A study on empirical ground motion estimation introducing fault rupture propagating effects

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ABSTRACT :

Fault rupture propagating effects such as radiation pattern and forward directivity, are introduced into empirical attenuation relationship of ground motion. In this study, those effects are theoretically defined using the directions of rupture propagation, fault slip, and wave radiation pattern of small sub-faults divided from target fault as used in the Green's function summation technique. Rupture heterogeneity is also considered as a weight of seismic moment for each small sub-fault. Empirical relationship between site amplification and average shear wave velocity are introduced to estimate shake map. The modification factors to correct the rupture propagating effects are applicable for any attenuation formulae of maximum acceleration or velocity, because the average of the factors for wide area around the target fault are defined to be constant value as one. Using the factors, different ground motion maps are obtained for strike and dip slip faults even using an attenuation formula with magnitude and fault distance which does not care about fault rupture type.
The effects of proposing modification factors are verified by using ground motion distributions derived from observed past earthquakes and wide frequency band waveform simulations. The proposing method provides more realistic ground motion distributions than those by original attenuation formula. The proposing technique can be applicable for quick estimations of ground motion distribution in wide target area as required in immediate action just after the earthquake.

KEYWORDS: Radiation pattern, forward directivity, slip heterogeneity, attenuation formulae, shake map

1. INTRODUCTION

Ground motion in near source area is strongly affected by fault rupture propagation. Pulse-like waves with large amplitude are observed through the recent damaging earthquakes. We know that the pulses are generated by forward directivity effect due to fault rupture propagation. We can simulate such forward directivity pulses by using the detailed method considering fault rupture process. Meanwhile, empirical attenuation of ground motions usually gives average ground motion without considering fault rupture process. These effects are considered experientially in several attenuation formulae to explain a phenomenon caused by fault rupture propagation in near source area [for example; Somerville et al., 1997], however, the affections are not gradual but binary; i.e. on or off, and the applicable scopes are not clearly defined.
Slip heterogeneity also affect on ground motion in near source area. Ohno et al. introduced equivalent hypocentral distance to empirical attenuation formula to explain spatiality of fault plane and slip heterogeneity. They used weighted average of slip energy over a fault plane to evaluate equivalent hypecentral distance. Their concept is applied to the proposed modification factors.
Simulation of ground motion records including forward directivity pulse is possible using detailed method, however, it takes time to estimate shake map of wide are including fault zone. And it requires a lot of parameters to be defined. Quick estimation of shake map is possible using attenuation formulae even using limited datum, however, they do not consider fault rupture propagation. It is meaningful to consider modification factors due to fault rupture effects for attenuation formulae. Here we propose the factors due to fault rupture effects for the previously proposed attenuation formulae. The factors are constructed by as a radiation pattern effect and a rupture directivity effect. Both effects are change gradually in space and their averages around the source fault are unalterably one.

2. MODIFICATION FACTOR

In this study, target fault plane is divided into several sub-faults, see figure 1. Slip heterogeneity is considered assuming slip distribution on the sub-faults. Rupture starting point is also assumed to explain rupture propagation effects. These conditions are same as detailed method. In figure 1, parameter *ang1* indicates an angle between a vector from a sub-fault to the site and a rupture propagating direction at the sub-fault. Parameter *ang2* is an angle between the vector above and a slip direction at the sub-fault. Using the parameters, the modification factors of radiation pattern and directivity effect are proposed.

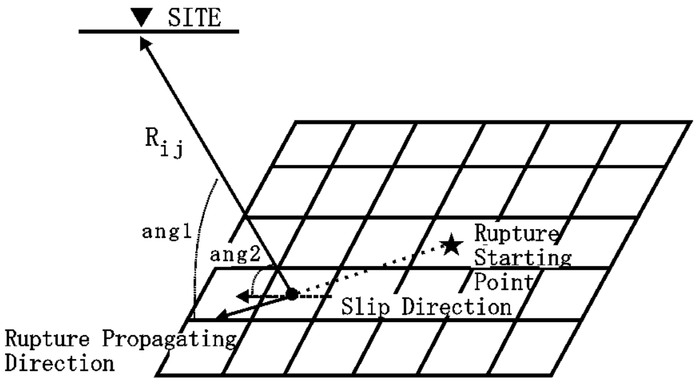

Figure 1 Parameters for rupture propagating effects

2.1. Directivity Effect

Assuming R_{ij} as a hypocentral distance and m_{0ij} as seismic moment on a sub-fault of location (i, j), where i and j indicate length and width directions respectively. Parameter M_0 indicates total seismic moment radiated from the target fault. Then directivity effect is evaluated using eqns. 2.1 to 2.3.

