DEVELOPMENT OF A NEW SI SENSOR

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SUMMARY

Tokyo Gas Co., Ltd. and Yamatake Corporation have developed a new SI sensor, and have already started to install it. The new SI sensor is very small and inexpensive as the result of the first trial usage of a three-axis silicon capacitive accelerometer made by micro-machining technology. The new SI sensor has multiple functions, as follows.

1) Analog output for telemeter function: SI value and maximum acceleration

2) Digital output for telemeter function: shut-off signal, liquefaction signal, and breakdown signal

3) Earthquake waveform memory function: three-axis acceleration waveforms, six earthquakes

4) Self-check function

Moreover, the new SI sensor has newly developed algorithms for SI value calculation and liquefaction judgement. The new SI value calculation is very precise, simple, and highly reliable. The new algorithm for liquefaction judgement is based on maximum acceleration, SI value, estimated displacement and estimated predominant period. (Estimated displacement is $2*SI^2/A_{max}$, Estimated predominant period is zero crossing period.) Therefore it is possible to detect liquefaction very inexpensively without large-scale construction like boring. In the future, 3,600 new SI sensors will be installed in the Tokyo metropolitan area ($3,100km^2$). This new SI sensor network is one of the largest and the highest density seismometer networks in the world. This network will be able to offer plane distribution of SI value, maximum acceleration, three-axis acceleration wave and liquefaction data.

INTRODUCTION

An 'SI sensor' is a seismograph which measures the SI (Spectrum Intensity) value. Damage to houses is strongly correlated with this SI value and, for this reason, Tokyo Gas has installed SI sensors in all regulators since 1986. When an earthquake of seismic intensity large enough to cause damage to pipes or buildings occurs, the sensor automatically stops the regulator, thus shutting off the gas supply. In this way, even if a pipe is broken, gas doesn't leak. Recently, however, some of the existing SI sensors have broken down or malfunctioned due to long usage. In addition, after the Great Hanshin Earthquake it has become necessary to raise the level of our disaster measures. Tokyo Gas has thus started to replace the existing sensors with new ones. Therefore Tokyo Gas and Yamatake Corporation have developed a new SI sensor (Figure 1), and have already started to install it.

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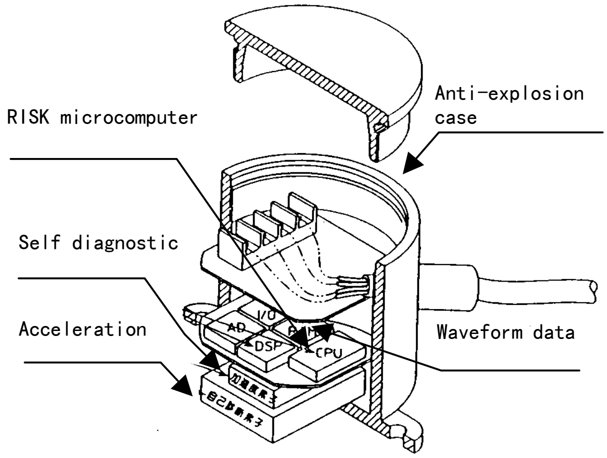

Figure 1: New SI sensor

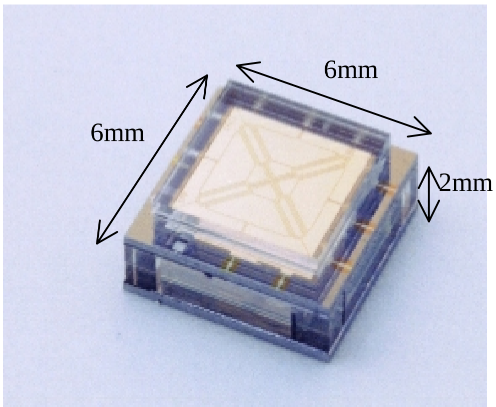

Figure 2: Acceleration pickup

ACCELERATION PICKUP

The new SI sensor uses new acceleration pickup. Figure 2 shows this new pickup. This pickup is a three-axial capacitive accelerometer applying silicon micro-machining technology, in which the chip-size is as small as about $6 \times 6 \times 2$ mm. This pickup consists of a fixed electrode and moveable electrode with a weight. The feature of this pickup is three-axis acceleration measurement by one tip based on the asymmetry of the electrode vibration (Figure 3). And as the moving electrode can be moved by applying a voltage to each electrode from the outside, and by taking advantages of this structure, self-diagnosis can be performed while the body of the accelerometer is fixed.

