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ENERGY-BASED DYNAMIC RELIABILITY ANALYSIS

S. Fukushima[1], M. Mizutani[1], Y. Akao[2] and H. Katukura[2]

[1]Tokyo Electric Power Services Co. Ltd., Tokyo, Japan
[2]Shimizu Corporation, Tokyo, Japan

ABSTRACT

Dynamic reliability analysis(DRA) of structures subjected to strong ground motions is one of the most important parts of the safety assessment of structures. So far many DRA methods based on probabilistic theory have been developed. Generally, DRA methods are divided into three phases; seismic hazard analysis, fragility synthesis, and evaluation of probability of failure. In most DRA method, the seismic hazard curves of peak ground acceleration(PGA) or spectral acceleration at a certain period is evaluated to show the occurence ratio of input motion in the seismic hazard analysis, and, in the fragility synthesis, random vibration theory is adopted to calculate the conditional probability of failure of structures given the occurance of input motion. Since random vibration theory is developed in the frequency domain, PGAs are transformed into information in the frequency domain by means of introducing so-called peak factors and power spectra. This fact suggests that it is more convenient for DRA researchers to define the seismic hazard by the indices defined in the frequency domain from the first.

In this paper, DRAs based on the two indices, *i.e.* PGA and total energy, are investigated in detail. Through the study, features and issues of DRA based on the total energy (hereafter called EDRA) are clarified from the viewpoint of the responses of the structure.

1 INTRODUCTION

Through investigations, we have shown the efficiency of employing the total energy as an index of SHC which can be determined in the time and frequency domains and has less variance than PGAs. In the stage of fragility synthesis, such indices are often combined with the corresponding spectral shape to yield response spectra for the calculation of structural responses. Variance of the response of structures is depends on variance of the spectral shape as well as on variance of the index. In addition, these two types of variances are correlated.

In this study, two response spectra are treated. One corresponds to the maximum response amplitude and the other to the total energy. For convenience, the latter is called "Energy Response Spectrum" hereafter. Energy response spectrum are defined such that it shows the total energy of the response of a SODF system.

Objectives of this study are (1) to estimate and compare the magnitude of each variance of the above two response spectra, (2) to clarify the effect of correlation between the variances of the index itself and the spectral shape, and (3) to show the advantage of EDRA.

2 RELATIONSHIPS BETWEEN INPUT MOTION AND RESPONSE

In this paper, concerns are given to the response of system as well as to the input motion. Figure 1 shows the relationships among several indices which characterize input motion and response. Energy response spectrum which shows the total energy of the response of a SODF system along the natural period axis, is newly introduced.

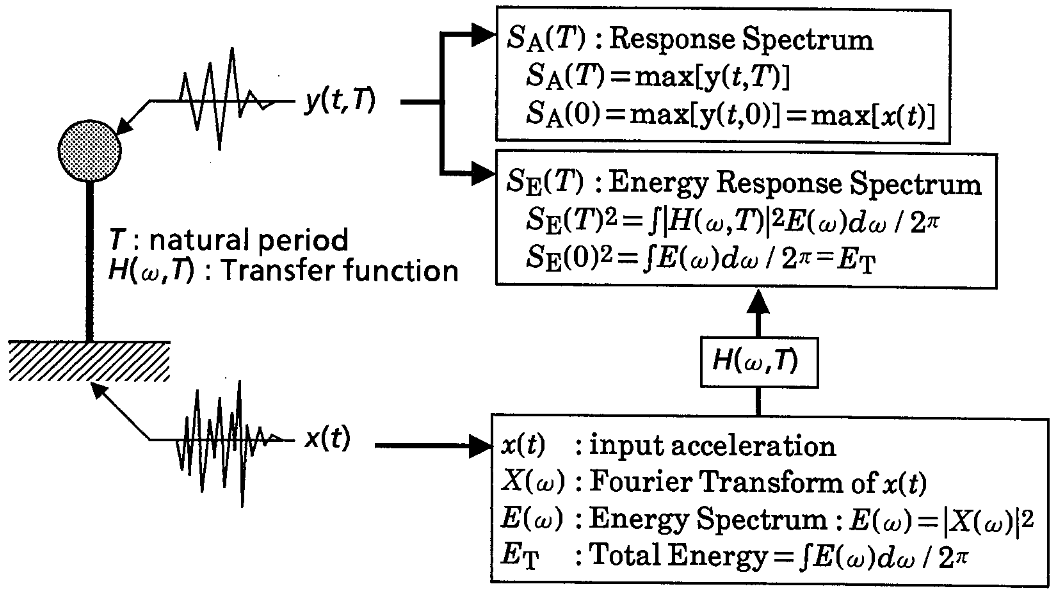

Fig. 1 Relationship between Input Motion and Response

To examine the statistical characteristics of these items, a set of recorded earthquake data was analyzed. The data set was obtained at Tomioka station in eastern Japan, which lies on a hard rock with thin alluvium and includes 58 records.

