The Simulation of Tangshan Earthquake Intensity Field Based on Stochastic Finite Fault Model

Jingyan Lan1,2*, Yanwei Wang1,2

1 College of architecture and civil engineering, Beijing university of technology, Beijing, 100022, China
2 College of civil engineering and architecture, Guilin University of technology, Guilin, Guangxi Province, 541004, China
*Corresponding author’s e-mail: lanjy1999@163.com

Abstract. The random ground motion simulation method based on the finite fault model is one of the proven methods in the field of simulating high frequency ground motion. Taking the extreme earthquake zone of the Tangshan earthquake in 1976 as the research goal, by combing the research results of the predecessors, the calculation model of the target zone was established and the parameters of the source model were determined. The local site data and the site dynamics parameters of the target zone were utilized. The quarter-wavelength method is used to obtain the local field amplification effect parameters. The strong ground motion simulation results of Tangshan earthquake are given by using the stochastic finite-fault model. The reliability and applicability of the method is confirmed by comparing with the historical seismic macro-intensity. The results will help improve the seismic design accuracy of the project in areas lacking strong vibration observation records, and have certain reference value and engineering significance for the development of urban earthquake prevention and disaster prevention measures.

1. Introduction

The strong ground motion caused by earthquake is the main cause and triggering factor of engineering structure damage and surface geological disaster. The occurrence, propagation and kinematics of strong ground motion are the main research contents of engineering seismology. Scientifically and reasonably predicting, estimating and simulating strong ground motion is an important way and means to effectively mitigate the loss of earthquake disasters. Therefore, this research is deeply concerned by the seismological and engineering fields.

As we all know, the strong vibration observation record is the important basic data of engineering seismic fortification basis and engineering seismology research. For the lack of strong earthquake record area, the basic parameters of strong ground motion (amplitude, spectrum, duration) are simulated by quantitative expressions. It is a very important research content. At present, the simulation methods for strong ground motion can be divided into three types: deterministic methods (Aki, 1968; Hartzell, 1978; Irikura, 1983), stochastic methods (Beresnev and Atkinson, 1998; Boore, 2003; Zeng, 1994; Irikura, 2000) and the hybrid method. In comparison, the finite fault model based on the stochastic method can satisfactorily reflect the randomness of short-period ground motions, and the ground motion of the high-frequency components of the near-field and large-seismic earthquakes is satisfactory, and the regional ground motion field can be developed. The method of ground motion can be used to simulate theoretical seismograms or intensity maps. The simulation and prediction of
ground motion fields using finite fault models in the past decade have been actively promoted in most urban active layer fault techniques (Tao et al., 2003; Wang et al., 2008; Liu et al., 2010; Sheng et al., 2012; Shen et al., 2013; Zhang et al., 2018), and received wide recognition from the engineering and seismological circles, and achieved a series of rich results.

On the basis of summarizing the previous studies, this paper is based on the characteristics of strong earthquake near-field vibration. Taking the Tangshan Ms7.8 earthquake on July 28, 1976 as the research background, the Tangshan earthquake extreme earthquake area is taken as the research scope, considering the front array. Near-field characteristics and near-fault effects, using Motazedian and Atkinson (2005) based on stochastic finite fault method to synthesize ground motion Exsim_Beta program, the simulation results of near-field strong ground motion of Tangshan earthquake are given. The reliability and applicability of the method is confirmed by comparing with the actual macro intensity. The research results have certain reference value for the research work of site effect in the Tangshan earthquake area in the future. It has certain theoretical and practical significance for guiding the seismic fortification requirements in high-intensity areas and improving the precision of design ground motion parameters in high-intensity areas.

2. Introduction to stochastic finite fault model

The basic idea of the stochastic finite fault model method is to treat the seismic fault plane as consisting of several \((n_l \times n_w)\) sub-faults, each sub-fault is a point source (or sub-source), where \(n_l\) is along the fault The number of divided sub-faults, \(n_w\) is the number of sub-faults divided along the trend of the fault, as shown in Figure 1. The rupture process of the earthquake is radiated outward from the starting point of the rupture at a certain rupture velocity (generally 0.8 times the shear wave velocity). When propagating to the center of each subsource, the subsource is triggered, and each sub-source is triggered. The acceleration time history of the fault at the observation point is calculated by the random point source model. The acceleration time history \(a(t)\) generated by the whole fault at the observation point is superimposed on the basis of reasonable time delay of the sub-fault.