The measuring range in each axis is ±2,000 Gal, and the frequency band (-3 dB) is DC ~50 Hz for the X and Y axes, and DC ~30 Hz for the Z axis. Its price is as low as less than about 1/10 of the price of the conventional servo type accelerometer because of the application of micro-machining technology. The sensors are also amendable to mass production.

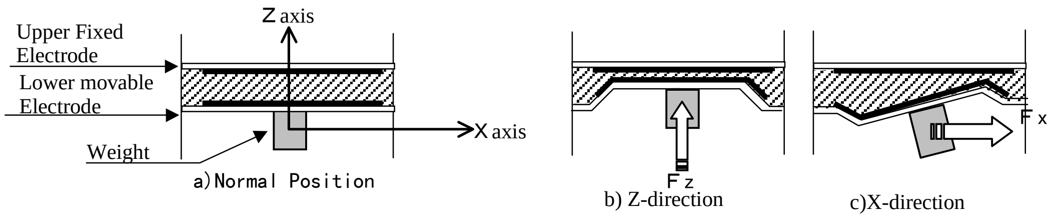

Figure 3: Measurement principle

SI VALUE CALCULATION

Real Time Calculation

We adopted a new calculation method on sensor development. Since the SI value is obtained from the Sv value calculated from the acceleration of a seismic wave, the Sv value should be abandoned once an earthquake is over, in order to separate it from the SI calculation for the next seismic wave. Conventional SI sensors set a threshold for acceleration. The start and termination of the SI calculation are made by matching with one seismic wave, and the maximum value is abandoned once the earthquake is over (Figure 4).

The new SI sensor calculates the SI value all the time, retains the Sv value within a time window, and then abandons it as time elapses (Figure 5). In other words, an ‘earthquake trigger’ is thus required in the conventional method. In the new calculation method, on the other hand, the CPU always performs the same operations, continuously calculating SI values, and so an ‘earthquake trigger’ is not required. In the new method, we have thus succeeded in simplifying the system and in improving the reliability of operation during an earthquake. As a result, an inexpensive CPU can be used in the new SI sensor.