3 VARIANCE OF RESPONSE SPECTRA

Figure 2(a) shows the standard deviations of spectral shape, normalized spectrum by the value at 0 period, of response or energy corresponding to the set of above mentioned 58 records. The normalized energy response spectrum has a similar tendency to that of the normalized response spectrum. Standard deviations tend to linearly increase with the logarithm of natural period of the system.

Figure 2(b) shows the correlation coefficient of the normalized energy spectrum and input motion, and that of the normalized response spectrum and input motion. Both correlation coefficients tend to change their signs at 0.1 sec.

Figure 2(c) shows the standard deviations of the energy response spectrum and the response spectrum. These two spectra are directly obtained from the responses in the time domain. Standard deviations of the energy response spectrum tend to increase for the natural period larger than 0.1 second.By comparison, It can be seen that the standard deviation of the response spectrum is smaller than that of the energy response spectrum at all through the natural period.

It must be noted that the energy response spectrum can also be obtained from the normalized energy response spectra and the correlation coefficient. This can also be adopted to the response spectrum. This fact suggests that, if the correlation coefficients are properly obtained, variance of response spectrum can be evaluated exactly using covariance of input motion and spectral shape.

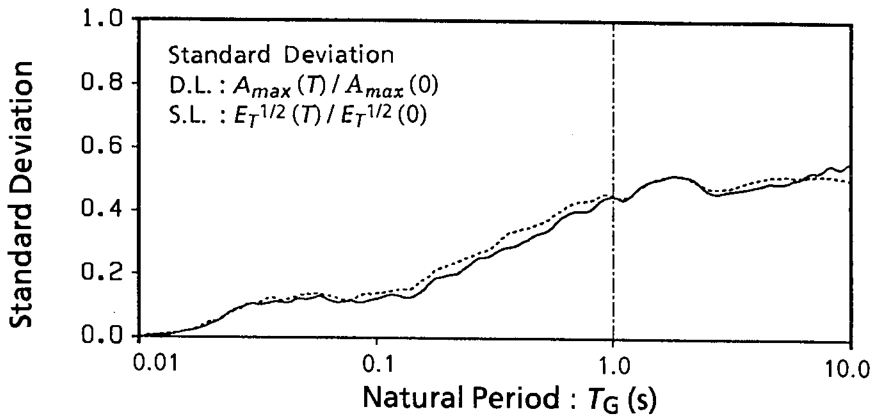

Fig. 2(a) Standard Deviation of Normalized Response Spectra

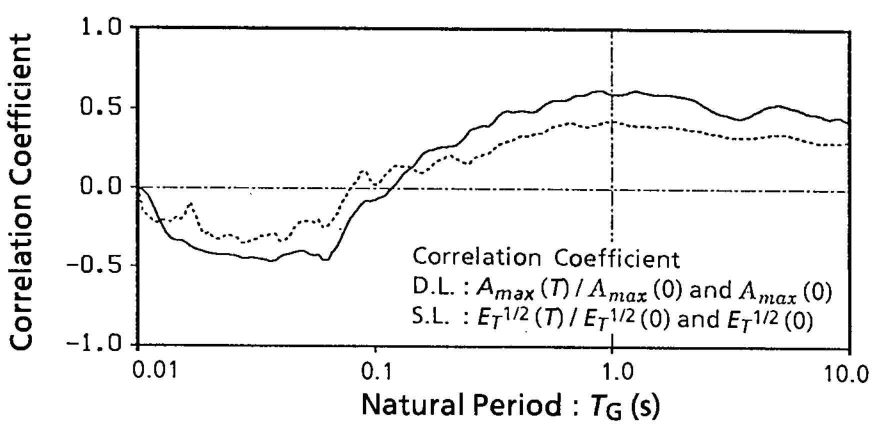

Fig. 2(b) Correlation Coefficient of Normalized Response Spectra

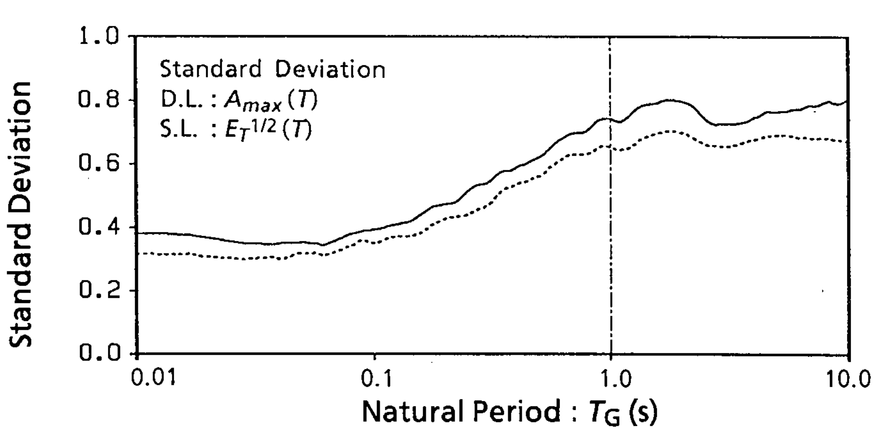

Fig. 2(c) Standard Deviation of Response Spectra

4 PERIOD DEPENDENT MAGNITUDE COEFFICIENT

Characteristics of total energy and peak acceleration on the natural period are related to the dependency of input motion on the earthquake magnitude. In order to show this relationship, Figs. 3(a) and 3(b) plot the total response energy and response acceleration with magnitude at three natural periods, 0.0sec.(input motion), 0.3sec., and 1.0sec.

