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# Demonstrative evaluation of variables indicating severity of earthquake applicable to earthquakes sensors for control

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ABSTRACT: By examining earthquake severity indicators according to structural damage in major past earthquakes, the applicability of each indicator for control use during earthquakes has been demonstratively evaluated. As has been frequently pointed out, maximum ground acceleration has proved to be rather unreliable as a severity indicator for control use. By contrast, maximum ground velocity and SI value give for more useful earthquake damage information by producing data of more than 90% precision regarding effects when operating at an appropriate threshold level.

## 1. INTRODUCTION

Most antiseismic control systems installed in industrial plants and factories measure the maximum ground acceleration as an indicator of ground motion severity, and halt the operation of systems or equipment in case of sensing strong ground motion beyond a given threshold of severity.

Some cases, however, were reported where seismic motion with an acceleration as great as 300 gal or higher caused little damage to neighboring lifelines or buildings, such as wooden houses. Because of this it has been pointed out that economic losses may be suffered by unnecessary suspension of production or processes in connection with unsubstantial earthquakes.

This study aims demonstratively to evaluate how an antiseismic control system with maximum acceleration as a severity indicator performed efficiently during past major earthquakes. This evaluation will be done by correlating each data of the measured maximum acceleration to the extent of the actual damage in the surrounding structures, such as lifelines and buildings. Also evaluated are control systems with alternative severity indicators such as the maximum ground velocity, maximum ground displacement, and the SI value described as shown in equation (1). As a conclusion, physical quantities to be used as a severity indicator of the system control are proposed for use in place of maximum acceleration.

## 2. CANDIDATES FOR THE SEVERITY INDICATOR OF EARTHQUAKE GROUND MOTION

The following are the physical quantities selected in this study for evaluation as appropriate severity indicators of antiseismic control.

- Maximum acceleration
- Maximum velocity
- Maximum displacement
- SI value

$$SI=\frac{1}{2.4}\int_{0.1}^{2.5} SVdT \; (h=0.2) \qquad (1)$$

## 3. SURVEY OF PAST MAJOR EARTHQUAKES DAMAGE

The relationship between the ground motion severity indicator and structural damage has been studied by Katayama et al. (1985). Their study classified a number of existing seismographic data according to structural damage found in the district surrounding the device. Although this classification did not go into detail because the study was made only through a literature survey of past earthquake damage reports, the conclusion was very clear that the relationship between the maximum acceleration and the extent of structural damage is not good enough to be used as an antiseismic controller of important industrial activities. On the contrary, in their paper the SI value shows good agreement to the extent of structural damage.

The aim of this study is to reinforce their results by incorporating the data of more recent earthquakes such as the Loma prieta and Chiba-toho-oki into more quantitative analyses of each severity indicator. Table 1 shows lists of analyzed earthquakes.

Table 1 Lists of Analyzed Earthquakes

| Name of Earthquake | Number of Data (locations) |
|---|---|
| Niigata (1964) | 2 (at 1) |
| Matsushiro (1965-66) | 46 (at 23) |
| Off-Tokachi (1968) | 10 (at 5) |
| Off-Miyagi (1978) | 8 (at 4) |
| Nihonkai-Chubu (1983) | 4 (at 2) |
| Chibaken-Toho-Oki (1987) | 24 (at 12) |
| Izu Peninsula eastern offshore (1989) | 10 (at 5) |
| Imperial Valley (1940) | 2 (at 1) |
| Kern County (1952) | 2 (at 1) |
| San Fernando (1971) | 24 (at 12) |
| Mexico (1985) | 16 (at 8) |
| Loma Prieta (1989) | 84 (at 42) |
| Total | 232 (at 116) |

Note: Earthquake wave data are recorded for two horizontal directions (X, Y) at one observation.

## 4. CLASSIFICATION OF EXTENT OF DAMAGE

The damage classification was made for one city, town, or village as a unit area, whose area would be around 10km$^2$ in general. Table 1 lists 116 seismograph locations. Although it is desirable to have common reference structures in the neiboring district of each seismograph for better comparison analysis, the possibility would be very low because of diversification of seismograph locations from city to countryside, domestic or foreign origin. Hence in this study we try to classify the damage according to two structural categories of building structures and civil engineering structures as shown in Table 2.

Table 2 Classification of Earthquake Damage to Structures

| Damage Class | Significant | No Damage | Moderate |
|---|---|---|---|
| Building structures (houses etc.) | 10 buildings or more collapsed. | No damage except non-structural parts such as roofing tiles | Other than cases on the left |
| Civil engineering structures (pipelines, bridge, dam etc.) | The occurrence of damage in pipelines exceeds 10. No damage to major civil engineering structures | No damage | Other than cases on the left |

According to Table 3, total classification has been done by incorporating the categorical classification results of the building structures and civil engineering structures. If damage was not clearly identified because of lack of data, no classification was made. Cases where no classification was adopted include the following examples.

