POTENTIAL DESTRUCTIVENESS OF STRONG EARTHQUAKES

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SUMMARY

In order to evaluate the potential destructiveness of strong ground motions, the most disadvantageous earthquake which produces the largest elastic-plastic response of a particular structure is generated in a purely analytical manner. A detailed study on the ductility factor response spectra both for the most disadvantageous earthquake and a number of recorded strong motion accelerograms reveals that the most disadvantageous earthquakes thus generated have some desirable properties as the means for evaluating the potential desturctiveness of strong ground motions.

INTRODUCTION

The earthquake response of a structure is uniquely determined when the mechanical properties of the structure and input ground acceleration are specified. Conversely, the potential destructiveness of various strong ground accelerations on a structure can be evaluated by comparing the maximum earthquake response of the structure. The situation becomes more complex, however, when the elastic-plastic response is considered, as not only the natural period but also the resistance capacities of the structure play an important role. Thus, the relative potential destructiveness of two particular ground motions may be reversed for structures with the same natural period but with different yielding strength. A careful choice of input accelerograms should be made when elastic-plastic response analyses are made for checking the seismic safety of a structure, such as it is the case for designing buildings of particularly high importance in Japan.

The most disadvantageous earthquake (MDE) is proposed in this paper to give an extreme measure for evaluating potential destructiveness of strong earthquakes. MDE is so constructed as to give possibly the maximum displacement response of a single degree-of-freedom system with the stiffness deteriorating elasto-plastic hysteresis model. It has the advantage of being constructed analytically with no direct reference to any statistical properties of recorded strong motion accelerograms. It guarantees, then, the upper bound of the displacement response even for the eventual accumulation of strong earthquake records. Quantitative evaluation of the potential destructiveness may be utilized not only in selecting the appropriate input earthquakes for designing structures of any assumed importance but also in generating synthetic accelerations for different purposes.

MOST DISADVANTAGEOUS EARTHQUAKE

Some Aspects of Elastic-Plastic Earthquake Response

From experience, each plastic deformation of a single degree-of-freedom system with elasto-plastic hysteretic rules, under earthquake excitations, takes place in very short period of time, say, 1/5 of the natural period in

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(I) Associate Professor, Inst. of Eng. Mech., Tsukuba University, Japan ordinary cases. It is expected, then, that detailed variation of ground accelerations within such a short interval may not give the major effects to the magnitude of plastic deformation. The magnitude of an individual plastic flow, x_p, under the simplest assumption of constant ground acceleration, D, is readily given by the following equation.

$$x_p = \frac{1}{2} \dot{x}_0^2 / (a_y - D) \qquad (1)$$

wherein a_y: yield acceleration

$\dot{x}_0$: initial velocity when plastic flow begins

It is evident that the plastic flow becomes unbounded when the ground acceleration is greater or equal to the yielding acceleration of the structure. When the duration time, T, of the ground acceleration is limited, however, the magnitude of the individual plastic flow is bounded and given by the following expression.

$$x_p = \frac{1}{a_y}\left[\frac{1}{2}C^2(1-a_y/d) + C\dot{x}_0 + \frac{1}{2}\dot{x}_0^2\right] \qquad (2)$$

wherein $C = D \cdot T$: area of rectangular ground acceleration

Elasto-plastic earthquake response analyses were made for single degree-of-freedom structures with the hysteresis rules shown in Fig 1 (a) to verify the validity of eq.(1). The ground acceleration level, D, was approximated by the average value of actual ground accelerations during the individual plastic flow (see Fig 2), while the exact initial velocities, $\dot{x}_0$, were used for evaluating eq.(1). Exact values of individual plastic flow are plotted against those approximated by eq.(1) for the initial natural periods of 0.2, 0.3, 0.5 sec and for the input ground motions of El Centro (NS) and Taft (EW) in Fig 3. Satisfactory agreement between the exact and approximate values is observed in Fig 3 (a) and (b) for different strength levels, $a_y/|\ddot{x}_g|_{max}=0.67$, 1.0, respictively, where $|\ddot{x}_g|_{max}$ represents the maximum ground acceleration. The results are improved considerably for structures with higher strength levels, since eq.(1) is only applicable for the cases, $a_y/D>1.0$. It is concluded that the rough assumption of average acceleration may lead to a satisfactory estimation on the magnitude of individual plastic flow. As is obvious from eq.(1), the major factors which govern the magnitude of individual plastic flow are the initial velocity, $\dot{x}_0$, and the strength level, $\gamma = a_y/D$.

