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Optimum Aseismic Design of Structures

Dimensionnement optimal de structures vis-à-vis des séismes

Optimale Bemessung von Bauwerken auf Erdbeben

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SUMMARY
A comprehensive and systematic procedure for optimum aseismic design of structures based on fuzzy set probabilistic theories is proposed. A case study is performed on an actual typical school building in reinforced concrete, at Kobe, Japan.

RÉSUMÉ
La contribution propose une procédure globale et systématique pour le dimensionnement optimal de structures, vis-à-vis des séismes, sur la base de la théorie probabiliste «Fuzzy Set». Une étude a été réalisée pour un bâtiment scolaire typique, en béton armé, à Kobe, Japon.

ZUSAMMENFASSUNG
Es wird ein umfassendes und systematisch aufgebautes Verfahren für die Bemessung von erdbebensicheren Bauwerken vorgestellt, welches auf der «fuzzy set»-Theorie beruht. Als Beispiel dient das Projekt eines typischen Schulhauses aus Stahlbeton in Kobe, Japan.

1. INTRODUCTION

The aseismic safety and quality of architectural structures should be assured from a comprehensive viewpoint. The Authors have already proposed an evaluation flow chart for seismic damages of structures [1] which is composed of three parts, i.e., EARTHQUAKE, STRUCTURE and DAMAGE as shown in Fig.1. By using this chart, the followings have become able to be performed easily; regional evaluation of seismic damages [1], aseismic reliability analysis [2] and fuzzy optimum aseismic design [3] of structures. The third fuzzy optimum design was carried out based on fuzzy set theory [4] and maximizing decision method [5] which enabled us to employ rationally multi-objective functions and subjective evaluations in the optimum aseismic design of structures [6][7].

In this paper, to make the fuzzy optimum design method mentioned above more real and practical, probabilistic expressions are applied to EARTHQUAKE in Fig.1, because occurrences and intensities of earthquakes belong essentially to natural scientific phenomena beyond human control. On the other hand fuzzy set conceptions are suitable to STRUCTURE and DAMAGE, because the design of structures and the evaluation of structural damages belong essentially to human decision making problems. The purpose of this paper is to propose such a new optimum aseismic design method of structures and to present a case study on a real type R/C building.

2. FUNDAMENTAL THEORY AND PROCEDURE

A probabilistic expression of EARTHQUAKE is able to be given by probabilistic density function of magnitude M and epicentral distance Δ[km], $f_e(M,\Delta)$, which is induced from the past observed earthquake occurrences [2]. When STRUCTURE is defined deterministically by a design parameter, γ , DAMAGE is calculated by a passage probability, p_x, which indicates the probability that a damage parameter, x , exceeds a critical one, x_c , more than one time in the future, i.e.,

$$p_x = p_r (x \geqq x_c \mid \gamma). \qquad (1)$$

In this paper, the damage parameter, x , is calculated through the earthquake limit response analysis proposed by the Authors [1], and the passage probability, p_x , is computed by the following two methods for comparison:

(1) Method based on classical probability theory
The passage probability at the next earthquake, p_x' , is given by

$$p_x' = \iint_{\Omega} f_e(M,\Delta)\, dM\, d\Delta , \qquad (2)$$

where Ω is the region with M above and Δ below the critical M-Δ curve on which $x = x_c$ as shown in Fig.2. When n_o is the expected number of earthquake occurrences in the next t_o years, the passage probability in the next t_o years, p_x , is given by

$$p_x = 1 - (1-p_x')^{n_o} , \qquad (3) \quad \text{in which} \quad n_o = n\, t_o / t , \qquad (4)$$

where n is the total number of earthquake occurrences in the past t years.

(2) Method based on Benjamin's probabilistic model
By using Bayesian theorem Benjamin proposed a probability of observing n_o future Poission events in time t_o having observed n events in time t, $p[n_o|t_o,n,t]$ [8]. When zero is substituted into n_o in it, the non-passage probability in the region Ω where $x \geqq x_c$ (See Fig.2) in the next t_o years becomes $p[0|t_o,np_x',t]$. Therefore, the passage probability in the next t_o years is given by

$$p_x = 1-p[0\ t_o,np_x',t] = 1-(1+t_o/t)^{-(np_x'+1)} . \qquad (5)$$

Finally, an optimum aseismic design of structures is able to be performed by the following maximizing decision equation as shown in Fig.3:

