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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]

$$C_t/A_0 = (C_i + E[C_f])/A_0 \qquad \dotfill (1)$$

where

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

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

$$C_f = L_p + L_s \qquad \dotfill (3)$$

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

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

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

where

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

The basic concept of losses is schematically illus-
trated 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 deter-
ministic or Gaussian random variables.

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 oc-
currence and probability distribution p(a) of maxi-
mum ground acceleration a, the expected value
of the total seismic loss C_f is calculated for
the case with deterministic resistance as,

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

where γ is a decreasing rate of structural value
with time. When structural resistances are ran-
dom 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

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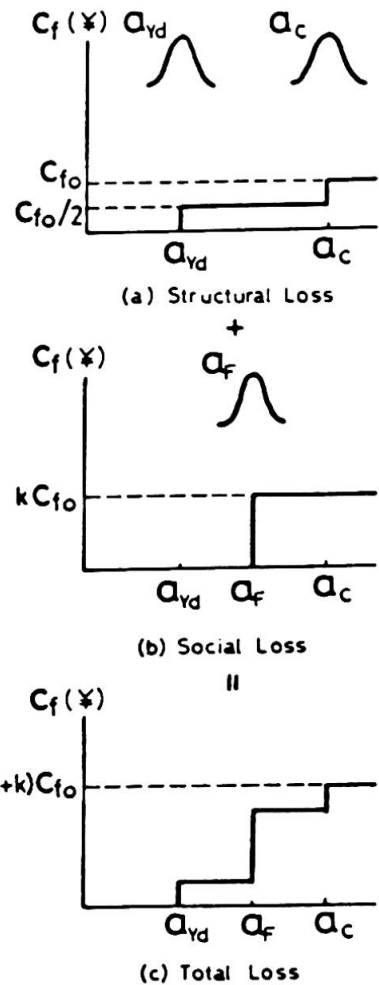
Probability density $f_M(m)$ of magnitude m of

(a) Structural Loss

+

(b) Social Loss

=

(c) Total Loss

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

$$f_M(m) = \frac{2.0\,e^{-2.0(m-5.0)}}{1 - e^{-2.0(7.9-5.0)}}$$
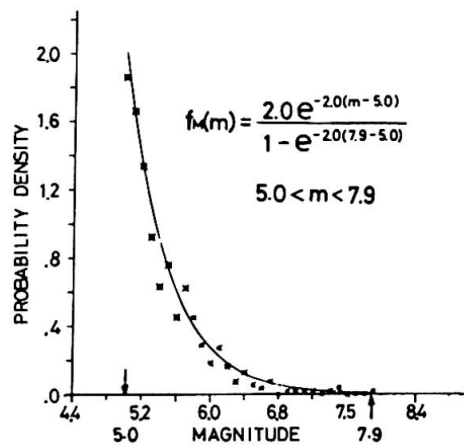
$$5.0 < m < 7.9$$

Fig.2 Probability Density
Function of Earthquake
Magnitude

earthquakes is determined from logN–M Curve
(N:number of earthquakes) of earthquake oc-
currence in western part of Japan as

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

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

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

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.

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 $\lambda=0.05$
and $\Delta=50$Km. Values of structural parameters
are given in the figures. COV expresses coef-
ficient of variation of Gaussian random
structural resistances.

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 re-
sistances. This effects is easily under-
stood from the fact that the larger vari-
ation of resistances brings higher proba-
bility of failure and hence needs the
higher total cost. When design level be-
comes very high ($a_{yd}>0.3$g), the probability
of failure is reduced greatly and the total
cost is almost not affected.

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
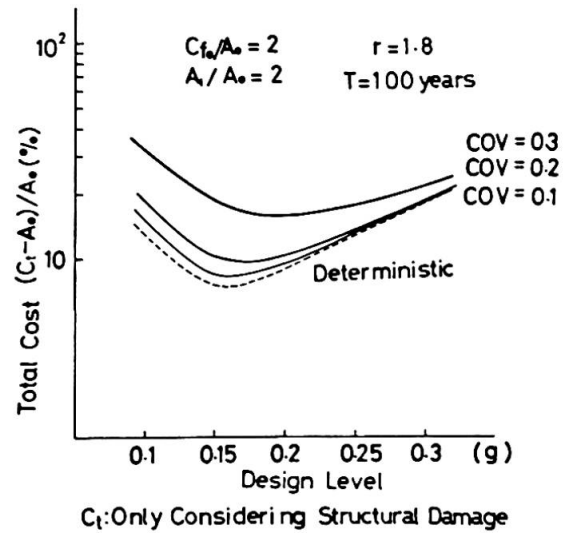10 to investigate effects of very high

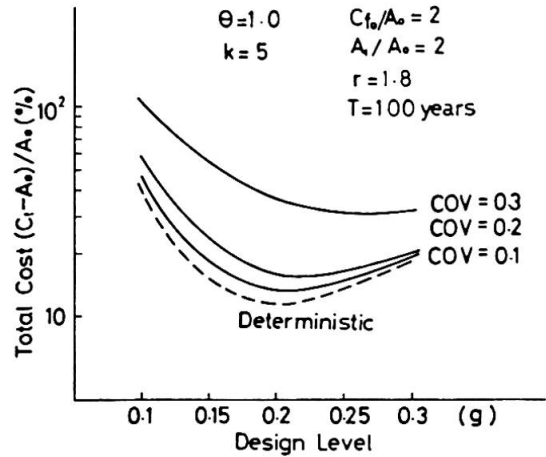Fig.3 The Normalized Total Cost
Without Social Loss