Generation of MDE

Concept of the most disadvantageous earthquake was first introduced by M. Hoshiya [Ref.1] (worst earthquake), which produces the possible largest response for a specific structure, under statistical considerations. In this study, however, MDE is generated analytically by combining the sinusoidal waves with the period corresponding to the initial slope of the elasto-plastic hysteretic model and the rectangular pulses which increase the individual plastic flow on the second slope. Although the wave forms thus produced do not guarantee the maximum displacement response of the structure, it is well known that the maximum response is strongly correlated to the maximum accumulation of individual plastic flow, since, in the usual cases, plastic flow of a structure does not occur too many times during a transient ground excitation. As a constraint to MDE, the envelope function shown in Fig 4 is tentatively employed. Moreover, the maximum periods of both the sinusoidal waves and rectangular waves are set to be one second because the extremely long duration of high ground acceleration is considered unrealistic. These conditions are of conventional nature and should be improved in accordance with the future progress in the strong motion seismology. The stiffness deteriorating elasto-plastic hysteretic model (model 1) is exclusively adopted together with the standard elasto-plastic model (model 2) for the purpose of comparison. MDE is then uniquely determined for each structure with the prescribed initial natural period, T, and strength level $\gamma = a_y / |\ddot{x}_g|_{max}$.

Time history of the generated MDE are illustrated in Fig 5 (a) and (b) for the two types of structure, having the same natural period of 0.5 second and different strength levels, $\gamma=1.33$ and $\gamma=5.0$, respectively. For the structure with the relatively low yielding strength (a), large stiffness deterioration takes place at the very early stage of excitation and the difference in initial natural periods are supposed to be inmaterial to the final maximum response. Plastic deformation of relatively strong structure occurs in limited number of times and for extremely short durations.

General Properties of MDE

Ductility factor response spectra of various MDE are plotted in Fig 6 (a) for different strength levels. On the whole, the ductility factors, μ, decrease monotonically with increasing natural period, T, especially for structures with relatively low strength levels ($\gamma<2.0$). For structures with large strength capacities, however, the spectra become more stable with almost constant values except for the extremely short natural periods, i.e., T=0.1 sec. The threshold value of γ which divide these different characters are very high, between $\gamma=3$ and 5. Monotonic decrease in spectra is inherent to the stiffness deteriorating hysteretic rules by which the difference in the initial periods of the structure vanishes at an early stage of excitation as indicated in Fig 5 (a). Ductility factor response spectra for the standard elasto-plastic hysteretic model are demonstrated in Fig 6 (b) to show a similar trend to (a). The spectral values are considerablly smaller in this case and the threshold value of γ seems to be less than 2. It should be noted here that the ductility factors of MDE only indicate the index of potential destructiveness although they sometimes take unrealistically large values, e.g., more than 100.

Another property of MDE is indicated by the local fluctuation of ductility factor spectra. This undesirable ruggedness of MDE to be a measure for evaluating potential destructiveness of strong earthquakes is due to the generation procedure of MDE. In calculating the elastic-plastic earthquake response of a structure by the standard procedure, the time interval is subdivided into smaller increments whenever the stiffness change occurs, so that the sinusoidal and rectangular wave forms shift from each other within the original time interval. Ignoring this effect and calculating the earthquake response for the generated MDE at the original sample points, somewhat different response may result other than those originally obtained. In order to check this effect, ductility factor responses are recalculated for structures with slightly varied natural periods, i.e., 15% smaller and larger than the original period. The modified ductility factor spectra obtained by taking the maximum value among these three slightly different systems are illustrated in Fig 7 for two particular hysteresis models. Smooth spectra are obtained as compared to the original ones, indicated by broken lines, and further smoothing effects can also be expected by taking more varying natural periods.

