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EARTHQUAKE LOAD EFFECT FOR STRUCTURAL RISK ASSESSMENT

Hitoshi KUWAMURA[1] and Theodore V. GALAMBOS[2]

[1]Civil Engineering Division, Nippon Steel Corporation, 1 Kimitsu, Chiba-ken 299-11, Japan
[2]Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, Minnesota 55455, USA

SUMMARY

Using an energy concept a seismic reliability criterion in the form of $W/Q_0 \geqq I_{Emax}$ is derived. W is the structural energy absorption capacity by elastic or plastic strain, Q_0 is the energy-response spectrum term, and I_{Emax} is the seismic hazard potential term. This criterion is verified by statistical investigation on energy response of SDOF elastic, elastoplastic and slip systems subjected to actual earthquake motions. This simple form is useful for calculating the probability of exceeding a limit state imposed from serviceability to collapse limit states of earthquake resistant structures.

INTRODUCTION

The commonly used criterion form for structural reliability analysis is $R \geqq Q$. R is the structural resistance and Q is the load effect. This is the basic mathematical representation for limit state criteria of probability-based design such as LRFD. R and Q are well defined by force parameters such as axial force and bending moment. R and Q are reasonably presumed to be statistically independent. This assumption facilitates the calculation of the reliability index or even the probability of exceeding an imposed limit state. However, totally different situations are encountered in earthquake reliability analysis: 1) The best physical parameter for R and Q may not be force, because deformability as well as strength is an important factor for R, and the peak of seismically induced inertia force is not necessarily the relevant index of Q; 2) R and Q may not be independent, because Q is influenced by the response characteristics such as natural period which is indirectly related to R; and 3) Q may not be determined only from structural engineering aspects, because Q is strongly dependent on seismological conditions around the structure's site. The purpose of this study is to clarify these difficulties and to propose a simple criterion form of $R \geqq Q$ for seismic reliability assessment.

CRITERION FORM BY ENERGY

For the ultimate limit state design of earthquake resistant structures, energy has been considered to be the best physical representation for R and Q (Refs.1,2). When the energy absorption capacity of a structure before its collapse is not less than the earthquake energy input, the structure can survive the earthquake. This idea can be extended to other limit states and a unified criterion can be constructed for the whole spectrum of limit states from serviceability to ultimate limit states as shown in the following discussion.

Energy equilibrium at time t of an SDOF-structure excited by base acceleration is given by

$$E_k(t) + E_h(t) + E_e(t) + E_p(t) = E_t(t) \quad (1)$$

where $E_k(t)$ is the kinetic energy, $E_h(t)$ is the energy absorbed by damping, $E_e(t)$ is the elastic strain energy, $E_p(t)$ is the cumulative plastic strain energy, and $E_t(t)$ is the total energy input. Reliability criteria for typical limit states in the form of $R \geqq Q$ can be given by :

$$1/2 \cdot k \cdot \delta_y^2 \geqq E_e \qquad \text{for yield limit state} \quad (2)$$

$$1/2 \cdot k \cdot \delta_d^2 \geqq E_e \qquad \text{for drift limit state} \quad (3)$$

$$C_p \cdot \eta_c \cdot k \cdot \delta_y^2 \geqq E_p \qquad \text{for ductility limit state} \quad (4)$$

where k is the horizontal stiffness, δ_y is the yield limit displacement, δ_d is the drift limit displacement less than δ_y, η_c is the allowable limit of the cumulative ductility factor, i.e., the ratio of cumulative plastic displacement to the yield limit displacement, and C_p is the adjustment factor for strain-hardening, strain-softening, strain-rate, and Bauschinger effects in the hysteresis behavior. Both for yield and drift limit states, $E_p(t)$ must be zero. On the right-hand sides of Eqs.2, 3, and 4, E_e is the peak of elastic strain energy for the duration t_o, and E_p is the final value of $E_p(t)$ at the end of the motion, as given by

$$E_e = \max\{E_e(t)\} \qquad \text{for } 0 < t \leqq t_o \quad (5)$$

$$E_p = E_p(t_o) \quad (6)$$

PARAMETER FOR SEISMICITY

The criterion forms of Eqs.2, 3, and 4 are useful only when earthquake ground motion is prescribed. In order to assess the structural risk in the span of a structure's lifetime, seismicity must be included in the criterion. The representative parameter for seismicity must be transformed into energy. Such a seismicity parameter is the integral of the squared ground acceleration defined as

$$I_E = \int_o^{t_o} (\ddot{z})^2 dt \quad (7)$$

where $\ddot{z}$ is the ground acceleration.