$$m_D(\gamma^*) = \underset{\gamma}{\mathrm{Max}}\ (m_\gamma \wedge m_{px}), \qquad (6)$$

where m_γ and m_{px} are the membership functions of design parameter γ and passage probability p_x , respectively. Here, the membership functions are supposed to be the satisfaction degrees from architectural, structural and economical points of view. In the case study, here, number of shear walls γ is adopted as a structural design parameter, and damage factor DF, the maximum response displacement x_m and duration until fracture t_f are employed as damage parameters. The physical meanings of these characters will be explained later. Consequently, the total procedure of the proposed optimum aseismic design of structures is able to be shown in Fig.4. The maximizing decision is performed by means of and/or tree as shown in Fig.5 [3].

3. STRUCTURE

A case study is carried out in regard to the first story of a typical R/C school building at Kobe in Hyogo prefecture, Japan, which is the same structure as adopted in the past evaluation studies [1][2][3] (See Figs.6,7), and is idealized to be a one degree of freedom system. The calculation conditions are given as follows: yield shear force T_y, slipping shear force T_s, yielding lateral displacement x_y and hysteresis loop area $A(x_a)$ are calculated as follows [2][3];

$$T_y=[(1-x_1)x_1+2\beta_s p_a(1-2d_1)]\sigma_{bo}bh^2/H, \qquad x_y=\varepsilon_y/3(1-2d_1)h,$$
$$T_s=(2\beta_s p_a-x_1)(1-2d_1)\sigma_{bo}bh^2/H, \qquad A(x_a)=(5T_y+9T_s)(x_a-x_y)/4, \qquad \} \; (7)$$

where $x_1=N/\sigma_{bo}bh$, (8) $\quad \beta_s p_a=\sigma_{ay}bh/\sigma_{bo}a$. (9)

The restoring force characteristic of shear walls is considered as shown in Fig.9. Ultimate shear force T_u, displacement x_u and the i-th hysteresis loop area $A(x_i)$ are calculated as follows:

$$T_u=\sigma_{bo}Lt\sin\theta\cos\theta/2, \qquad x_u=0.002L/\cos^2\theta,$$
$$A(x_i)/T_u x_u=(x_i/x_u)^2-(x_{i-1}/x_u)^2/2. \qquad \} \; (10)$$

Design parameter, γ ,i.e., the number of shear walls is counted by a unit shear wall within a span between C_1,C_2 and C_3 columns in the span and ridge directions.

4. EARTHQUAKE

4.1. Earthquake Ground Motion Spectrum [1][2][3]

When M,Δ and predominant period T_G of surface ground are given, earthquake ground motion spectra are given as shown in Fig.10, and ground motion duration t_o[s] is calculated by $t_o=10^{0.5M-2.28}$. The average slip velocities faults of interplate- and intraplate-type earthquakes are assumed to be $\bar{d}$=15 and 50[cm/s], respectively. Out of the source region, the earthquake ground motion spectra are calculated by multiplying the values in Fig.10 by $(\Delta_B/\Delta)^2$.

4.2. Probabilistic Expression of Earthquake Occurrences

Cumulative distribution functions are approximated to the distributions of observed interplate- and intraplate-type earthquakes within the circles with radii 2000 and 200[km] round Kobe City in Japan, respectively. By differentiating them probability density distributions $f_e(M,\Delta)$ are calculated as follows [2]:

$$f_e(M,\Delta)=0.1583(e^{-M}-e^{-9})-1.322\cdot10^{-7}(\Delta-2000) \quad \text{for interplate-type,} \qquad (11)$$
$$f_e(M,\Delta)=1.778\cdot10^{-6}(8-M)^6+1.573\cdot10^{-8}\Delta^2 \quad \text{for intraplate-type,} \qquad (12)$$

and shown in Fig.11. Numerical calculations of M and Δ are carried out by the following meshes; ΔM=0.1, $\Delta\Delta$=100[km] for interplate-type earthquakes and ΔM=0.1, $\Delta\Delta$=10[km] for intraplate-type earthquakes.

