Optimum aseismic design level of structures

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Optimum Aseismic Design Level of Structures

Dimensionnement optimal des structures contre les tremblements de terre

Optimale erdbebensichere Bemessung von Tragwerken

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SUMMARY
Optimum aseismic design level of structures in urban region is examined from the total cost which involves initial construction cost, aseismic design cost and expected direct structural and secondary social losses due to earthquakes damages. Discussions especially concern effects of social losses and variation of aseismic resistance of structures using a probabilistic approach. Reliability analysis of a system which consists of several structures is also conducted.

RESUME
Le dimensionnement optimal des structures construites en ville est examiné du point de vue des dépenses totales comprenant les frais initiaux de construction, les dépenses engagées vis-à-vis des tremblements de terre, les dégâts à la structure et les pertes sociales causées par les tremblements de terre. L'influence des pertes sociales et la variation de la résistance des structures contre les tremblements de terre sont spécialement discutées à l'aide de la théorie des probabilités. L'analyse de la sécurité d'un ensemble de structures est aussi présentée.

ZUSAMMENFASSUNG
Die optimale Bemessung von Tragwerken in städtischen Regionen gegenüber Erdbeben wird untersucht im Hinblick auf Erstellungskosten, Kosten für die Sicherung gegen Erdbeben, die durch Erdbeben ausgelösten direkten Tragwerkschäden und die weiteren sozialen Kosten. Wahrscheinlichkeitstheoretisch werden speziell die Einflüsse der sozialen Kosten und die Variation des Tragwerkwiderstandes behandelt. Auch die wahrscheinlichkeitstheoretische Analyse von aus mehreren Tragwerken bestehenden Systemen wird behandelt.

1. INTRODUCTION

Since earthquake motions impose strong and random loads on structures, there may be alternative ways to design structures, depending on concepts of safety and practical economic limitations, as stated in the Introductory Report.[1]

A common philosophy of aseismic design under economic restrictions is to design structures to be undamaged for earthquakes expected a few times or more in the life time of the structure and to avoid total collapse and life loss (although permitting structural damage) for earthquakes which are expected once or less in the structure's life time. This aseismic design may be achieved by sophisticated designing of each structural element without much expense in the future.

However, most structures in Japan are now designed for earthquake loads according to structural codes which specify equivalent horizontal and vertical static forces in terms of seismic coefficients K_h and K_v, respectively. K_h is estimated by the product of the standard seismic coefficient K_0 (usually 20% of gravity), regional seismicity coefficient K_1, local soil condition coefficient K_2 and an importance factor K_3:

$$K_h = K_0 K_1 K_2 K_3$$

Thus, K_3 is the only parameter which can possibly reflect ideas of safety and the consequences of secondary socio-economic and human losses due to earthquake damage. In Japan, the range of K_3 is specified as 0.8-1.0 for bridges, 0.5-1.5 for port structures, 0.9-1.1 for railway structures and 1.0-1.2 for building.[2] These ranges are not determined from analytical trade-offs between seismic design cost and expected structural and social losses but from design experiencies considering the practical importance of the structure.

The purpose of this paper is to examine critically the relation between the importance factor and the optimum aseismic level of structures in terms of the total cost which is defined as the sum of contruction cost and structural and secondary losses. Effects of variation of structural resistance and redundancy of a system on the probability of seismic failure are also investigated through reliability analyses.

2. OPTIMUM ASEISMIC DESIGN LEVEL OF A STRUCTURE BY TOTAL COST

2.1 Model of Total Cost

As a measure of optimization, the total cost C_t consisting of construction cost C_i and expected value of direct and secondary losses C_f is adopted., i.e.,[3]

$$C_t/A_0 = (C_i + E[C_f])/A_0 \qquad \text{..............(1)}$$

where

$$C_i = A_0 + A_1 a_{yd}^2 \qquad \text{......................(2)}$$

A_0 is the initial construction cost and it is assumed that aseismic design cost $A_1 a_{yd}^2$ is proportional to the square of designing level a_{yd} which has the dimension of acceleration. The total seismic loss C_f is calculated from the sum of the direct structural loss L_p and secondary socio-economic loss L_s as