A clear dependency on the magnitude is observed at each period. Then the inclination of the axis which is obtained by liner regression analysis of Figs. 3(a) and 3(b), is defined as magnitude coefficient in this study. For example, Magnitude coefficient a for peak acceleration is given by the following equation.

$$log_{10}A_{\max} = aM + c + \varepsilon$$

Where, M denotes magnitude and c is a constant. ε expresses the scattering of data. Magnitude coefficients of total energy and peak acceleration versus natural period are shown in Fig. 3(c).

There exists the tendency that the magnitude coefficient increases with the natural period. The magnitude coefficients of total energy is larger than that of peak acceleration. The relationship between magnitude coefficients and natural period is very similar to that between the standard deviation and period shown in Fig. 2(c). It is natural that the standard deviation increases with the natural period, as the scattering of data increases with the natural period because of increase of depending on magnitude.

5 VARIANCE OF RESPONSE SPECTRA WITHOUT MAGNITUDE DEPENDENCY

To eliminate the magnitude dependency, scattering of data shown in Figs. 3(a) and 3(b) is rearranged with respect to the axis whose inclination is the magnitude coefficient. The variance of the response after eliminating the magnitude dependency are shown in Figs. 4(a), 4(b), and 4(c).

Figure 4(a) shows the standard deviations of spectral shape, normalized spectrum by the value at 0 period, of response or energy corresponding to the set of above mentioned 58 records. Figure 4(b) shows the correlation coefficient of the normalized energy spectrum and input motion, and that of the normalized response spectrum and input motion. Figure 4(c) shows the standard deviations of the energy response spectrum and the response spectrum. all through the natural period.

Standard deviations of energy response spectrum and response spectrum have little dependency on the natural period and are rather uniform. In the period range less than 1 second, standard deviation of energy response spectrum is smaller than that of the response spectrum. In the range greater than 1 second, the situation is reversed.

Standard deviations of normalized energy response spectrum and normalized response spectrum have the same value in the range less than 1 second, however, that of the normalized energy response spectrum show larger variation in the larger period range than 1 second.

Above tendencies could be due to the fact that data used in this study are S-waves of the records and have relatively short duration time to avoid the effects of surface waves, and the components of the longer periods have less accuracy. Especially, the examination of the components more than 10 seconds can not be done. On the other hand, peak accelerations have less influences of duration time and can be examined properly.

Namely, the comparison in the period range less than 1 second can have the meanings. In this range, the standard deviations of energy response spectrum is smaller than that of the response spectrum.

