Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VII)

13-2-10

# DEVELOPMENT OF SEISMIC WAVE ENERGY SENSING-TYPE EARTHQUAKE DETECTOR

Yoshimitsu ONODA[1] and Eiji IKEDA[2]

[1]Hitachi Elevator Engineering & Service Co., Ltd.,
Tokyo, Japan
[2]Industrial Dept., Hitachi Ltd.,
Tokyo, Japan

## SUMMARY

On operational control systems during earthquakes for elevators and other equipment, acceleration-type earthquake detectors have been adopted conventionally. Although these detectors function effectively in ordinary buildings, there have been occasions where they do not function appropriately in superhigh-rise buildings.

Under such circumstances, Hitachi Group has developed an earthquake detector that can sense maximum values of seismic wave energy possessing close correlations with seismic intensities. This detector has been actually installed on an elevator operational control system for earthquakes in a superhigh-rise building.

## INTRODUCTION

Operational control systems during earthquakes have been adopted on elevators and other equipment with the objective of minimizing damage that may be caused by earthquakes. Earthquake detectors, designed to issue commands to these systems, conventionally have been an acceleration type that is actuated by the acceleration of earthquakes. Such a conventional-type detector, effective for ordinary buildings, often fails to function appropriately for superhigh-rise buildings.

Hitachi Group conducted a fundamental review of earthquake detectors and succeeded in developing the world's first seismic wave energy sensing-type earthquake detector. Reported in this paper are the results of research applied to achieve such development.

## OPERATION AND PROBLEMS OF CONVENTIONAL ACCELERATION-TYPE EARTHQUAKE DETECTORS FOR USE ON ELEVATORS IN SUPERHIGH-RISE BUILDINGS

Table 1 shows an example of operational control during earthquakes on elevators installed in building A, one representative of superhigh-rise buildings in Tokyo. As is evident from the data in Table 2, this building experienced an intense quake of ±10cm at the top floor by the Central Japan Sea Earthquake that occurred on May 26, 1983. With a quake of this intensity, there was fear that the movable cables (tail cords), which supply signals and electric power to the elevator cars, would develop resonance and create a quake of ±2m amplitude. Since this would result in developing an accident, operational control during earthquakes should have been initiated. However, only because quake acceleration did not reach 30 Gal, the operational control was not actually applied.

Table 1 Operational control during earthquakes for building A

| Low acceleration sensing | High acceleration sensing |
|---|---|
| Set level: 30 Gal<br>Stops at the nearest floor for 10 minutes and returns to normal operation. | Set level: 60 Gal<br>Stops at the nearest floor and suspends service. After inspection, returns to normal operation. |

Table 2 Situation during earthquakes of building A

| | Situation of quake | Situation of control |
|---|---|---|
| May 26, 1983<br>Top floor | 0.2Hz<br>±16 Gal<br>±10cm | It was necessary to be controlled; however, operational control was not applied. |
| August 8, 1983<br>Top floor | (3Hz, ±30 Gal, ±0.08cm) → (0.2Hz, ±1.6 Gal, ±1cm) | Operational control was unnecessarily applied. |
| Pit in hostway (Usually slight quake) | 50Hz<br>±13 Gal<br>±0.13$\mu$m | – |

In another fairly intense earthquake that occurred on August 8, 1983 with its epicenter in the western part of Kanagawa Prefecture, quake intensity on the top floor of the same building was not severe enough to cause stopping the elevators. On the other hand, since acceleration reached 30 Gal, the acceleration-type earthquake detector sensed this level, and operational control was effected.

In this building, a seismograph was additionally installed later on. This device was set to automatically start recording should quake acceleration at the lowest floor exceed 5 Gal. However, recording began immediately after the sensor was installed on the floor surface. The floor remained in a stationary state that caused nobody to believe a quake was in progress. Upon our investigation, it was found that vibration was transferred from an air compressor installed in the vicinity, and this vibration actually created a floor quake of 50 Hz ± 13 Gal (±0.13$\mu$m).