Expressed as:

\[
a(t) = \sum_{i=1}^{N_l} \sum_{j=1}^{N_w} \sum_{k=1}^{N_s} a_{ij}(t + \Delta t_{ijk})
\]

Figure 1. Geometric Schematic of Stochastic Finite Fault Model (Wang et al., 2012)

Where \(N_l\) and \(N_w\) are the number of sub-faults along the strike and down-dip directions respectively; \(N_s\) is the number of times the sub-source is triggered; \(\Delta t_{ijk}\) is the time delay of the seismic wave propagating from the fracture start point to the \(ij\)-th sub-source and the sub-source The sum of the propagation time delays to the observation point; \(a_{ij}(t)\) is the ground motion caused by the shear wave at the observation point of the \(ij\)th subsource.

3. Model establishment and determination of calculation parameters

3.1. Determination of source model parameters in target area
Taking the Tangshan earthquake in 1976 as an example, this paper establishes a stochastic finite fault source model and determines the relevant parameters of the model. According to the seismogenic tectonic analysis and focal mechanism results provided by the National Seismological Bureau's "Tangshan Earthquake" in 1976 (1982), the Tangshan earthquake is considered to be a near-slip earthquake, which occurred in the Tangshan fault zone in the Tangshan diamond-shaped block. Zhang Zhili et al. (1989) recalculated the possible rupture length of 77 km according to the relocated source position and more supplementary data, which is the result obtained by using the epicenter epicenter distribution map and Chen Yuntai et al. (1979) using terrain inversion. The result (84 km) is basically the same. Taking these results into consideration, the plane geometry model of the Tangshan earthquake we selected is shown in Figure 2.

![Figure 2. Target area active fault distribution map](image)

According to the results of the predecessors, the Tangshan earthquake fault orientation (Strike/dip) 45°/88°, moment magnitude Mw 7.6, and focal depth 15 km were set in the 1976 Tangshan earthquake, and the epicenter position was set to 118.2° east longitude and 39.6° north latitude. The path duration and geometric diffusion function, the site response items are considered by the quality factor of North China. The empirical relationship proposed by Beresnev and Atkinson is used. The study area is delineated at (39°N-40°N, 117°E-119°E) with a grid accuracy of 0.03° (~3 km) for a total of approximately 2,000 grid points. The key results were calculated including the peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and the shortest distance D of the grid point to the fault for each grid point. In summary, the model parameters used to simulate the 1976 Tangshan earthquake are shown in Table 1.

| Name of parameters                          | Value of parameters          |
|---------------------------------------------|------------------------------|
| Fault orientation                          | 45°/88°                      |
| The scale of the fault along the strike and down direction /km | 80×30                        |
| Sub-fault size /km                         | 2×2                          |
| Fault depth /km                            | 5                            |
| Latitude and longitude of the upper boundary of the fault | 39.43°N 118.01°E            |
| Mw                                          | 7.6                          |
| Q(\(f\))                                   | 202 \(f^{0.7}\)             |
| Ground motion path duration                 | 0.16R (10<R<70km)            |
|                                           | -0.03R (70<R<130km)          |
At present, the methods used to evaluate the amplification effect of the site mainly include standard spectral ratio method, ground pulsation method and wave impedance method. For a specific site, only the ground soil distribution and wave velocity structure can be used to estimate the impact of the site on the bedrock ground motion. The standard spectral ratio method requires a station in a stable bedrock as a reference station, and assumes that the seismic waves received by the two stations are identical and ignores the attenuation of the seismic waves between the two observation stations. The ground pulsation method is based on a single spectral ratio method. It is widely used in the engineering field because of its simplicity and convenience. However, it is important to assume that the H/V spectral ratio at the bedrock is 1. In some studies, this assumption is still debatable. The wave impedance method, also known as the quarter-wave method, relies on the local site data and site dynamics parameters of the study area, and is given by statistical analysis. It is suitable for areas with rich engineering geological data and shear wave velocity data, and shallow The site model can more realistically reflect the amplification effect of the site.

