ESTIMATION OF THE EXPECTED NEAR-FIELD MAXIMUM
VELOCITY ON BEDROCK

by

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SUMMARY

The methodology to estimate the near-field maximum ground velocities on a bedrock level for earthquake resistant design of structures is investigated in this paper.

The fundamental assumption is as follows;

$$\left.\begin{aligned} |\overline{V}^j_{max}(t)| &\doteqdot |\overline{V}^j_{SYN}(t)_{max}| + \Delta V^j \\ \Delta V^j &= < V_{EMP} > - |V^j_{SYN}(t)_{max}| \end{aligned}\right\} \quad (1)$$

where, $|\overline{V}^j_{max}(t)|$ is the absolute maximum velocity of jth. earthquake event in the near-field region, and $|\overline{V}^j_{SYN}(t)_{max}|$ is the near-field synthetic velocity determined deterministically by simple propagating fault model (Haskell, 1969). ΔV^j is the correction coefficient which is defined by the difference between the empirical velocity $< V_{EMP} >$ (Kanai, 1966) and synthetic far-field maximum velocity, $|V^j_{SYN}(t)_{max}|$, (Haskell, 1969).

In order to compare the estimated value $|\overline{V}^j_{max}(t)|$ with the observed values, three earthquakes, Izu-Ohshima earthquake (1978), Ohita earthquake (1975) and Parkfield earthquake (1966) are analyzed. From the result of analysis, one can see that the observed maximum velocities during the three events can be estimated reasonably well. The average error is about 16%.

INTRODUCTION

The estimation of the strong earthquake ground motions on a bedrock level in a near-field region for earthquake resistant design of structures is of general interest to engineers. There are two methodologies currently available to evaluate the earthquake ground motions; (i) the first is the statistical empirical method based on past earthquake data obtained in the far-field region (Kanai, 1966; Esteva and Rosenblueth, 1964; Esteva, 1970; etc.); (ii) the second is based on a simple propagating fault model (Haskell, 1969; Brune, 1970; etc.). The former methodology should be used to estimate the ground motions not in a near-field region but in a far-field region because they are built by using the teleseismic earthquake data. On the other hand, it is difficult to explain the features of short

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period seismic waves ($T < 1 \sim 2$ sec.) which influence the structures quite significantly by using second method. Recently, the complex phenomenon of fault movement, which plays an important role in the short period motions, has been qualitatively studied by many researchers. However, no analytically tractable mathematical model is currently available to estimate near-field motions.

Considering the limitations mentioned above, this paper develops a simple and semi-empirical approach to estimate the near-field maximum bedrock velocities.

METHODOLOGY FOR ESTIMATING THE NEAR-FIELD MAXIMUM VELOCITY ON A BEDROCK

Under the assumption that the earthquake ground velocity can be explained reasonably by the finite Fourier series, we have the following equations.

$$\begin{aligned} V^j(t) &= \sum_{i=1}^{N} a_i^j \cos(\omega_i t + \phi_i^j) \\ &= \sum_{i=1}^{m} a_i^j \cos(\omega_i t + \phi_i^j) + \sum_{i=m+1}^{N} a_i^j \cos(\omega_i t + \phi_i^j) \end{aligned} \tag{2}$$

(Far-Field)

$$\begin{aligned} \overline{V}^j(t) &= \sum_{i=1}^{N} b_i^j \cos(\omega_i t + \overline{\phi}_i^j) \\ &= \sum_{i=1}^{m} b_i^j \cos(\omega_i t + \overline{\phi}_i^j) + \sum_{i=m+1}^{N} b_i^j \cos(\omega_i t + \overline{\phi}_i^j) \end{aligned} \tag{3}$$

(Near-Field)

Here, a_i^j and b_i^j are Fourier coefficients of jth. earthquake ground velocity in a far-field and a near-field region, respectively. ϕ_i^j and $\overline{\phi}_i^j$ are phase lags. $V^j(t)$ and $\overline{V}^j(t)$ are far-field and near-field ground velocities on a bedrock level.

Eqs. (2) and (3) imply that the ground velocity can be expressed by the superposition of low-pass and high-pass filtered ground motions.

Accordingly,

$$|V^j_{max}(t)| = \left|\sum_{i=1}^{m} a_i^j \cos(\omega_i t_2 + \phi_i^j)\right| + \Delta V^j \tag{4}$$

(Far-Field)

$$|\overline{V}^j_{max}(t)| = |\sum_{i=1}^{m} b^j_i \cos(\omega_i t_2 + \overline{\phi}^j_i)| + \Delta\overline{V}^j \qquad (5)$$

(Near--Field)

Where, $|V^j_{max}(t)|$ and $|\overline{V}^j_{max}(t)|$ are absolute maximum velocities in the far-field and near-field regions. $|\sum_{i=1}^{m} a^j_i \cos(\omega_i t_1 + \phi^j_i)|$ and $|\sum_{i=1}^{m} b^j_i \cos(\omega_i t_2 + \overline{\phi}^j_i|$ are absolute maximum velocities of low-pass filtered far-field and near-field ground velocities, respectively. ΔV^j and $\Delta\overline{V}^j$ are correction coefficient in each region.