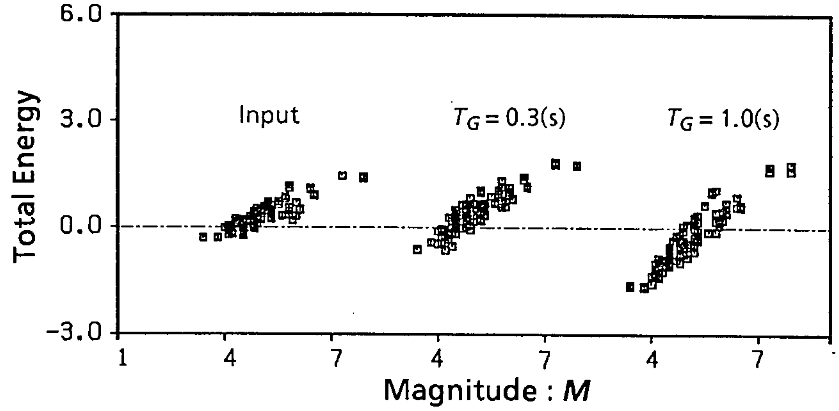

Fig. 3(a) Relation between Magnitude and Total Energy

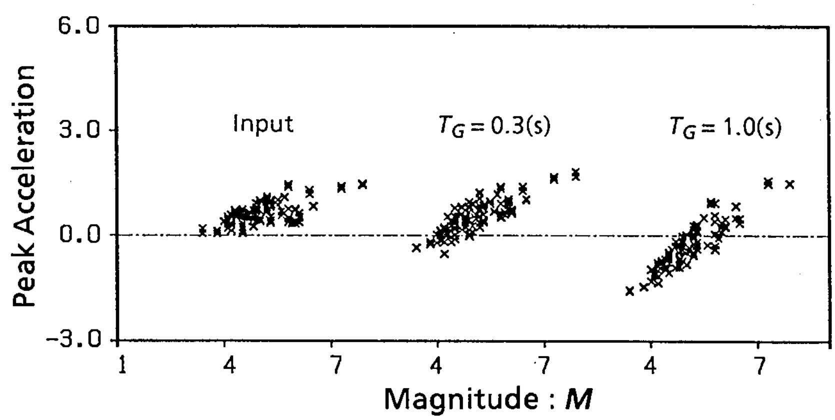

Fig. 3(b) Relation between Magnitude and Peak Acceleration

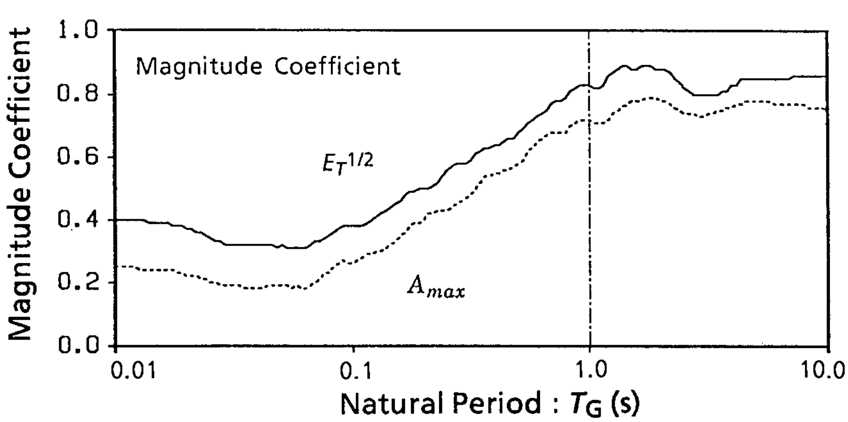

Fig. 3(c) Magnitude Coefficient

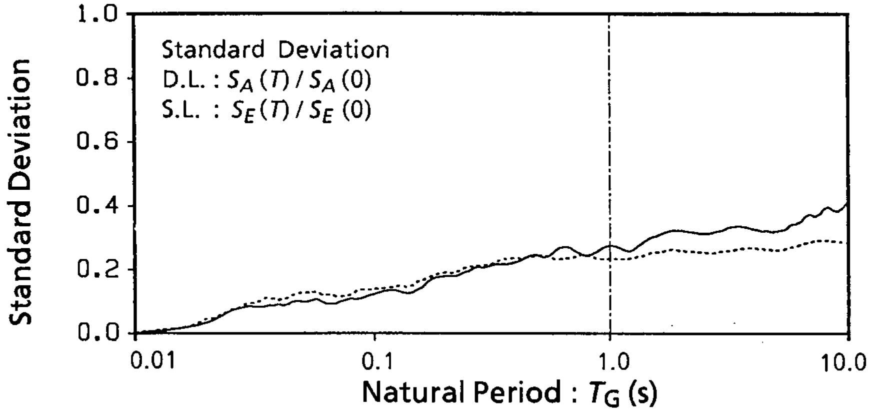

Fig. 4(a) Standard Deviation of Normalized Response Spectra without Magnitude Dependency

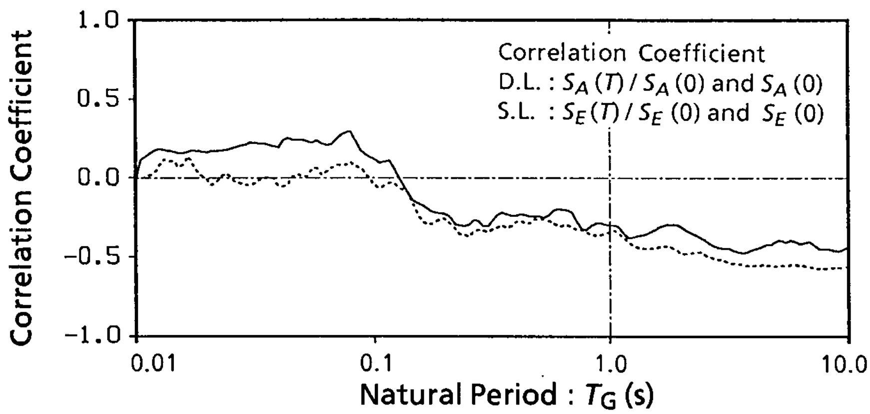

Fig. 4(b) Correlation Coefficient of Normalized Response Spectra without Magnitude Dependency