RESPONSE ANALYSES FOR RECORDED ACCELEROGRAMS

Ductility Factor Spectra

In order to understand the nature of the actual ground motions, ductility factor response spectra are calculated for two horizontal components of the recorded strong motion accelerograms listed in Table 1. The mean values of all the 26 acceleration records for various strength levels of the structure, shown by solid lines in Fig 8, indicate the general tendencies of the strong ground motions. They are somewhat similar to those of MDE, as follows. The ductility factor spectra are, in general, monotonically decreasing functions of the natural period and assume more stable values as the relative strength of the structure increases. The relative magnitude of the ductility factors and the threshold value of strength levels which differentiate the stable and unstable spectral shapes are considerably greater for the stiffness-deteriorating hysteresis than in the standard elasto-plastic model. The only difference appears in that the spectral values for MDE are far greater than the mean spectral values of the recorded accelerograms.

Variations of spectral values due to the different input motions are illustrated in Fig 9 together with the corresponding MDE spectrum. Extremely large variations are observed especially for short period structures with relatively low yielding strength. This is a consequence of stiffness deterioration at the beginning phase of the response which depends mainly on chance. Although the upper bound of all the spectra gives far less values than the MDE spectrum, they are quite similar in shape, indicating a desirable feature of MDE for measuring the destructiveness of ground motions. For comparison purposes, the same illustration is given for the standard elasto-plastic model in Fig 10. Although the spectral variation due to different input accelerograms is smaller and discrepancies between their envelope and MDE spectrum become less than those for model 1, general characters of actual ground motions remain the same.

Equivalent Acceleration Amplitude

Refering to the generation process of MDE, it should be understood that the maximum amplitude of MDE represents the averaged accelation levels rather than the absolute maximum of the ground acceleration. This suggests the introduction of the equivalent acceleration amplitudes to the recorded accelerograms. They are determined by taking moving average over the time length of one half the natural period of the structures. Some illustrative examples of the equivalent acceleration levels for structures with various natural periods are shown in Fig 11. The manner of decreasing effective amplitudes with the natural period are different for each accelerogram and the reduction ratios vary from 0.2 to 0.6 for the period of 1.0 second.

Fig 12 shows the revised version of Fig 9 using the equivalent acceleration amplitude for the recorded earthquakes. By comparison with Fig 9, the magnitude of ductility factors is increased, in general, to reach and cross the MDE spectrum in the long period range. This is due to the complete lack of frequency components less than 1.0 Hz in MDE and also the fact that the maximum response of elastic-plastic systems does not depend entirely on the average amplitude of the ground acceleration but is possibly affected by tne absolutely maximum acceleration. Mean spectral values for the equivalent amplitudes are also indicated by broken lines in Fig 8 to show the considerable increase in the long period range.

SUMMARY

Main results obtained from this series of numerical analyses are summarized as follows:

1. An analytical procedure of generating the MDE which produces the largest cumulative plastic deformation on a particular structure is proposed. MDE gives extremely large displacement response as compared to the recorded strong ground motions, although it is not guaranteed to give the possible maximum response of the structure.

2. Ductility factor spectra of the MDE shows a monotonically decreasing function of natural periods for the stiffness-deteriorating type hysteresis models. Fluctuations of ductility factors are reduced as the yielding strength becomes higher and the stiffness deterioration is supressed.

3. It has been verified that MDE spectra not only give the upper bound of the ductility factor spectra for various recorded accelerograms, but also show very similar spectral shape to the mean values and envelope values for the real earthquakes. These properties of MDE are considered appropriate as a measure for evaluating the potential destructiveness of strong ground motions.