The integral of the squared ground acceleration is related to the total energy input in the following equations (Refs.3, 4) :

$$E_t = (0.15 \cdot M \cdot T^2/T_c \cdot C_v^2) \cdot I_E \qquad \text{for } T \leqq T_c \quad (8a)$$

$$E_t = (0.15 \cdot M \cdot T_c \cdot C_v^2) \cdot I_E \qquad \text{for } T > T_c \quad (8b)$$

where M is the mass of the SDOF system, T is the elastic natural period, C_v is the error coefficient, and E_t and T_c are defined as follows :

$$E_t = \max\{E_t(t)\} \qquad \text{for } 0 < t \leqq t_o \quad (9)$$

$$T_c = T_o/1.2 \quad (10)$$

where T_o is the predominant period of the ground motion. The number 1.2 is an adjustment. Equations 8a and 8b are derived from the facts that the equivalent velocity response spectrum defined by Eq.11 can be approximated by a bi-linear curve as shown in Fig.1 or Eqs.12a and 12b, and that the upper bound of the equivalent velocity V_{Eo} is related to I_E by Eq.13 :

$$V_E = \sqrt{2 E_t/M} \quad (11)$$

$$V_E = V_{Eo} \cdot (T/T_c) \cdot C_v \qquad \text{for } T \leqq T_c \quad (12a)$$

$$V_E = V_{Eo} \cdot C_v \qquad \text{for } T > T_c \quad (12b)$$

$$V_{Eo} = \sqrt{T_o \cdot I_E}/2 \quad (13)$$

Equations 8a and 8b show that E_t is proportional to I_E. An example of the time-histories of E_t and I_E is shown in Fig.2, from which it is observed that they are strongly correlated. Furthermore, Eqs.8a and 8b show that the total energy input is given by a product of the structural response term and the earthquake intensity term I_E. Thus, the maximum value of I_E during the structural lifetime, which is denoted by I_{Emax}, can represent the seismicity.

STATISTICAL PROPERTIES OF V_E-SPECTRUM

The statistical properties of the error coefficient C_v associated with the bi-linear approximation for the V_E-spectrum were investigated from response analysis. The conditions of the analysis are as follows : 1) the earthquake motions are 5 typical ones shown in Table 1, in which the values of T_o were determined from smoothed Fourier spectra ; 2) the structures are SDOF systems with elastoplastic and slip-type hystereses as shown in Figs.3a and 3b ; 3) the yield shear coefficient α defined as the ratio of the yield shear strength to the weight of the structure has the following values : 0.1, 0.2, 0.3, 0.4, 0.6, and 99.0 (for elastic behavior) for Hachinohe and Mexico motions, while 0.2, 0.4, 0.6, 0.8, 1.0, and 99.0 for the other motions ; 4) the fraction of critical damping h has the values from 0.0 to 0.10 with the interval of 0.01 ; and 5) the elastic natural period T has the values from 0.1 to 4.0sec with the interval of 0.05 for Mexico motion, while from 0.1 to 2.0 with the interval of 0.025 for the other motions.

The V_E-spectra obtained from the response analysis and approximation using Eqs.12 and 13 are compared in Figs.4a to 4e for the elastoplastic model. Basically the same response analysis results were obtained for the slip model except that V_E for $T \leqq T_c$ tends to be larger. The approximation appears acceptable irrespective of the amount of plastic deformation except Mexico motion. An adjustment is necessary for Mexico motion, because the bi-linear approximation is not applicable to the V_E-spectrum of such a sinusoidal motion. An example of adjustment using a trapezoid approximation is show in Fig.4e. The inelastic V_E-spectrum curves appear indentical with the smoothed Fourier spectrum curves shown by broken lines. The mean and the coefficient of variation of C_v for the El Centro/ elastoplastic case are shown in Fig.5. The same tendencies were observed for the other cases, and the mean and COV are roughly estimated as follows except for Mexico motion :

$$E[C_v] = 1.0, \text{ and } COV[C_v] = 0.2 \qquad (14)$$

STRAIN ENERGY INPUT

Strain energy input is the load effect both for elastic and plastic problems as indicated in Eqs.2, 3, and 4. The strain energy input can be derived from the total input energy using the following damping reduction factor :

$$D = D_e = \sqrt{E_e / E_t} \quad \text{for the elastic problem} \qquad (15a)$$

$$D = D_p = \sqrt{E_p / E_t} \quad \text{for the plastic problem} \qquad (15b)$$

An example of the damping reduction factor is demonstrated in Fig.6. The damping reduction factor tends to decrease with the increase in h and decrease in η. The following empirical formulae are proposed for D_e and D_p:

$$D_e = \frac{1}{1 + 2(3h + 1.2\sqrt{h})} \qquad (16a)$$

$$D_p = \frac{\eta / (\eta + 0.15)}{1 + 20(3h + 1.2\sqrt{h}) / (\eta + 10)} \qquad (16b)$$

