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Research Note

The inversion of anelastic coefficient, source parameters and site respond using genetic algorithm*

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It gradually becomes a common work using large seismic wave data to obtain source parameters, such as seismic moment, break radius, stress drop, with completing of digital seismic network in China (Hough, *et al*, 1999; Bindi, *et al*, 2001). These parameters are useful on earthquake prediction and seismic hazard analysis. Although the computation methods of source parameters are simple in principle and the many research works have been done, it is not easy to obtain the parameters accurately. There are two factors affecting the stability of computation results. The first one is the effect of spread path and site respond on signal. According to the research results, there are different geometrical spreading coefficients on different epicenter distance. The better method is to introduce trilinear geometrical spreading model (Atkinson, Mereu, 1992; Atkinson, Boore, 1995; WONG, *et al*, 2002). In addition, traditional site respond is estimated by comparing with rock station, such as linear inversion method (Andrews, 1982), but the comparative estimation will introduce some errors when selecting different stations. Some recent research results show that site respond is not flat for rock station (Moya, *et al*, 2000; ZHANG,. *et al*, 2001; JIN, *et al*, 2000; Dutta, *et al*, 2001). The second factor is to obtain low-frequency level and corner frequency from displacement spectrum. Because the source spectrum model is nonlinear function, these values are obtained by eye. The subjectivity is strong. The small change of corner frequency will affect significantly the result of stress drop.

The seismic record is the seismic information recorded by a seismograph when an earthquake occurs. It is a comprehensive information including the characters of seismic sources, spreading path of seismic wave and site respond *etc*, therefore, it is necessary to distinguish the effects of seismic source, spread path and site respond. The method proposed by Atkinson and Mereu can better solve this problem (Atkinson, Mereu, 1992), but it is based on the data of fixed seismic network. In this condition, the site responds are independent of frequency basically and fluctuate around a constant in all stations. For the data of mobile network, there are some errors of source parameters using this method because the site responds of some seismic stations change largely, however, the results of geometry spread coefficients and anelastic coefficient do not change using this method. In order to calculate the data in mobile seismic network, Moya, *et al* proposed a new method (Moya, *et al*, 2000). It can compute source parameters and site respond at the same time using genetic algorithm (Holland, 1975), but the method assume that the geometry spread and anelastic coefficients are known. Therefore, The digital seismic wave

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data of strong motion network distributed in Tangshan during July 1982 to December 1984 by China-US cooperation project is used in the paper (China-US joint project on strong ground motion measurement, 1989). Combing the advantage of the above two methods, the quality factor Q, source parameters and site respond are calculated in Tangshan area. The principle and computation steps of the two methods are introduced. The problems and the comparison with other research results are discussed.

1 seismic data

After Tangshan large earthquake on July 28, 1976, the observation network of strong motion with definite scale is set up in China. Many strong motion seismographs are built by international cooperation. The Tangshan international cooperation networks (such as China-USA, China-Japan) of strong motion are built. The observed data of strong motion network distributed in Tangshan during July 1982 to December 1984 by China-US cooperation project is used in the paper. Total 20 3-component acceleration seismographs are set up in the project, and the 218 digital acceleration records of 52 earthquakes (M_L=2.5~5.7) are obtained. We obtain 185 records. If we demand that each earthquake is recorded at least by 3 stations and each station must record 3 seismic records, only 90 records can be used, which include 13 earthquakes and 10 stations. Table 1 is station parameters. Table 2 is earthquake parameters and stations with obtained record.

Table 1 Station parameters

No.	Code	j_N/(°)	l_E/(°)	Altitude/m	site condition
1	TS01	39.760	118.407	6	ground rock
2	TS02	39.742	118.475	407	ground soil
3	TS03	39.755	118.577	45	ground soil
4	TS07	39.748	118.690	45	ground soil
5	TS15	39.747	118.397	−822	tunnel rock
6	TS16	39.748	118.400	48	ground soil
7	TS17	39.747	118.378	38	ground soil
8	TS18	39.728	118.410	47	ground soil
9	TS19	39.754	118.406	−553	tunnel rock
10	TS21	39.745	118.378	38	ground soil

It can be seen from the table that the magnitude range is 2.8~4.2 and epicenter distance range is 6~24 km. The epicenter distance is calculated using the time difference of S-P, not using the longitude and latitude of station and source position. The purpose is to reduce the error of epicenter distance due to the uncertainty of epicenter position. All records are acceleration record. Sample rate is 100 sps. The data of SH wave is used in the paper, which can obtaind by rotating 2 components in horizontal direction. When doing FFT, the time window is 5 seconds and 5% Hanning taper is used. In addition, Hanning window with 0.5 Hz lengths is used to smooth obtained acceleration spectrum.

