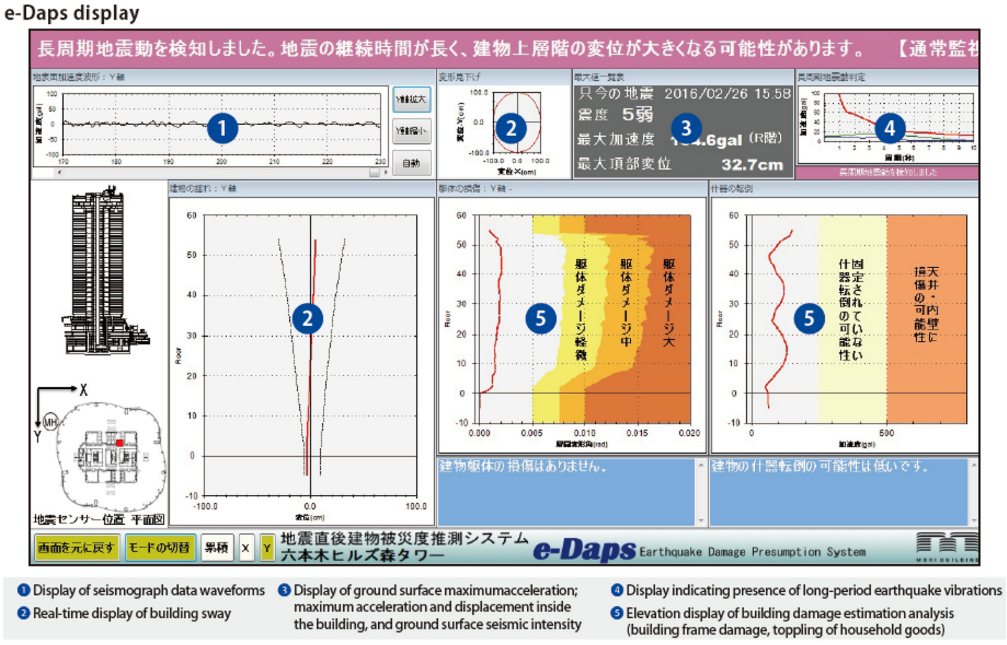


Figure 11. Screen Configuration of Damage Assessment System.



Figure 12. Buildings With Damage Assessment Systems.

were estimated using the 1st-3rd modes.

Acceleration measured at the floors where the accelerometers are installed was double-integrated every 0.1 second and converted to displacement, and the excitation functions for the 1st to 3rd modes were fitted by the least squares method to estimate the displacements of intermediate floors, and the story drift angle at each point in time was calculated. See Fig. 13. The method of calculation is shown below. Using the values of displacement (acceleration) on the 1st, 20th, 40th and 54th floors at each point in time, curve fitting was carried out by linearly superimposing the 1st-3rd modes by the least squares method. It was found that divergences occurred when higher order modes were used, and suitable estimation was not possible. It was therefore decided to use the 1st-3rd modes.

	Actual values	1st mode	2nd mode	3rd mode
1st floor	X1	C11	C12	C13
20th floor	X2	C21	C22	C23
40th floor	X3	C31	C32	C33
54th floor	X4	C41	C42	C43

Assuming the above, the residuals were calculated as follows.

$$R=\left(X_1-\sum_{i=1}^{3}a_iC_{1i}\right)^2+\left(X_2-\sum_{i=1}^{3}a_iC_{2i}\right)^2 +\left(X_3-\sum_{i=1}^{3}a_iC_{3i}\right)^2+\left(X_4-\sum_{i=1}^{3}a_iC_{4i}\right)^2 \quad (1)$$

And the values of a1-a3 which minimize the residual were found. Assuming that the mode shapes are M1 to M3, the synthesis using a1-a3 is a fitted curve.

$$\sum_{i=1}^{3}a_iM_i \quad (2)$$

There are two methods of determining values - the variational method and partial differentiation, however both are essentially the same.

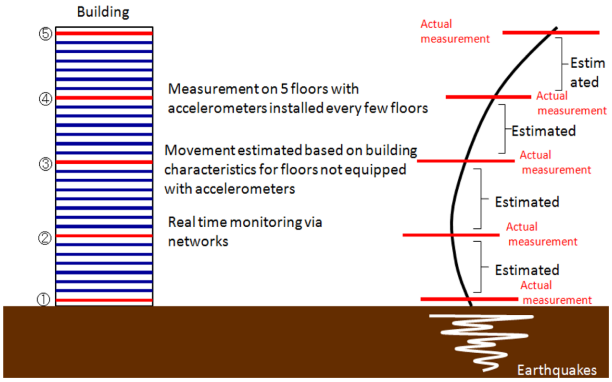


Figure 13. Assessment for Intermediate Floors.