5. DAMAGE

5.1. Earthquake Limit Response Analysis [1][2][3]

According to the principle of the maximum response, the momotonic maximum displacement x_m is given, when velocity and acceleration pulse spectra (v-pulse and α-pulse spectra) are in contact with the ground motion spectrum as shown in Fig.12, where the approximated bi-linear pulse response spectra are used for simplicity. T_1, T_2, v_{m1} and v_{m2} at the corners are calculated as follows:

Elastic response displacement:

$T_1=4/\omega$, $v_{m1}=\omega x_p/2$, (13) $T_2=2/\omega$, $v_{m2}=\pi\omega x_p/2$, (14)

Plastic response displacement:

$T_1=4\mu_u\sqrt{\omega/2\mu_u-1}$, $v_{m1}=\omega x_y\sqrt{2\mu_u-1}/2$, (15) $T_2=2\mu_p/\omega\sqrt{2\mu_p-1}$, $v_{m2}=\pi\omega x_y\sqrt{2\mu_p-1}/2$. (16)

where $\omega=\sqrt{k/m}$, (17) $T=2t_p$, (18); k is modulus of elasticity; m is mass; $\mu_p=x_m/x_y$ (19) in the velocity pulse spectrum, and $\mu_u=x_m/x_y$ (20) in the acceleration one. The physical meanings of these characters are shown graphically on the left hand side in Fig.12.

Response displacement x_a and the number of response cycles N_c are given at the crossing point of a finite resonance response acceleration capacity spectrum C_{RA}^f and the earthquake ground motion spectrum (See Fig.13) as follows [1][3]:

$C_{RA}^f= A(x_a)/1.2\pi + 2T_a/3\pi$, (21) $N_c=t_o/Te$, (22)

where $T_e=2\pi/\sqrt{mx_a/T_a}$ is equivalent elastic natural period and T_a is restoring force amplitude.

5.2. Damage Parameters and Critical Values

One of damage parameters, the maximum displacement x_m is able to be calculated as the larger of the ones by pulse response analyses. Damage factor DF is calculated as follows [1][3]:

In the case of monotonic responses by pulse response analysis;

(1) DF of columns; $DF_{mc}=x_m/x_u$, (23)

where $x_u= \Phi_y H^2/6 + hH(\Phi_B - \Phi_y)/2$, (24) $\Phi_y=2\varepsilon_y/(1-2d_1)h$, (25)

$\Phi_B=0.004/(x_1-d_1)h$, (for concrete) (26)

$\Phi_B=150\Phi_y/(1-x_1-d_1)h$, (for reinforcing bar) (27)

(2) DF of shear walls; $DF_{mw}=x_m/x_u$ (28)

In the case of cyclic response by finite resonance response analysis;

(1) DF of columns; $DF_{cw}=N_c/N_B$ (29)

where $N_B=10^{8[1-x_1h\Phi_a(0.004+d_1h\Phi_a)]}$, (for concrete) (30)

$N_B=[300\Phi_y x 0.5^{3/4}/\{(1-2d_1)h\Phi_a-2\varepsilon_y\}]^{4/3}$, (for reinforcing bar) (31)

$\Phi_a= 2(x_a-x_y)hH + \Phi_y$. (32)

(2) DF of shear walls; $DF_{cw}=x_m/x_B$, (33) where $x_m=\mathrm{Max}(x_i)$.

In the both monotonic and cyclic cases, DF is assumed to be zero for elastic range of columns $x_m, x_a < x_y (=\Phi_y H^2/6)$, and non-cracked range of shear walls $x_m, x_i \leqq x_{cr} (= 2(1+1/6)\sigma_{bo}H/2\cdot 10^6)$. In the each case of monotonic or cyclic response the maximum values of DF is adopted as DF_m or DF_c, respectively. The duration until fracture t_f is calculated as follows:

$t_f = \infty$ for DF < 1, $t_f = N_B T_e$ for DF $\geqq$ 1. (34)

The effect of t_p derived from pulse response analysis on t_f are neglected here.

The critical values of DF_m, DF_c, x_m and t_f are assumed to be 1.0,1.0,H/100 and

300[s], respectively. H is the clear height of columns. DF=1.0 means the fracture of structures. At the displacement, x_m=H/100, window glasses surrounded by alminium sashes are cracked. It is supposed that 300[s] is sufficient for refuge time.