$$e_{rup} = \frac{\sum_{(i,j)} \frac{m_{0ij}/M_0}{R_{ij}} \cos(ang1)}{\sum_{(i,j)} \frac{m_{0ij}/M_0}{R_{ij}}} \tag{2.1}$$

$$e_{rake} = \frac{\sum_{(i,j)} \frac{m_{0ij}/M_0}{R_{ij}} \cos(2 \times ang2)}{\sum_{(i,j)} \frac{m_{0ij}/M_0}{R_{ij}}} \tag{2.2}$$

$$E_{rup} = 2.0^{e_{rup}} \qquad E_{rake} = 2.0^{e_{rake}} \tag{2.3}$$

Effect of rupture propagating angle e_{rup} is explained by *ang1*. It gives maximum value one when *ang1* equals to zero degree, minimum value minus one when *ang1* is 180 degrees. The value is zero, means no effects, when *ang1* equals to 90 degrees. Effect of rake angle e_{rake} is explained by *ang2*. Effect of rupture heterogeneity is also introduced considering weighted average of moment release from each sub-fault after Ohno et al. (1993). It gives maximum value one when *ang2* equals to zero degree, minimum value minus one when *ang2* is 90 degrees. It gives no effects, when *ang2* equals to 45 degrees. As the results, factors E_{rup} and E_{rake} in eqn. 2.3 give value between 0.5 and 2.0.

$$E_{rup\&rake} = \sqrt{E_{rup} \times E_{rake}} \tag{2.4}$$

We assume a modification factor of rupture directivity $E_{ruprake}$ as geometric mean of E_{rup} and E_{rake} explained in eqn. 2.4. The value $E_{ruprake}$ of spreads between 0.5 and 2.0.

2.2. Radiation Pattern

Next, we assume a modification factor of radiation pattern as eqn. 2.5. Where parameters SH_{ij} and SV_{ij} indicate radiation coefficients of SH and SV waves on a sub-fault of location (i, j). Eqs. 2.5 means normalization of radiation coefficients against average radiation coefficient of shear waves [Boore and Boatwright, 1984] with slip heterogeneity modification.

$$E_{rad} = \frac{\sum_{(i,j)} \frac{m_{0ij}/M_0}{R_{ij}} \cdot \frac{\sqrt{SH_{ij}^2 + SV_{ij}^2}}{0.63}}{\sum_{(i,j)} \frac{m_{0ij}/M_0}{R_{ij}}} \tag{2.5}$$

Total modification factor is proposed as geometric mean of eqns. 2.4 and 2.5. The factor has distribution characteristics with average one. It means that the factor does not affect on the average of original attenuation formulae.

3. EFFECT OF PROPOSED FACTORS

Effects of the proposed factors are demonstrated. Figure 2 shows a fault rupture model. Fault length and width are assumed as 40 km and 18 km respectively. Dimension of each sub-fault is 2km square. Depth of fault top is set as 2 km. Dense shadow areas indicate asperities and others are background slips. Two rupture starting points, star symbols in figure 2, are assumed. Detailed rupture parameters are evaluated using a Recipe proposed by Irikura et al. (2004). Total seismic moment is 2.46×10^{19}Nm, M_W=6.9, and stress drop on the asperities is 14.1 MPa. Shear wave velocity of the target area is assumed as 600 m/s.

