A METHOD OF ESTIMATING PROBABILISTIC SEISMIC LOAD FOR SHORT DURATIONS

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This paper presents the use of the past seismic data to predict seismic motion intensity for short duration. The factors that affect this predicted value are studied, and application to a selected site of the straits of Akashi is presented. The study using a areal source model with assumed seismicity in each divided zone showed that earthquake of relatively small magnitude in the site plays an important role for estimating expected seismic load of the site. For structures under construction, an attempt to estimate the expected value of restoration cost for a three-span suspension bridge by probabilistic approach is also presented.

Keywords : seismic risk analysis, short duration, suspension bridge, restoration cost

1. INTRODUCTION

For design purposes, it is necessary to assess properly the expected intensity of seismic motions for sites where structures are to be constructed. The seismic motion intensity varies from site to site depending on the surrounding state of seismic occurrence. For this, the existing specifications for earthquake-resistant design use a modified method with regional correction factor to derive the seismic intensity for design[1]. However, it has become necessary to estimate a detailed seismic motion intensity based on the level of seismic activities at the surrounding area of a site for designing long span bridges. For this reason, the seismic motion intensity with some degree of accuracy has so far been predicted on the past seismic records[2]. An expected value of the seismic motion intensity obtained contains many unclear factors, and these factors may become the cause of variation in predicted values of seismic motion intensity[3,4].

The construction of long span bridges has a tendency for prolonged construction period. These structures in some cases are not in stable conditions while being constructed as compared to those in service. In general, the seismic motion intensity is smaller during the construction period compared to that after completion, and depending on the earthquake-resistant design under construction, the risk of damage exists. This can possibly be reduced on site experiences, or by the technical ingenuity of the personnel responsible for the construction technique, although it is difficult to reduce the risk to zero. This kind of seismic loads for relatively short durations has not been clarified by the existing specifications for earthquake-resistant design, thus, it is necessary to have a proper predicting method for this purpose[4-6].

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This study presents a probabilistic evaluation method for seismic motion intensity in relatively short durations. The factors that affect the seismic motion intensity of the short durations are evaluated and an application of the evaluation method to the installation models of a long-span suspension bridge is presented by using the probabilistic approach, in which initial construction costs, the probability of failure by seismic motion intensity and restoration costs are taken account of.

2. PREDICTING METHOD FOR SEISMIC LOAD[10)]

(1) State of seismic activity of source region

The relation for the magnitude and frequency of occurrence of past earthquakes is represented by Gutenberg-Richter formula, hereafter called G-R Formula, is as follows ;

$$\log n(m) = a - b \cdot m \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (1)$$

where $n(m) \cdot dm$ is the frequency of the seismic occurrence between magnitude m and $m+dm$. The maximum magnitude of earthquakes may be taken as a parameter m_u, and Eq. (1) may be modified as follows[8)] ;

$$
\begin{aligned}
\log n(m) &= a - b \cdot m & (m \leq m_u) \\
n(m) &= 0 & (m > m_u)
\end{aligned}
\quad\quad\quad\quad (2)
$$

and,

$$
\begin{aligned}
\log n(m) &= a - b \cdot m + \log(m_u - m) & (m < m_u) \\
n(m) &= 0 & (m \geq m_u)
\end{aligned}
\quad\quad\quad\quad (3)
$$

Eq. (2) and Eq. (3) are generally called the truncated G-R formula and the modified G-R formula respectively. For using Eq. (2) and Eq. (3), the cumulative density functions $F_M(m)$, respectively are as follows ;

$$F_M(m) = \frac{1 - \exp\{-\beta(m - m_0)\}}{1 - \exp\{-\beta(m_u - m_0)\}} \quad\quad\quad\quad\quad\quad\quad\quad (4)$$

and

$$F_M(m) = \frac{1 - \{1 - \beta(m_u - m)\}\exp\{-\beta(m - m_0)\} - \beta(m_u - m_0)}{1 - \exp\{-\beta(m_u - m_0)\} - \beta(m_u - m_0)} \quad\quad\quad\quad (5)$$

where $\beta = b \cdot \ln 10$, and m_0 is the minimum magnitude to be used for analysis.