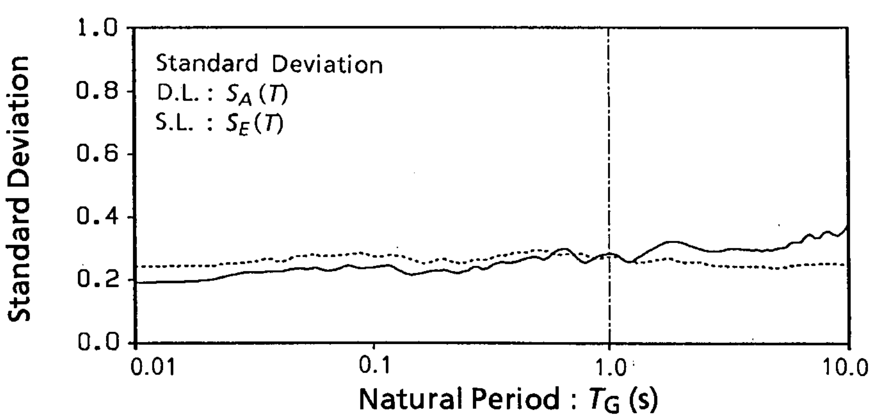

Fig. 4(c) Standard Deviation of Response Spectra without Magnitude Dependency

6 EXPECTED RESPONSE SPECTRA

Figures 5(a), 5(b), 5(c), and 5(d) show the expected energy response spectra and the expected response spectra, which are obtained from the regression analyses regarding magnitude. For convenience, said spectra are converted to the pseudo velocity response spectra. Characteristics of variance are maintained after the conversion. Similar to the correlation coefficients of input motion and spectral shape, normalized spectra have a tendency that they cross one another at a period adjacent to 0.1 second. Energy response spectra have ripples in the range of long period. This is related the insufficient accuracy of the components in this range as mentioned before.

The expected value of input motion for the magnitude of 8 is read to be 10 cm/s from Fig. 5(d). This value seems reasonable.

7 ADVANTAGE OF USE OF TOTAL ENERGY

From the comparison of the energy response spectrum and the response spectrum, the following results are derived.

1) Based on the conventional procedure, expected energy response spectrum and its variance are obtained. This fact suggest that procedure based on the total energy can be one of the alternatives in the reliability analysis.
2) The major difference between the method based on the total energy and that based on the peak acceleration is the size of variance. If the effect of magnitude dependency can be eliminated, variance of the total energy is smaller than that of peak acceleration in the shorter range less 1 second. In the longer range, more data will be needed for accurate examination. This suggests the advantage of use of total energy.
3) Variance of energy response spectrum and conventional response spectrum can be considered uniform, if the effect of magnitude dependency is properly considered. Variance of normalized spectra tend to increase in proportion to the logarithm of natural period of the system. This tendency is agree with the existing researches. Correlation coefficients of input motion and spectral shape change their signs at the period adjacent to 0.1 second.

Namely, it is apparent that reliability analysis based on the total energy can be formed. Several of the advantages of the use of the total energy are described here. However, it may not be strong enough to change the framework of DRA. Some more additional advantages should be presented.

In this section, it will be attempted to demonstrate the advantage of use of total energy based on the following two features.

(1) variance measured by magnitude of earthquake
(2) response spectrum controlled by duration time

7.1 VARIANCE MEASURED BY MAGNITUDE OF EARTHQUAKE

So far, variance of Index I is expressed as follows.

$$log_{10}I = aM + c + \varepsilon$$

Where, M denotes magnitude and a and c are constants. ε which expresses the scattering of data, corresponds to the index I directly. On the other hand, variance measured by magnitude is expressed as follows.