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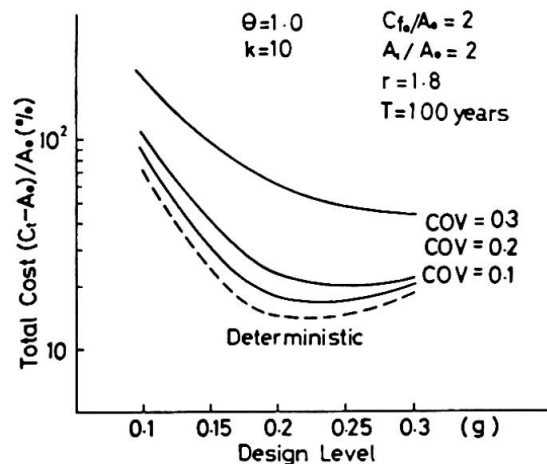With Social Loss (K=5)

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

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 re-
sistances are large. Especially for a structure with
K=10 and COV=0.3, it is quite difficult to determine
the optimum design level.

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, im-
portant civil engineering structures and public facili-
ties can be considered as a system for emergency oper-
ations, 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 dis-
tributed in the area and the region.

When the system has no redundancy, relia-
bility 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 proba-
bility 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

Model 1. (4 Sites)
(D=50km, L=100km)

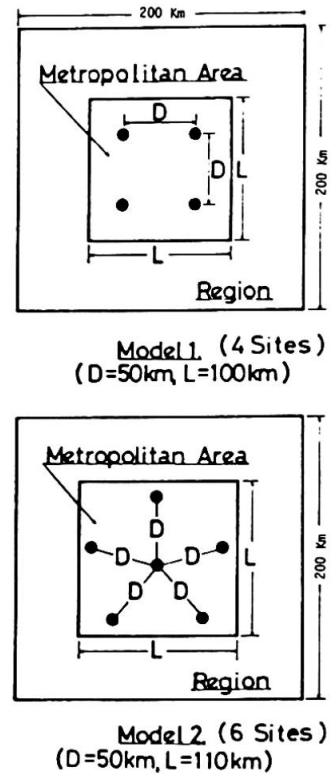

Model 2 (6 Sites)
(D=50km, L=110km)

Fig.6 Models of
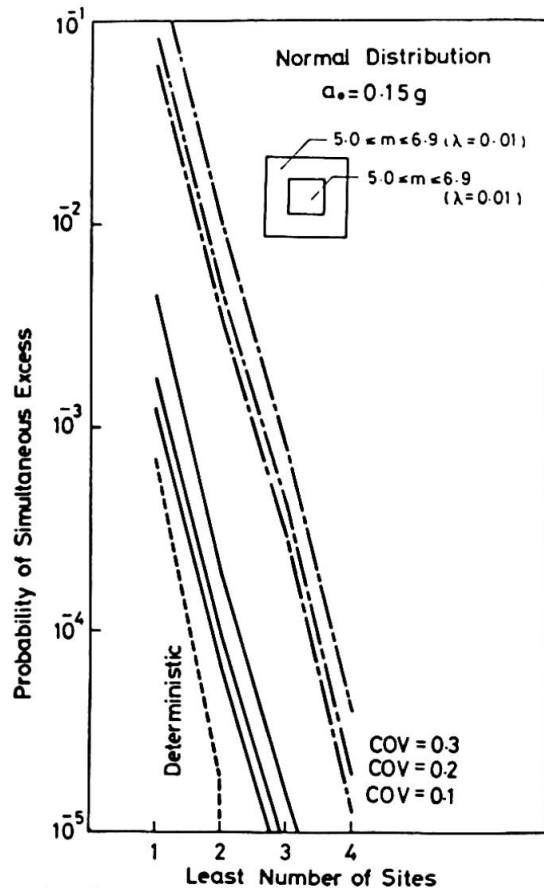Metropolitan Area and
Seismic Region

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 de-
terministic 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 proba-
bility 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 vari-
ation of resistance. When the sites are
deterministic or random (with small vari-
ation 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 vari-
ation 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 back-
ground 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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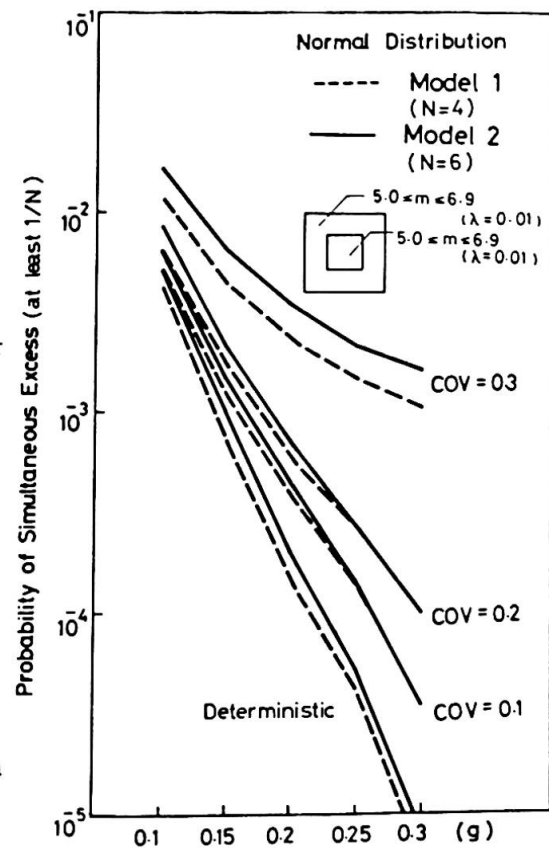   Acceleration Response Spectra, Proc. of JSCE, No.275, 1978 (in Japanese).