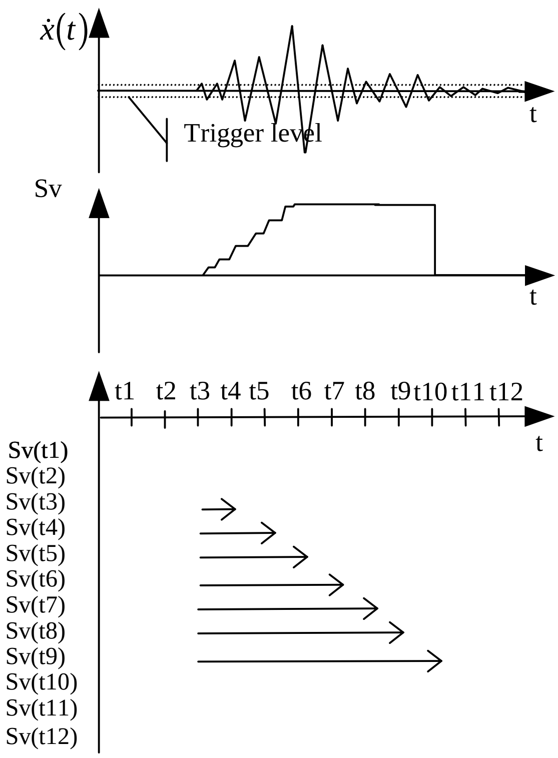

Figure 4: Conventional SI value calculation

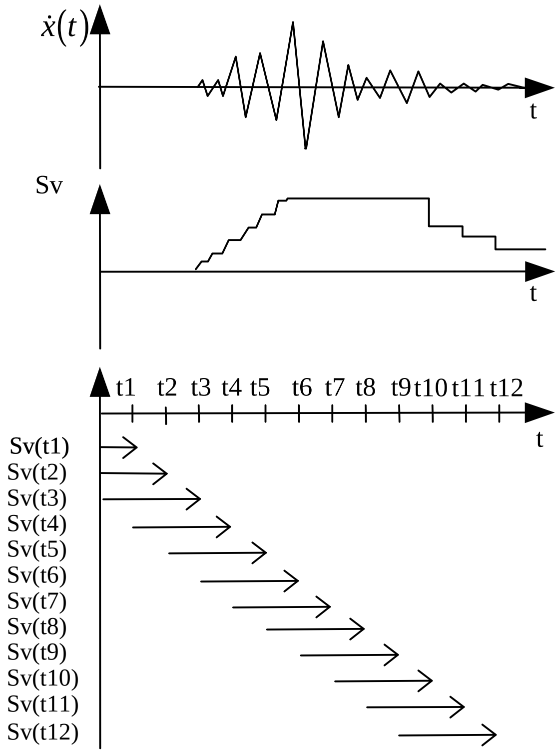

Figure 5: New SI value calculation

As for determining the length of such a time window, when the transient state of velocity response was analyzed and studies were made using 30 waveforms of past earthquakes, it was confirmed that, if a time window which expands or shrinks for 10 - 20 seconds was used, the SI value obtained even in the worst case can have a precision of 99% or better against the SI value obtained by setting the length of the time window at a level covering one full seismic wave (represented by the value of 100%). Therefore, a time window with such length will allow an calculation of the SI value with a satisfactory level of precision (Table 1).

Table 1: Relationship between time window length and calculation precision

Time window length[sec]	4.0	6.0	7.0	8.0	9.0	10.0	12.0
Precision of SI value[%]	98.0	98.5	98.7	98.8	98.9	99.0	99.1

Angular Dependence of the SI Value

An SI calculation is principally made for a system with one degree of freedom. However, because the SI value derived from an earthquake has a high dependency on the angular direction in a horizontal plane, it is necessary to provide a system with two degrees of freedom and to seek the SI values in plural directions on a horizontal plane (Figure 6). As a result of simulation studies made using 30 seismic waves, it was confirmed that obtaining the SI values in eight directions will yield the optimum results (Table 2).

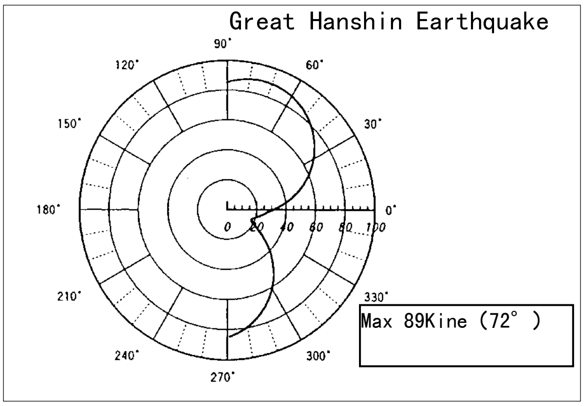

Figure 6: Angular dependence

Table2: Relationship between number of calculation directions and calculation precision

Number of calculation direction	360	12	9	8	6	5	4	3	2
Calculation precision	1.00	0.99	0.99	0.99	0.98	0.98	0.98	0.97	0.92

LIQUEFACTION JUDGEMENT

The new SI sensor also incorporates new algorithms for liquefaction judgement. Liquefaction of the ground during an earthquake is an important issue for gas companies, because this phenomenon can increase the amount of damage to pipelines. It is thus desirable to be able to detect liquefaction easily.