Table 2 Earthquake parameters and stations with obtained record

No.	code	Date	j_N(°)	l_E(°)	M_L	01	02	03	07	15	16	17	18	19	21
1	83077	83-08-08	39.71	118.47	2.9	1	0	1	0	1	0	0	1	1	0
2	83079	83-08-09	39.68	118.48	3.8	1	1	1	0	1	1	0	1	1	0
3	83081	83-08-13	39.69	118.46	3.6	1	1	1	1	1	1	1	1	1	0
4	83099	83-09-24	39.77	118.50	3.5	1	1	0	0	1	0	1	1	1	0
5	83103	83-09-26	39.77	118.45	3.3	1	0	1	0	1	1	1	1	1	0
6	83104	83-09-26	39.74	118.39	4.2	1	1	1	1	1	1	1	1	1	0
7	83108	83-10-02	39.80	118.47	2.8	1	1	0	0	1	1	1	1	1	0
8	84029	84-02-16	39.76	118.51	3.7	0	1	1	1	1	0	0	0	1	0
9	84117	84-11-05	39.78	118.48	2.9	1	1	1	1	1	0	0	0	1	0
10	84132	84-10-12	39.83	118.50	3.5	1	1	1	1	1	1	0	1	0	1
11	84138	84-11-12	39.84	118.46	3.8	1	1	1	1	1	0	0	1	0	1
12	84139	84-11-12	39.84	118.45	3.9	1	1	1	0	1	0	0	1	1	1
13	84142	84-11-12	39.84	118.44	3.5	1	1	1	1	1	0	0	1	1	1

Note: 1 is station with obtained record, 0 is station without obtained record

2 Computation methods and results

2.1 Quality factor Q

Because the maximum epicenter distance of used data is only 24 km, the geometry spread coefficient of seismic spectrum amplitude with distance is comparative simple, *i.e.*, it is R^{-1}. The Fourier spectrum amplitude (It may be displacement, velocity or acceleration, here, it is acceleration) of S wave observed in the *j*-th station for the *i*-th earthquake is represented as (Hartzell, 1992),

$$O_{ij}(f) = S_i(f) G_j(f) \frac{\exp\left(-\frac{\pi R_{ij} f}{Q(f) v_S}\right)}{R_{ij}} \tag{1}$$

where f is frequency, $O_{ij}(f)$ is the spectrum amplitude observed in the *j*-th station for the *i-th* earthquake, $S_i(f)$ is the source spectrum amplitude of the *i*-th earthquake, $G_j(f)$ is the site respond of the *j*-th station, R_{ij} is epicenter distance between the *i*-th earthquake and the *j*-th station, v_S is velocity of S wave, $Q(f)$ is quality factor of S wave.

Doing logarithm for the above formula, it can be obtained

$$\lg O_{ij}(f) = \lg S_i(f) - \lg R_{ij} - c(f) R_{ij} + \lg G_j(f) \tag{2}$$

The relation between anelastic coefficient $c(f)$ and quality factor $Q(f)$ is

$$Q(f) = \frac{\lg(e) \pi f}{c(f) v_S} \tag{3}$$

The method proposed by Atkinson and Mereu (1992) is used to calculate anelastic coefficient $c(f)$. Its principle is: assuming that the site responds of all stations are 1, *i.e.*, not considering site respond, the source spectrum amplitude can be obtained by correcting geometry spread and anelastic attenuation of station record for a given anelastic coefficient $c(f)$. The residual of source spectrum amplitudes obtained by different stations for one earthquake become minimum by adjusting value c. The source spectrum of an earthquake is given by the average value of source spectrum amplitudes obtained by different stations, and the logarithm of site respond of a station is given by the average value of differences between the logarithm of source spectrum amplitude obtained by the station and that of the same earthquake. Finally, corrected source spectra are recalculated by considering the site respond obtained by stations. The residual of source spectrum amplitudes for the same earthquake are made minimum by adjusting value c.

The definition of residual is

$$k_{ij} = [\lg S_i(f)]_j - \overline{\lg S_i(f)} \tag{4}$$

where $\overline{\lg S_i(f)}$ is the logarithm of source spectrum amplitude for the *i*-th earthquake, which can be obtained by averaging $[\lg S_i(f)]_j$ of all stations for the earthquake.

The solution of anelastic coefficient $c(f)$ is obtained by letting

$$sum = \sum_i \sum_j \left| k_{ij} \right| \tag{5}$$

become minimum value. Thus, the steps of the above method is

(1) Given that the logarithm of site respond in all stations are equal to 0, make the residual of summation of equation (5) minimum by selecting suitable parameter $c(f)$.

