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New earthquake-induced ground motion severity sensing apparatus for reliable system shutdown

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ABSTRACT: We have developed a new earthquake-sensing apparatus that performs highly accurate system shutdown control in case of earthquake-induced damage to major physical facilities. This apparatus is designed to determine whether any damage has actually occurred at the time of an earthquake. As the earthquake motion severity indicator, we employed SI value the Velocity Spectrum Intensity SI value. To detect this value we developed a low-cost, noise-proof mechanism. Moreover, to be accepted widely in any environment, the sensor should satisfy the following specifications: no need of air conditioning, explosion-proof, drip-proof, and low installation cost. Through realizing these conditions, the sensor was able to be installed widely. Tokyo Gas has now adopted this apparatus to their 3000 gas-pressure regulators (equipment that decompresses gas so that it can be supplied to general consumers). By employing this sensor, the supply of gas is expected to stop automatically in case of any significant damage as a result of a major earthquake.

1. INTRODUCTION

Conventional earthquake sensors for control purposes often utilize maximum acceleration as the earthquake motion severity indicator. With recent seismic observations, however, we have found that in some cases physical facilities such as surrounding buildings and underground pipes remained undamaged even when great acceleration (over 300 gal) was recorded. It has been pointed out that when acceleration is employed as a severity indicator, considerable economic losses might occur as a result of unnecessary system shutdown.

In contrast, the SI value, defined as Equation (1), corresponds faithfully with structural damage. Figure 1 prepared by Sato et al. (1985), shows that earthquakes with recorded acceleration greater than 250 gal in many cases result in no damage, whereas almost all earthquakes with an SI value greater than 25 produce in significant damage. Iwata et al. in their detailed study of earthquakes (1991) that includes recent earthquakes at Loma prieta and Chiba-ken-toho-oki concluded that the SI value corresponded to the occurrences of significant damage with 90% accuracy.

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

SV : Velocity spectrum
T : Period [sec]
h : Damping coefficient

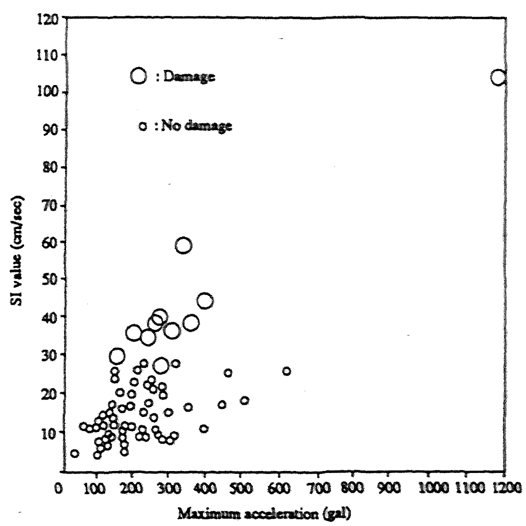


Figure 1 Relationship between SI value and maximum acceleration in regard to damage

2. MECHANICAL MECHANISM FOR DETECTING SI VALUE

Although it is extremely important for an earthquake sensor to correspond accurately with significant damage occurrence, it is also essential to avoid unnecessary shutdown at ordinary times. To detect the SI value, the output of a highly accurate accelerometer is usually processed. With this method, however, there is always the danger of obtaining inaccurate output by noise coming through the accelerometer pickup, which is so sensitive that it can be activated by field electromagnetic waves. For this reason, we concluded that this output cannot directly be connected to the controlled system. To detect the SI value we finally applied a principle that dictates that displacement of the overdamping pendulum is in proportion to the maximum velocity.

First, we created a mechanical model numerically by using the single-degree-of-freedom system with spring and dash pot. Then we used a number of wave data of past earthquakes recorded by seismographs as input and conducted numerical analyses. Through this approach we checked whether the reproducibility of the SI value with this mechanism would fall within the range of ±13%. The result we obtained was satisfactory. We therefore concluded that as long as the frequency of the pendulum and damping constant are set properly, this mechanism will perform satisfactorily.

3. SENSOR'S MECHANISM

This mechanism must satisfy the following requirements.

① The same sensitivity for all directions of earthquake waves

② A damping mechanism with sensitivity that does not change amid temperature fluctuations

③ A fail-safe mechanism mainly to cope with electromagnetic wave noise

In the following, the above-requirements are explained in more detail.

(1) Basic mechanism

To detect the SI value using an ordinary seismograph, it is necessary to vector-synthesize signals from two sets of seismographs.

In contrast, using the method shown in Fig. 2, there is no such need while the mechanism is simple and satisfies the above three requirements as well.

Moreover, since this mechanism uses light to detect displacement there is no harmful reaction to the pendulum and no component wear.

