Stochastic Finite-Fault Method Based on Dynamic Corner Frequency to Simulate the Mw6.2 Tottori earthquake in Japan

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Abstract: Stochastic finite-fault method is the main method to simulate near field strong earthquakes in current seismic engineering. For specific ground motion, the accuracy of parameter selection is important, such as field effect, because the number of rock sites is scarce in many areas of China, the calculation of crustal amplification and site amplification of a specific soft soil site can not only eliminate the limitation of station selection, but also improve the accuracy of simulation results. In this paper, a stochastic finite-fault method based on dynamic corner frequency is used to simulate the Mw6.2 Tottori earthquake on October 21, 2016 in Japan. The comparison with the actual records shows that the simulation results are in good agreement with the short period and have great feasibility. This paper discusses the differences between the simulated response spectra (PSA) of stations with various azimuths and the observed one. Meanwhile, it also demonstrates the dissimilarities in simulation results between the stations located on the hanging wall and those located on the flat wall of the fault plane. The results show that for soft soil sites, crustal amplification and site amplification, as well as the geometrical position relationship between stations and faults have a certain impact on the simulation results. Based on the calculation of specific crustal amplification and site amplification in a specific region, the location relationship between stations and faults is included in the analysis, so that the future earthquake can be predicted more accurately, and an important reference can be provided for the disaster assessment in this region and the site selection of major projects.

1. Introduction

At 14:07 on October 21, 2016, an Mw6.2 earthquake occurred in the central Tottori in western Japan. More than 20 people were injured and more than 300 houses were damaged or completely destroyed. The spatial distribution of aftershocks measured by National Research Institute of Earth Science and Disaster Resilience (NIED) indicates that the earthquake is a left-lateral strike-slip earthquakes in shallow crust from NNW to SSE. The focal mechanism solution shows that the strike angle and dip angle of the earthquake are 162°N and 88°E, respectively. The starting point of the rupture is 35.3806°N and 133.8545°E, and the depth is 11.58km. According to 594 sets of recordings obtained by K-NET and KiK-net of NIED, the maximum peak ground acceleration reaches 1494gal, which occurred in Kurayoshi. Strong earthquake sensations were also observed in surrounding areas such as Okayama and Shimane.
2. The Stochastic Finite-Fault Method Based on Dynamic Corner Frequency

Boore[1] proposed the a stochastic point source method (SMSIM) to simulate ground motion. This method is based on the viewpoint that the geometric size of fault can be neglected as a point source for far-field earthquakes, but for the near-field earthquake, fault geometry can’t be neglected. So in 1998, Beresnev and Atkinson[2] proposed a stochastic finite-fault method based on static corner frequency (FINSIM). In order to eliminate the dependence of the FINSIM method on the size of subfaults and ensure the conservation of high frequency energy, Motazedian and Atkinson[3] improved the FINSIM method and proposed a stochastic finite-fault method based on dynamic corner frequency, hereinafter referred to as EXSIM method.

In the EXSIM method, the synthesized acceleration time history \( a(t) \) expressed as the superposition result of the acceleration time history of all subfaults after a certain time delay.

\[
a(t) = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} a_i(t + \Delta t_{ij})
\]

where \( N_i \) and \( N_j \) are the number of subfaults along fault strike and dip, respectively. \( a_i \) is the shear wave acceleration of the subfault in the column \( j \) of line \( i \). \( \Delta t_{ij} \) is the corresponding time delay. Each subfaults is considered as a point source based on the \( \omega^2 \) model of Brune[4]. The acceleration spectrum of S-wave can be expressed as:

\[
a_{ij}(t) = \frac{CH_{ij} \mu_{0ij} (2\pi f)^2}{1 + (f / f_{0ij})^2} \exp\left(-\pi \kappa \exp\left(-\pi \beta / Q \right) f_{0ij} \right)
\]

Where \( M_{0ij}, f_{0ij} \) and \( R_i \) are the \( ij \)th subfault seismic moment, corner frequency and distance from the observation point, respectively. \( H_q \) is the high frequency energy compensation factor. The constant \( C = R_i F V / (4\pi \beta F) \). \( R_i \) is a radiation pattern, which is usually taken as a constant of 0.55, and some references are taken as a value of 0.63. \( F \) is the effect of the free surface, usually taken as a value of 0.63. \( V \) is the horizontal component pattern with a value of 0.707. \( \rho \) is the density of the medium at the source of the earthquake. \( \beta \) is the shear wave velocity at the source of the earthquake. \( \exp(-\pi \kappa) \) is the high frequency attenuation. \( \kappa \) is the high frequency attenuation factor (kappa). \( \exp(-\pi \beta / Q) \) is high frequency attenuation, and \( Q \) is the quality factor. \( 1 / R_i^2 \) is the a path-dependent geometric spreading parameter.