(2) The site respond of stations can be calculated by the obtained parameter

$$\lg G_j(f) = \frac{1}{m_j} \sum_{i=1}^{m_j} k_{ij} \tag{6}$$

where m_j is the earthquake number recorded by the *j*-th station.

(3) The parameter $c(f)$ is calculated again by inputting the result of site respond. Repeating step 2 and step 3, the residual summation will be reduced further.

By repeating iteration, the anelastic coefficients $c(f)$ in the region can be obtained, and the quality factor $Q(f)$ is gotten by equation (2). Figure 1 is the result. It can be seen that value Q is not obtained by this method when the frequency is less than 8 Hz. In order to solve this problem, we introduce the value Q results in Beijing and nearby areas by JIN and Aki using coda wave method (JIN, Aki, 1988). Their data of value Q are mostly around 1 Hz, and there are some data in low frequency. Integrating above data, the relation between quality factor $Q(f)$ and frequency is

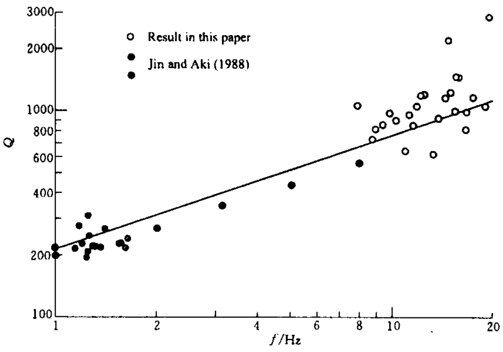

Figure 1 The relation between quality factor $Q(f)$ and frequency

$$Q(f)=214f^{0.55} \tag{7}$$

2.2 The determination of source spectrum parameter and site respond

The Moya method is used to determine the source spectrum parameter of earthquakes and the site respond of stations (Moya, *et al*, 2000). The method is that each earthquake is assumed to be satisfied to Brune source spectrum model firstly (Brune, 1970), the parameters of source spectrum can be used to calculate the site respond of stations which record this earthquake. Assuming that the site respond of station is same for all earthquakes, the parameter of source spectrum can be determined using genetic algorithm by obtaining the minimum standard error of station site respond for different events.

The Fourier spectrum amplitude in the j-th station for the i-th earthquake is corrected by geometry spread and anelastic attenuation, and the acceleration spectra are transformed into displacement spectra.

$$O_{ij}^{corr}(f) = O_{ij}(f) R_{ij} \exp(\pi R_{ij} f / Q(f) v_s)/(2\pi f)^2 \tag{8}$$

Given the parameters of displacement spectrum for each earthquake (low-frequency level Ω_0 and corner frequency f_c of each source spectrum), the theoretical source displacement spectra are obtained by

$$S_i(f) = \frac{\Omega_{0i}}{1+(f/f_{ci})^2} \tag{9}$$

According to the definition, the site respond of the j-th station in the k-th frequency for the i-th earthquake is

$$G_{ij}(f_k) = O_{ij}^{corr}(f_k)/S_i(f_k) \tag{10}$$

The average value and standard error of site respond in the j-th station can be calculated with different earthquake records in the k-th frequency.

$$d_{jk} = \frac{std(G_{ij}(f_k))}{mean(G_{ij}(f_k))} \text{ (Standard error and average value for } i\text{)} \tag{11}$$

The following formula becomes minimum by adjusting the parameter of source spectrum for all earthquakes using genetic algorithm.

$$\text{sum} = \sum_j \sum_k d_{jk} \tag{12}$$

Figure 2 gives site respond of different type station. The thin line is site respond of station obtained by each earthquake record, and the thick line is average value of site respond in the station. At the same time, Figure 2 gives source spectrum of earthquakes with different magnitude. The thin line is source spectrum recorded by each station and thick line is fitting theoretical source spectrum. The detail source parameter can be seen in Table 3.