$$C_f = L_p + L_s \qquad \text{..........................(3)}$$

L_p and L_s are estimated from maximum ground acceleration of the earthquake and parameters of structural resistances as,

$$L_p = \begin{cases} 0 & (a \le a_{yd}) \\ C_{f0}/2 & (a_{yd} < a < a_c) \\ C_{f0} & (a_c \le a) \end{cases} \quad ....(4)$$

$$L_s = K\, C_{f0} \quad ....(5)$$

where

$$\theta = (a_f - a_{yd})/(a_c - a_{yd}), \quad r = a_c/a_{yd} \quad .....(6)$$

The basic concept of losses is schematically illustrated in Fig.1 where a_{yd}, a_f, a_c are yielding (= design level), failure of function level and level of total collapse, respectively. It is assumed that the structural loss between the levels of a_{yd} and a_c is one half of total collapse. In calculation, structural parameters are treated as either deterministic or Gaussian random variables.

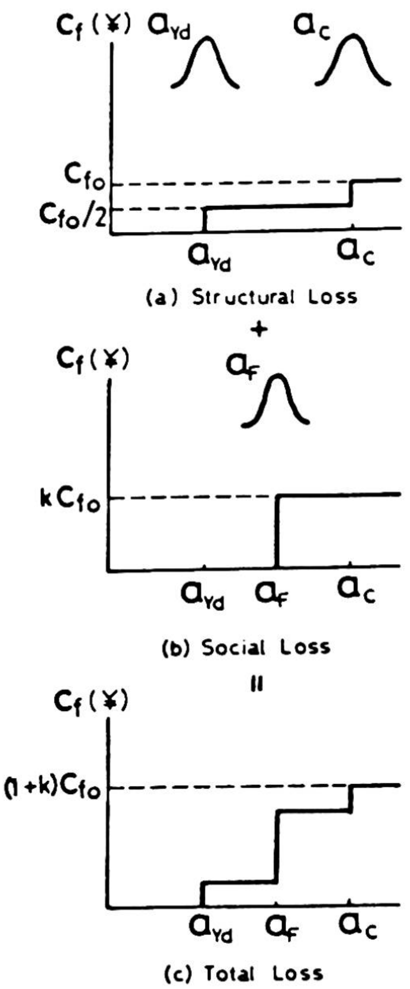

Fig.1 Schematic Illustration of Total Cost due to Seismic Effects

Estimation of secondary socio-economic loss L_s is a complex and difficult task, especially when human life is involved.[4] In this study, L_s is simply measured by a parameter K which shows the degree of socio-economic loss as compared to structural loss C_{f0} for purposes of examining its effects on optimum aseismic design level. The social loss is modeled to occur from the level of a_f which is located between a_{yd} and a_c.

When we know the annual rate λ of earthquake occurrence and probability distribution p(a) of maximum ground acceleration a, the expected value of the total seismic loss C_f is calculated for the case with deterministic resistance as,

$$E[C_f/A_0] = (\lambda/A_0)\int_0^T\int_0^\infty (L_p e^{-\gamma t} + L_s)\, p(a)\, da\, dt \quad ....(7)$$

where γ is a decreasing rate of structural value with time. When structural resistances are random variables, it is necessary to calculate the probability of exceeding the levels of a_{yd}, a_f, a_c from reliability analysis.

2.2 Random Earthquake Loads

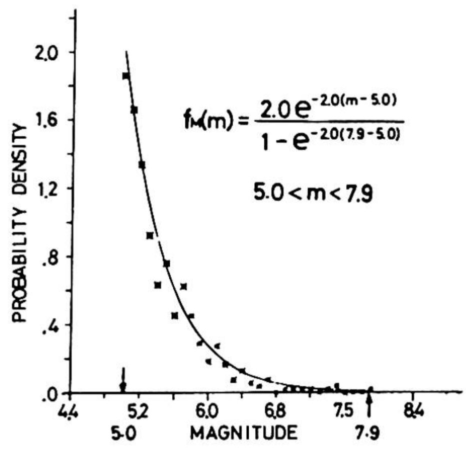

Fig.2 Probability Density Function of Earthquake Magnitude

Probability density p(a) of maximum ground acceleration is calculated from so called M-Δ (magnitude and epicentral distance) analysis.