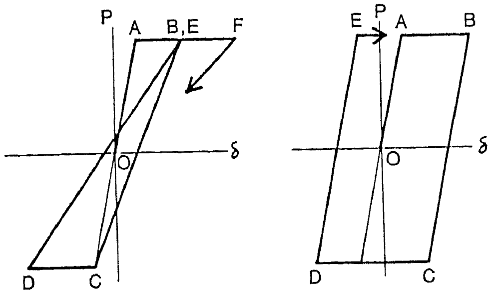
REFERENCES

[1] M. Hoshiya et al, "Analysis of The Worst Pseudo Earthquake in Aseismic Design", Trans. J.S.C.E., Vol.231, 1974

[2] T. Minami, Y. Sonoda and Y. Osawa, "Evaluation of Potential Destructiveness From Recorded Strong Motion Accelerograms", Proc. 7-WCEE, 1980

Table 1. List of Accelerograms

El Centro 1940	Hachinohe 1968
Taft 1952	Tohoku Univ. 1978
Olympia 1949	N.J.R. Sendai 1978
El Centro 1934	Sumitomo Bank 1978
Vernon 1933	77 Bank 1978
Pacoima Dam 1971	
Millican Lib. 1971	
Hollywood Strg. 1952	



a) model 1 b) model 2

Fig.1 Hysteretic Models

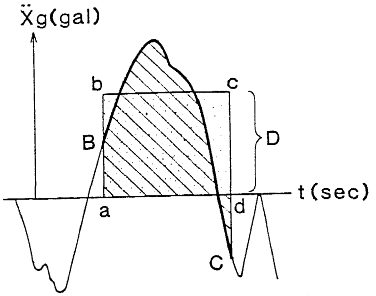


Fig.2 Average Amplitude

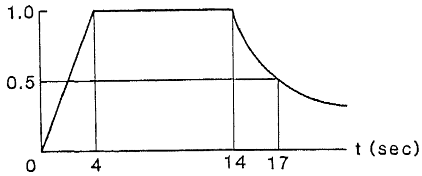


Fig.4 Envelope Function

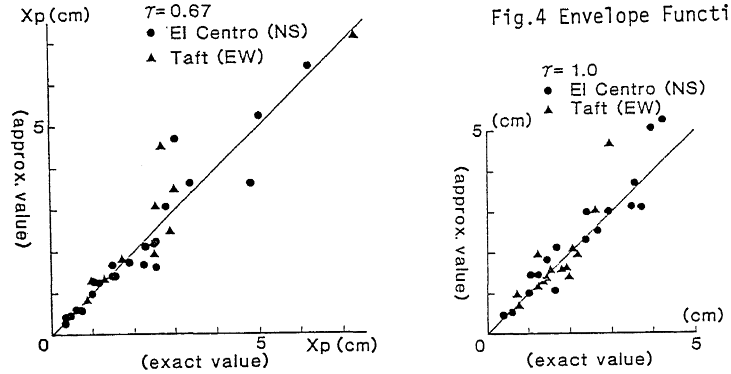
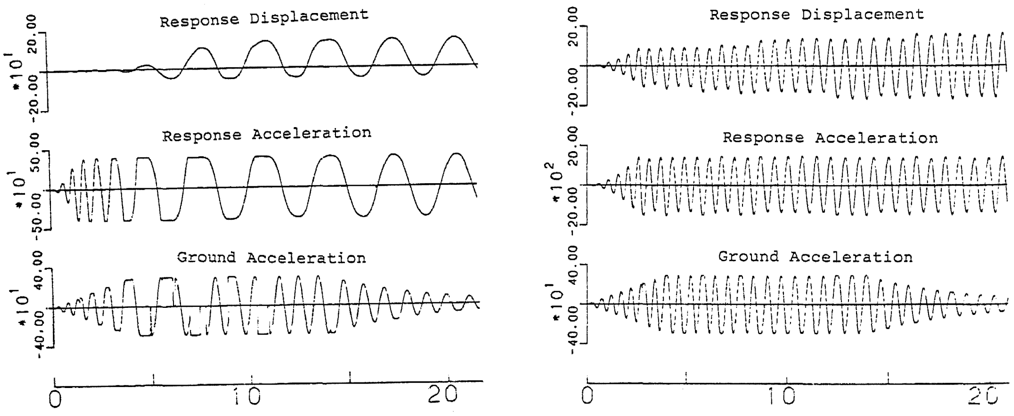
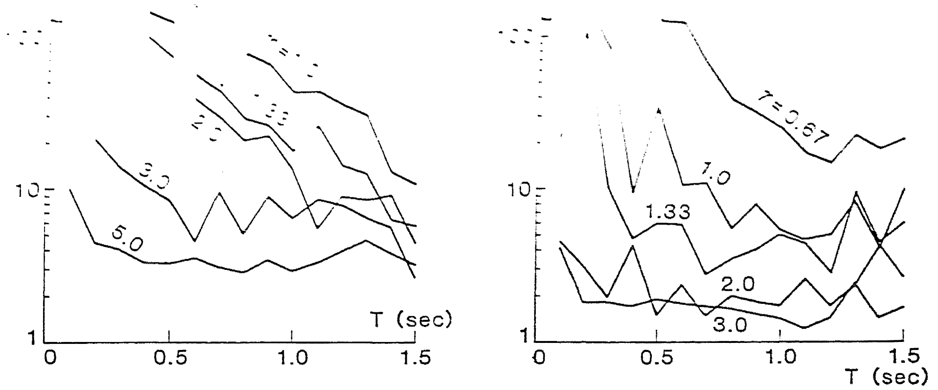