Table 3 The inversion results of source spectra and source parameters of earthquakes

No.	Date	j_N/(°)	l_E/(°)	M_L	Ω_0/(cm-s)	f_c/Hz	$M_0/10^{13}$N·m	r/m	Δs/bar
1	83-08-08	39.71	118.47	2.9	88.78	6.7	2.18	177.9	16.9
2	83-08-09	39.68	118.48	3.8	258.16	4.9	5.98	243.2	18.2
3	83-08-13	39.69	118.46	3.6	479.24	4.9	11.1	243.2	33.7
4	83-09-24	39.77	118.50	3.5	140.55	5.7	3.25	209.1	15.6
5	83-09-26	39.77	118.45	3.3	157.72	5.0	3.65	238.4	11.8
6	83-09-26	39.74	118.39	4.2	6.23	3.9	9.41	305.6	14.4
7	83-10-02	39.80	118.47	2.8	129.81	5.3	3.01	224.8	11.6
8	84-02-16	39.76	118.51	3.7	289.06	5.6	6.69	212.8	30.4
9	84-11-05	39.78	118.48	2.9	128.93	5.9	2.99	202.0	15.8
10	84-10-12	39.83	118.50	3.5	433.05	5.0	10.0	238.4	32.4
11	84-11-12	39.84	118.46	3.8	380.63	3.5	8.82	340.5	9.8
12	84-11-12	39.84	118.45	3.9	201.10	5.4	4.66	220.7	19.0
13	84-11-12	39.84	118.44	3.5	220.71	4.2	5.11	283.7	9.8

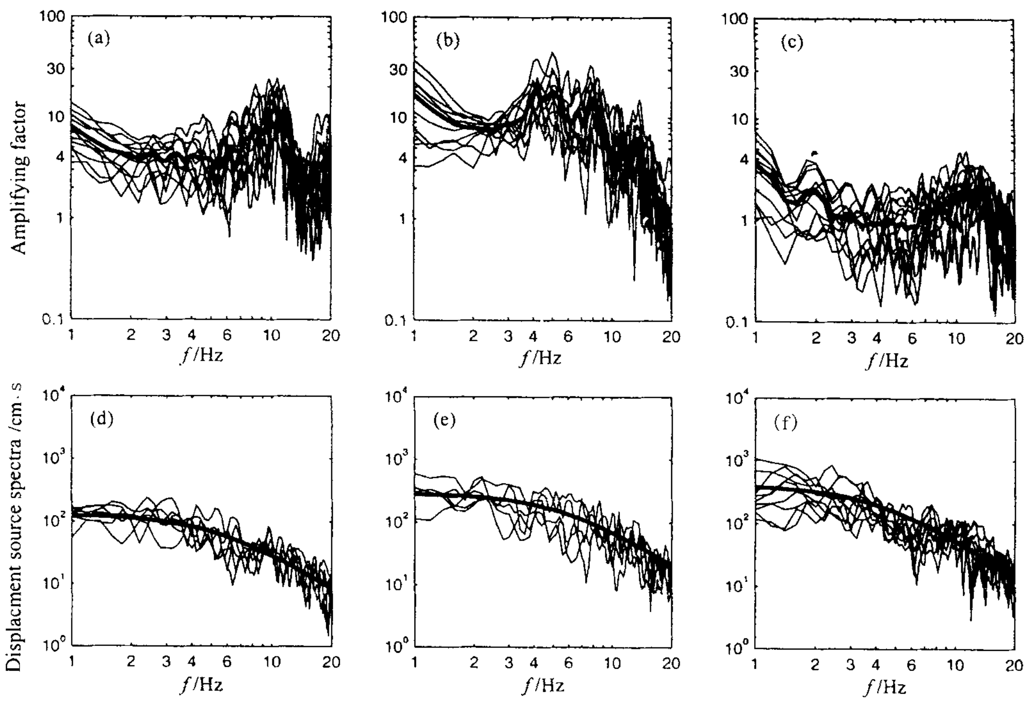

Figure 2 The site respond function of different type station and source spectra of earthquakes with different magnitude and their fitting theoretical source spectrum

(a) ground rock station 1, (b) ground soil station 2, (c) tunnel rock station 5, (d) the 7th earthquake (M_L=2.8), (e) the 8th earthquake, (f) the 6th earthquake (M_L=4.2)

2.3 source parameter

The various source parameters can be obtained by the above source spectrum parameters according to Brune model (1970). The seismic moment is

$$M_0 = \frac{4 p r v_S{}^3 \Omega_0}{R_{qj}} \tag{13}$$

where r is density, here is 2.7 g/cm^3. v_s is velocity of S wave, here is 3.2 km/s. R_{qf} is the coefficient of radiation pattern. Because the solution of each fault plane is not known, R_{qf} is supposed as a constant and the average value of SH wave is 0.48 in whole source sphere. For source scale, the source radius based on disk-type source model is

$$r = -\frac{2.34 v_S}{2\pi f_c} \tag{14}$$

stress drop is

$$\Delta s = \frac{7M_0}{16r^3} \tag{15}$$

According to the above formula, the source spectrum parameters and source parameters of 13 earthquakes is given in Table 3. Using least linear square method, the relation between seismic moment M_0 (N·m) and magnitude M_L in 13 earthquakes are

$$\lg M_0 = 12.35 + 0.39 M_L \tag{16}$$

The slope of this curve is only 0.39. It is comparatively low. From Table 3, stress drop is between 9×10^5~40×10^5 Pa in 13 earthquakes, but there is not obvious dependent relation between stress drop and seismic moment.

