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SI-SENSOR FOR THE IDENTIFICATION OF DESTRUCTIVE EARTHQUAKE GROUND MOTION

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SUMMARY

A new type of seismic sensor, called SI-Sensor, has been developed for realtime identification of the destructiveness of earthquake ground motion. The sensor utilizes the spectrum intensity (=SI), in addition to the peak ground acceleration, to estimate whether or not ground shaking is strong enough to cause damage to structures. From the analyses of about 170 components of strong ground motion records, it was found that the SI values of the ground motions at the sites where damage was reported nearby are generally greater than 30 cm/s irrespective of the values of peak acceleration. Based on the results of analysis, a control unit was so designed that the sensor issues control signal by taking into account both SI value and peak acceleration.

INTRODUCTION

There are a variety of earthquake ground motion sensors being used for preventing (or mitigating) seismic-induced malfunction of systems. Arrivals of seismic waves are detected to simply give warnings in some cases. The signal from a sensor is often used to switch off systems to prevent potential secondary disasters or to switch on (or activate) emergency systems such as standby power supplies. In case of strong ground shaking, kerosene stoves should be turned off, the Shin Kansen trains should be slowed down and stopped, and city gas supply should be suspended.

The specification of such a sensor is different according to its purpose and the system to which the sensor is applied. For disaster preparedness activities taken at extremely important installations, the earliest possible detection of earthquake occurrence itself may be essential even before the major shaking begins at the site. In certain cases, it may be sufficient to detect the strong ground motion at the site. A typical example of the latter case is the closing of fuel supply to a kerosine stove. When a system can be easily reset, it is also possible to use a relatively low threshold to activate the control system.

In some other cases, however, it may be important to know, before any decisive action is taken, whether or not the seismic ground motion has really caused damage to the system under consideration. What is essential here is the detection of the potential damagability of earthquake motion. This kind of detection is especially important when the system has a wide areal coverage of service and when restoration of the system is difficult and time-consuming once it has been shut down. A city gas system is one of typical such systems.

DAMAGE AND PEAK ACCELERATION

Most of the presently available seismic sensors use the peak acceleration as the trigger signal. Ground motion is detected either by pendulum devices or dislodging of a ball from a seating to close contacts when a threshold acceleration level is exceeded. However, recent experiences in Japan have shown that engineered structures do not suffer substantial damage simply because the peak acceleration is large.

The most recent example is the Chibaken-Toho-Oki earthquake of December 17, 1987. This M6.7 earthquake produced strong ground motions with peak accelerations of 350-400 cm/s^2 in Chiba City with a population of 800,000 located at an epicentral distance of about 45 km. However, damage to engineered structures was almost negligible. Even buried utility pipelines, which are known to be most vulnerable to seismic disturbance, did not suffer any recognizable damage.

Figure 1 shows two accelerograms with the same level of peak accelerations but with very different durations. It may be easily imagined that the effects of these motions on structures are considerably different. This can be seen from the velocity response spectra of the two motions shown in Fig.2. In fact, engineered structures will not be damaged by Type (a) ground motion even if its peak acceleration is of the order of 300 cm/s^2.

DAMAGE AND SPECTRUM INTENSITY

The "spectrum intensity" originally defined by G.W. Housner (1952) is the area under the velocity response spectrum between T=0.1 s and T=2.5 s, where T is the natural period of a single-degree-of-freedom oscillator. However, in this paper, SI is defined as the average amplitude (cm/s) of the 20%-damped velocity response spectrum in the abovementioned period range. This modified definition was adopted because of its more direct interpretation as the average response velocity from the engineering point of view.

Although SI has been often reported to have better correlation with the damage potential of the ground shaking, it has not been used for setting the threshold level for an earthquake ground motion sensor. This is mainly because SI is a complicated quantity, when compared with the peak acceleration, to be utilized for realtime detection. However, recent progress in electronics has made it possible to manufacture a low-cost sensor to perform realtime analysis of an earthquake ground shaking.

Figure 3 shows the SI's computed for strong-motion accelerograms recorded in Japan and the US against their respective peak accelerations. Most of the accelerograms used for the analysis have peak accelerations greater than 100 cm/s^2, and only the larger of the two SI's for the two horizontal components of a record is plotted in Fig.3. It is noted, for example, that the SI's corresponding to the peak acceleration of about 0.2g vary in a wide range from 5 cm/s to 40 cm/s.

