Earthq Sci (2014) 27(1):101–106
DOI 10.1007/s11589-014-0065-0

RESEARCH PAPER

Application of passive source surface-wave method in site engineering seismic survey

Chaofan Wang · Jian Zhang · Lihui Yan · Hui Liu · Dong Zhao

Received: 2 September 2013 / Accepted: 7 January 2014 / Published online: 1 February 2014

Abstract Site engineering seismic survey provides basic data for seismic effect analysis. As an important parameter of soil, shear-wave velocity is usually obtained through wave velocity testing in borehole. In this paper, the passive source surface-wave method is introduced into the site engineering seismic survey and practically applied in an engineering site of Shijingshan District. By recording the ubiquitous weak vibration on the earth surface, extract the dispersion curve from the surface-wave components using the SPAC method and obtain the shear-wave velocity structure from inversion. Over the depth of 42 m underground, it totally consists of five layers with interface depth of 3.31, 4.50, 7.23, 17.41, and 42.00 m; and shear-wave velocity of 144.0, 198.3, 339.4, 744.2, and 903.7 m/s, respectively. The inversion result is used to evaluate site classification, determine the maximum shear modulus of soil, provide basis for further seismic hazard analysis and site assessment or site zoning, etc. The result shows that the passive source surface-wave method is feasible in the site engineering seismic survey and can replace boreholes, shorten survey period, and reduce engineering cost to some extent.

Keywords Passive source surface-wave method · Shear-wave velocity · Dispersion curve · Seismic effect · Engineering seismic survey

C. Wang · J. Zhang
Key Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing 100049, China

C. Wang · J. Zhang (✉)
College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China
e-mail: zhangjian@ucas.ac.cn; 13701117058@139.com

L. Yan · H. Liu
North China Institute of Geological Engineering Co. Ltd., Beijing 100085, China

D. Zhao
Geogiga Technology Corp., Calgary T3A5P2, Canada

1 Introduction

Using the special techniques, engineering seismic survey can determine the engineering seismic conditions, assess the possible seismic effect of future earthquake on construction site, evaluate the anti-seismic property of construction site, provide the design parameters of ground motion for the seismic design of building structures, and provide the scientific foundation and basis for engineering measures and disaster reduction (Peng 2004; Jiang et al. 1993). Engineering seismic conditions of site mainly include the topography and landform, hydrogeology and engineering geology, soil structure, shear-wave velocity, soil–rock types, dynamic properties of soils, liquefaction of sand, seismic subsidence of soft soil, geological structure and fault activity, seismic stability of slope soil, etc. The geotechnical investigation mainly studies the bearing capacity and deformation characteristics of foundation soil, while the engineering seismic survey mainly studies the shear-wave velocity and dynamic property of foundation soil. During the engineering seismic survey; in order to understand the spacial variation of foundation soil, provide the soil–rock parameters relating to the wave velocity, calculate the dynamic shear modulus of soil, analyze the foundation soil type and building site classification, and calculate the seismic effect of foundation soil; the shear-wave velocity data of soil must be studied.

In the engineering survey of site seismic effect, the shear-wave velocity is usually obtained through the wave velocity testing in boreholes. In order to satisfy the requirement of seismic safety evaluation on engineering site and seismic effect analysis of site soil, three boreholes with depth reaching the bedrock or shear-wave velocity not less than 700 m/s are necessary for the major projects such as the nuclear power plant, and two control boreholes with depth reaching the bedrock or shear-wave velocity not less than 500 m/s for other major building projects. Because of the large number of boreholes, it is not only increasing the project costs, but also extending the construction period. For the engineering seismic survey, it will have important practical significance to find a method which can minimize the number of boreholes and provide the shear-wave velocity of soil within a sufficient depth. The passive source surface-wave method would be a good choice on the basis of our studies.

2 Passive source surface-wave method

The active source surface-wave method in engineering survey is to excite the seismic wave with manual or mechanical source and detect the underground structure using its surface-wave components. The passive source surface-wave method is to probe the underground structure using the surface-wave information carried by the microtremor or random vibration on the earth surface.