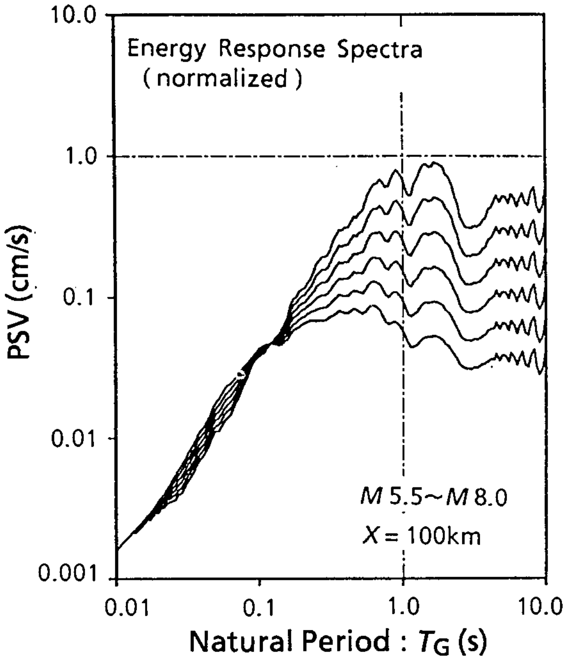

Fig. 5(a) **Expected Normalized Energy Response Spectra**

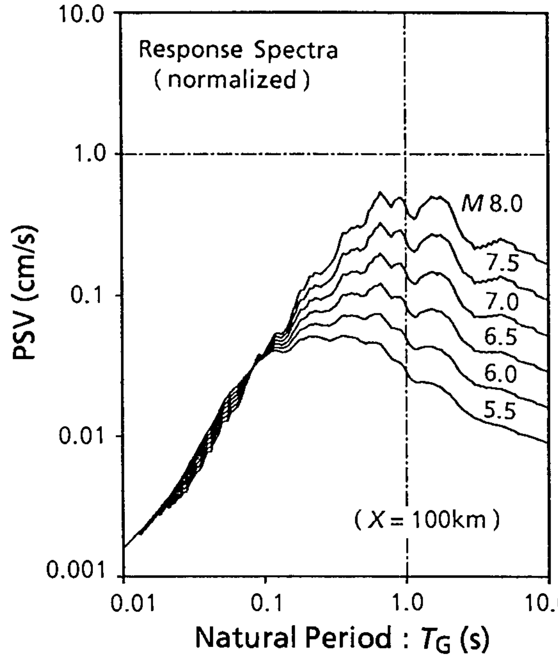

Fig. 5(b) **Expected Normalized Response Spectra**

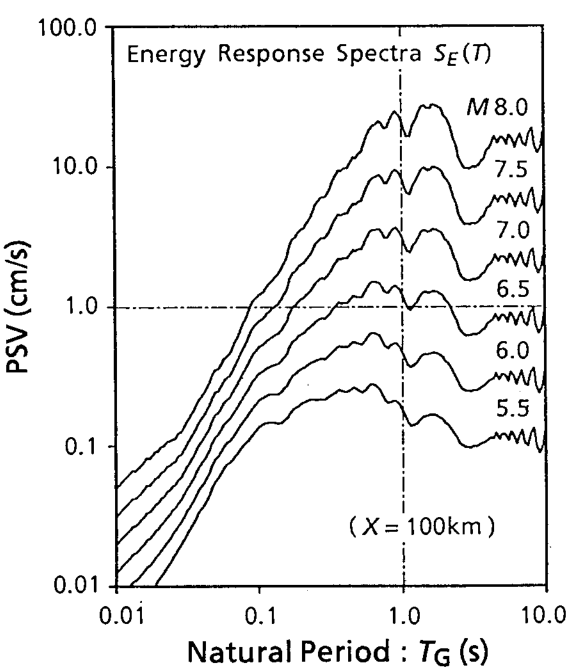

Fig. 5(c) **Expected Energy Response Spectra**

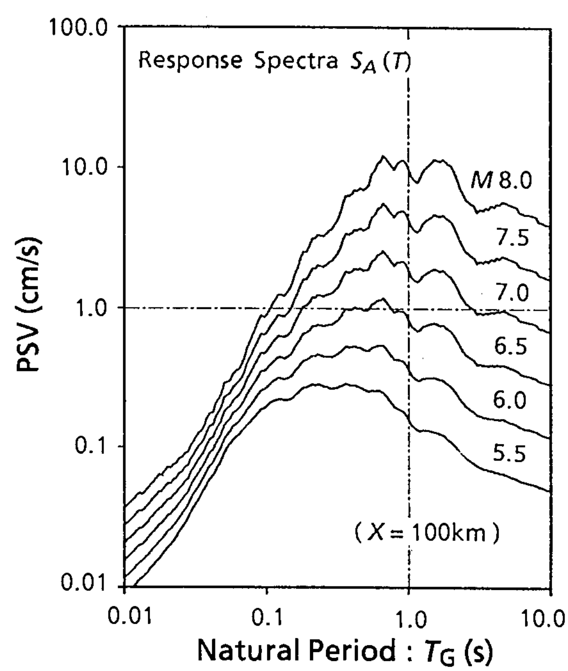

Fig. 5(d) **Expected Response Spectra**

$$M = \left(log_{10}I\right)/a - c/a - \varepsilon/a$$

or

$$log_{10}I = a(M + \varepsilon/a) + c$$

Therefore, by multiplying $1/a$ to the variance obtained for the index I, variance measured by magnitude can be calculated.

Figure 6 shows the standard deviations of energy response spectrum and response spectrum measured by magnitude. In this case, there exist the large deference between them, and then the advantage of total energy can be clearly identified.

In many reliability analyses, it is required to define the magnitude distribution of the earthquake source which yields the specified peak acceleration at the site. Similar to this, for the EDRA, it will be necessary to define the magnitude distribution which yields the specified total energy. Namely, Fig.6 suggest that the magnitude distribution which yields the specified total energy can be estimated more accurately than that for the peak acceleration. This apparently shows the advantage EDRA.