Larger circles in Fig.3 correspond to the records obtained at the sites where substantial damage was reported nearby. It may be observed that damage was negligible for many of the ground motions with peak accelerations greater than 250 cm/s^2. On the contrary, the ground motions having SI greater than about 30 cm/s inflicted damage in the nearby areas almost without exceptions. Note that the definitions of "damage" and "nearby areas" here are ambiguous. Strong-motion has rarely been recorded right at the center of the damaged area. Therefore, Fig.3 should be interpreted to illustrate a quantitative but only very general trend.

Past Japanese experiences have clearly shown that the general level of damage is well correlated with the degree of damage to wooden houses. Therefore, it is useful to investigate the relationship between SI and the equivalent collapse rate of wooden houses. The equivalent collapse rate here is defined as the ratio of the equivalent number of houses destroyed beyond repair, which is the sum of the number of houses destroyed beyond repair, 50% of the number of heavily damaged houses and 10% of the number of lightly damaged houses, to the total number of houses in the area under consideration.

Figure 4(a) shows the relation between the equivalent collapse rate and SI. Although the collapse rate is generally small, it is more strongly correlated with SI than with the peak acceleration [see Fig.4(b)]. The line of best fit obtained from Fig.4(a) is

$$\text{Equivalent Collapse Rate (\%)} = \exp[0.124 \cdot SI - 6.33]$$

Note that the analysis is again of macroscopic nature since no consideration is given to the effects of site ground conditions and other factors which are known to have strong influences on the seismic response of wooden houses.

PRINCIPLE OF SI-SENSOR

To obtain the SI of a ground motion, it is necessary to compute the responses of a number of single-degree-of-freedom systems with different natural periods for a fixed value of damping factor h=0.2. However, since the velocity response spectrum of a heavily damped system has a relatively smooth shape as exemplified in Fig.2, it was attempted to obtain an approximate SI by minimum computation. From the results of several trial-and-error analyses, the 20%-damped velocity response spectrum may be approximated by the trapezoid shown in Fig.5. This trapezoid is constructed by plotting the larger of the amplitudes SV(T=1.5 s) and SV(T=2.5 s) at T=1.5 s. Figure 6 shows the plots of exact SI's and approximate SI's. Agreement is more than satisfactory. It was concluded from this analysis that simple evaluation of SI is possible and that use of SI for trigger level setting is practical.

The general concept of the new sensor system is summarized in Fig.7. As ground motion acceleration is taken into the control unit, the responses of 1.5s and 2.5s single-degree-of-freedom systems are realtime evaluated. This step utilizes two analogue circuits. The maximums of the peak acceleration and the velocity responses of 1.5s and 2.5s ocsillators (h=0.2) are continuously renewed during the duration of the earthquake. The approximate SI is evaluated and combined with the peak acceleration to decide whether or not a control signal is to be issued to shut down the system. This process is performed by a microprocessor built in the control unit.

What is most difficult is the suitable choice of threshold levels. To detect whether or not the ground motion has caused widespread damage in the concerned area, the relation previously shown in Fig.3 seems to be useful because the general degree of seismic damage is strongly related to the extent of wooden house damage. Tentative, but yet reasonable thresholds may be 30 cm/s for SI and 400 cm/s^2 for the peak acceleration. In other words, control signal is issued (1) when the SI value greater than 30 cm/s is detected or (2) when the peak acceleration exceeds 400 cm/s^2 if SI<30 cm/s. By increasing the threshold of the peak acceleration to 400 cm/s^2, systems will not be closed for most of the ground motions which are characterized by small SI and large peak acceleration.

The prototype sensor unit uses the vectorial sum of two horizontal motions for the evaluation of SI and peak acceleration. An IC memory card may be attached to record acceleration time history for further research purposes.

APPLICATION TO UTILITY NETWORK

The new sensor is particularly suitable to be used for the immediate post-earthquake control of utility systems with large service areas. The effects of suspension of service are generally widespread in such a system, and survey and repair of damage is often difficult and extremely time-consuming. Therefore, a critical action should be taken only when damage is substantial enough to justify the outcome of the action in view of the secondary harmful effects on society. The new sensor is a reasonable one because it distinguishes damaging earthquake motion from those having only large peak accelerations.