3 Discussion and conclusions

In the one hand, when anelastic attenuation coefficient $c(f)$ (or quality factor $Q(f)$) is calculated using Atkinson method, the logarithm of site respond by this method is minus value for the station with small site respond (such as rock station) because the site respond of each station is determined by comparing with average value (Figure 3). Therefore, the obtained site respond is comparative, not real one. In the other hand, because the residual value is that source amplitude spectra minus its average value for one earthquake from the definition of residual equation (5), the obtained residual is the same even if all site responds of stations is multiplied by an constant (their logarithm value is correspond to add an constant) from equation (2). It means that anelastic coefficient $c(f)$ is the same even if using comparative site respond for each station, but, if source amplitude spectra is calculated by Atkinson method, the obtained source spectrum parameter Ω_0 is lower comparing with real result because the obtained site respond is lower than an constant comparing with real site respond.

In addition, if the site responds of rock stations is assumed as 1 and the values of the other station is added a value when doing the first iteration, the site respond of all stations is close to real site respond. It will eliminate the error of source spectrum parameter in large degree using this method. But, because the site respond is not complete flat in frequency, some errors will be produced using this method. This problem should be paid attention to in practical work.

On contrary, the source parameters and site responds by Moya method is close to real ones because the site responds is not restricted in advance. But, there is a restriction using Moya method, *i.e.*, the initial value of source spectrum Ω_0 of each earthquake must be less than low-frequency level of source amplitude spectrum of rock station. Its implied assumption is that the site respond of rock station is close to 1. In addition, because all source spectrum parameters are calculated at the same time, the convergence velocity is very slow and computation time is very long using genetic method when there are more earthquakes. On contrary, because the source spectrum parameters of only one earthquake are calculated each time by Atkinson method, the computation velocity is very fast.

Figure 3 is the site responds using the two methods for different type stations and their ratios. It can be seen that the site responds by the first method is 3~4 times lower than the values of the second method in most frequencies, but, they are not a constant. The ratio results are similar for different stations.

The Quality factor Q in Tangshan area computed by Zhang *et al* is $Q(f)=29f^{0.91}$ (ZHANG, 2000) and $Q(f)=67f^{1.1}$ (ZHANG, *et al*, 2001) using linear inversion method. Compared with the results in the other area in the world and the results in Beijing area by JIN, *et al* (1988), the result in low frequency is low (WONG, *et al*, 2002). But the result using Atkinson method is consistent with above results, thus, the relation of Q value by Atkinson method is used in the paper. In addition, the contribution of anelastic coefficient to seismic wave amplitude attenuation is determined not only by this parameter, but also by the epicenter distance between earthquake and station. When the coefficient is smaller or epicenter distance is smaller, the product of two factors ($c(f)R_{ij}$) is in the error range of obtained source spectra amplitude by stations. The parameter $c(f)$ can not be determined by this method on this condition. This is a reason that only the anelastic coefficient above 8 Hz can be obtained in the paper and that the result above 2 Hz can be obtained in Guangdong digital seismic network (Wong, *et al*, 2003).

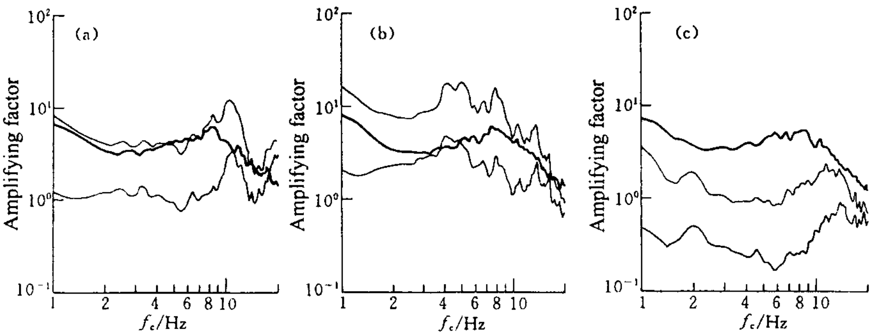

Figure 3 The site respond by two methods and their ratio
(a) station 1: ground rock, (b) station 2: ground soil, (c)station 3: tunnel rock
(The down thin line is site respond by Atkinson method, The up thin line is that by Moya method, The thick line is ratio by two methods)

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