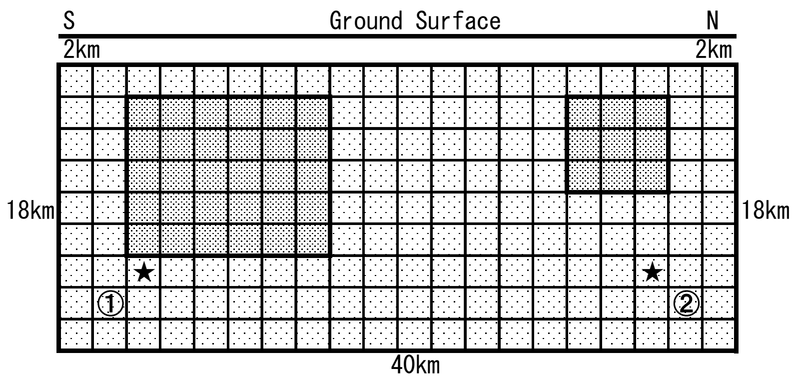

Figure 2 Assumed fault rupture model for demonstration

3.1. Strike Slip Fault

Figure 3 shows distribution of modification factors assuming the fault in figure 2 as strike slip with 90 degrees, vertical, dip angle. The directivity factors are different for the case of two rupture stating points. Figure 4 is distributions of JMA, Japan Meteorological Agency, scale seismic intensity. The left panel shows the distribution by original attenuation [Si and Midorikawa, 1999] and the center and the right panels are those with considering modification factors. JMA intensities are calculated from peak ground velocities [Midorikawa et al., 1999]. Different shake maps are obtained from two rupture starting points. It is an advantage of introduction of the modification factors due to rupture propagation effects.

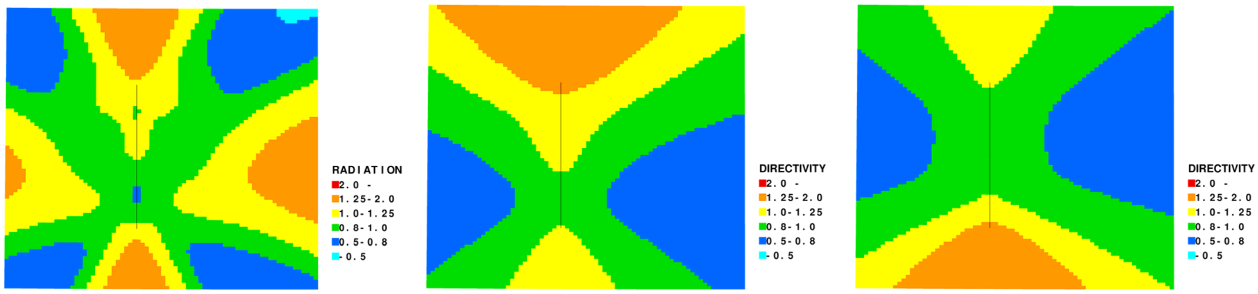

Figure 3 Distributions of modification factors due to strike slip fault
Left: radiation pattern, Center and Right: directivity
from rupture starting points 1 and 2.

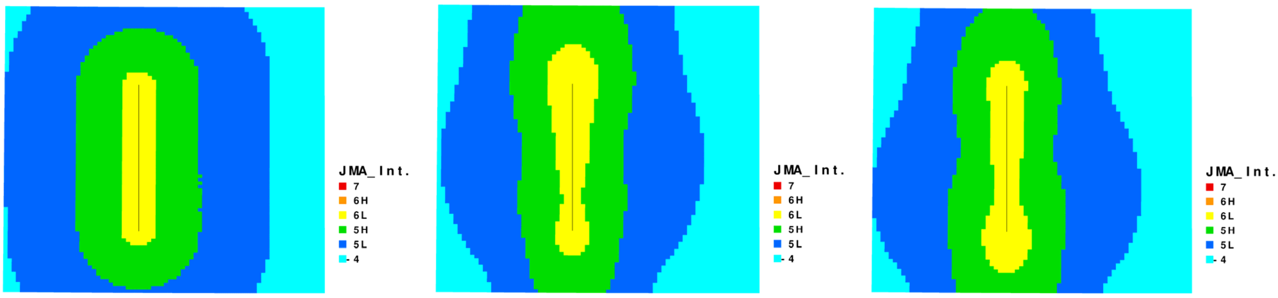

Figure 4 Comparison of shake maps by original and modified attenuation formulae
Left: original, Center and Right: modified from rupture starting
points 1 and 2.