In fact, this sensor has been developed by a cooperative research between the Institute of Industrial Science (University of Tokyo) and Tokyo Gas Co., Ltd. by assuming its application to a real system.

The service area of Tokyo Gas Co., Ltd. with about 6.6 million customers is located in Southern Kanto Plain, where seismicity is known to be very high. Based on the experiences learned from past earthquakes such as the 1964 Niigata and the 1978 Miyagi-Ken-Oki earthquake, the entire service area has been divided into 9 large isolation areas of approximately 300 km^2, each of which can be isolated by tele-control signals by microwave transmission. This makes it possible to independently close gas supply to any of the isolated areas by continuing supply to the rest of the service area at the same time. To take into account more local variation of seismic damage, the large isolation areas are further permanently subdivided into a total of about 100 small isolation areas.

It is planned that a total of about 400 SI sensors be installed in the whole service area, i.e. four sensors on average in each small isolation area, so that local variation of strong ground motion can be realtime telemetered. As of August, 1988, a total of about 100 SI sensors have been already installed mostly in the western part of the service area in and near the area designated under the Large-Scale Earthquake Countermeasures Act for preventing possible seismic disaster by the Tokai earthquake. Systemic operation of these sensors is now being investigated. Additional 300 sensors are scheduled to be installed in the next five years. There are, on average, 30 district regulators in each of the small isolation area, each of which supplies low-pressure gas to 1000-3000 customers. The total number of district regulators is about 3000 in the whole service area of Tokyo Gas Co., Ltd. The present plan, although yet to be finalized, is to install simplified mechanical sensors, develpoed based on the same principle as the SI sensor, at each of the district regulator houses.

Investigation is presently under way how to integrate the signals radio-transmitted from some 400 SI sensors for the optimum contorol of the total gas supply system immediately after damaging ground shaking. The key issue here is how to take account of local ground conditions into an engineering decision process. However, if this system is completed, the area under consideration will become the area where earthquake motions are most densely and systematically monitored for practical purposes.

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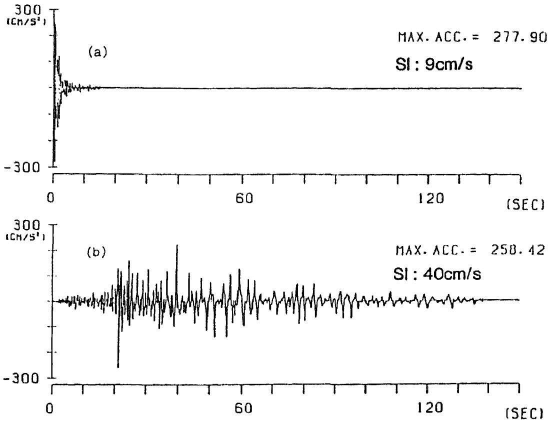

Fig.1(↑) Two Accelerograms with Very Different Durations but Having Similar Levels of Peak Accelerations