The passive source surface-wave method has been applied in the measurement of overburden velocity structure in the early 1950s (Aki 1957), and systematically developed in 1990s (Okada 2003; Ling 1994). This method was introduced into China in 1980s (Wang 1986), and experimented successfully later (Ran 1994). In recent years, this method was also tried in the engineering investigation in addition to the application in the geothermal prospecting (Xu et al. 2009, 2012; Ye 2004; He et al. 2007).

Extraction of frequency dispersion curve is the core for data processing of the passive source surface-wave method (Zhao 2010). There are two methods to extract the Rayleigh wave dispersion curve. One method is the frequency–wavenumber method based on 2D wave field transform, and another is the space autocorrelation method based on the correlation analysis (Capon 1969; Park et al. 2005; Aki 1957; Okada 2006). This paper uses the spatial autocorrelation method in data processing of the passive source surface-wave method.

2.1 Spatial autocorrelation method

In one group of given passive source surface-wave receiving stations, one of these stations is located in the center of circle, while the remaining stations are distributed on the r-radius circumference at equal angles. Assuming that the signal is composed of a series of plane waves with incidence angle of φ, angular frequency of ω, and wavenumber of k, and corresponds with the stationary random process, the signals at the circle center C (0,0) and circumference P (r,θ) can be expressed as follows when only discussing the vertical component of signals:

$$X(0,0,t) = \int_{-\infty}^{\infty}\int_{0}^{2\pi} \exp(\mathrm{i}\omega t)\mathrm{d}\zeta(\omega,\varphi) \tag{1}$$

$$X(r,\theta,t) = \int_{-\infty}^{\infty}\int_{0}^{2\pi} \exp\{\mathrm{i}\omega t + upirk\cos(\theta-\varphi)\}\mathrm{d}\zeta(\omega,\varphi) \tag{2}$$

The spatial autocorrelation function S (r, θ) between the station C and P is defined as follows:

$$S(r,\theta) = \int_{-\infty}^{\infty} g(\omega,r,\theta)\mathrm{d}\omega \tag{3}$$

and

$$g(\omega,r,\theta) = \int_{0}^{2\pi} \exp\{\mathrm{i}rk\cos(\theta-\varphi)\}h(\omega,\varphi)\mathrm{d}\varphi \tag{4}$$

Equation (4) is the spatial covariance function which indicates the covariance of signals recorded by the stations C and P at the location of angular frequency of ω. $h(\omega,\varphi)$ is the frequency-azimuth spectrum density, and $h(\omega,\varphi)\mathrm{d}\omega\mathrm{d}\varphi$ reflects the power provided by the plane wave between φ and $\varphi + \mathrm{d}\varphi$ for the incidence angle and between ω and $\omega + \mathrm{d}\omega$ for the angular frequency (Xu et al. 2009).

By taking the average azimuth from the covariance function of all the observing stations on the circumference, the average covariance function $\overline{g}(\omega,r)$ is defined as follows:

$$\begin{aligned}\overline{g}(\omega,r) &= \frac{1}{2\pi}\int_{0}^{2\pi} g(\omega,r,\theta)\mathrm{d}\theta \\ &= \frac{1}{2\pi}\int_{0}^{2\pi}\int_{0}^{2\pi} \exp\{\mathrm{i}rk\cos(\theta-\varphi)\}h(\omega,\varphi)\mathrm{d}\varphi\mathrm{d}\theta \\ &= J_0(rk)\int_{0}^{2\pi} h(\omega,\varphi)\mathrm{d}\varphi \\ &= g(\omega,0,0)J_0(rk)\end{aligned} \tag{5}$$

where J_0 is the type-I zeroth-order Bessel function.

The spatial autocorrelation factor $\rho(\omega, r)$ is defined as follows:

$$\rho(\omega, r) = \overline{g}(\omega, r)/g(\omega, 0, 0) = J_0(rk) \quad (6)$$

When processing the passive source surface-wave data using the SPAC method, the measured records are first divided into several data segments and the large disturbance data segments were removed; narrow-band filter with different center frequencies is used to process each data segment and extract the frequency components being analyzed. Then, by calculating the spatial autocorrelation function between the center point and circumferential points for each frequency component and obtaining the spatial autocorrelation factor $\rho(\omega,r)$ after azimuth average, the argument rk of zeroth-order Bessel function can be obtained through the equation $\rho(\omega,r) = J_0(rk)$; finally, obtain the phase velocity $v(f)$ through the equation $k = 2\pi f/v(f)$ to get the dispersion curve (Zhao 2010; Xu et al. 2009).