5.3. Passage Prbability

The passage probabilities of DF_m, DF_c and x_m, i.e., p_{DFm}, p_{DFc} and p_{xm} are able to be derived from Eqs.(3),(5). As for t_f, the non-passage probability p_{tf} ($t_f \leqq 300$[s]) is also able to be given by using Eqs.(3),(5). Supposing that DF_m and DF_c are statistically independent, the passage probability of the damage factor p_{DF} is calculated as follows [2]:

$$p_{DF} = p_{DFm} + p_{DFc} - p_{DFm} \cdot p_{DFc} \quad (35)$$

6. FUZZY OPTIMUM ASEISMIC DESIGN

6.1. Membership Functions of Satisfaction Degree [3]

According to the architectural demand that buildings without shear walls are prefered and reffering to the real number of shear walls in the typical R/C school building shown in Fig.7, the satisfaction degree of the number of shear walls m_γ is supposed as the following membership function (See Fig.14):

for span direction; $\gamma \leq 6$: $m_\gamma=0$, $6<\gamma \leq 13$: $m_\gamma=1.24(\gamma-13)^2$, $\gamma>13$: $m_\gamma=1$. (36)

for ridge direction; $\gamma=0$: $m_\gamma=0$, $0<\gamma<4$: $m_\gamma=12.76(\gamma-4)^2$, $\gamma>4$: $m_\gamma=1$. (37)

Acoording to economic and mental demands, the satisfaction degrees of the passage probabilities, m_{DF}, m_{xm} and m_{tf} are supposed to have several patterns as shown in Fig.15 (a)-(e), which reflect the mentalities of cool, pessimistic, optimistic, emotional and ordinary man, respectively. The Authors adopted the satisfaction degree type in Fig.15 (e) and the following is assumed in this paper:

$$m_{xm}=-4(p_x-0.5)^3+0.5\,, \quad (38) \quad \text{where } p_x=p_{xm},\ p_{DF} \text{ and } \overline{p_{tf}}$$

6.2. Maximizing Decision

Now, using the and/or tree such as shown in Fig.5, the maximum satisfaction degree $m_D(\gamma^*)$ has become able to be calculated. Calculations are performed in the following 16 cases:(1) Ridge and span directions of the building shown in Fig.7, (2) Interplate- and intraplate-type earthquakes, (3) Predominant natural periods of surface groud, T_G=0.1 and 0.8[s], (4) Classical probability theory and Benjamin's probabilistic model for passage probability. Figs.16,17 show the total distributions of satisfaction degrees of γ, p_{DF}, p_{xm} and $\overline{p_{tf}}$ with respect the number of shear walls, γ. The peak values of m in the hatched zone is $m_D(\gamma^*)$ and γ at the point is γ^* which are shown in Table 1.

7. DISSCUSSION AND CONCLUSIONS

As the result of applying fuzzy set and probability theory to the optimum aseismic design of a typical R/C school building, the following are made clear.

1)Using the simple evaluation procedure for aseismic damages of structures proposed by the Authors, it is possible to show clearly the relations among the satisfaction degrees of γ, DF, x_m and t_f by scanning the design parameter, γ.
2)In the cases of hard surface ground (T_G=0.1[s]), span direction and interplate earthquake, the maximum satisfaction degree is higher than in the case of soft surface ground (T_G=0.8[s]), ridge direction and intraplate earthquake, respectively. This tendency is reasonable and the same as the ones of the different type evaluations which the Authors have already carried out [1][2][3].
3)The final satisfaction degree is almost decided by the ones of the number of shear walls and the duration until fracture.
4)In the local range of γ, the satisfaction degree of the damage factor of the building decreases as γ increases. This tendency is against our experimental ones. This reason is that the damage factor is decided by two different damage factors of columns and shear walls, DF_c and DF_w.

5)In the case of the interplate-type earthquake the satisfaction degrees of the maximum displacement, and the duration until fracture by the method based on Benjamin's probabilistic model are lower than by the method based on classical probability theory, because the passage probabilities based on Benjamin's probabilistic model are higher than the ones based on the classical probability theory (See Figs.16,17). Even if zero is substituted into n in Eq.(6), there exist the passage probabilities p_{xm}, p_{DF} and non-passage probability $\overline{p_{tf}}$.
6)The reason why the number of shear walls in the ridge direction at the maximizing decision point is nearly zero is that its satisfaction degree is supposed according to the architectural demand that very few shear walls are prefered in the ridge direction.