Assume the vector vi of four components to be:

$$v_i=\begin{pmatrix}C_{1i}\\C_{2i}\\C_{3i}\\C_{4i}\end{pmatrix} \quad (3)$$

The coefficients of synthesis of each mode are also represented by vectors.

$$a=\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix} \quad (4)$$

4×3 matrix C is assumed to be:

$$C=(v_1 \quad v_2 \quad v_3) \quad (5)$$

The state in which the 1st-3rd modes are superimposed is expressed by the following equation.

$$Y=a_1v_1+a_2v_2+a_3v_3=(v_1\ \ v_2\ \ v_3)\begin{pmatrix}a_1\\a_2\\a_3\end{pmatrix}=Ca \tag{6}$$

The measured values are also expressed as vectors:

$$X=\begin{pmatrix}X_1\\X_2\\X_3\\X_4\end{pmatrix} \tag{7}$$

The residual R (see above) is therefore written as:

$$R=|X-Y|^2=|X-Ca|^2 \tag{8}$$

To find a vector that minimizes R by moving A, for a given w and t (real number), let b be the value of the vector a that minimizes R, since it must be minimal at $t = 0$.

$$\begin{aligned}\frac{df}{dt}(0)&=\frac{d}{dt}\langle X-Cb-tCw,\ X-Xb-tCw\rangle(0)\\&=2\langle X-Cb,Cw\rangle=0\end{aligned} \tag{9}$$

For any w,

$$0=\langle X-Cb,Cw\rangle=\langle \hat{C}X-\hat{C}Cb,w\rangle \tag{10}$$

(*where $\hat{C}$ is the transposition of matrix C*)

$$\hat{C}Cb=\hat{C}X \tag{11}$$

Therefore the vector b that minimizes R is obtained by calculating

$$b=(\hat{C}C)^{-1}\hat{C}X \tag{12}$$

Written in practice as:

$$\hat{C}C=\begin{pmatrix}C_{11}C_{21}C_{31}C_{41}\\C_{12}C_{22}C_{32}C_{42}\\C_{13}C_{23}C_{33}C_{43}\end{pmatrix}\begin{pmatrix}C_{11}C_{12}C_{13}\\C_{21}C_{22}C_{23}\\C_{31}C_{32}C_{33}\\C_{41}C_{42}C_{43}\end{pmatrix}$$

$$=\begin{pmatrix}\sum_{k=1}^{4}C_{k1}C_{k1}&\sum_{k=1}^{4}C_{k1}C_{k2}&\sum_{k=1}^{4}C_{k1}C_{k3}\\\sum_{k=1}^{4}C_{k2}C_{k1}&\sum_{k=1}^{4}C_{k2}C_{k2}&\sum_{k=1}^{4}C_{k2}C_{k3}\\\sum_{k=1}^{4}C_{k3}C_{k1}&\sum_{k=1}^{4}C_{k3}C_{k2}&\sum_{k=1}^{4}C_{k3}C_{k3}\end{pmatrix} \tag{13}$$

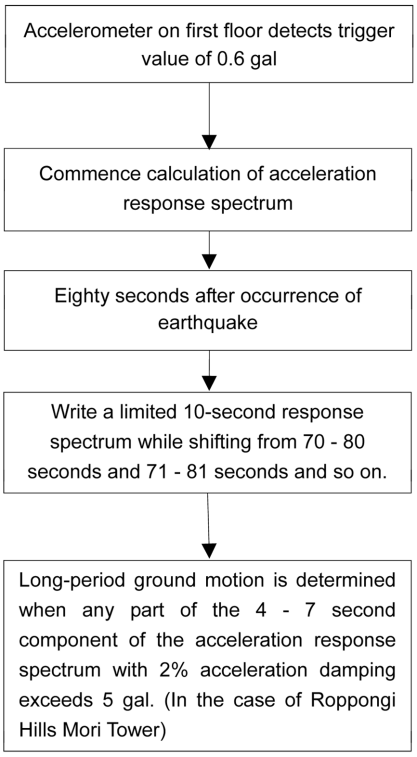


Figure 14. Long-period Ground Motion Evaluation Flow.

$$\hat{C}X=\begin{pmatrix}C_{11}C_{21}C_{31}C_{41}\\C_{12}C_{22}C_{32}C_{42}\\C_{13}C_{23}C_{33}C_{43}\end{pmatrix}\begin{pmatrix}X_1\\X_2\\X_3\\X_4\end{pmatrix}$$

$$=\begin{pmatrix}\sum_{k=1}^{4}C_{k1}X_k\\\sum_{k=1}^{4}C_{k2}X_k\\\sum_{k=1}^{4}C_{k3}X_k\end{pmatrix} \tag{14}$$

3.3. Early Detection Alert Function for Long-period Ground Motion

The system for diagnosing the severity of damage also incorporates a mechanism for detecting long-period seismic motion (as observed during the Great East Japan Earthquake) at an early stage of the earthquake and issuing alerts. Long-period seismic ground motion contained in the waveform is evaluated by calculating the acceleration response spectrum every 10 seconds when the primary motion decreases at 80 seconds after start of an earthquake.