(2) Attenuation property of seismic motion

The attenuation property of seismic motions is required for predicting seismic motion intensities at a site based on the state of the seismic activities in the source region. To this, the attenuation formula proposed in reference 9) is adopted as follows ;

$$\overline{y} = f(m, \ r) = A \cdot 10^{B \cdot m} \cdot (r + r_0)^C \quad\quad\quad\quad\quad\quad\quad\quad (6)$$

where $\overline{y}$ is the expected value of seismic motion intensity used for analysis, r is the distance from epicenter and A, B, C, r_0 are parameters. When the parameters A, B, and C are determined from multiple regression analysis by using past seismic data, dispersion exists between the predicting formula and the measured values. The index of the dispersion is defined as a ratio $U = y_{ob}/\overline{y}$, of measured value and predicted value. The value of y_{ob} is the measured value of seismic motion intensity. The value of log U is approximately normally distributed, therefore the seismic motion intensity is also of logarithmic normal distribution.

(3) Expected value of seismic motion intensity

An expected value of seismic motion intensity is analyzed by a model of areal sources. The truncated G-R formula is used for evaluating the probability of exceeding a predetermined value defined as y for a site having seismic motion intensity defined as Y, when earthquake occurs in i-th areal source $(i=1, 2, \cdots, N)$. The probability is as follows ;

$$P(Y > y \,|\, E_i) = 1 - \frac{1 - \exp[-\beta_i\{g(y,\ r) - m_0\}]}{1 - \exp[-\beta_i\{m_{ui} - m_0\}]} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

If the modified G-R formula is used, then the probability is as follows ;

$$P(Y > y \,|\, E_i) = 1 - \frac{f(y)}{1 - \exp\{-\beta_i(m_{ui} - m_0)\} - \beta_i(m_{ui} - m_0)} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (8)$$

where $f(y) = 1 - [1 - \beta_i\{m_{ui} - g(y,\ r)\}] \cdot \exp[-\beta_i\{g(y,\ r) - m_0\}] - \beta_i(m_{ui} - m_0)$,
$m = g(y,\ r)$, and m_{ui} is the maximum magnitude for i-th areal source.

Defining the rate of the annual mean seismic occurrence, ν_i in i-th areal source, and the common origin of a circle with radius $r_i = r_{1i} \sim r_{2i}$, and angle $\theta_i = \theta_{1i} \sim \theta_{2i}$, then the frequency of occurrence $\lambda_i(y)$ for earthquakes in i-th areal source of $Y > y$ is as follows ;

$$\lambda_i(y) = \nu_i \cdot \theta_i \int_{r_{1i}}^{r_{2i}} P(Y > y \,|\, E_i) \cdot r \, dr \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (9)$$

The probability of $P(Y > y \,|\, E_i)$ in Eq. (9) is obtained either from Eq. (7) or Eq. (8). Further, if there are N areal sources, then the frequency of occurrence $\lambda(y)$ at a site after taking consideration of all areal sources for $Y > y$ is as follows ;

$$\lambda(y) = \sum_{i=1}^{N} \nu_i \cdot \theta_i \int_{r_{1i}}^{r_{2i}} P(Y > y \,|\, E_i) \cdot r \, dr \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (10)$$

(4) Poisson process

The relation between $\lambda(y)$ and y is based on seismic motion intensity of earthquakes observed. The Poisson process is adopted for inducing the probability of seismic occurrence[11]. The probability of n times occurrences for seismic motion intensity Y greater than y within a duration t, is as follows,

$$P(E)_n = \frac{\{\lambda(y) \cdot t\}^n}{n\,!} \cdot \exp\{-\lambda(y) \cdot t\} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (11)$$

3.   DATA RELATED TO EARTHQUAKE AND ATTENUATION PROPERTY

The straits of Akashi (135° 02′E, 34° 36′N) was chosen as the site in this study. The following are the data are used.

(1) Seismic data

The seismic data were provided by references 12), 13), 14), 15) and 16). Accordingly the magnitudes for the period from 1885 to 1925, 1926 to 1974 and 1975 to 1984 are taken to be, respectively, above 6.0, above 5.5, and above 5.0. The ratio of occurrence per unit area for magnitudes above 5 are grouped in the same range, as shown in **Fig. 1**. The maximum seismic magnitudes for the period of 416 and 1984 are shown in **Table 1**[12].

(2) Attenuation property

The ground condition of the straits of Akashi is formed by rocky formation. The maximum seismic motion is expressed as follows[9] ;

$$A_{\max} = 1073.0 \times 10^{0.221 \cdot m} \cdot (r + 30)^{-1.251} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (12)$$

and acceleration response spectra with damping factor of 5% is expressed as follows ;

$$S_A(T_k) = A(T_k) \times 10^{B(T_k) \cdot m} \cdot (r + 30)^{C(T_k)} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (13)$$

where $A(T_k)$, $B(T_k)$, and $C(T_k)$ for various natural periods T_k are shown in **Table 2**.