In other words, in this building, quake acceleration from 13 Gal to 30 Gal was sensed, and in case of 50 Hz 13 Gal, an almost stationary status existed that could never be considered to involve even the feeblest vibration. As for the case of 3 Hz 30 Gal, it was felt as an earthquake but not so intense as to require a suspension of elevator operation. When 0.2 Hz 16 Gal occurred, it involved an intense quake of ±10cm that did require elevator stoppage.

Under such circumstances, it was obvious that the use of conventional earthquake detectors, which sense only quake acceleration, is not appropriate for superhigh-rise buildings.

## SEISMIC INTENSITY AND DEVELOPMENT OF SEISMIC WAVE ENERGY SENSING-TYPE EARTHQUAKE DETECTOR

Based on the above-mentioned background reasons, we have applied fundamental reviews of earthquake detectors.

According to the definition of seismic scales set by the Japan Meteorological Agency (JMA), seismic scale V is the level of intensity that starts causing damage to building structures. As for the elevator earthquake-resistance design and installation guidelines established under supervision of the Ministry of Construction, when a JMA seismic scale V occurs, elevator cars must be moved to and stopped at the nearest floor by means of operational control systems interlinked with earthquake detectors.

To detect this designated level of seismic intensity, conventionally adopted are relations between quake acceleration and seismic intensity scales determined by Dr. Kawasumi and others. However, according to studies initiated by Dr. Katsumata and Dr. Ichikawa, the correlation between these is small (Ref. 1).

Research on devices that can appropriately measure seismic intensities are being developed in various circles. For instance, Dr. Takagi, studying correlations between seismic intensities and different physical quantities, reports that the quantities possess close correlation with maximum values of seismic wave energy (Ref. 2).

In this connection, Hitachi Group decided to study the methods of quickly obtaining such maximum values of seismic wave energy. Since P-waves need not be considered in terms of energy formation, only S-waves were taken into our account.

When a half period elapses after S-waves reach the tiny area dS shown in Fig. 1, the seismic waves move forward by half-wavelength—namely, $\lambda/2$ ($\lambda$: wavelength). In this case, since S-waves are transversal waves, quake displacement y is created in the direction perpendicular to the traveling direction. By differentiating this y with time t, quake velocity $v_y$ at the point can be obtained. Now, by assuming wave energy in the cubic volume of $dS\cdot(\lambda/2)$ as W, this W—calculated as follows—becomes the maximum value of wave energy applied in a single direction.

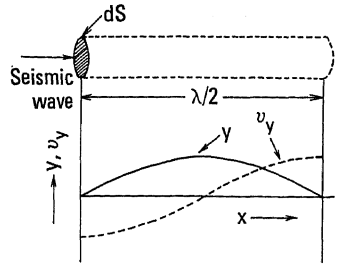


Fig. 1 Situation of seismic S-wave

$$W = dS\cdot(\frac{\lambda}{2})\cdot\frac{1}{(T/2)}\int_0^{T/2}\left\{\frac{1}{2}\rho(\frac{dy}{dt})^2+\frac{1}{2}\mu(\frac{dy}{dx})^2\right\}dt \quad (1)$$

where, T: Time period of earthquake

$\rho$: Mass per unit cubic volume of medium

$\mu$: Rigidity of medium

In this case, quake displacement y is expressed by the equation—

$$y = D\cdot\sin 2\pi ft \quad (2)$$

where, f = 1/T (quake frequency). Then, the following equation can be established by assuming $v_s$ as the traveling speed of S-waves:

$$v_s = dx/dt = \sqrt{\mu/\rho} \quad (3)$$

By substituting the above result into Eq. (1), the follwing relations are set:

$$W = \pi^2\cdot dS\cdot\sqrt{\mu\cdot\rho}\cdot(D^2/T) \quad (4)$$

Since $\pi^2\cdot dS\cdot\sqrt{\mu\cdot\rho}$ under Eq. (4) is approximately constant, W can be clarified by obtaining the value of $D^2/T$. In this case, however, the following problems are involved:

(1) Period T cannot be clarified until at least one cycle is completed. Especially, when a wave shape is irregular, it is very difficult to obtain this period T.