As far as the target area is concerned, we have completed a large number of seismic safety evaluation reports in Tangshan, and accumulated a wealth of site condition data. It is easier to obtain the parameters of the local site amplification effect than the other two methods. Therefore, this work selects the wave impedance method to determine the amplification effect of the site. A total of 130 shear wave velocity data of seismic boreholes up to 100 meters deep were collected in the study area. Most of the boreholes are distributed in Lubei District, Lunan District and Fengnan District of Tangshan City, covering a total of 480 square kilometers, covering 1976. The Tangshan earthquake has a range of XI and X degrees. After combing analysis, the shear wave velocity was analyzed statistically with depth (Fig. 3).
Using the quarter-wave method (Boore, 1997), the amplification factor for different frequency bands of the local site is calculated. In order to calculate the field amplification factor, according to the empirical formula (2) given by Roten (2012), the relationship between the shallow shear wave velocity $V_s$ and the quality factor $Q_s$ is established. The calculated amplification factor of the target zone is shown in Table 2.

$$Q_s = \begin{cases} 13 & v_s < 0.3 \text{km} \cdot \text{s}^{-1} \\ -16 + 104.13v_s - 25.22v_s^2 + 8.21v_s^3 & v_s \geq 0.3 \text{km} \cdot \text{s}^{-1} \end{cases}$$ (2)

| F(Hz) | $A_m$ | F(Hz) | $A_m$ |
|-------|------|-------|------|
| 0.33  | 1.24 | 5.00  | 5.01 |
| 0.50  | 1.46 | 10.0  | 5.01 |
| 1.00  | 3.86 | 11.1  | 5.01 |
| 1.67  | 4.36 | 14.3  | 5.01 |
| 2.50  | 4.66 | 20.0  | 5.01 |
| 3.33  | 4.81 | 1000  | 5.01 |

4. Simulation result analysis

4.1. Strong ground motion field distribution results

According to the above-mentioned determined source parameters, propagation medium and site parameters, the stochastic method and program of finite faults are used to calculate 10 times, and the average ground motion field generated by Tangshan fault is calculated.

In order to be able to give a relatively complete peak acceleration field, peak velocity field and peak displacement field, this work has expanded the calculation range, the grid point spacing is $0.03^\circ \times 0.03^\circ$, a total of 1984 calculation control points.
4.2. Comparison of macro intensity data

As we all know, the seismic intensity is an important indicator to measure the degree of damage to the surface and engineering buildings. It is a relatively abstract concept. It is generally based on the site assessment of earthquake damage, because of the subjective factors of the assessed person and the structure of the building. The impact is not accurate, so the seismic intensity is not an accurate parameter. With the accumulation of ground motion observation records worldwide, the replacement of seismic intensity with ground motion parameters has become an important way for the development of seismic design codes in various countries. China has also changed from the fourth generation seismic zoning map (2001). The ground motion parameter zoning of acceleration and characteristic period replaces the previous intensity division.

In China's current seismic design specifications, there is a certain conversion relationship between peak acceleration and seismic intensity. Some studies have shown that there is a certain irrationality in the single use of a certain ground motion parameter. The main reason is the seismic intensity and Peak acceleration (PGA) and peak velocity (PGV) are highly correlated. Peak acceleration (PGA) decays faster with distance and can reflect near-field intensity distribution. Peak velocity (PGV) can respond to far-field intensity with slower distance attenuation. Distribution (Shen Wenhao et al., 2013). Worden et al. used the California earthquake data collected by USGS “Did you feel it” to give the empirical relationship between different types of ground motion parameters and modified McCalley intensity (MMI), and pointed out that combining two ground motion parameters. The MMI is smaller than the standard deviation of the MMI obtained from the single ground motion parameter.