The dispersion index, U with respect to maximum seismic motion and its response spectra are $\sigma_{\log} U_{A_{\max}} \fallingdotseq 0.216$ and $\sigma_{\log} U_{S_A} \fallingdotseq 0.252$ respectively.

4.   INFLUENCE OF DECISION FACTOR OF SEISMIC LOAD FOR SHORT DURATION

(1) G-R formula

The comparison between two formulae of G-R formulae was carried out. The value of m_u are the maximum values that occured in the respective areal sources between the period of 416 and 1984 as shown in
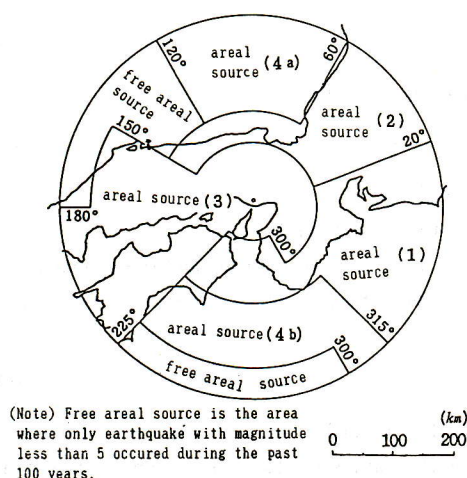
(Note) Free areal source is the area where only earthquake with magnitude less than 5 occured during the past 100 years.

Fig. 1　Areal sources model.

Table 1　Maximum magnitude for the period between 416 and 1984.

Areal source	m_u	The data and epicenter of observed earthquakes for maximum magnitude in the period between 416 and 1984			
1	7.9	Dec. 17	1096	137.3° E	34.2° N
		Dec. 23	1854	137.8° E	34.1° N
		Dec. 7	1944	136° 37'E	33° 48'N
2	8.0	Oct. 28	1891	136° 36'E	35° 36'N
3	6.9	Nov. 23	880	132.8° E	35.4° N
		Jun. 2	1905	132° 30'E	34° 06'N
4	8.1	Aug. 26	887	135.0° E	33.0° N

Table 1. The parameters a and b in G-R formulae are shown in **Table 3**. No significant difference was found out between the two formulae in the case of short duration. The truncated G-R formula, Eq. (2) is adopted in this analysis.

（ 2 ）　**The minimum magnitude**

For specifying seismic load for the short duration, extrapolation of the G-R formula is required to predict the range of the magnitudes below 5.0. By taking the basic value as possible as smaller than 0.1, the reduction ratio with respect to duration t for $m_0 = 2.0$, 4.0 and 5.0 is obtained as shown in **Fig. 2**. In this case, m_u is the maximum magnitude in the period years between 416 and 1984 as shown in **Table 1**. It can be considered that the expected value of maximum seismic motion for one year becomes stable at the minimum magnitude, m_0 of 2.0 or less.

（ 3 ）　**Conceivable maximum magnitude**

The conceivable maximum magnitude was estimated in the following three cases.

（ a ）　The maximum value in the period between 416 and 1984, is used for the respective areal sources.

（ b ）　The maximum value obtained from the seismic data in the period between 1885 and 1984 is used for the respective areal sources.

（ c ）　The maximum value of 8.1 from reference 17), is used for the entire areal source.

Table 2　Parameter for attenuation formula (quoted from reference 9)).

natural period	parameter for attenuation formula of seismic response spectrum		
Tk(sec)	A(Tk)	B(Tk)	C(Tk)
0.1	2090	0.202	-1.200
0.15	2543	0.219	-1.199
0.2	1558	0.260	-1.258
0.3	1140	0.313	-1.447
0.5	111.0	0.261	-0.9239
0.7	60.24	0.286	-0.9687
1.0	57.69	0.366	-1.321
1.5	13.47	0.469	-1.428
2.0	10.77	0.454	-1.422
3.0	2.466	0.485	-1.331

Table 3　Parameter of Gutenberg-Richter formula.

areal source	truncated Gutenberg-Richter formula			modified Gutenberg-Richter formula		
	a	b	m_u	a	b	m_u
1	5.01	0.854	7.9	3.31	0.612	7.9
2	3.93	0.704	8.0	2.22	0.465	8.0
3	4.15	0.774	6.9	1.72	0.352	6.9
4	2.95	0.558	8.1	1.46	0.391	8.1

The minimum magnitude, M_0 is taken as possible as smaller than 0. 1, when the maximum value from the record between 416 and 1984 is taken as the basic value. The ratio of increase for the other two cases are shown in **Fig. 3**. Thus, M_u does not exert influence in the short period one years or less.