(2) Also, even if period T is clarified, arithmetic operation of $D^2/T$—namely, division—is quite complicated. Further, a sophisticated and expensive device is required.

We made a further study on how quickly the maximum value W of wave energy can be obtained. We established the following equation by assigning $e_t$ to the product between quake displacement y and quake velocity $v_y$:

$$e_t = y\cdot v_y = D\cdot\sin 2\pi ft\cdot D\cdot\cos 2\pi ft = \pi(D^2/T)\cdot\sin 4\pi ft = e\cdot\sin 4\pi ft \quad (5)$$

where, e is the amplitude of $e_t$ and the relations below also hold true:

$$e = \pi(D^2/T) = (\pi\cdot\sqrt{\mu\cdot\rho}\cdot dS)^{-1}\cdot W \quad (6)$$

Since $(\pi\cdot\sqrt{\mu\cdot\rho}\cdot dS)^{-1}$ is approximately constant, e is directly proportionate to W. Therefore, e has been termed the "wave energy coefficient." Because command signals can be generated in the form of comparison with $e_t$, this $e_t$ can also be considered as the actual wave energy coefficient.

Wave energy coefficients can be easily clarified from the circuit shown in Fig. 2. The wave energy coefficient in an optional direction within a plain surface can be obtained by adding together the wave energy coefficients in two directions perpendicularly crossing each other on the plain surface. On a seismic wave energy sensing-type earthquake detector, the coefficients obtained in this manner were compared with the comparator to generate command signals.

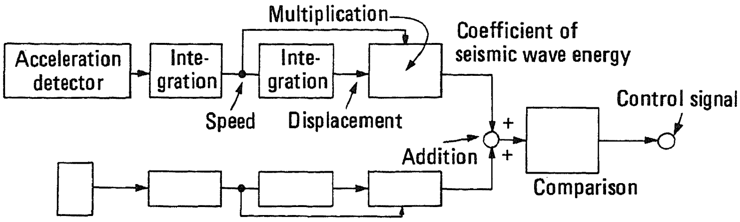


Fig. 2 Block diagram of seismic wave energy sensing-type earthquake detector

As for correlations between the quake acceleration and the seismic intensity, Dr. Kawasumi has published the study results, and pertaining to correlations between the quake velocity and the seismic intensity, study results have been published by Dr. Muramatsu. Regarding correlations between the wave energy coefficients and the seismic intensity, we have determined these correlations by coordinating the study results by Dr. Takagi with those of Dr. Muramatsu, as listed in Table 3. Fig. 3, reflecting study results on Matsushiro earthquake swarm, shows closer correlations of wave energy coefficients. Further, while F. Neumann has clarified correlations between the maximum quake acceleration and the predominant periods under the M. M. seismic scale VIII, his results indicated close congruity with the correlations obtained by us between the periods and acceleration under the wave energy coefficient of 3 kine•cm, as shown in Fig. 4.

Table 3 Correlations between wave energy coefficients and seismic scale of JMA

| Seismic scale of JMA | 0 | I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|---|---|
| Coefficient of seismic wave energy (kine•cm) | 0 - 0.003 | 0.003 - 0.03 | 0.03 - 0.3 | 0.3 - 3 | 3 - 30 | 30 - 300 | 300 - 3,000 | More than 3,000 |