The approximation error in the above empirical equations is represented by the error coefficient C_d defined as the ratio of exact D to empirical D. The mean and COV of C_d are shown in Fig.7 for the El Centro/elastoplastic case. They have the same tendencies for the other cases investigated in this study, and they are roughly estimated as follows :

$$E[C_d] = 1.0, \text{ and } COV[C_d] = 0.1 \qquad (17)$$

UNIFIED FORM FOR EARTHQUAKE RELIABILITY CRITERIA

From Eqs.8 and 15, the mathematical representation for any limit state imposed from serviceability to ultimate limit states is given by

$$W \geqq Q_o \cdot I_{Emax} \qquad (18)$$

where W is the structural energy absorption capacity limited by the imposed limit state of the structural performance such as the left-hand side terms of Eqs.2, 3 and

4, I_{Emax} is the maximum of I_E during the structural lifetime and Q_o is given by

$$Q_o = 0.15 \cdot M \cdot (T^2 / T_c) \cdot D^2 \cdot C_v^2 \cdot C_d^2 \quad \text{for } T \leqq T_c \qquad (19a)$$

$$Q_o = 0.15 \cdot M \cdot T_c \cdot D^2 \cdot C_v^2 \cdot C_d^2 \quad \text{for } T > T_c \qquad (19b)$$

where D is replaced by D_e for the elastic problem and by D_p for the plastic problem. Equation 18 is transformed into

$$W / Q_o \geqq I_{Emax} \qquad (20)$$

This final form satisfies all the requirements : simplicity as the form of $R \geqq Q$, statistical independency between W/Q_o and I_{Emax}, and inclusion of seismological aspects in I_{Emax}.

From the distribution functions of W/Q_o and I_{Emax}, the probability of exceeding a limit state can be calculated from

$$P_f = \int_0^\infty f_{W/Q_o}(x) \cdot [1 - F_{I_{Emax}}(x)]\, dx \qquad (21)$$

The distribution function of W/Q_o can be assumed to be a log-normal distribution, because W/Q_o is given by a product of many random variables. From the means and COV's of the random variables involved in W/Q_o, the first-order-second-moment method provides the mean and COV of W/Q_o. Thus, the distribution function of W/Q_o can be uniquely determined. An example of I_{Emax}-distribution function is presented in Ref.5.

CONCLUSIONS

Using an energy concept the reliability criterion form of $W/Q_o \geqq I_{Emax}$ is constructed for calculating the probability of exceeding a limit state of earthquake resistant structures. W is the energy absorption capacity by elastic or plastic strain of the structure, Q_o is the response spectrum term, and I_{Emax} is the seismic hazard potential term. This criterion form has the following advantages : it can cover all the limit states from serviceability to collapse limit states ; it has the simple form of $R \geqq Q$ as used in the current probability-based design ; it is composed of statistically independent terms W/Q_o and I_{Emax}; and it includes the seismicity aspects in I_{Emax}.

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TABLE AND FIGURES

Table 1. Major Properties of Earthquake Motions Examined in This Study

Name	Length (sec)	Peak Acc (gal)	To (sec)	Tc (sec)	I_E (cm²/sec³)	$\sqrt{T_o \cdot I_E}/2$ (cm/sec)
El Centro, NS, 5/18/1940	28	342	0.55	0.46	103,000	119
Parkfield No2, N65E, 6/27/1966	15	480	0.62	0.52	109,000	130
Pacoima Dam, S16E, 2/9/1971	12	1148	0.40	0.33	478,000	219
Hachinohe, EW, 5/16/1968	34	204	0.90	0.75	77,000	132
Mexico SCT, EW, 9/19/1985	64	168	2.0	1.67	146,000	270