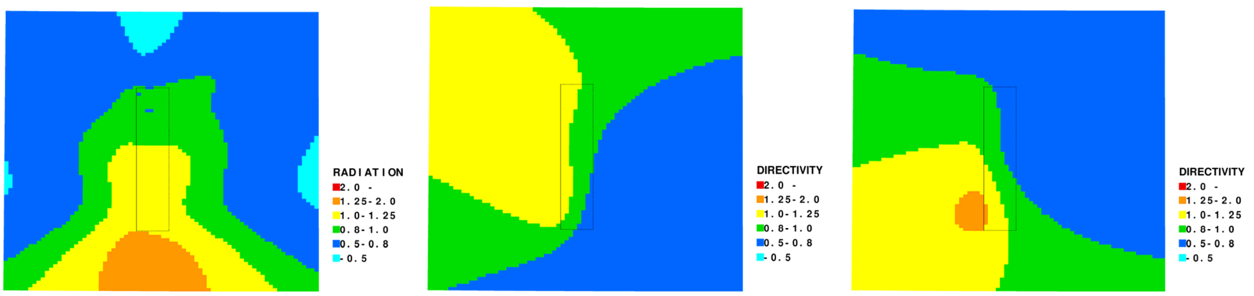

Figure 5 Same as figure 3, but for dip slip fault

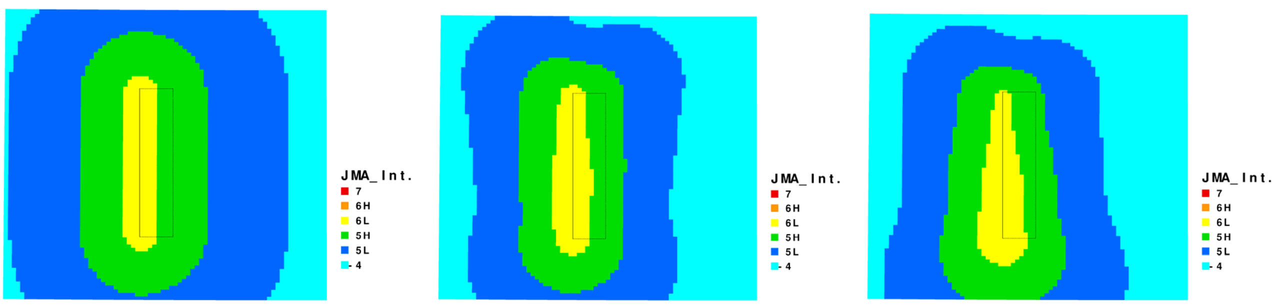

Figure 6 Same as figure 4, but for dip slip fault

3.2. Dip Slip Fault

Figure 5 shows distribution of modification factors assuming the fault in figure 2 as dip slip with 60 degrees dip angle. The effects of modification factors are different from those of strike slip case. Figure 6 is distributions of JMA scale seismic intensity. Dip slip fault shows different shake maps from those of strike slip fault. It is not possible by using previous empirical attenuation formula.

4. EXAMPLE

Shake maps of a damaging earthquake, the 1995 Hyogo-ken Nanbu (Kobe) earthquake, are shown in figure 7. In the maps, site amplifications are considered empirically using AVS30 [Midorikawa et al., 1992, Wakamatsu et al., 2005]. Source model is after Yamada et al. (19999). The original attenuation underestimate ground motion in the Kobe city area, northern part of Osaka prefecture, and Kyoto city area where forward directivity effects were considered to be dominant. Using the proposed modification factors, ground motions in the areas above increase as observed by damage distributions.