The first terms of the right hand side of eq. (4) and (5), which indicate the low-pass filtered ground velocities, are assumed to be approximately similar to the synthetic ground velocities, $V^j_{SYN}(t)$ and $\overline{V}^j_{SYN}(t)$, in a period range $T > 1 \sim 2$ sec calculated by a simple propagating fault model (Haskell, 1969). Therefore, one can substitute $\sum_{i=1}^{m} a^j_i \cos(\omega_i t_1 + \phi^j_i)$ and $\sum_{i=1}^{m} b^j_i \cos(\omega_i t_2 + \overline{\phi}^j_i)$ with $V^j_{SYN}(t)_{max}$ and $\overline{V}^j_{SYN}(t)_{max}$.

Hence,

$$|V^j_{max}(t)| \doteqdot |V^j_{SYN}(t)_{max}| + \Delta V^j \qquad (6)$$

(Far-Field)

$$|\overline{V}^j_{max}(t)| \doteqdot |\overline{V}^j_{SYN}(t)_{max}| + \overline{V}^j \qquad (7)$$

(Near-Field).

If the equality $\Delta V^j \doteqdot \Delta\overline{V}^j$ is approximately acceptable on the bedrock level in a period range of interest for earthquake engineering, then

$$|\overline{V}^j_{max}(t)| - |V^j_{max}(t)| \doteqdot |\overline{V}^j_{SYN}(t)_{max}| - |V^j_{SYN}(t)_{max}| \qquad (8)$$

Conversely, if the attenuation of observed maximum velocity in eq. (8) on a bedrock level is approximately assumed to be equal to that of synthetic velocity in the period range of interest for structures, the relation $\Delta V^j \doteqdot \Delta\overline{V}^j$ should be valid.

Generally the seismic waves generated by the fault movement will be attenuated by the compound effects of geometrical divergence factor and the dissipating attenuation, $\exp\left(-\frac{\omega r}{2QV}\right)$, on the bedrock level.

According to Hasegawa (1974), the attenuation of the amplitude of Fourier spectra at sties with different wave propagating distance ($r = 10 \sim 100$ Km) from the fault are similar to each other in frequency range $10 \sim 10^{-2}$ cps under the consideration of attenuation effects mentioned above.

Hence the approximate relation, $\Delta V^j \doteqdot \Delta \overline{V}^j$, can be assumed to be valid.

Accordingly, the near-field maximum velocity on a bedrock level can be estimated approximately using ΔV^j, if the far-field maximum velocity $|V^j{}_{max}(t)|$ can be estimated.

The following statistical equation was proposed by Kanai (1966) for estimating the mean value of far-field maximum velocities on the bedrock during earthquakes.

$$< V_{EMP} > = 10^{0.61M - \left(1.66 + \frac{3.60}{x}\right)\log x - \left(0.631 + \frac{1.83}{x}\right)} \tag{9}$$

Here, M is a magnitude and x is a hypocentral distance. Replacing the $|V^j_{max}(t)|$ in eq. (6) with the $< V_{EMP} >$, the following equation is obtained.

$$< V_{EMP} > = |V^j_{SYN}(t)_{max}| + \Delta V^j \tag{10}$$

Consequently, the maximum velocity in the near-field region can be obtained from the following equation.

$$|\overline{V}^j_{max}(t)| \doteqdot |\overline{V}^j_{SYN}(t)_{max}| + \left\{< V_{EMP} > - |V^j_{SYN}(t)_{max}|\right\} \tag{11}$$

Eq. (11) also implies that the maximum velocity on a bedrock can be expressed by the superposition of deterministic part, $|\overline{V}^j_{SYN}(t)_{max}|$, and static part, $\left\{< V_{EMP} > - |V^j_{SYN}(t)_{max}|\right\}$.

RESULTS OF ANALYSIS
- IZU-OHSHIMA EARTHQUAKE (1978) -

Figure 1 shows the results of analysis of Izu-Ohshima earthquake (M_j= 7) of 1978. Figure 1(b) shows the estimated maximum velocities $|\overline{V}^j_{max}(t)|$ and Figure 1(c) indicates the comparison of the observed and estimated maximum accelerations. In order to calculate the corresponding accelerations from estimated maximum velocities, the empirical relation between magnitude of earthquake and predominant period (Seed, 1968, 1969) was used here. The maximum velocity was given by the vector notation of the two horizontal components to compare with observed one.