The new algorithm for liquefaction judgement makes use of the fact that this phenomenon needs a large-scale quake and that the waveform’s predominant period and displacement are extended after liquefaction acceleration (Figure 7). Therefore, it was decided to use the maximum values for SI, acceleration, and assumed displacement among the eight directions, and the base line the maximum SI value eight, the maximum acceleration, the maximum assumed displacement eight, zero-cross intervals of the acceleration in eight directions, as parameters for identification of liquefaction. When every one of these parameters exceeded the threshold, a liquefaction was defined as taking place. Because a displacement can be assumed from an calculation expression for the SI value and the maximum acceleration (Equation (1)), a displacement thus assumed, D, was used for definition of liquefaction. And because the maximum value of the base line zero-cross intervals of the acceleration was found (as a result of an analysis of seismic waves) to differ greatly depending on the direction on the horizontal plane of X and Y axes, a system to detect the same by eight directions was employed.

$$D = 2SI^2 / A_{max} \quad [\mathrm{cm}] \qquad (1)$$

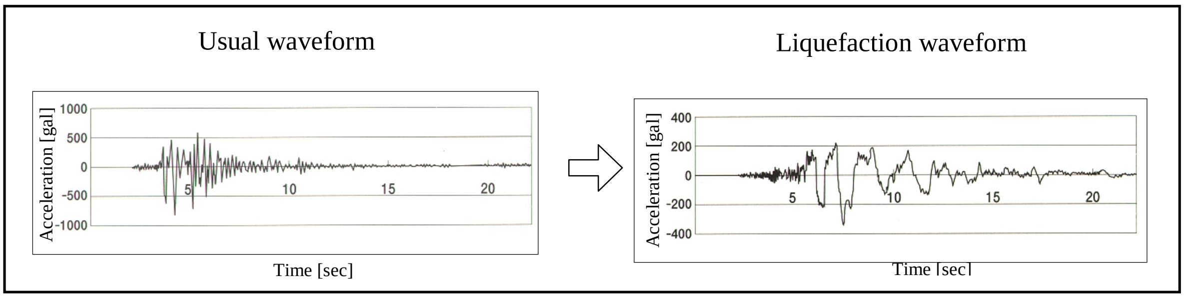

Figure 7: Usual and liquefaction waveforms

The following conditions are the developed criteria to detect liquefaction. Equation (2)

$$A_{max} \geq 100[\mathrm{gal}], \qquad SI \geq 20[kine], \qquad D \geq 10[cm], \qquad T \geq 2.0[\mathrm{sec}] \qquad (2)$$

Almost all (100%) observed liquefaction data can be separated from non-liquefaction data by the criteria (Figure 8). These parameters can be calculated easily by the new SI sensor. Therefore it is possible to detect liquefaction very inexpensively, without large-scale construction like boring.