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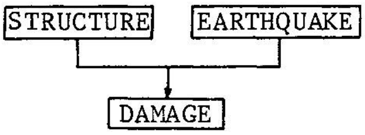

Fig.1 Outline of Evaluation Flow Chart for Aseismic Damages

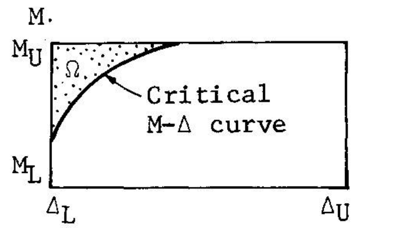

Fig.2 Region Ω and Critical M-Δ Curve

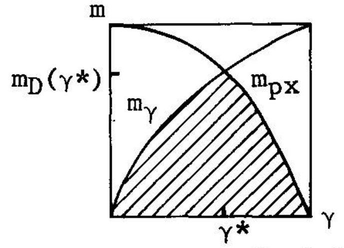

Fig.3 Maximizing Decision

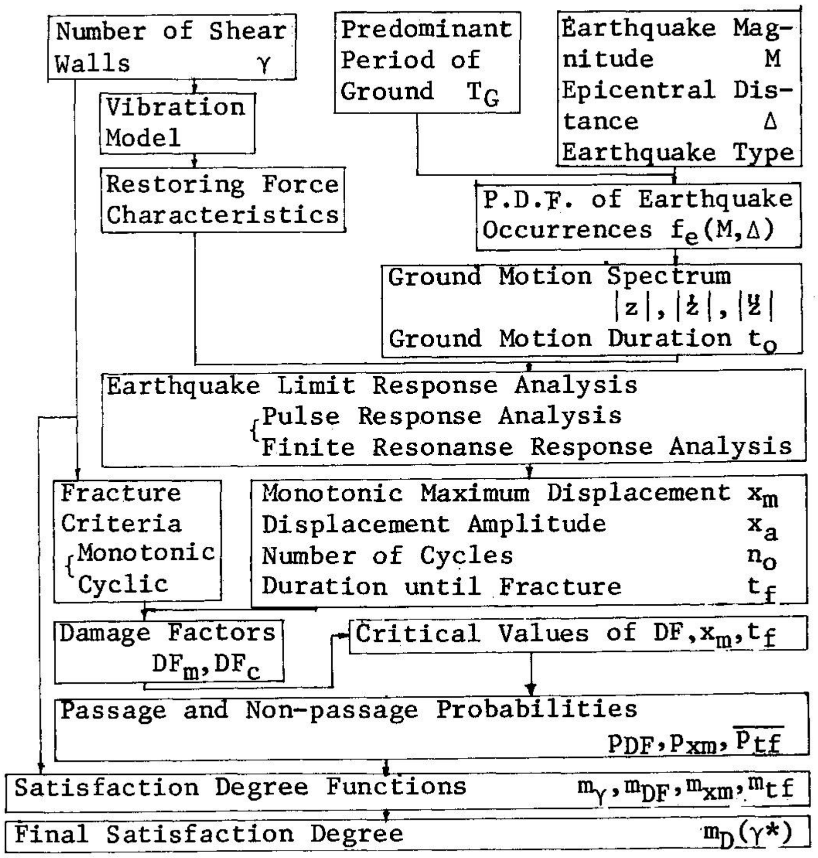

Fig.4 Flow Chart of Optimum Aseismic Design of Buildings

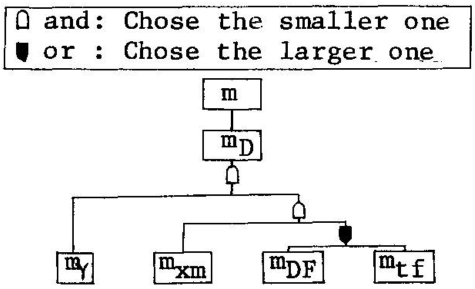

Fig.5 And/or Tree

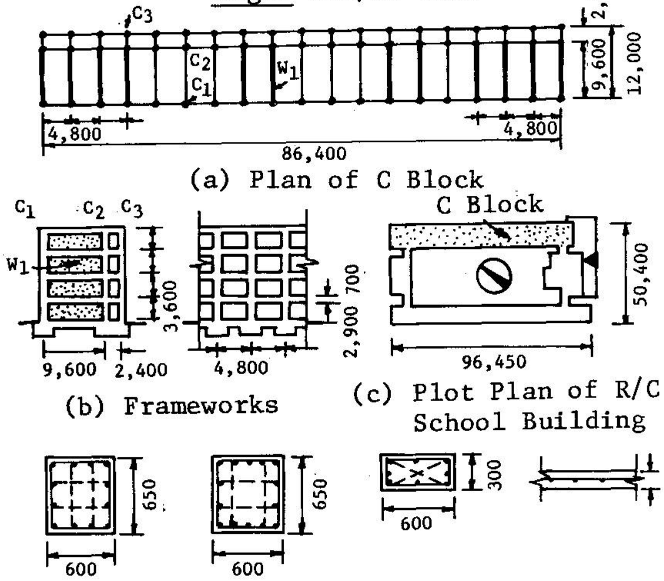