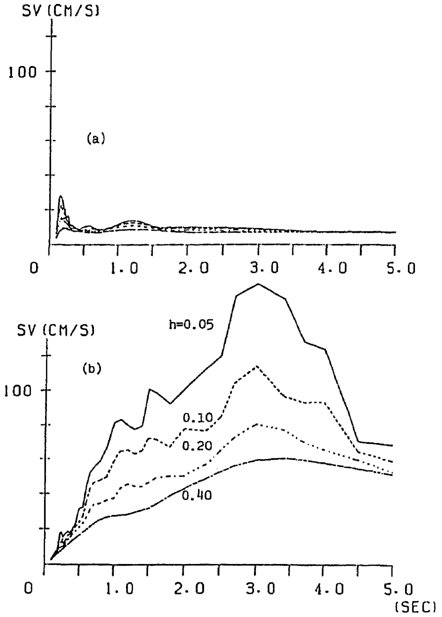

Fig.2(→) Velocity Response Spectra of the Records in Fig.1

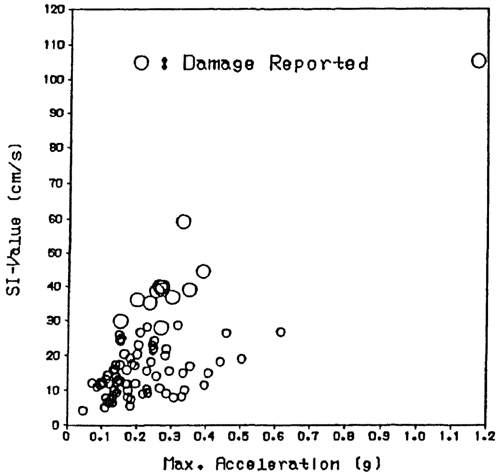

Fig.3 Relation Between SI and Peak Acceleration

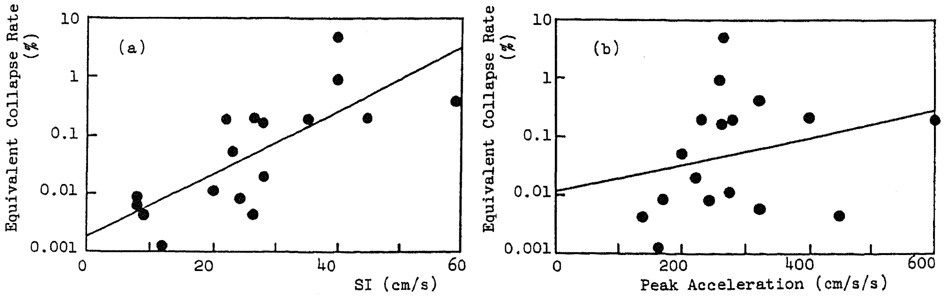

Fig.4 Wooden House Damage vs. (a) SI, and (b) Peak Acceleration

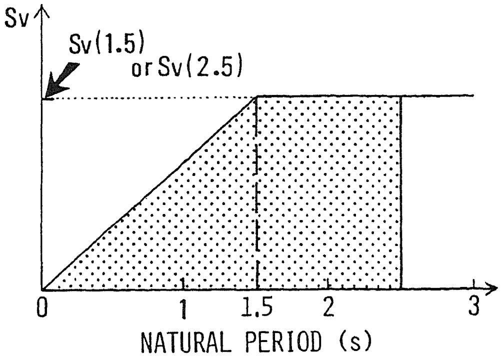

Fig.5 Simplification of Velocity Response Spectrum (h=0.2)

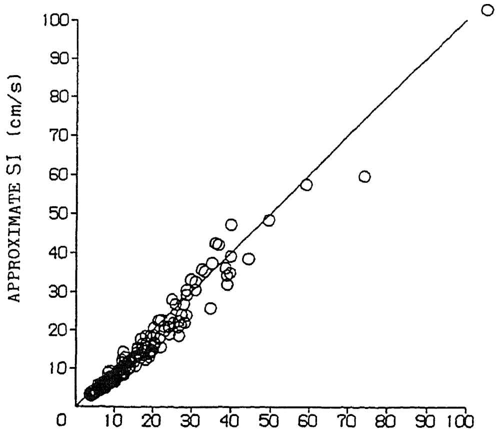

Fig.6 Relationship Between Exact and Approximate SI

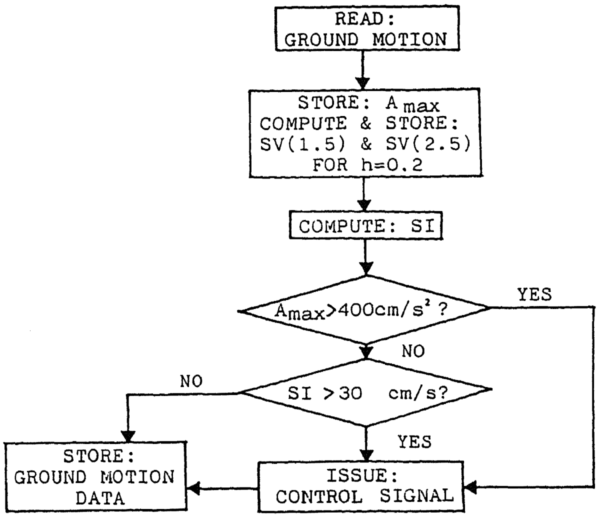

Fig.7 Conceptual Flow of the New Detector