Atkinson and Sonley (2000) based on California earthquake data, considering the factors of peak acceleration (PGA), peak velocity (PGV), magnitude and epicentral distance, and explored the relationship between the modified McCalley intensity (MMI):

\[
\begin{align*}
\text{MMI} &= -9.32 + 6.08 \log(\text{PGA}) + 2.81 \log(D) - 0.18M \\
\text{MMI} &= 6.81 + 5.86 \log(\text{PGV}) + 2.16 \log(D) - 1.52M
\end{align*}
\]

(3)

In view of the fact that MMI is similar to the definition and classification of the intensity specified in China's GB/T 17742-2008 China Earthquake Intensity Scale, using the formula (2), the MMI of the study area is calculated, and the results are compared with the 1976 Tangshan earthquake macroscopic intensity survey. Comparing the seismic lines (Fig. 4), it can be seen that the range of the intensity of the random simulation at 8 and 9 degrees agrees well with the macroscopic data, but due to the limitation of the formula (2) itself. The intensity of the area near the fault is less than the scope of the extreme earthquake zone. In addition, formula (2) is an empirical formula given by Atkinson and Sonley based on California earthquake data. Due to different geological structures and site attenuation characteristics in different places, the coefficients of the conversion formula will also be different. There will also be some differences of the results between the actual conditions and theoretical result.

It can be seen from Fig. 4 that the acceleration, velocity and displacement fields are distributed along the fault, the contour of the source region is relatively complex, and the fault is distributed in an elliptical shape near the fault. The farther away from the fault, it gradually evolves into a circular shape, which is in line with the existing scientific understanding. The ground motion field far from the rupture point of the earthquake is higher than the rupture point near the earthquake, and the contour is more smooth and smooth, showing the directional effect of the near fault. The calculation results show that the peak acceleration is 1734 gal, the peak velocity is 187.1 cm/s, and the peak displacement is 116.8 cm.
5. Conclusion

Tangshan is located in the center of the Bohai Bay. It is the economic center of Hebei Province, with dense population and developed economy. In the seismic tectonic system, the Tangshan area is located at the intersection of the seismic belt of the North China Plain and the Zhangjiakou-Bohai seismic belt. The seismic activity is frequent and is greatly affected by the historical earthquake. It is shocked by the 7.8-level Tangshan earthquake in China and abroad. The intensity of the earthquake zone is as high as XI. From the perspective of engineering geological conditions, the geological environment in Tangshan area is complex, tectonic development, and various geological disasters occur frequently. The Quaternary overburden of tens to hundreds of meters is common in the surface layer of Tangshan area. The soil type of the site is weak and the liquefied soil is widely distributed. It is an unfavorable part of the earthquake risk of the site. At the same time, due to the relatively deep research on seismic activity, tectonic geology and engineering geology in Tangshan area, a large number of major construction projects have been carried out in recent years, and a large number of on-site drilling data have been accumulated. With the establishment and operation of the strong vibration observation network, some earthquake records have been made, making this research possible.

Based on the above background, based on the research results of Tangshan earthquake drilling data, engineering geological data, seismic activity, active fault detection and seismic hazard assessment, combined with the previous work results, the regional seismic stress drop was determined. Calculation parameters such as crustal attenuation parameters (quality factor, overlap distance) and site high-frequency attenuation factor, based on the source kinematics model, determine all the global parameters and local parameters of the source, and calculate the target area by using the stochastic finite-fault model method. The results of the strong ground motion prediction of the active fault (Tangshan-Guye fault), the main conclusions are as follows:

(1) Collecting the shear wave velocity data of 130 boreholes in the study area, establishing the relationship between the shallow shear wave velocity Vs and the quality factor Qs, and determining the shallow magnification factor of the target zone by using the quarter-wavelength method.

(2) According to the determined source parameters, propagation medium and site parameters, the ground motion acceleration field, velocity field and displacement field generated by Tangshan fault are given by using the stochastic method and procedure of finite fault. The results fully indicate Tangshan ancient The directional effect of the smelting fracture.

(3) Using the conversion relationship between ground motion parameters and intensity, the simulated intensity contour results are calculated and compared with the macro seismic damage intensity. The random finite fault model method is used to simulate the high frequency ground motion simulation feasibility and applicability.
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