Fig.3 Comparative Magnitude of Individual Plastic Flow



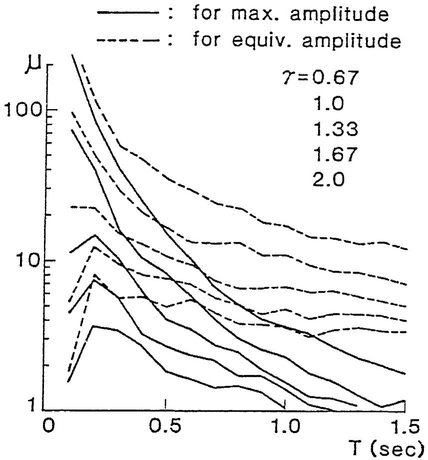
(a) γ = 1.33 (T = 0.5 sec) (b) γ = 5.0 (T = 0.5 sec)

Fig.5 Time History of Typical MDE

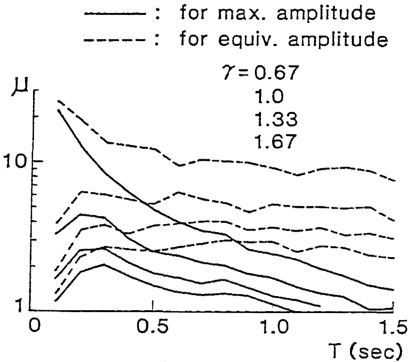


a) model 1 b) model 2

Fig.6 Ductility Factor Response Spectra of MDE



a) model 1



b) model 2

Fig.8 Averaged Ductility Factor Spectra

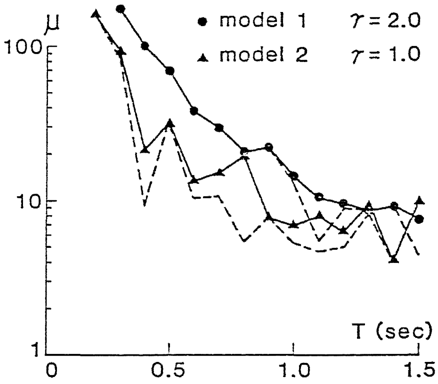


Fig.7 Modified MDE Spectrum