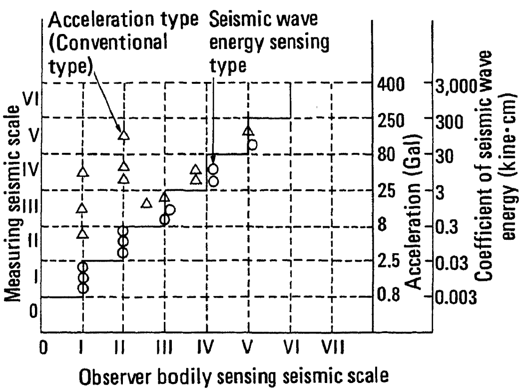


Fig. 3 Simulation results of Matsushiro earthquake swarm

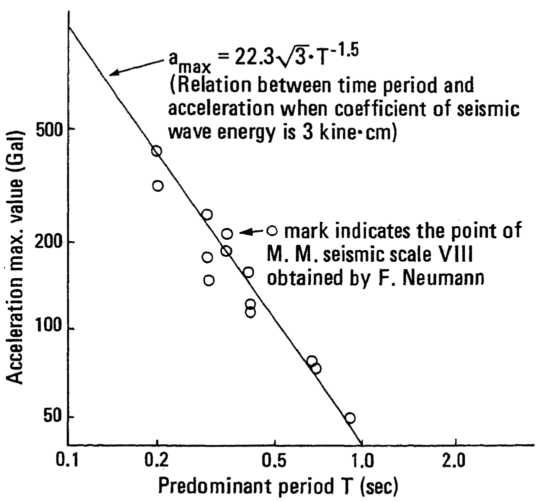


Fig. 4 Relation between predominant period and maximum acceleration in the case of M. M. seismic scale VIII

## COMPARISON UNDER ELEVATOR OPERATIONAL CONTROL DURING EARTHQUAKES

While the term "accelerative seismic intensity" is used to represent the intensity obtained from correlations between the quake acceleration and the seismic scale, and the term "wave energy intensity" is assigned to the intensity obtained from correlations between the seismic wave energy coefficients and the seismic scale in Table 3, a seismic wave energy sensing-type earthquake detector can be considered as a device that functions by seismic wave energy intensity.

As shown in Fig. 5, acceleration remains constant on the accelerative seismic intensity regardless of the frequencies involved. On the other hand, on the wave energy intensity, acceleration varies in direct proportion to 1.5 power of the frequencies. Therefore, seismic wave energy sensing-type earthquake detector can function appropriately as is evident from Table 4. Our explanations up to this point have pertained primarily to building A. Our experiments on other superhigh-rise buildings also displayed similar results as shown in Table 5. In other words, it can be expected that a seismic wave energy sensing-type earthquake detector can satisfactorily perform its intended functions on any type of earthquake.

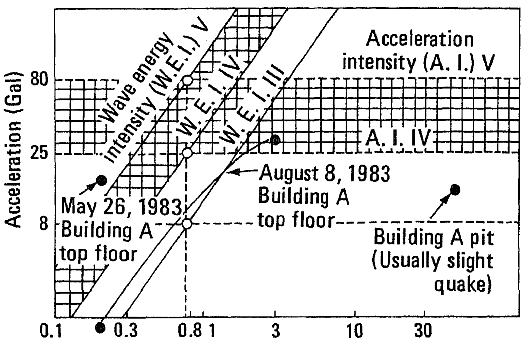


Fig. 5 Frequency characteristics of acceleration seismic intensity and wave-energy seismic intensity

Table 4 Acceleration seismic intensity and wave-energy seismic intensity measured at building A

| | Situation of quake | Acceleration intensity | Wave energy intensity |
|---|---|---|---|
| May 26, 1983 Top floor | 0.2Hz ±16 Gal ±10cm | III | V |
| August 8, 1983 Top floor | (3Hz, ±30 Gal, ±0.08cm) → (0.2Hz, ±1.6 Gal, ±1cm) | IV → I | II → III |
| Pit in hostway (Usually slight quake) | 50Hz ±13 Gal ±0.13μm | III | 0 |

Table 5 Actuation status of earthquake detectors installed in superhigh-rise buildings

| | Acceleration sensing | Energy sensing |
|---|---|---|
| Large-magnitude earthquakes with distant hypocenters requiring controlled elevator operations | X (No detector actuation observed) | O (Detector actuated) |
| Small-magnitude earthquakes with nearby hypocenters not requiring controlled elevator operation | X (Detector actuated in certain cases) | O (Detector not actuated) |
| Large-magnitude earthquakes with nearby hypocenters requiring controlled elevator operations | O (Detector actuated) | O (Detector actuated) |

NOTE: O denotes appropriate detector functioning
X denotes inappropriate functioning

## THEORETICAL STUDIES ON CORRELATIONS BETWEEN SEISMIC WAVE ENERGY COEFFICIENTS AND SEISMIC INTENSITY SCALES INVOLVING BUILDING DAMAGE

It can be estimated from the actual measurement results obtained up to now that seismic wave energy sensing-type earthquake detectors are able to properly detect intensities that involve building damage. We further apply theoretical studies to confirm this point.