- The ground condition where the seismograph was placed was much different from that of the damaged structures in the surrounding area.
- Only extremely strong structures exist in the surrounding district of seismographs.

Table 3 Total Damage Classification Matrix

| | | Civil engineering structures | | | |
|---|---|---|---|---|---|
| | | Significant | Moderate | No damage | No classification |
| Building structure | Significant | Significant | Significant | Significant | Significant |
| | Moderate | Significant | Moderate | Moderate | Moderate |
| | No damage | Significant | Moderate | No damage | No classification |
| | No classification | Significant | Moderate | No classification | No classification |

## 5. OUTLINE OF THE DAMAGE CLASSIFICATION RESULTS

Damage in 74 of 116 locations could be classified. The remainder was given no classification. Wooden and brick houses top the list of damaged buildings in number. Among damaged civil engineering structures, buried pipelines were most numerous.

Table 4 Outline of damage classification results

| Name of earthquake | Classification results (in number) | | | |
|---|---|---|---|---|
| | Significant | Moderate | No damage | Total |
| Niigata earthquake | 1 | 0 | 0 | 1 |
| Matsushiro earthquake | 1 | 2 | 20 | 23 |
| Off-Tokachi earthquake | 3 | 0 | 0 | 3 |
| Off-Miyagi earthquake | 2 | 0 | 2 | 4 |
| Nihonkai-Chubu earthquake | 2 | 0 | 0 | 2 |
| Chibaken-Toho-Oki earthquake | 0 | 2 | 7 | 9 |
| Izu Peninsula eastern offshore earthquake | 0 | 2 | 2 | 4 |
| Imperial Valley earthquake | 1 | 0 | 0 | 1 |
| San Fernando earthquake | 3 | 2 | 1 | 6 |
| Mexico earthquake | 2 | 0 | 0 | 2 |
| Loma Prieta earthquake | 13 | 2 | 4 | 19 |
| Total | 28 | 10 | 36 | 74 |

## 6. EVALUATION FOR DESIRABLE SEVERITY INDICATORS

The role of severity indicators is to determine whether to suspend the operation of industrial systems or equipment in terms of likelihood of significant damage from earthquakes. Therefore, the indicator should have an appropriate threshold value, above which damage to structures will very likely happen. At the same time it is important that below the threshold value, damage to structures would be very minor. In terms of antiseismic control the former condition corresponds to probability P1 that a decision made with such a severity indicator threshold to stop the operation would be appropriate. The latter case is for probability P2 whereby a decision made with a severity indicator threshold to continue operations would be correct.

Figure 1 is a schematic explanation for determination of the optimum threshold value, with severity indicator values as X axis and P1 and P2 as Y axis. In the Figure, P1 should increase steadily according to severity indicator values and become infinitely close to 1. P2 should increase as the indicator becomes less and become 1 when the indicator is 0. Therefore there is a single threshold value at which P1 and P2 simultaneously become greater.

A general evaluation function for the determination of the optimum threshold value is shown as Equation (2).

$$\text{Evaluation function} = a \times P1 + b \times P2 \qquad (2)$$

In Equation (2) "a" and "b" are weight values for anti-earthquake control policy. If avoiding unnecessary shut-down of the operation is of vital importance, "a" should be larger than "b." If negative consequences because of continuation of the operation should be staved off, a large value for "b" compared to "a" would be recommended.

In this study both are hypothesized as 1.

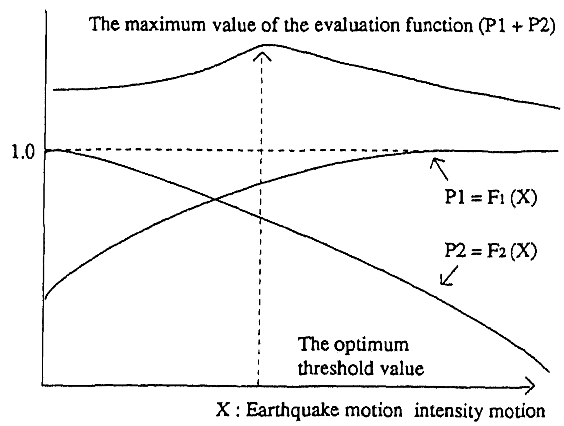


Figure 1 The optimum value of the earthquake motion

## 7. CORRELATION BETWEEN DAMAGE AND EACH SEVERITY INDICATOR

In the manner described in Fig. 1, the optimum P1 threshold value and P2 are examined for each severity indicator by using 74 sets of seismographic data and damage classification results.