See Fig. 14. Observation using accelerometers over many years has shown that long-period components are already included in the initial component of the seismic motion. Long-period earthquake ground motion gradually increases in amplitude due to resonance in a skyscraper, and the building continues to shake for several tens of minutes. This long-period seismic-motion evaluation function allows resonance of skyscrapers and their continuing large-amplitude vibration to be forecast, and to provide useful assistance in evacuation to tenants on higher floors. The system also helps to prevent panic by issuing advance warnings. It is known that elevator cables, the lifeline of a skyscraper, resonate due to the long-period seismic motion and may become damaged by being entangled with protrusions in the elevator shaft. The system can be used to prevent such damage by moving the elevator itself to a floor at which resonance does not readily occur.

3.4. Output of Assessment Information

This data is processed in real-time and displayed in the disaster prevention center of each building as shown in Fig. 15. Automatic voice announcements are issued to

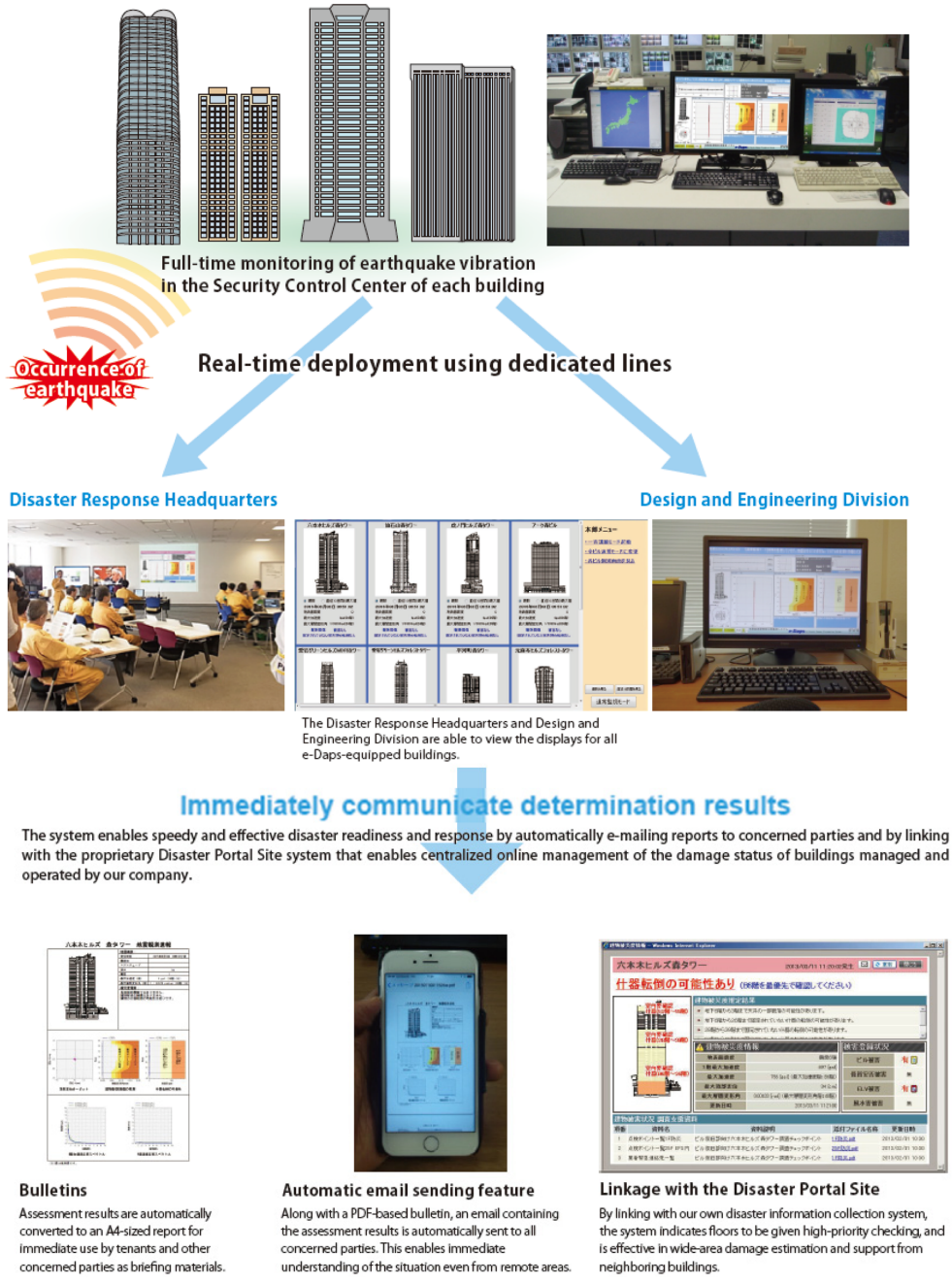


Figure 15. Disaster Assessment Information Output Flow.