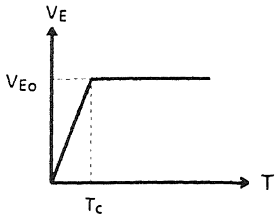
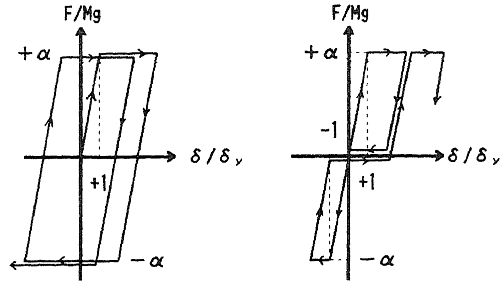


Fig. 1 Bi-Linear Approximation for V_E-Spectrum



(a) Elastoplastic Model (b) Slip Model

Fig. 3 Force-Displacement Relations in This Study

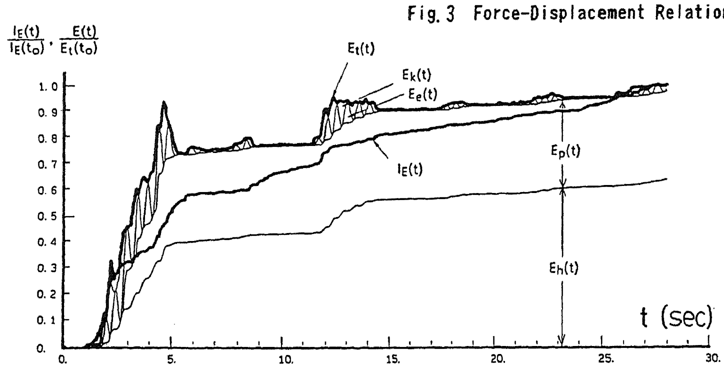
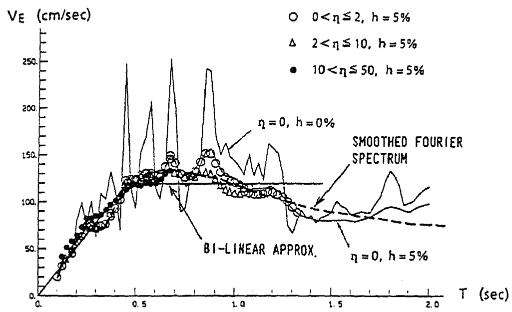
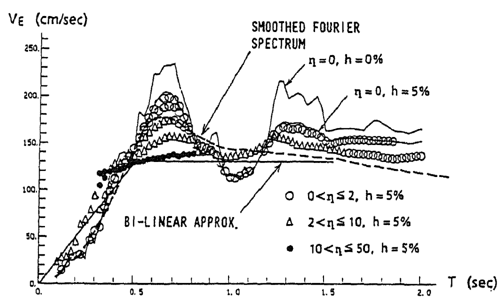


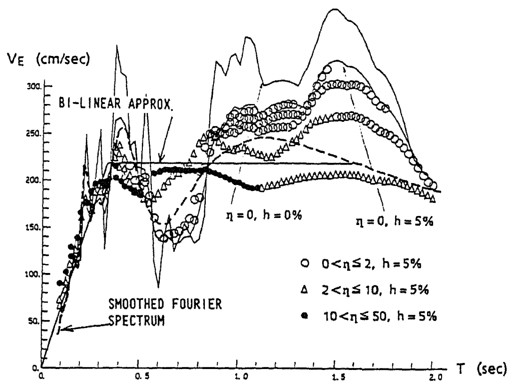
Fig. 2 Time Histories of Energy Input and Integral of the Squared Ground Acceleration for Elastoplastic Model, El Centro, α=0.3, h=5%, and T=1.0sec.