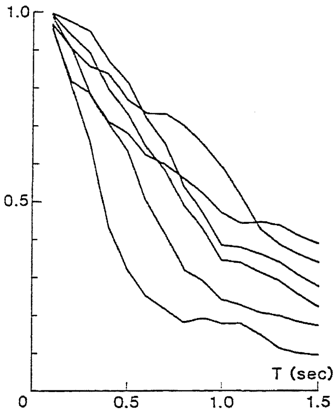
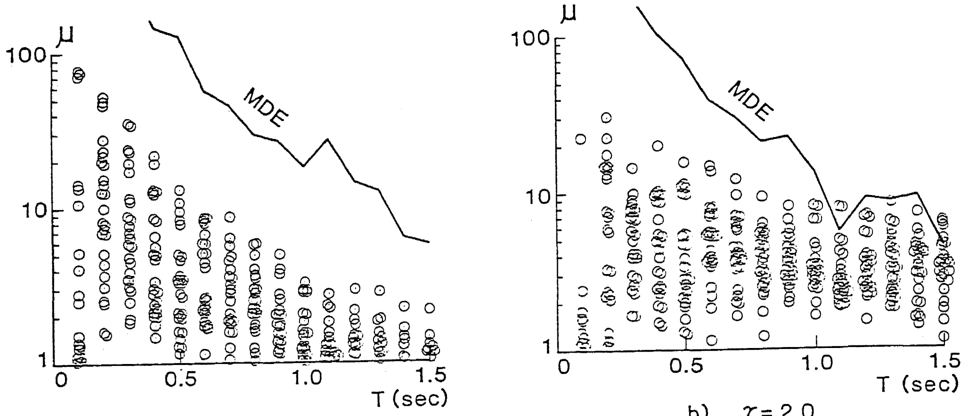
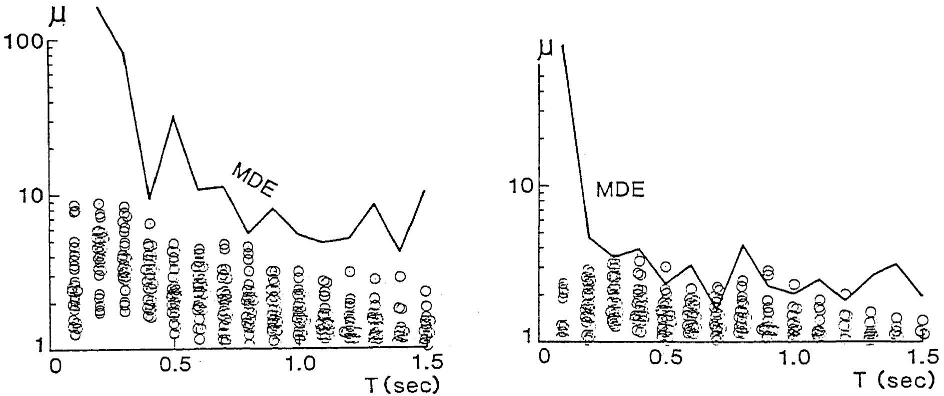


Fig.9 Reduction of Equivalent Amplitudes



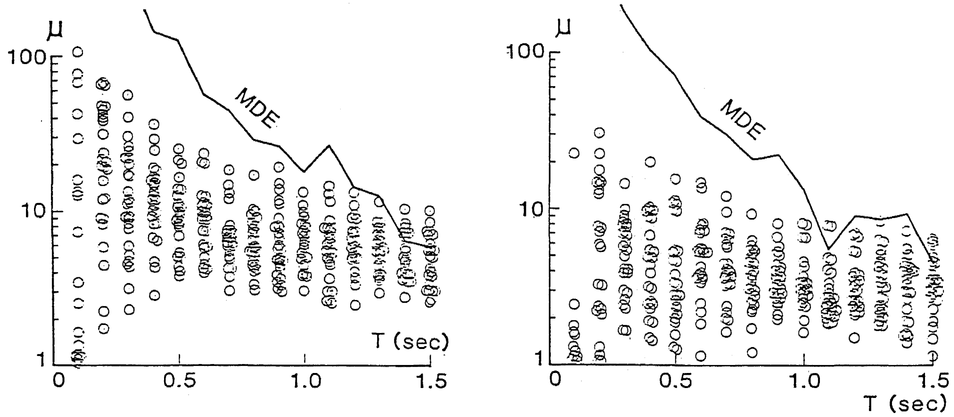
a) $\gamma = 1.33$ b) $\gamma = 2.0$

Fig.10 Variation of Ductility Factors (model 1)



a) $\gamma = 1.0$ b) $\gamma = 1.67$

Fig.11 Variation of Ductility Factors (model 2)



a) $\gamma = 1.33$ b) $\gamma = 2.0$

Fig.12 Revised Ductility Factor Spectra (model 1)