MULTIPLE FUNCTION

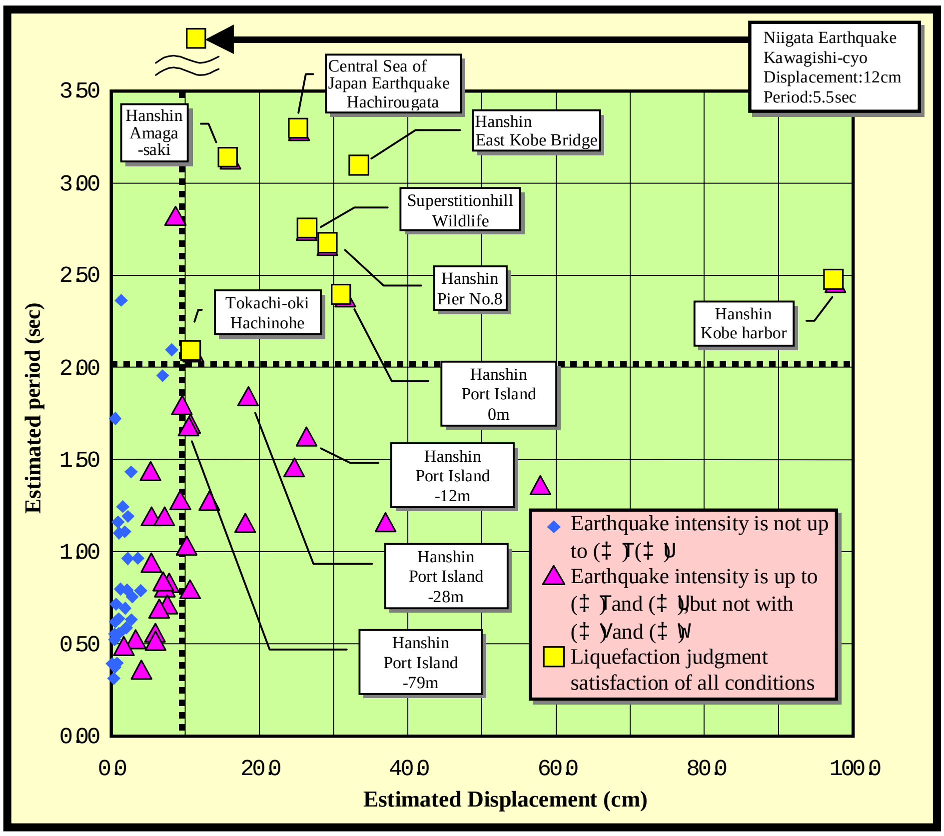

Figure 8: Judgement of liquefaction

The new SI sensor has multiple functions as follows, in spite of being much smaller and cheaper than the conventional SI sensor.

Analog output
The new SI sensor has analog output for the SI value and acceleration (4-20mA), and can be directly connected to a general-purpose telemeter.

Digital output
The new SI sensor has some digital outputs. These are shut-off signals, liquefaction signals and breakdown signals. The new SI sensors output two types of breakdown signals, one for “major breakdowns” requiring immediate response, and the other for “minor breakdowns” affecting incidental equipment not requiring immediate response.

Earthquake waveforms memory function
The new SI sensor can memorize three-axis acceleration waveforms of six earthquakes. It has a resolving power of 1/8 gal, sampling frequency of 100 Hz and recording time of 50 seconds per earthquake. Figure 9 shows the waveforms for the Izu Peninsula Earthquake recorded on May 3, 1998.

Self-check function
A high-performance self-check function was developed for reduction of maintenance work. With this, the worker need only push one button for regular maintenance on site, and no dirty work is necessary. Of course, self-check is carried out continuously. When troubles are found, the new SI sensor can send out breakdown signals immediately through telemeter units.

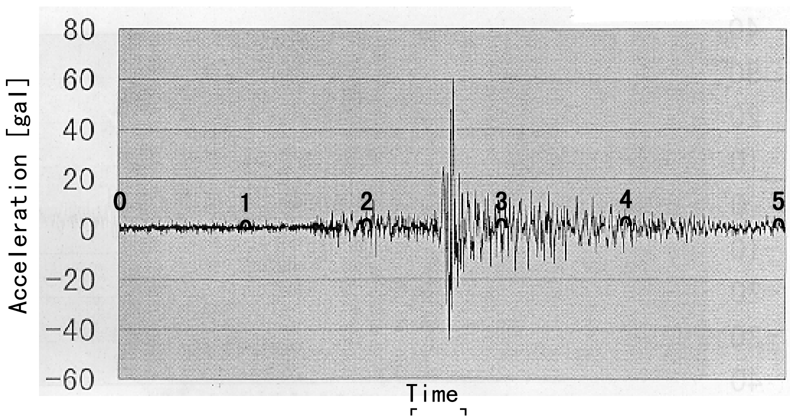

Figure 9: Izu Peninsula Earthquake in Chigasaki

CONCLUSION

The new SI sensor applies the most advanced silicon micro-machining accelerometer. A RISC microcomputer was used to develop a self-diagnosis function, real time SI value algorithm, and function to identity ground liquefaction. These features were combined to produce a completely unique seismograph, absolutely unparalleled around the world. Tokyo Gas is planning to install this new SI transducer at all 3,600 locations of shut off valves its in gas supply pipes.

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