In EXSIM method, the corner frequency \( f_{0ij} \) decreases with the increase of the rupture area. It is a function closely related to rupture time. When the fracture ends, there is \( f_{0ij}(t_{fracture}) = f_0 \), \( f_0 \) is the corner frequency of the whole fault proposed by Boore[1]. \( f_{0ij}(t) \) is shown in equation (3):

\[
f_{0ij}(t) = 4.9 \times 10^6 (4\pi \beta M_{0ij} / \Delta \sigma N_i)^{0.87} \sigma^{-1/3}
\]

In equation (3), \( M_{0ij} \) is the average seismic moment, \( M_{0ij} = M_i / N_i \), and \( M_i \) is the seismic moment of the earthquake studied. \( \Delta \sigma \) is stress drop. \( N_i(t) \) is the function of the number of rupture subfaults varying with rupture time.

The dynamic corner frequency will cause the spectral level of the subfaults to decrease as the corner frequency decreases, so radiant energy in the high frequency band to decrease with the corner frequency. Therefore, in 2005, Motazedian and Atkinson[3] introduced the high-frequency energy compensation factor \( H_q \), and the equation (4) is its discretized expression:

\[
H_q = \left( \frac{N \sum \left[ f I \frac{1 + \left( f / f_{00} \right)^2}{\left( f / f_{00} \right)^2} \right]^2}{\sum \left[ f I \frac{1 + \left( f / f_{00} \right)^2}{\left( f / f_{00} \right)^2} \right]^2} \right)^{1/2}
\]
3. **Strong motion data and the selection of input parameters**

Tottori earthquake fault is only 20 km long. Since the soil layer amplification effect is also considered in this paper, we selected 22 stations in K-NET and KiK-net with a focal distance of less than 60 km from NIED. The distribution of stations is shown in Figure 1.

![Figure 1. Seismic stations distribution map of Tottori earthquake on October 21, 2016](image)

For the source parameters, according to the focal mechanism solution provided by F-net, the source of the Tottori earthquake is located at 35.3806°N, 133.8545°E, and the focal depth is 11.58 km. The strike angle and the propensity angle are 162°N and 88°E, respectively. The fault geometry is 20 km long and 16 km wide, and the length and width of the subfaults are set to 2 km. The results of the inversion by Kubo[5] et al. in 2017 show that the entire rupture reaches the final slip after about 6 s, and the maximum slip is about 70 cm. The distribution of fault slip is shown in Figure 2.

![Figure 2. Fault slip distribution map](image)

The stress drop obtained by the combination of the source spectrum ratio method and the equation (3) is 2.797 MPa. Duration uses the model that Beresnev and Atkinson[7] predicted the ground motion in Eastern North America.

The crustal amplification factor is calculated using the quarter-wave method proposed by Boore and Joyner[8]. In addition, for the soil site, the site amplification should be considered. The vertical magnification effect is not significant in horizontal seismic magnification frequency band of soil site, so the magnification effect of site can be estimated according to the ratio of geometric mean value of horizontal acceleration amplitude to vertical acceleration amplitude[9]. This method is called H/V...
spectral ratio method.

The geometrical spreading uses the three-stage model of Beresnev and Atkinson[7]. The quality factor uses the quality factor of the Japanese Polygon2 shallow source earthquake in 2011 by Oth and Bindi[10], \( Q(f) = 127 \cdot f^{0.64} \). For frequency-independent high-frequency attenuation, Anderson and Hough[11] define it as the linear attenuation of the acceleration amplitude spectrum starting at a high frequency after a certain frequency in semi-logarithmic coordinates, and use the slope value (\( \kappa \)) of the amplitude spectrum on the linear frequency band to characterize this attenuation. Equation (5) is the relation between the \( \kappa \) obtained by the least squares fitting and the epicenter distance \( R \).

\[
\kappa = 0.026 + 2.065 \times 10^{-5} R
\]

(5)

The basic parameters used for Tottori earthquake simulation are listed in Table 1.

| Parameter name                      | Parameter value |
|-------------------------------------|-----------------|
| Seismic moment (Mw)                 | 6.2             |
| Source location                     | 35.3806°N, 133.8545°E |
| Depth (km)                          | 11.58           |
| Trend and tendency                  | 162°N, 88°E    |
| Fault size (km)                     | 20 × 16         |
| Stress drop (MPa)                   | 2.797           |
| density (g/m³)                      | 2.7             |
| Shear wave velocity (km/s)          | 3.6             |
| Pulse percentage                    | 50%             |
| Geometric attenuation               | Atkinson and Boore (2006) |
| Quality factor \( Q(f) \)           | 127 \( \cdot f^{0.64} \) |
| kappa                               | 0.026           |

4. Results and discussion

For the simulation, 22 stations within an epicenter distance of 60km were selected in this paper, and all stations were simulated with the EXSIM program. We take station OKY005 and OKYH11 as examples, the comparison of simulation results and records of the two stations is shown in Figure 3.