As shown in Figure 1(b), the estimated maximum velocities at Inatori, Imaihama and Nashimoto stations in the near-field region are 24 cm/sec, 18 cm/sec and 14 cm/sec, respectively. The corresponding maximum accelerations are estimated to be 486 cm/sec^2 (Inatori), 365 cm/sec^2 (Imaihama) and 284 cm/sec^2 (Nashimoto). The observed maximum accelerations at each site were 330-390 cm/sec^2 (Inatori), 330-380 cm/sec^2 (Imaihama) and 310-370 cm/sec^2 (Nashimoto) with mean accelerations of 360 cm/sec^2, 355 cm/sec^2 and 340 cm/sec^2, which were estimated by observing the overturning of tombstones. From Figure 1(c) it can be seen that the estimated maximum accelerations reasonably agree with observed values.

- OHITA EARTHQUAKE (1975) -

Figure 2 shows the results of analysis of Ohita earthquake ($M = 6.4$) of 1975. The maximum accelerations in the near-field region during the earthquake were investigated by Omote (1975) by observing the overturning of tombstones.

Figure 2(b) indicates the estimated maximum velocities on the bedrock level, and Figure 2(c) is the comparison of the observed and estimated accelerations. The solid line in the figure indicates the envelope of observed maximum accelerations versus normal distance from the fault strike (Omote, 1975). The estimated maximum accelerations appear to be smaller than the observed values. Considering some errors of the estimated and observed values, both of them seem to agree well.

- PARKFIELD EARTHQUAKE (1966) -

Figure 3 shows the results of analysis of Parkfield earthquake ($M = 5.8$) of 1966. The estimated maximum velocities at Cholame No. 2 and No. 3 stations are 23 cm/sec and 5 cm/sec, respectively. Unfortunately, however, only perpendicular components to the fault strike was recorded at No. 2 station. So, estimated maximum velocity of this component (▲ marked in Figure 3) becomes 13 cm/sec. On the other hand, the observed maximum velocities at these stations during event are 78 cm/sec (No. 2) and 34 cm/sec (No. 5), respectively (Trifunac, 1974). One can see the large differences between estimated and observed velocities.

According to the previous study (Ishida, 1977), the amplitude characteristics of the surface layer at Cholame station did not give significant effects to the magnitude of maximum velocity. Therefore, it is difficult to explain the difference between them by the characteristics of surface layer.

As mentioned in the previous section, the basic idea of estimating the absolute maximum velocity $|\overline{V}^J_{max}(t)|$ on the bedrock level in the near-field is based on the assumption that the far-field maximum velocity on a bedrock must be estimated, on the average, by eq. (9). This equation is completely defined by a magnitude and a hypocentral distance. The statistical averaged dislocation ($\overline{D}_o$) over the fault plane related to the magnitude of earthquake can be evaluated by the following empirical equation which is based on the data on active faults in the U.S.

$$\log \overline{D}_o = 0.57M - 3.91 \qquad \text{(Bonila, 1970)} \qquad (12)$$

By substituting the magnitude of the Parkfield event into eq. (12), the averaged dislocation $\overline{D}_o = 25$ cm is obtained. That is, the velocity $< V_{EMP} >$ in eq. (9) during this earthquake is the value for the dislocation $\overline{D}_o = 25$ cm. However, the averaged dislocation over the fault plane was investigated by the analysis of seismograms to be $D_o = 100 \sim 140$ cm (Aki, 1968). The ratio between the two values is about $D_o/\overline{D}_o = 4 - 5.6$. In spite of the small earthquake, the dislocation D_o was too large. This means that we should consider the Parkfield earthquake to be statistically a special case. The amplitude of ground motions are proportional to the dislocation, so the estimated maximum velocities mentioned above must be corrected by the ratio $D_o/\overline{D}_o = 4 - 5.6$.

The Figure 3(c) shows the comparison of the corrected and observed maximum velocities at No. 2 and No. 5 stations. At No. 2 station, the final estimated maximum velocity was 52-73 cm/sec with mean 63 cm/sec and 20-30 cm/sec with mean 25 cm/sec at No. 5 station. It can be seen that the corrected estimated maximum velocities agree reasonably well with the observed values.

EVALUATION OF ERROR OF ESTIMATED MAXIMUM VELOCITY

As mentioned above, the estimated maximum velocities using eq. (11) give the mean value on a bedrock level. One should evaluate the degree of error between the estimated maximum velocities and the mean value of observed velocities.