Fig.7 Structural Outline of C Block in Standard R/C School Building

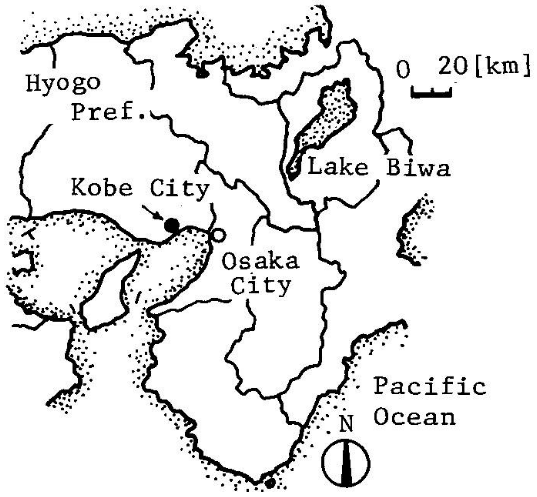

Fig.6 Location of typical R/C School Building (Kobe City, Hyogo Prefecture, Japan)

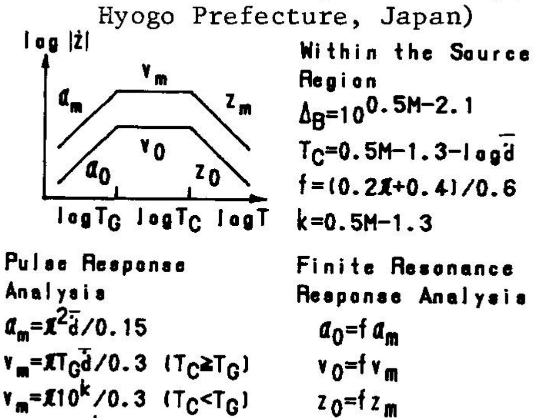

Fig.10 Earthquake Ground Motion Spectra [3]

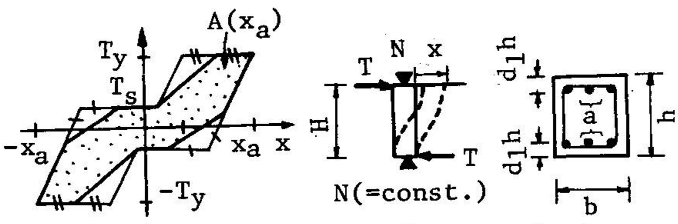

Fig.8 Restoring Force Characteristics of Columns [3]

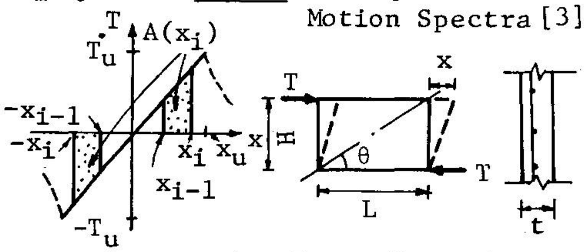

Fig.9 Restoring Force Characteristics of Shear Walls[3]

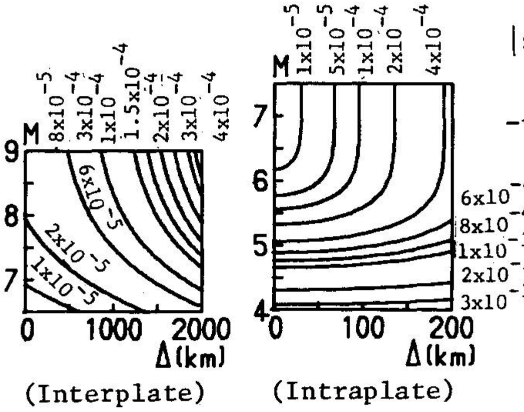

Fig. 11 Assumed Probability Density Distributions[2]