(4) Earthquake ground motion

The four conditions are used for evaluating the expected value of the ground motion intensity for an application period for short durations.

(a) The truncated G-R formula is used.

(b) The minimum magnitude, M_0 of 2. 0 is used.

(c) The conceivable maximum magnitudes, M_u are taken as the maximum value from the seismic catalogue in reference 12).

(d) The radious of the entire areal source is 300 km.

The relation of $\lambda \sim S_A$ is shown in **Fig. 4** and the expected value of acceleration response spectra in the respective divisions is shown in **Fig. 5**.

5. NUMERICAL EXAMPLE

(1) Model of the installation of the bridge

The numerical example is examined in the case of three span suspension bridge under construction. In the installation term of five years or more, the stiffened truss suffers from an earthquake during its installation period of one year eight months. The installation model assumes that there are five stages in the installation of the stiffened truss and each stage is four months long. Five major installation models are shown in **Fig. 6**.

The following are the assumption in the evaluation of the axial force of the stiffened truss that resulted from the earthquake effect as shown in **Fig. 4** and 5.

(a) Assuming the inphase ground motion in the entire truss.

(b) Neglecting all loads except earthquake loads and dead loads.

(c) In the natural periods of 0. 1 second or less and 3. 0 seconds or more, the response spectra are extrapolated.

The axial resistant force of the stiffened truss chord and brace is determined by the yield strength of the material of each member. The mean value and standard deviation at the yield strength of the steel material is used.

(2) Probability of the failure

The probability of the failure of the chord, $P_{f,k,l,n}$ is given as follows ;

$$P_{f,k,l,n} = \sum_{j=1}^{N_j} P(E)_{j,k,n} \cdot P(F \mid E)_{j,k,l} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (14)$$
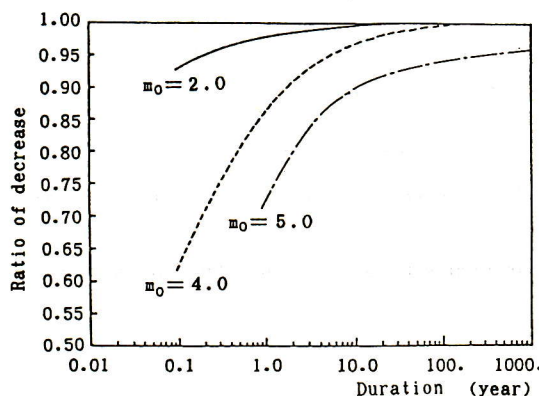
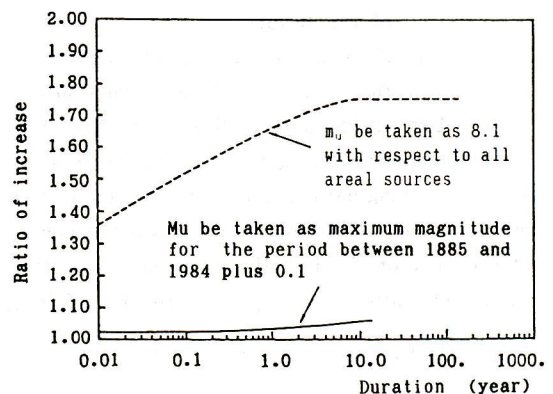Fig. 2 Ratio of decrease expected value of maximum ground motion for variation in M_0.

Fig. 3 Ratio of increase of expected value of maximum ground motion for variation in M_u.
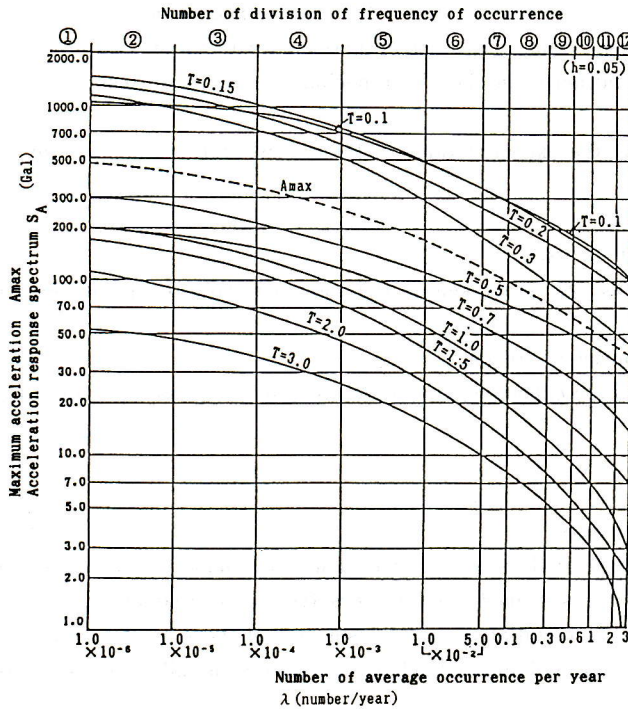
Number of division of frequency of occurrence