Figure 4 shows the comparison of estimated and observed maximum velocities during Izu-Ohshima earthquake, Ohita earthquake and Parkfield earthquake. The dot dashed line shown in this figure is a linear regression line;

$$V_{obs} = 1.16\ V_{est} \tag{13}$$

where, V_{obs} is the observed maximum velocity and V_{est} is the estimated value from eq. (11), respectively. The unbiase conditional standard deviation, $S_{V_{obs}|V_{est}}$, was estimated as follows under the assumption that the variation was constant over the V_{est} value;

$$S_{V_{obs}|V_{est}} = 5.2 \tag{14}$$

If the estimated maximum velocities on the bedrock level, on the average, are equal to the observed values, the regression line has a 45° slope with the V_{est} axis. The result, however, is 16% larger than that. Hence, it can be said that, on the average, the estimated maximum velocity has an error of 16% (V_{est} is smaller than V_{obs}) when compared with observed maximum velocity.

From the results of this analysis, it can be concluded that, in spite of the empirical and approximate estimation of maximum velocity on bedrock level, eq. (11) is very useful relationship for estimating the maximum velocity on a bedrock level in a near-field region.

CONCLUDING REMARKS

In order to establish a simple and rational methodology for estimating the near-field maximum velocity on a bedrock, an empirical approach was proposed in this paper. Comparison was made between the estimated and observed maximum values during Izu-Ohshima earthquake (1978), Ohita earthquake (1975) and Parkfield earthquake (1966). From the results of this study, it can be said that the mean value of maximum velocities on a bedrock level in a near-field could be reasonably estimated. Since only a few earthquake records are currently available in the near-field region, this study must be repeated in the future when additional near-field data is made available to check the validity of this method.

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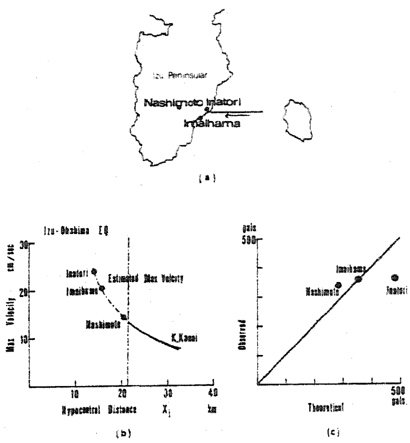

Fig. 1 The comparison of estimeted max. ground motions and observed ones during Izu-Oshima earthquake(1978).

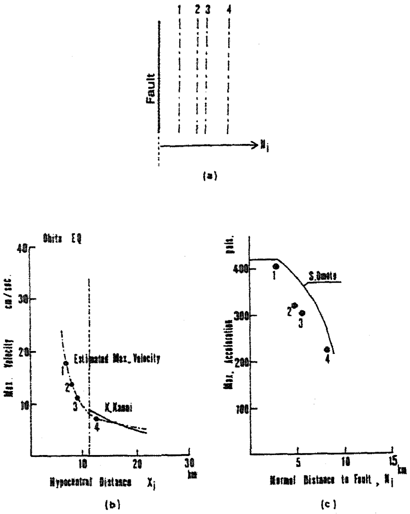

Fig.2 The comparison of estimated max. ground motions and observed ones during Ohita earthquake(1975).

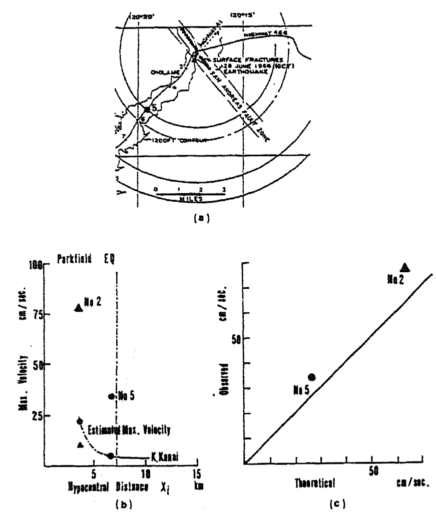

Fig.3 The comparison of estimated max. ground motions and observed ones during Parkfield earthquake (1966).

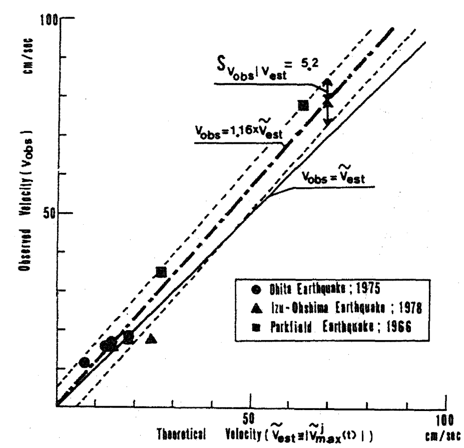

Fig. 4 Evaluation of error of estimated near-field max. velocities with mean value of observed max. velocities. The dot dashed line is a linear regression line estimated by a method of least square.