Seismic waves generated from the ground propagate through the interiors of buildings after passing through foundation structures. Since the propagation speed of these waves is decelerated as they approach the ground surface, in most cases seismic waves run vertically through the foundation structures or building bases.

In terms of effects of energy, only S-waves should be considered. However, since S-waves are transversal waves, these waves cause the building bases to quake horizontally. Further, generally adopted on superhigh-rise buildings is a flexible (shearing-type) structure. Consequently, these buildings are liable to develop quakes in the horizontal direction.

W. Housner et al. reveal that the factor that contributes to the final destruction of structures is the kinetic energy developed by the actual structures during earthquakes. This kinetic energy becomes most intense when both predominant period T during earthquakes and primary natural period $T_s$ of a building develop resonance. In this case, quake displacement y (Z, t) at height Z can be expressed as—

$$y(Z, t) = D_0 \cdot \sin\left\{(\pi/2h)Z\right\} \cdot \cos\left\{(2\pi/T_s)t\right\} \tag{7}$$

where, $D_0$: Amplitude of quake displacement at highest building level, and h: Building height.

Kinetic energy $W_e$ of entire building becomes as follows:

$$W_e = S \cdot \int_0^h (1/2)\rho(dy/dt)^2 \cdot dZ = W_{emax} \cdot \sin\left\{(2\pi/T)t\right\} \tag{8}$$

where, $\rho$: Average mass per unit cubic volume, and $W_{emax}$: Maximum value of $W_e$—

$$W_{emax} = (\pi^2/4) \cdot S \cdot \sqrt{\mu \cdot \rho}\ (D_0{}^2/T_s) \tag{9}$$

Next, the product between quake displacement y (h, t) at a building top and quake velocity $\upsilon$ (h, t)—namely, $e_t$ (h, t), is expressed as—

$$e_t(h, t) = y(h, t) \cdot \upsilon(h, t) = -\pi(D_0{}^2/T_s) \cdot \sin\left\{(4\pi/T_s)t\right\} \tag{10}$$

Since the value of $(\pi^2/4) \cdot S \cdot \sqrt{\mu \cdot \rho}$ under Eq. (9) remains constant, $W_{emax}$ can be clarified by calculating $(D_0{}^2/T_1)$, while the amplitude under Eq. (10) holds proportionate relations under $\pi(D_0{}^2/T_s)$. This $\pi(D_0{}^2/T_s)$, previously defined as the seismic wave energy coefficient, can be sensed by seismic wave energy sensing-type earthquake detectors, thereby enabling appropriate detection of earthquakes with intensities that start causing building damage.

## CONCLUSION

Explanations have been given pertaining to study results applied for development of seismic wave energy sensing-type earthquake detector.

This detector, already installed in a superhigh-rise building in Tokyo, has successfully yielded anticipated results.

## ACKNOWLEDGMENTS

The authors express sincere gratitude to Dr. Muramatsu, a professor emeritus of Gifu University, Dr. Katsumata, and staff members of Meteorological Research Laboratory and Hitachi Group who rendered highly contributive guidance on our studies. Concurrently we are profoundly appreciative of the cooperation extended regarding development of devices by Tokyo Sokushin Co., Ltd.

## REFERENCES

1. Katsumata, M. and Tokunaga, K., Q. J. of Seismology, vol. 36, No. 3, 4, pp. 89-96, (1971).
2. Takagi, S., Papers in Meteorology and Geophysics, vol. 20, No. 1, pp. 79-89, (1969).