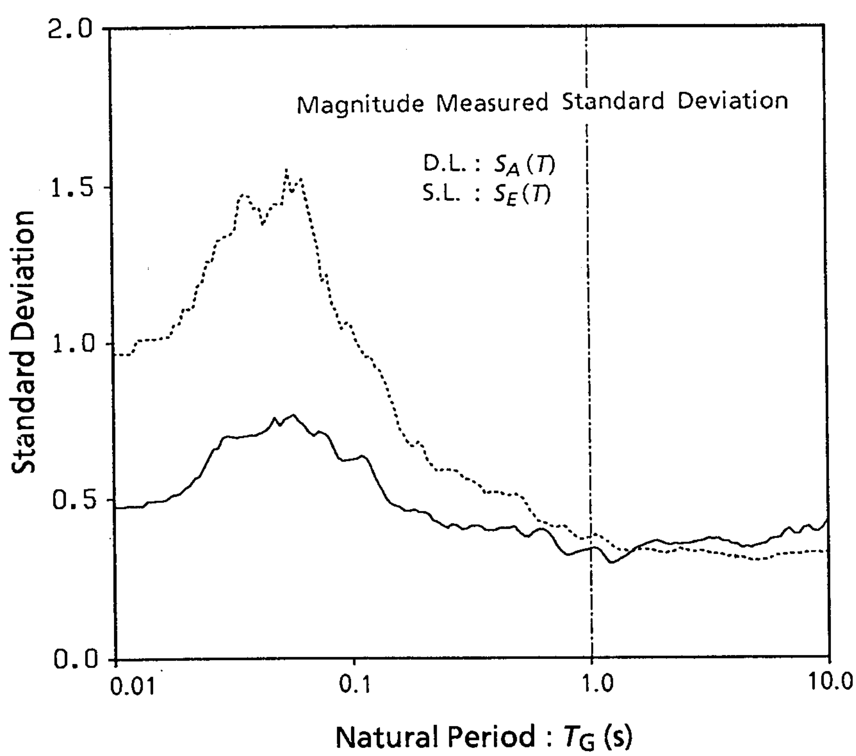

Fig. 6 Magnitude Measured Standard Deviation of Normalized Response Spectra

7.2 RESPONSE SPECTRUM CONTROLLED BY DURATION TIME

Generally, it is said that seismological knowledge can be reflected well on the estimation of the duration time. It is possible to estimate the duration time accurately by assuming the direction of propagation of rapture for the fault corresponding to the magnitude. At least, in this case, variance of duration time can be reduced comparing with the case in which duration time is estimated by mere statistical approach.

Therefore, in the reliability analysis, it will also be preferable to estimate the duration time as accurate as possible. The improvement of the duration estimation can be directly reflected to the EDRA.

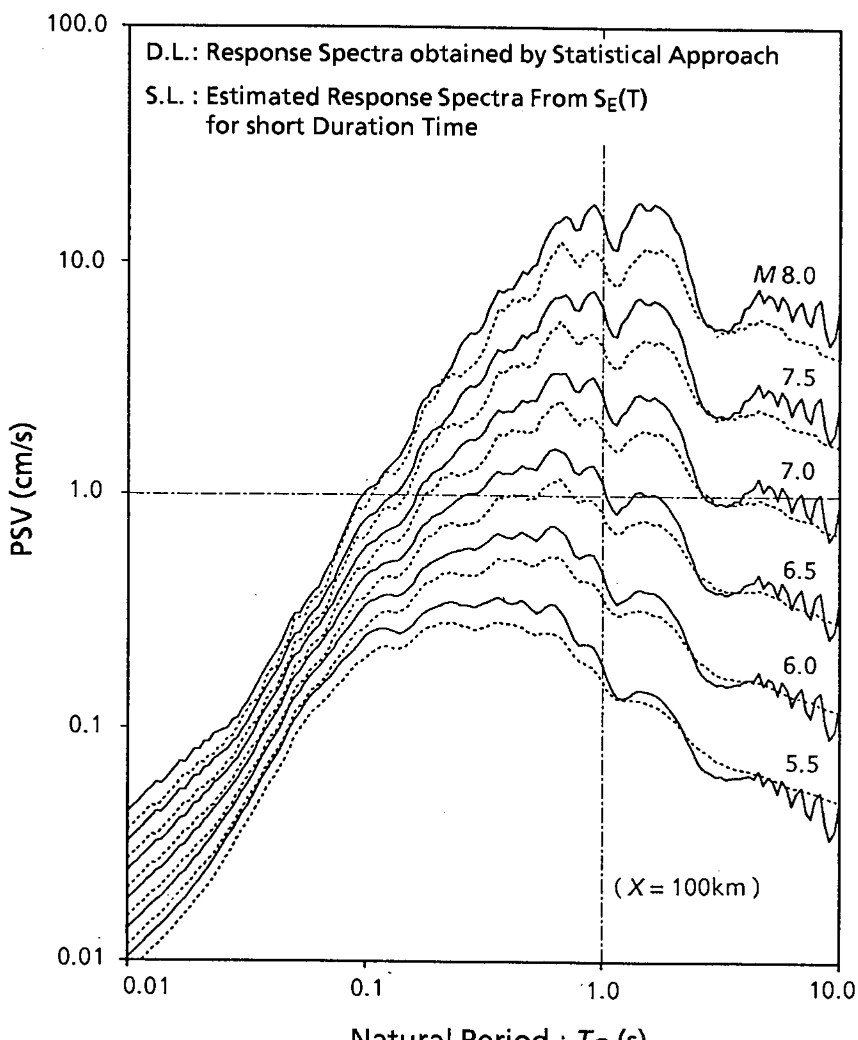

Fig. 7 Expected Energy Response Spectra for short Duration Time

For example, two types of earthquakes can be identified, one has a rupture going away and the other has a rupture coming up. And it will be necessary to estimate the duration times for these earthquakes.