Probability density $f_M(m)$ of magnitude m of earthquakes is determined from logN-M Curve (N:number of earthquakes) of earthquake occurrence in western part of Japan as

$$f_M(m) = 2.0e^{-(m-5)}/(1-e^{-5.8}) \quad \ldots\ldots\ldots(8)$$

Attenuation of maximum ground acceleration due to epicentral distance Δ is governed by next equation, of which parameters are determined from earthquake data in Japan. [5]

$$a = 0.02\, e^{0.7m}\, \Delta^{-0.8} \quad \ldots\ldots\ldots\ldots\ldots(9)$$

Combination of Eqs. (8) and (9) gives p(a) at any construction site if epicentral distance is given. In this study, local soil conditions which can be included in Eq. (9) are not considered.

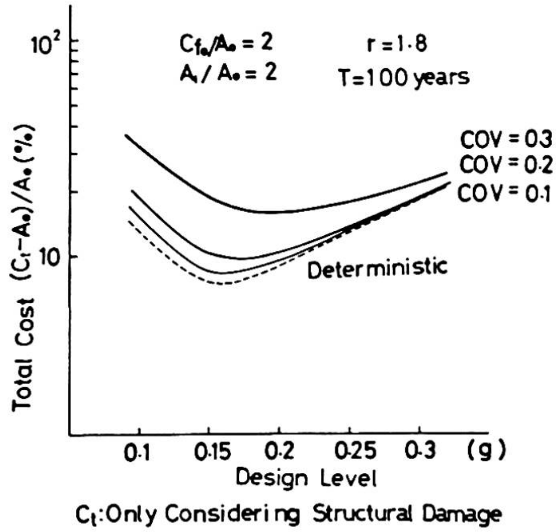

Fig.3 The Normalized Total Cost Without Social Loss

2.3 Calculated Results and Discussions

In Figs.3,4 and 5, the normalized total cost which consists of aseismic design cost $A_1 a_{yd}^2$ and seismic loss C_f is shown against design level a_{yd}. Seismicity parameters are λ=0.05 and Δ=50Km. Values of structural parameters are given in the figures. COV expresses coefficient of variation of Gaussian random structural resistances.

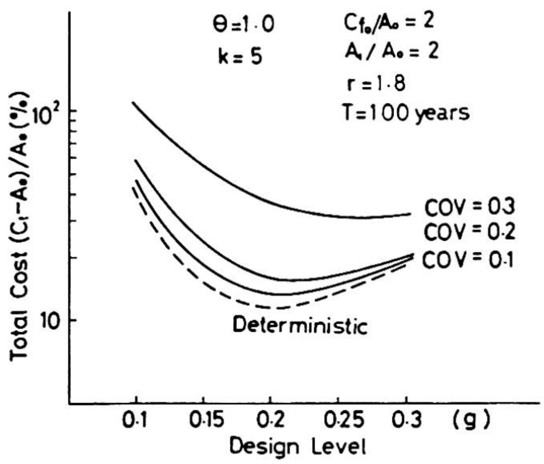

Fig.4 The Normalized Total Cost With Social Loss (K=5)

The total cost without secondary social loss (i.e., K=0.0) is plotted in Fig.3 to show the higher optimum design level for structures with larger variation of resistances. This effects is easily understood from the fact that the larger variation of resistances brings higher probability of failure and hence needs the higher total cost. When design level becomes very high (a_{yd}>0.3g), the probability of failure is reduced greatly and the total cost is almost not affected.