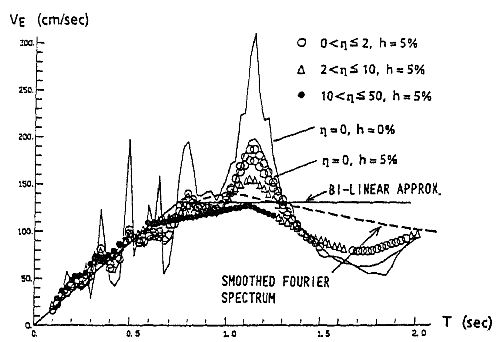
(a) El Centro/Elastoplastic



(b) Parkfield/Elastoplastic

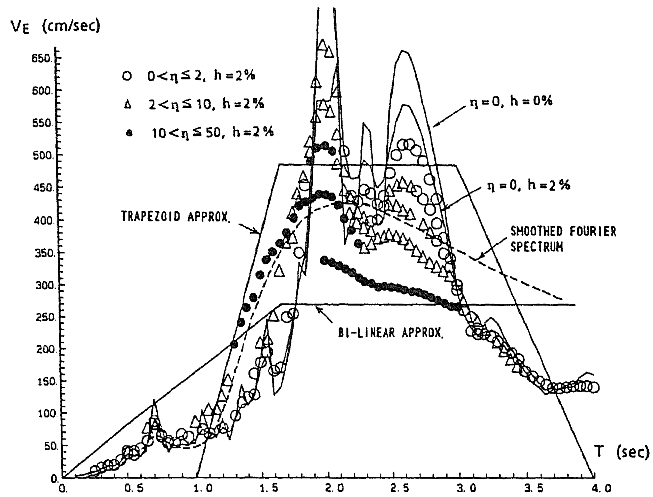


(c) Pacoima Dam/Elastoplastic



(d) Hachinohe/Elastoplastic

Fig. 4 V_E-Spectra of Exact Solution and Approximation together with Smoothed Fourier Spectra



(e) Mexico/Elastoplastic

Fig. 4 V_E-Spectra of Exact Solution and Approximation together with Smoothed Fourier Spectra (conti)

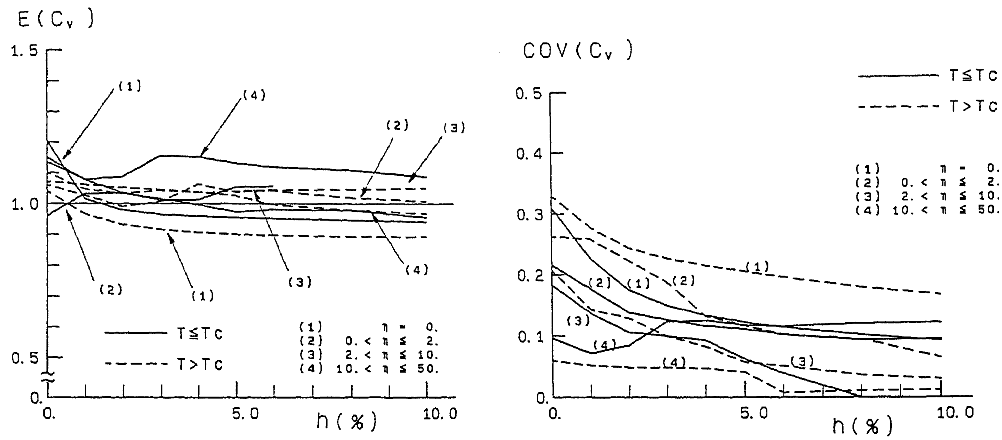


Fig. 5 Mean and COV of Error Coefficient C_v for El Centro/Elastoplastic Model

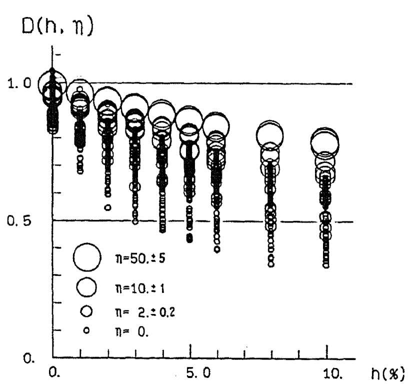


Fig. 6 Damping Reduction Factor for Pacoima Dam/Elastoplastic Model

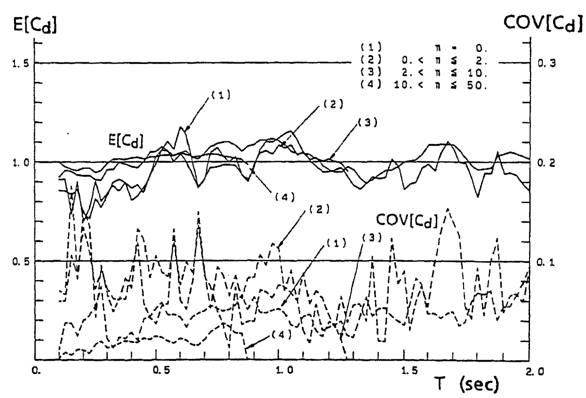


Fig. 7 Mean and COV of Error Coefficient C_d for El Centro/Elastoplasic Model