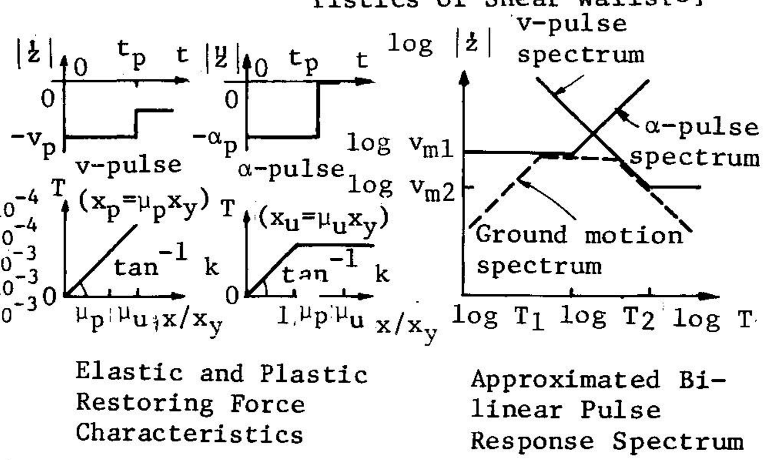

Fig.12 Pulse Response Analysis[2][3]

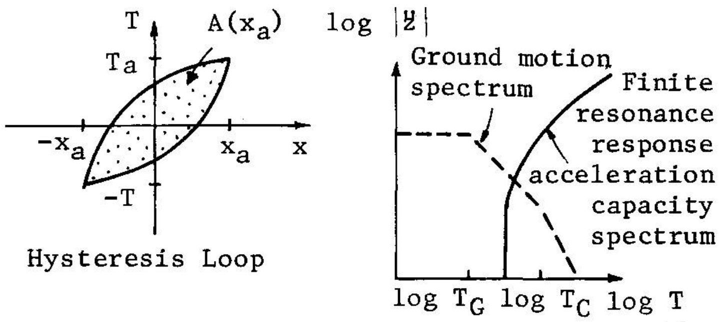

Fig.13 Finite Resonanse Response Analysis

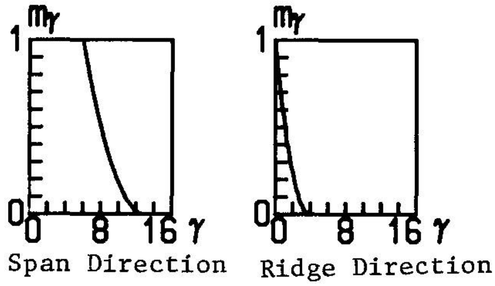

Fig.14 Satisfaction Degrees of Number of Shear Walls

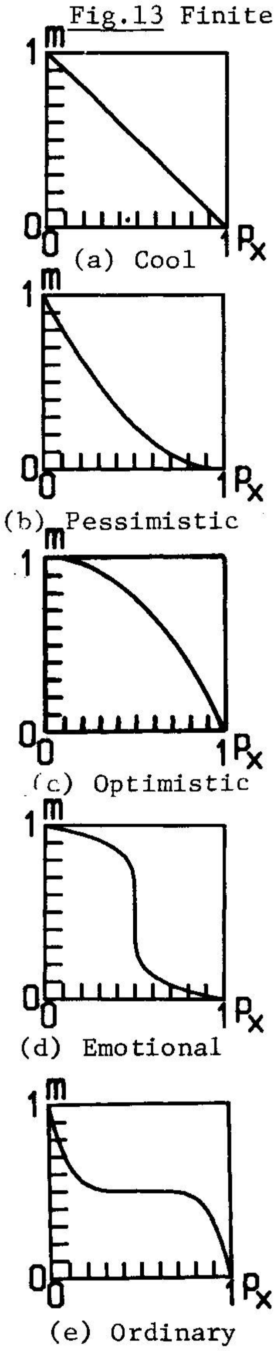

Fig.15 Satisfaction Degrees of Passage Probability

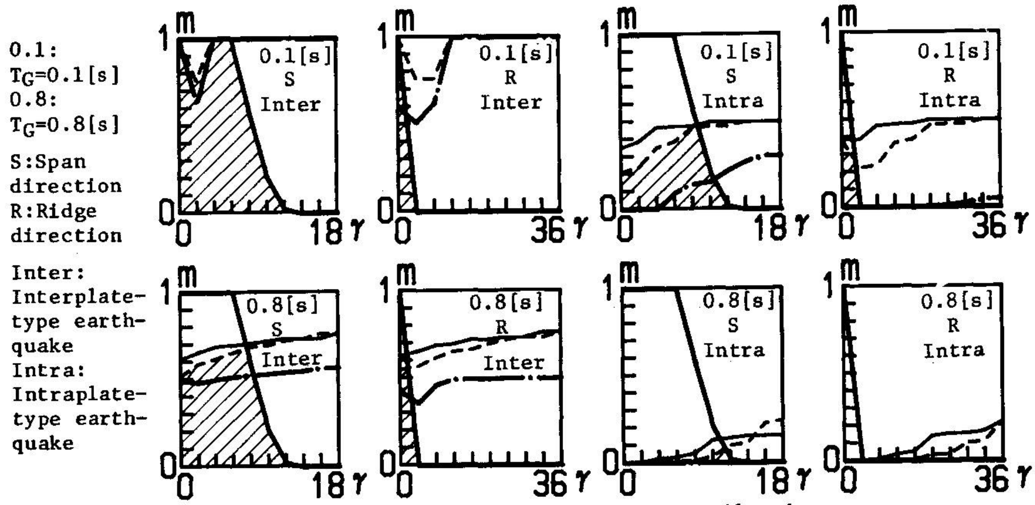

Fig.16 Satisfaction Degree Distributions Based on Classical Probability Theory

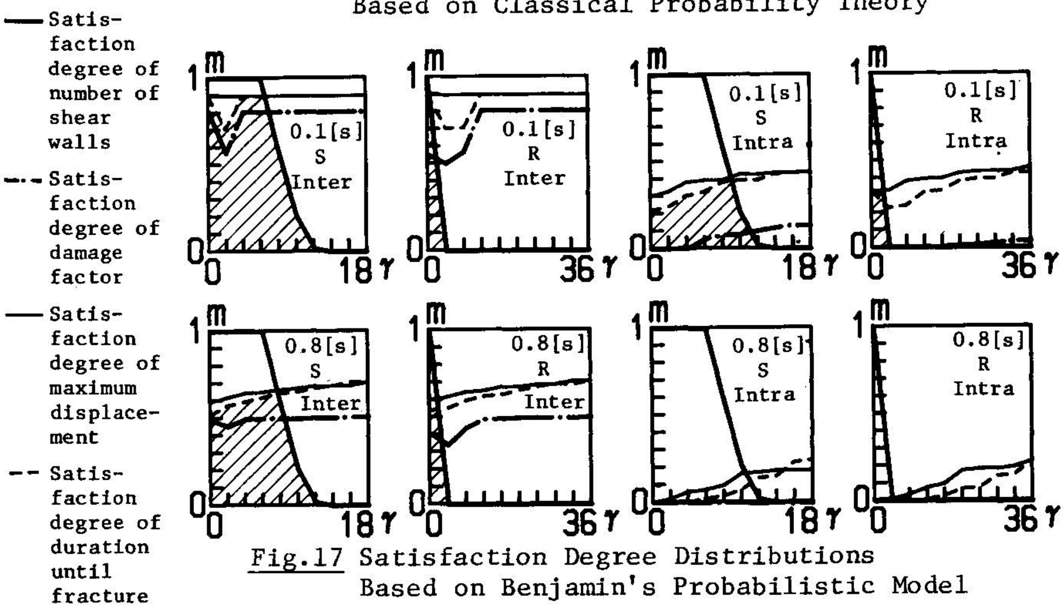

Fig.17 Satisfaction Degree Distributions Based on Benjamin's Probabilistic Model

Table 1 Values of Maximizing Decision Point of $m_D(\gamma^*)$

Environment parameters / Probability theories	T_G	Interplate-type		Intraplate-type	
	[s]	Span	Ridge	Span	Ridge
Based on Classical	0.1	1 (0,4-6)	1 (0)	0.46 (8)	0.38(0)
Probability Theory	0.8	0.65 (6)	0.55(0)	0.03 (0)	0(0-36)
Based on Benjamin's	0.1	0.90(0,4-6)	0.90(0)	0.38 (8)	0.32(0)
Probabilistic Model	0.8	0.62 (6)	0.54(0)	0.07(10)	0(0 36)