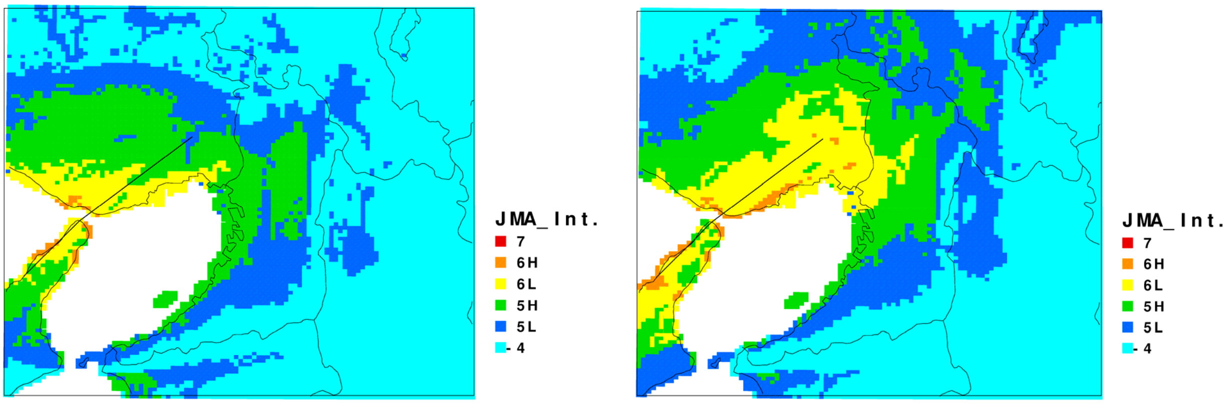

Figure 7 Example of shake maps due to the 1995 Hyogo-ken Nanbu (Kobe) earthquake
Left: original attenuation using equivalent hypocentral distance,
Right: modified by proposed factors.

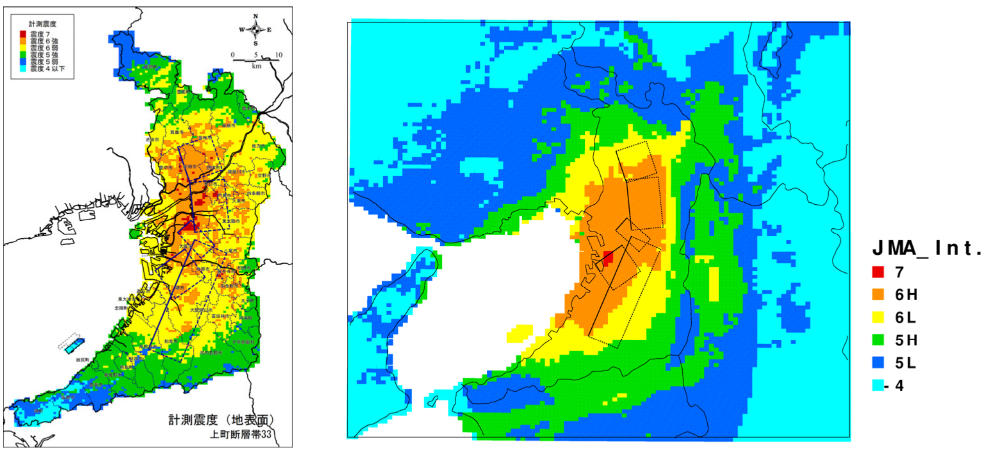

Figure 8 Example of shake maps due to the hypothetical Uemachi fault earthquake
Left: simulation by detailed method [Osaka Pref., 2007],
Right: by proposed method.

The proposed method is compared with a detailed simulation in Figure 8. The left panel shows a shake map calculated by hybrid technique with stochastic Green's function method and 3-D finite difference. Non-linear site response is also considered. Shake map by the proposed method, right panel, gives acceptable result.

5. CONCLUSIONS

Modification factors of fault rupture propagation effects are proposed for empirical attenuation formulae of ground motion. The results of this study are as follows.

1) Effects of source radiation pattern and forward directivity are introduced into empirical attenuation formulae of ground motion.
2) The proposed modification factors spatially change gradually around the source fault.
3) The averages of the factors around a source fault are unalterably one. It means the factors are applicable for any attenuation formulae without changing their average ground motion..
4) Rupture heterogeneity is also considered in the modification factors.
5) The proposed factors affect clearly on shake maps in the vicinity of a target source fault.
6) Estimated ground motion distribution due to the past damaging earthquake is more realistic than that by original attenuation formula.

We have to adjust the modification constants by using ground motion distribution of past earthquakes to give more accurate ground motion. After the process, we need to create new attenuation formula which considers the effects proposed in this paper. We hope it gives smaller dispersion than previous attenuation formulae.

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