According to Figure 3, the PGA of OKY005 is 124.56gal, 105.96gal and 115.46gal, respectively. And, the PGA of OKYH11 were 111.31gal, 122.7gal and 103.89gal, PGA the overall fitting of ideal, but the duration is significantly shorter than record, the ground motion is in addition to the relationship with the magnitude and distance may also be affected by the terrain effect. When simulating the 2014 Ludian earthquake in Yunnan province, Wang[12] pointed out that the shorter duration of the simulations than the records might be related to the topographic effect of the mountain. Station OKY005 located the Chugoku mountain, Therefore, so this situation may be due to the mountain effect.
For the acceleration response spectrum PSA, the geometric mean of the east-west and south-north PSA of OKY005 and OKYH11 as the horizontal PSA. Figure 4 shows the comparison between horizontal PSA of the records and simulation PSA with damping ratio of 5%. It can be seen that the PSA of the two stations is larger in the long period, but the results in the short period are in good agreement with the actual record.

In order to explore the relationship between the simulation results and the spatial position of the stations, as well as the directive effect of the rupture, we will discuss the results of all 22 stations. As for the relationship between the station azimuth and the simulation results, we examined the relationship between the residual and azimuth of PSA at six period points of \( T = 0.1 \)s, \( T = 0.2 \)s, \( T = 0.5 \)s, \( T = 1.0 \)s, \( T = 2.0 \)s and \( T = 5.0 \)s, respectively. As shown in Figure 5, there is a significant spatial correlation between the residual and azimuth of PSA. Fault strike angle is 162 °, in Figure 5 at the front of a rupture range (azimuth angle 150 ° ~ 210 °) simulation results is lower than other azimuth (azimuth angle 60 ° ~ 120 ° and 240 ° ~ 300 °), especially in the period of more significant for a long period of time. It can be concluded that in the long period, the simulation results of the region behind the fracture are generally lower than the actual records, while the results of the region ahead of the fracture are more reasonable. The influence of azimuth of the short period between 0.1s and 0.5s on the simulation results is not significant compared with that of other periods. Generally speaking, there is little difference between the simulation results and the actual results when studying the high frequency band of ground motions, and the influence of azimuth on the relatively low frequency band is not significant.
For near field ground-motion, hanging wall and flat wall of the fault are an important part of the engineering characteristics. Tao and Wang[13] studied the expression of seismic mode on the directive effect and hanging wall effect of rupture by simulating three rock stations of Northridge earthquake in the United States, and they believe that the finite fault method is feasible in showing the directive effect and hanging wall effect. Therefore, we only study the influence of the hanging wall and flat wall on the simulation results. The information of each station is shown in Table 2, where the negative fault distance indicates that the station is located at the flat wall of the fault, and vice versa. The residuals of horizontal PGA and the simulation PGA is shown in Table 2. The residuals of stations located at the hanging wall are close to zero line, but the residuals of stations located at the flat wall are far from the zero line. This shows that the simulation results of stations located at the hanging wall are better than the stations located at the flat wall.

Table 2. Station information at the upper and lower wall of the fault

| Station code | Fault distance (km) | Horizontal PGA (gal) | EXSIM PGA (gal) | Residuals |
|--------------|---------------------|----------------------|----------------|----------|
| OKY001       | 18.36               | 147.00               | 149.24         | -0.10    |
| OKY015       | -4.54               | 379.69               | 558.54         | 0.53     |
| OKYH09       | 22.84               | 196.70               | 229.48         | 0.32     |
| TTR002       | -46.68              | 69.44                | 76.7           | -0.39    |
| TTR003       | -42.44              | 170.87               | 100.58         | -0.02    |
| TTR004       | -28.20              | 174.09               | 165.35         | -0.15    |
| TTR007       | 38.54               | 114.51               | 100.49         | 0.13     |
| TTR009       | 59.46               | 109.44               | 103.1          | -0.11    |
| TTRH02       | 49.86               | 86.10                | 96.04          | 0.06     |

5. Conclusions

In this paper, the main aftershock records and borehole information obtained from K-NET and KiK-net are used to simulate the earthquake of Mw6.2 in Tottori, Japan. The stochastic finite fault method is still based on the stochastic point source approach. Therefore, the synthetic acceleration time history adopted inverse-Fourier utilizes the random phase, which makes the synthetic
acceleration time history and observation recordings considerably different. In this case, PGA and PSA of records and simulation are studied. Results show:

1. According to the discussion in the previous section, the site amplification and crustal amplification can’t get ideal simulation results for the stations with soil mainly composed of gravel soil and sandy soil, and the site amplification of various soil materials can be further classified and explored in the future.

2. The simulated PSA of stations located at the rear area of fault (azimuth angle 60° ~ 120° and 240° ~ 300°) underestimates the observed PSA in the period greater than 0.5s. Moreover, the simulated PSA of stations located at the area ahead of the fault (azimuth angle 150° ~ 210°) is consistent with the observed PSA in the whole period. The accuracy of the high frequency random finite fault method is acceptable.

3. The simulated PGA residuals of the stations located at the hanging wall of the ruptured fault are closer to the zero line than the stations located at the flat wall, and the results are more ideal. The simulation results in the high frequency band and the records fitting better, especially the simulation results of stations located at the hanging wall or at the area in front of rupture are more accurate than those of other stations, so the simulation results of the above regions can be used as a more reliable reference for the seismic structural design of buildings, site selection, response spectrum analysis in the affected areas and disaster prediction in some areas where stations are scarce.

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