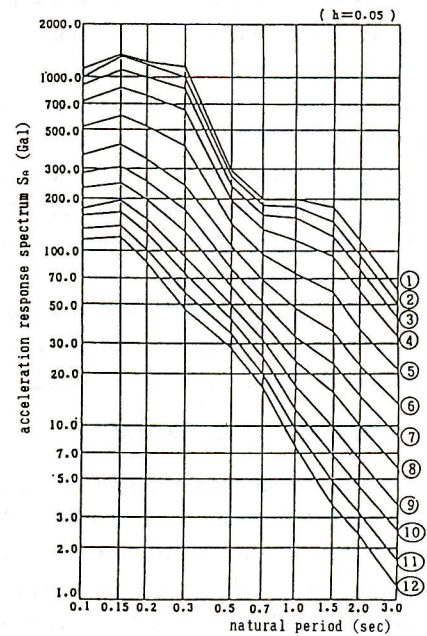Fig. 4 Acceleration response spectrum for duration of 0.1 year to 1 year.

Fig. 5 Response spectrum curve for division of frequency of occurrence.

where

$P(E)_{j,k,n}$: Probability of the failure of the j-th division of the frequency of the occurrence,

N_j : Division number designated in **Fig. 4**,

k : Sequence number of the stage of the installation period,

l : Sequence number of the panel of the stiffened truss,

n : Sequence number of the occurrence of the failure,

j : Sequence number of the division of the frequency of the occurrence.

(3) Expected value of the restoration cost

In restoring the damaged portion of the truss as same as the original construction, the restoration cost is assumed to be equal to the installation cost,

Fig. 6 Construction model of 3-spans suspension bridge.

but the cost of the installation term longer than the original schedules is not taken into account.

The restoration cost $C_{k,l}$ is defined as follows ;

$$\overline{C}_{k,l} = \sum_{n=1}^{\infty} P_{f,k,l,n} \cdot r_{c,k,l} \cdot C_u \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (15)$$

where

$r_{c,k,l}$: Reduction coefficient of the restoration cost,

Table 4 Yield strength of steel member[18].

steel grade	mean value $\overline{\sigma}_Y$ (MN/m²)	standard deviation $\sigma_{\overline{\sigma}_Y}$ (MN/m²)	coefficient of variation δ_R (%)
SS41	294.	23.5	8.
SM50Y	373.	29.4	8.
SM58	431.	25.5	6.
HT70	667.	27.5	4.

Table 5 Ratio of restoration cost.

predetermined condition	ratio of restoration cost R_c (%)
Reduction of 50% for 2nd. panel from tip of the installation, and reduction of 25% for 3rd. and 4th panel from tip of the installation	5.5
reduction is not considered	7.5

C_u : Restoration cost of a unit panel when the failure occures in a completely installed stiffened truss.

The expected value of the total restoration cost of the stiffened truss, $\overline{C}$ is as follows;

$$\overline{C} = \sum_{l=1}^{N_l} \sum_{k=1}^{N_k} \overline{C}_{k,l} \quad \cdots\cdots (16)$$

where

N_k : Total number of division of installation,

N_l : Total number of panels.

The restoration cost ratio, R_c of the restoration cost to the original construction cost is as follows;

$$R_c = C/C_0 \quad \cdots\cdots (17)$$

where

C_0 : Initial construction cost $(= N_l C_u)$.

Table 5 shows the expected value of failure frequency of the entire panels of the stiffened truss, and the restoration cost ratio. In this case, the total number of panel is 274.

6. CONCLUSION

In this paper a probabilistic evaluation method for seismic loads in short durations and an example of its application are presented. The main results may be summarized as follows;

(1) The expected value of the maximum ground motion for short durations becomes stable at the minimum magnitude $M_0 = 2.0$ or less,

(2) The conceivable maximum magnitude for short durations has a small effect upon the value of ground motion intensity estimated by using either the maximum value from the recent seismic data in the period between 1885 and 1984 or the maximum value indicated by historical seismic data.

7. ACKNOWLEDGEMENTS

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(Note : Asterisk, ✳ indicates the title literally translated from Japanese.)