Figure 16. Medium-height Buildings Scheduled for Installation of the Damage Assessment System.



Figure 17. IT Strong Motion Accelerometer.

provide an understanding of the situation without checking the screen. The system is also connected to the Earthquake Headquarters of Mori Building via a private line to ensure that the damage situation of each building can be understood at the headquarters. The information is sent automatically by email to approximately 200 employees managing the building by converting the bulletin to pdf format. In the event of major damage due to a large earthquake, the structural engineer will eventually need to investigate the site, verify the damage situation in detail, and develop a recovery plan. An instantaneous diagnostic system available at the time of the earthquake becomes a useful disaster-prevention tool, allowing an extremely flexible understanding of safety at the time of the earthquake as primary screening in the confused situation immediately after the earthquake. This diagnostic function is available not only at the time of the earthquake, but also for earthquake disaster training using time-history response analysis of the building assuming inland-type earthquake and ocean-type long-period earthquake ground motions. The data from these accelerometers is recorded continuously on the server for a period of four months. It can be used for verification of fluctuations in the natural period before and after the earthquake, and for verification of the amount of motion of the building during strong winds etc.

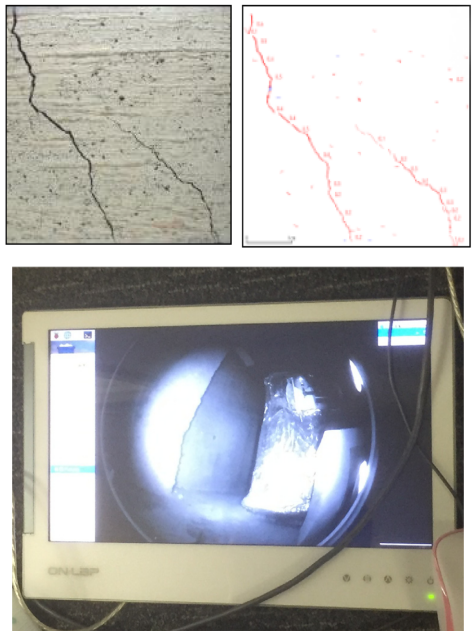


Figure 18. Infrared Camera-based Crack Detection System (under development).

3.5. Expansion of Application to Medium and Low-rise Buildings

This system for estimating the damage on each floor using mode shapes is not applicable to all buildings. It is applicable to regular buildings such as skyscrapers where there are no extreme changes in rigidity between floors. Difficulties arise in application to low-rise buildings with sudden changes in rigidity between floors, large eccentricities resulting in torsional vibration, and brittle behavior, where mode shapes are easily disturbed. To enable application to medium and low-rise buildings of RC construction, a system for damage assessment in medium and low-rise buildings was developed in which inexpensive accelerometers (IT Strong Motion Accelerometers) are installed on each floor, enabling improved accuracy by providing an understanding of damage through the progress of cracks in seismic walls. As well as determining the story drift from the accelerometer data, cracks (recognized as an earthquake trigger indicator) in the seismic walls are photographed with infrared cameras installed in pipe

spaces in the building. These photographic images are processed to color the cracks and to display crack width as a digital value. The interior of the pipe spaces provides bare concrete surfaces of shear wall as the most suitable areas for visualizing directly the severity of damage to the building. This system is scheduled to be installed in the Toranomon 30th building.

4. Summary

In this paper we have shown an analysis of the effectiveness of vibration damping devices using measurement data from accelerometers installed in Roppongi Hills Mori Tower located in Tokyo's Minato Ward during the Great East Japan Earthquake of March 11, 2011. It was found that acceleration and deformation were greatly reduced in comparison with the case where no such equipment is installed.

As a contribution to disaster prevention following the Great East Japan Earthquake, story drift angle and acceleration at each floor of the building are estimated in real time using accelerometers. Based on the results, an instantaneous diagnostic system was developed to infer the health and internal situation of buildings, and the equipment installed in buildings operated.

In future, widespread use of this system to rapidly and easily determine the severity of damage will be useful in operations immediately after earthquakes, and in preventing panic during earthquakes.

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