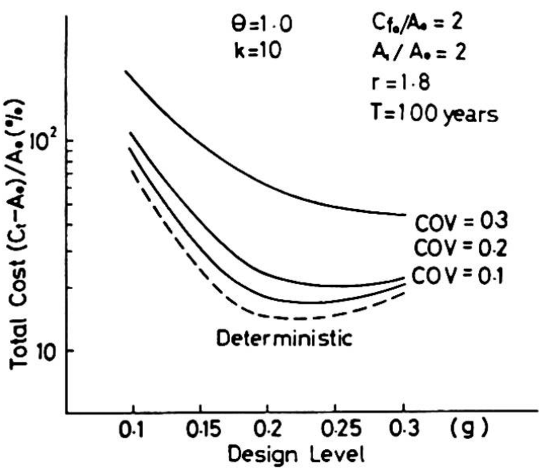

Fig.5 The Normalized Total Cost With High Social Loss (k=10)

In Fig.4, the socio-economic loss L_s which is 5 times as large as the structural loss C_{f0} (K=5) is considered for the same structure in Fig.3. This may be a case of important structures or buildings which are usually used by many people. It is found that the optimum design level is increased 5% in g and the total cost is also increased about 5%, except for a structure with a high variation of resistance (COV=0.3).

In Fig.5, the value of K is increased to 10 to investigate effects of very high secondary socio-economic loss. This may be a case of critical structures or buildings which should be used for purposes of evacuation from fire or rescue operations immediately after earthquake occurence. Both the optimum design level and the total cost are found to be increased by 7-10% as compared to Fig.3, except for the case of COV=0.3 which shows monotonous decrease of the total cost. It should also be noted that the range of optimum design level (=minimum total cost) becomes wide when the social loss and the variation of structural resistances are large. Especially for a structure with K=10 and COV=0.3, it is quite difficult to determine the optimum design level.

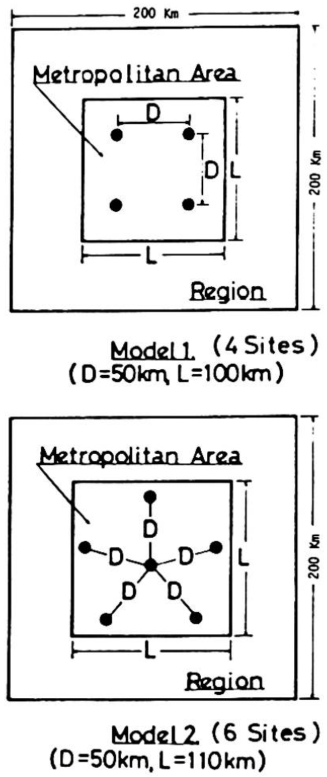

Fig.6 Models of Metropolitan Area and Seismic Region

The effect of θ, which shows at which level the social loss starts to occur between a_{yd} and a_c, were also examined by numerical results, which are not shown in this paper. They were found to be very small both for the optimum design level and the total cost.

3.RELIABILITY OF STRUCTURES AS A SYSTEM

3.1 Model of A System and Its Reliability

Just after a big earthquake hits an urban region, important civil engineering structures and public facilities can be considered as a system for emergency operations, such as evacuation and rescue. In this study, a simple system which consists of several structures with the same resistance is considered. Models are shown in Fig.6 where important structures or facilities are located at each site. In a metropolitan area, there are 4 and 6 sites in models 1 and 2 with independent failure modes. Hypocenters of earthquakes are modeled as uniformly distributed in the area and the region.

When the system has no redundancy, reliability of the system becomes a weakest linkage problem. That is, the probability of the system is that of any one of the site. On the other hand, when the system has sufficient redundancy, the probability of failure of it is that of all of the sites.

3.2 Calculated Results and Discussions

In Fig.7, the probability of simultaneous excess of design level a_0 (=0.15g) of model 1 is plotted. Horizontal axis is the least number of sites where the maximum ground acceleration exceeds this level. Continuous lines are probability for 1 year and broken lines are for 50 years. Annual rate λ of earthquake occurence was