Figure 7 shows the energy response spectrum which has short duration time. In this case, the duration time is given by median minus one standard deviation, which are obtained by regression analyses. It is apparent that the energy response spectra increases when assuming the short duration time.

Figure 8 shows the energy response spectrum which has a long duration time, on the contrary. The duration time is given as median plus one standard deviation. the energy response spectra decreases by assuming the long duration time. This also shows the advantage EDRA.

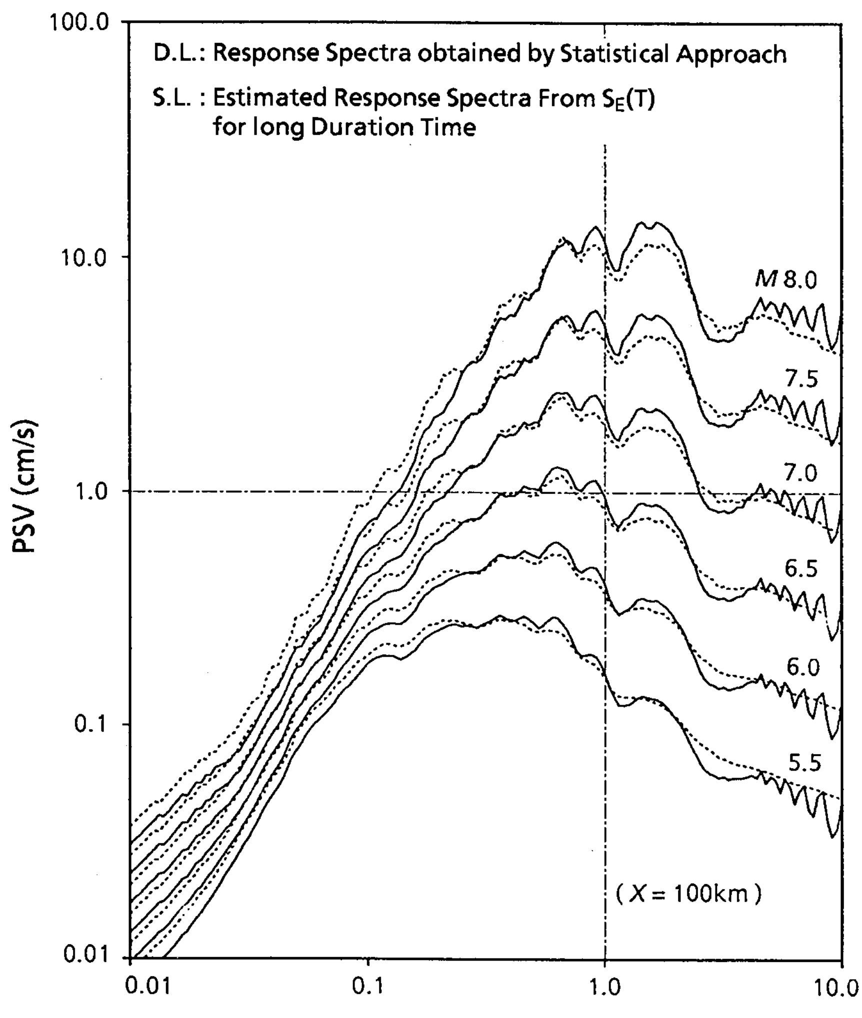

Fig. 8 Expected Energy Response Spectra for long Duration Time

8 CONCLUSIONS

Following results are obtained in this study.

1) The procedure based on the total energy can be one of the tools of seismic reliability analysis. This means that it is possible to estimate seismic hazard and structural response, based on the total energy.
2) It is confirmed that, as long as magnitude dependency is properly treated, the standard deviation of estimation error in the energy response spectrum approach is smaller than that of the peak acceleration approach, for the structures whose natural period is less than 1 second.
3) In addition to above, there exist two advantages of use of total energy are demonstrated. They are the smaller variance when measured by magnitude, and energy inclusion of duration time estimation.
4) Regarding variance measured by magnitude, the meaning of the variance is explained and it is shown that variance of the total energy is considerably smaller than that of the peak acceleration.
5) Regarding the energy response spectrum controlled by duration time, it is shown that the energy response spectra can properly express the effect of duration time. As the seismological knowledge is now expected to give more accurate duration time of the seismic wave released from an active fault, the use of energy response spectra will have an advantage.

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