Fig. 2a illustrates that the maximum acceleration of 230 gal is the threshold value, and at this value P1 = 0.68 and P2 = 0.77. The P1 value of 0.68 means that according to past earthquake results the system control with the maximum acceleration as its severity indicator would make the right decision to suspend operations in six to seven cases of 10 earthquakes. In the remaining three to four times, however, the control would unnecessary halt operations.

Conversely, P2 of 0.77 signifies that the control with the maximum acceleration to continue operations would be appropriate in eight cases of 10.

Figs. 2b, 2c, and 2d are for the maximum velocity, the maximum displacement, and the SI value, respectively.

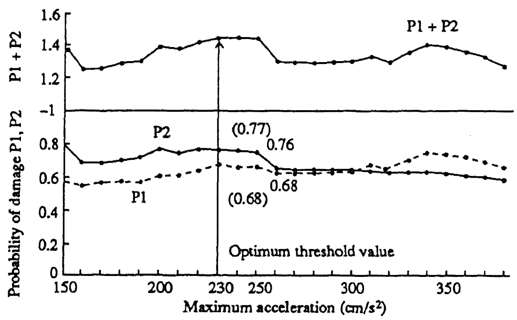


Figure 2a Earthquake motion intensity indicator and the evaluation function

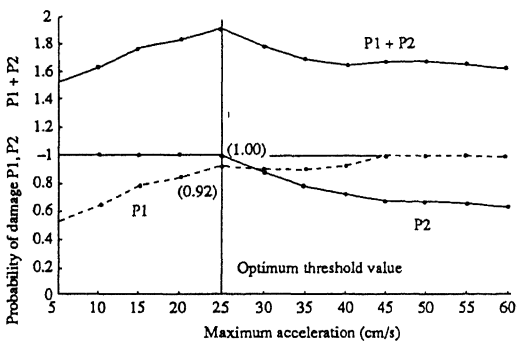


Figure 2b Earthquake motion intensity indicator and the evaluation function

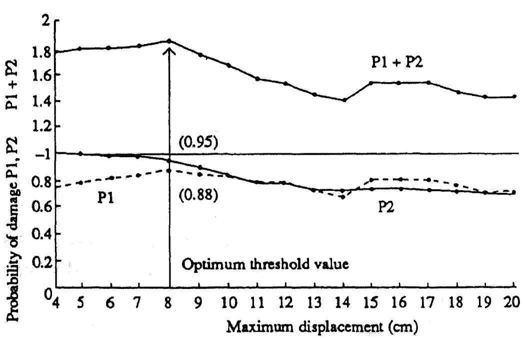


Figure 2c Earthquake motion intensity indicator and the evaluation function

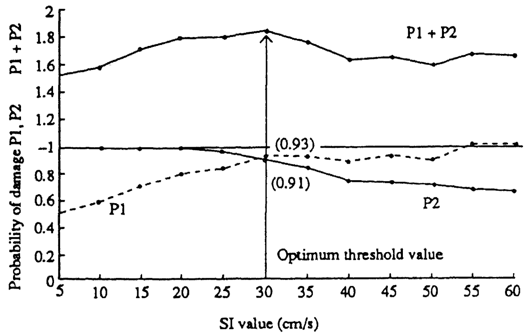


Figure 2d Earthquake motion intensity indicator and the evaluation function

For each severity indicator the P1 optimum threshold value and P2 are shown in Table 5.

As shown in Table 5, there are significant differences among the candidate severity indicators in correlation with the extent of structural damage. The maximum velocity and the SI value would perform far better than the maximum acceleration. The maximum displacement shows a high value. As indicated, however, in Fig. 2c, P1 tends to decline with values above 8cm. This strange behavior implies that the maximum displacement value might not be evaluated precisely. Accordingly, P1, P2, and (P1 + P2) ÷ 2 for the displacement should be treated as mere reference values and be in parentheses in the Table.

## 8. CONCLUSION

The maximum velocity and SI value are considered to be appropriate severity indicators for antiseismic control system. With either of them, emergency decisions on operational suspension could be performed with 90% propriety. In contrast, the maximum acceleration would be ineffective in the seismic control decision for suspension of industrially important activities.

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Table 5 Optimum threshold values for each severity indicator

| Severity indicator | Optimum threshold | At the threshold value | | |
|---|---|---|---|---|
| | | P1 | P2 | (P1 + P2)÷2 (%) |
| Max accel. | 230 gal (cm/s²) | 0.68 | 0.77 | 0.73 |
| Max Veloc. | 25 kine (cm/s) | 0.92 | 1.00 | 0.96 |
| Max disp. | 8 CM | (0.88) | (0.95) | (0.92) |
| SI | 30 kine (cm/s) | 0.93 | 0.91 | 0.92 |

Note: Both P1 and P2 were calculated with data including moderate damage classification

Kataoka, Demonstrative evaluation of variables indicating severity of earthquake applicable to earthquake sensor for control, 21st JSCE Earthquake Engineering Symposium, JSCE, (1991).