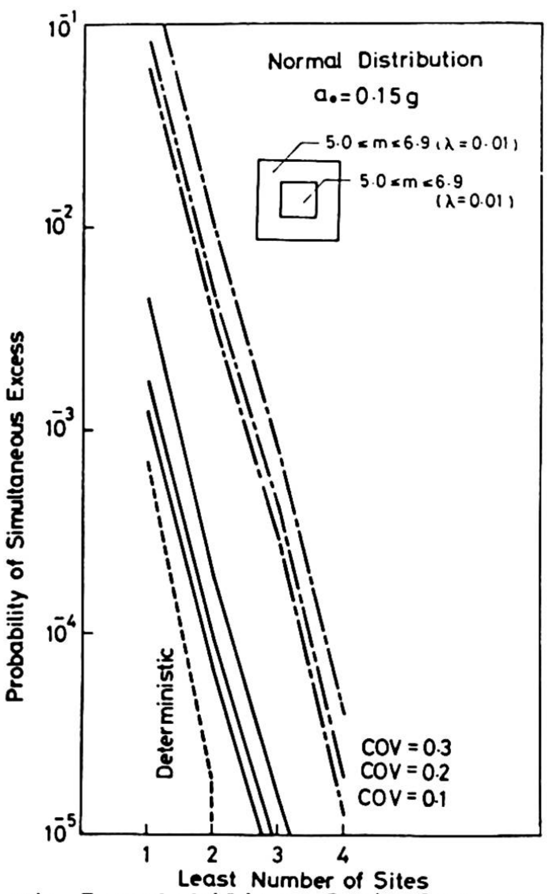

Fig.7 Probability of Simultaneous Excess of a_0 (Model 1)

set relatively small, at 0.01, because of limited epicentral region. Resistance of the sites is also treated as either deterministic or a random variable. It is clearly seen that the probability of simultaneous excess decreases sharply with the number of sites. Probability of failure of at least one of the sites is about 10^4 times higher than that of all of the sites, which verifies the importance of redundancy of these systems. The larger variation of resistance of sites results in a higher probability of failure, as expected.

Effects of the design level on the probability of at least one of the sites of models 1 and 2 on one year are shown in Fig.8. It is important to notice that the probability of failure decreases with different ratios, depending on the variation of resistance. When the sites are deterministic or random (with small variation of resistance), an increase of design level efficiently reduces the probability of failure. On the contrary, an increase of design level of sites with high variation of resistance has a small effect.

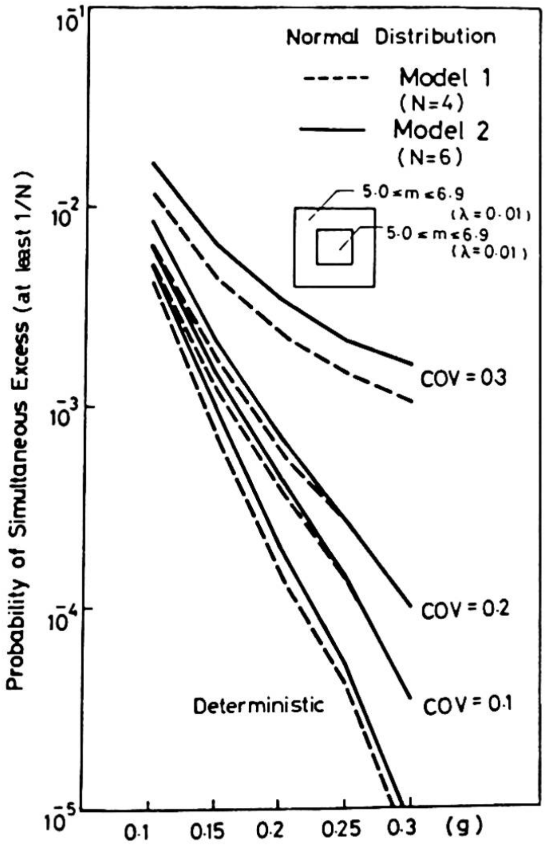

Fig.8 Probability of Simultaneous Excess of a_0 against Design Level

4. CONCLUSION

Optimum aseismic design level of a structure is determined from the total cost, which consists of construction cost and direct structural and secondary socio-economic losses. When the secondary loss of important public structures is assumed to be 10 times as large as the structural loss, the optimum design level is found to be increased by about 10%. This result gives an analytical background to present Japanese aseismic design codes, most of which define a 20% increase in design level for important and critical structures.
Larger variation of structural resistances gives higher probabilities of failure and consequently higher total cost and design level.
High effectiveness of an increase of design level in order to increase the probability of safety can not be expected for structures with high variations of resistance.
The desirability of redundancy is verified to decrease the probability of failure of a system significantly, from reliability analysis of structures treated as a system.

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