(2) Temperature characteristics of damping mechanism

This sensor's sensitivity (Sv) can be obtained by Equation (2).

$$S=\frac{1}{4\pi\omega o\cdot h}\cdot A\omega^2 \qquad (2)$$

ωo: natural frequency of pendulum
h: damping constant

At ordinary times, light is being masked. But when the displacement of light exceeds the limit, light reaches the light-accepting element and an electric current flows.

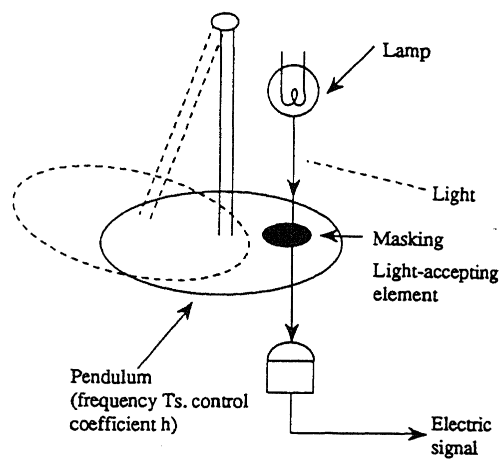


Figure 2 Sensing mechanism

The sensitivity of the accelerometer is determined only by the natural frequency of the pendulum (wo), but in the case of the SI sensor, a damping constant as well as the pendulum's natural frequency affects sensitivity. For this reason, the temperature characteristic of the damping mechanism, which is not an important factor in an accelerometer, must be kept closely controlled in this sensor.

The damping mechanism in this apparatus employs the eddy-current method and its damping force (F) is given by Equation (3).

$$Fn=\frac{B^2\cdot\nu\cdot\beta}{\rho}\cdot v \qquad (3)$$

B: magnetic flux density of damping plate
ρ: electric conductivity
ν: constant related to the volume of damping plate
β: constant related to the area and shape of damping plate
v: velocity of damping plate

To obtain the designed damping constant, a permanent magnet with an extremely large energy integral is required. We therefore experimented with a ferrite magnet but its temperature characteristics proved unsatisfactory (0.19%°C).

We then looked into recently developed rare-earth metal. This rare-earth metal is made of lanthanum and had a satisfactory temperature characteristic (–0.03%°C) with its maximum energy integral being 200 KJ/m³. Its strength is so large that once two magnets come together they cannot be separated manually.

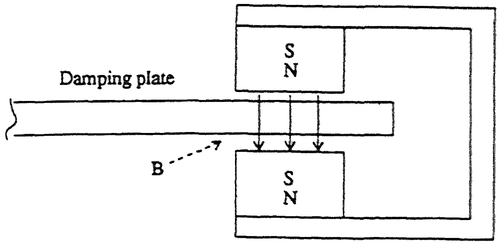
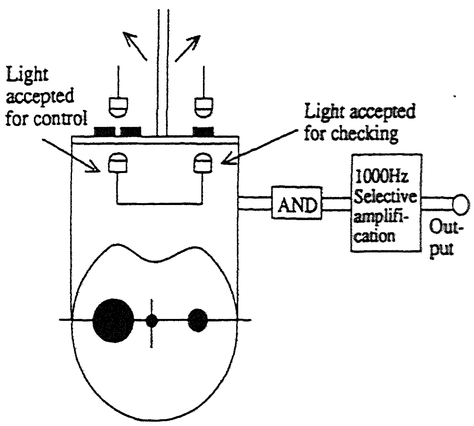


Figure 3 Damping mechanism



	For control	For checking	Output
Ordinary times	ON	OFF	Normal
At the time of an earthquake	ON	ON	Control output
	Continuing conditions other than above		Failure

Figure 4 Fail-safe mechanism

For a damping plate, we first used pure aluminum in as much as it was necessary to lower the weight. But its temperature characteristic of electrical resistance proved unsatisfactory (0.42%/°C) and we had to search elsewhere. Finally, we found an aluminum alloy.

Using this material, the overall temperature characteristic turns out to be 0.31%/°C which is well within the temperature range

(−10°C-50/°C) where in the sensor will be used. The sensitivity stays within the range of ±12%.

(3) To cope with electromagnetic wave noise and to realize a fail-safe mechanism

Because this sensor operates only by light interception controlled by the interruption of a 12-volt direct current, it will be unaffected by electromagnetic noise.

Table 1 Result of Excitation Experiment
(SI value obtained by mechanical sensor)

Earthquake wave	6 kine (cm/s) controlled		12 kine(cm/s) controlled	
	SI value	Acceleration (for reference)	SI value	Acceleration (for reference)
Sodegaura	5	83	12	85
El centro	6	138	12	239
Hachinohe	6	159	14	380
Taft	6	120	11	215

Chiba-toho-oki earthquake (1987)

Furthermore, in case of a failure of the light source lamp (an LED is used) and the light-accepting element, the fail-safe mechanism shown in Fig. 4 is expected to operate to prevent malfunction and to detect any problems.

Moreover, all the signals are made with a burst signal of 1000Hz and amplified selectively so that no malfunction can occur even in case of disconnection or a short circuit.

4. SPECIFICATION OF MECHANICAL SI SENSOR

The sensor is made to satisfy the following conditions.

1) Detection direction: Horizontal nondirectional
2) Control output: No voltage contact output
3) Explosion-proof structure: Possible to use with flammable gas
4) Drip-proof structure: Possible to use outside
5) Electrical noise protection: Lightning, electrostatic, and electromagnetic wave protection 10KHz-10Hz 10V/m
6) Surrounding temperature range: −10°C - +50°C
7) Average time between failures: over 20 years

5. CONFIRMATION TEST USING SHAKING TABLE

The mechanical SI sensor was set on a twin-shaft hydraulic shaking table, and (a) a random excitation experiment applying actual earthquake waves, and (b) a sine wave excitation experiment were conducted.

To measure the SI value, a device was used that displays both the maximum SI value and acceleration at real-time. These values are computed by a digital math circuit by using the output of the accelerometer.

Table 1 shows the test result of the reproducibility of the mechanical sensor using actual earthquake waves. These figures overlap in reliable probability with the computed SI values.

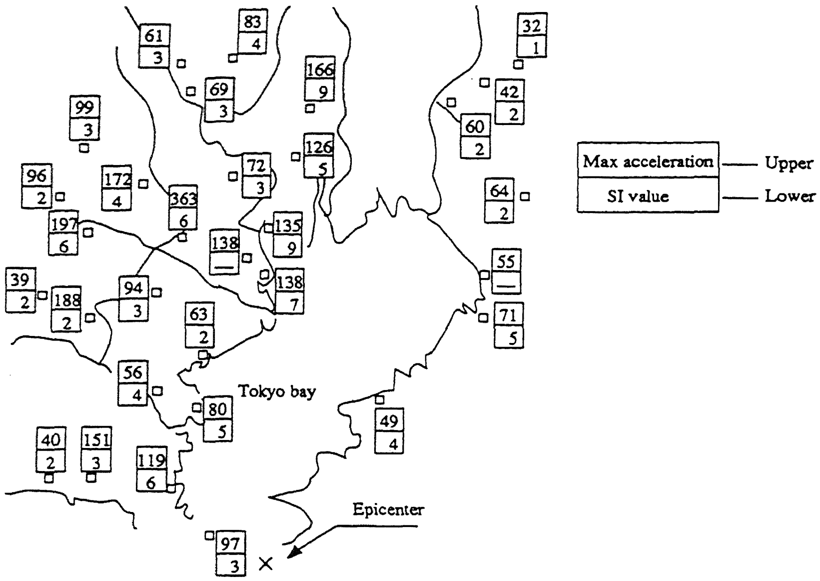


Figure 6 SI values and maximum acceleration distributions from the Tokyo bay earthquake (1992 Feb. 2nd)

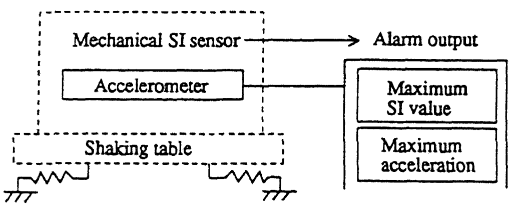


Figure 5

6. SENSOR'S PERFORMANCE RECORD

The first sensor put to practical use was made in 1988. 400 sensors were fitted to pressure regulators in Tokyo Gas Company's service area where a total of 3000 pressure regulators are installed. Since then, a number of small improvements have been made. Presently, a total of 2000 sensors are being used successfully to control gas supply shutdown in the event of a major earthquake. Up to the present, several earthquakes have occurred but no damage resulted to physical facilities. The sensor, moreover, did not activate. The case of the Tokyo bay earthquake should be specially mentioned. This earthquake occurred on Feb. 2, 1992. As shown in Fig. 3, the recorded earthquake motion was greater than 300 gal but there was no major damage to general housing or underground pipes. At this time none of the 2000 installed sensors reacted to the earthquake motion. The SI value calculated by accelerometer was about 6 at the most. It may thus be said that with this level of SI value it is probable that no damage occurs and that no sensor will react. We have concluded from the fact that no sensor performed any incorrect operation under this quite strong earthquake vibration that this sensor has proved to be very reliable as a control sensor in the actual field.

7. ACKNOWLEDGMENTS

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