2.2 Inversion of dispersion curve

After extracting the dispersion curve from the passive source surface wave, the next step is to inverse the shear-wave velocity structure. As most of the other geophysical inversion problems, the inversion of Rayleigh wave dispersion curves is an optimum control problem with highly nonlinear, multiparameter, and multi-extremum.

An important idea of solving the nonlinear inversion problem is linearization; first convert the nonlinear problem into linear one by Taylor's expansion and then compute iteratively using the local linearized algorithm. The procedure of this method starts from an initial model, then gradually modify and update the model using the iterative perturbation algorithm to realize the best fit between the forward modeling result and the measured data of the theoretical model, and the final model parameters will be the inversion results (Song 2010). At present, the least square method is one of the most popular local linearized algorithm for inversion of surface-wave dispersion curve.

The reliability of inversion results from the local linearized algorithm heavily depends on the initial model. Better results could be achieved only when the initial model is close to the measured, otherwise wrong result may be easily made due to falling into the local minimum. Comparing with the local linearized inversion method, the nonlinear global optimization algorithm does not strongly depend on the initial model, and has a better global convergence ability. This paper uses the genetic algorithm for inversion of dispersion curve (Shi and Jin 1995).

Genetic algorithm is a kind of nonlinear global optimization algorithm that simulates the natural selection and genetic process of biological evolution and is devised according to the law of "survival of the fittest" (Stoffa and Sen 1991; Shi and Jin 1995; Zhao et al. 1995). The analysis procedures for the inversion of surface-wave dispersion curve using this method are as follows: (1) define the addressing space of one solution and then randomly generate N models; (2) calculate the theoretical dispersion curve of each model, and evaluate the advantages and disadvantages of each model on the basis of the difference between the theoretical value and the observed; (3) eliminate the inferior models in a certain proportion and retain the superior, select models according to the probability of the superior and the inferior, and then process the selected models by intercrossing and mutating; (4) combine the retained models with the models processed by intercrossing and mutating, obtain a new model; and (5) repeat the above procedures until the difference between the model's theoretical dispersion curve and the observed value is small enough (Sun et al. 2009). The solution that inverts the subsurface structure from the surface-wave dispersion curve using the genetic algorithm can be searched globally in a wide range, and cannot miss the optimum model due to the bad selection of initial models (Shi and Jin 1995).

3 Application examples

We determined the shear-wave velocity structure by passive source surface-wave method during the engineering seismic survey in a site in Shijingshan District, Beijing city. Figure 1 shows the field recording geometry, and the small dots in the figure denote the location of the observation stations. According to the requirements of investigation depth, we can use the geophone with different resonant frequencies. In the case that the geophone satisfies the requirements, the investigation depth is 3–5 times of the maximum radius of the recording array. We used 4 Hz

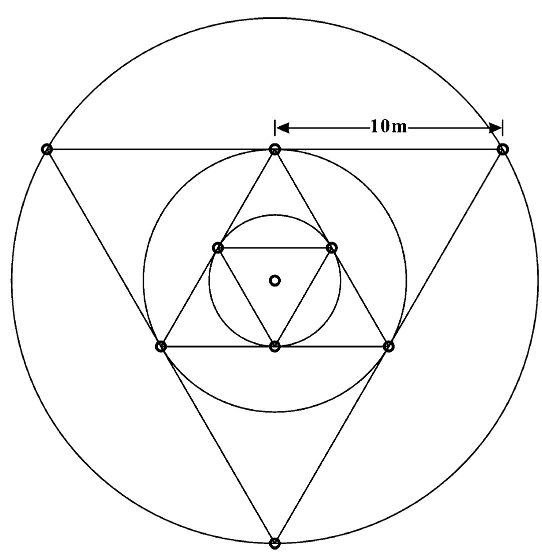

Fig. 1 Schematic outline of the field recording geometry. (*Small dots* in the figure indicate the location of observation stations)

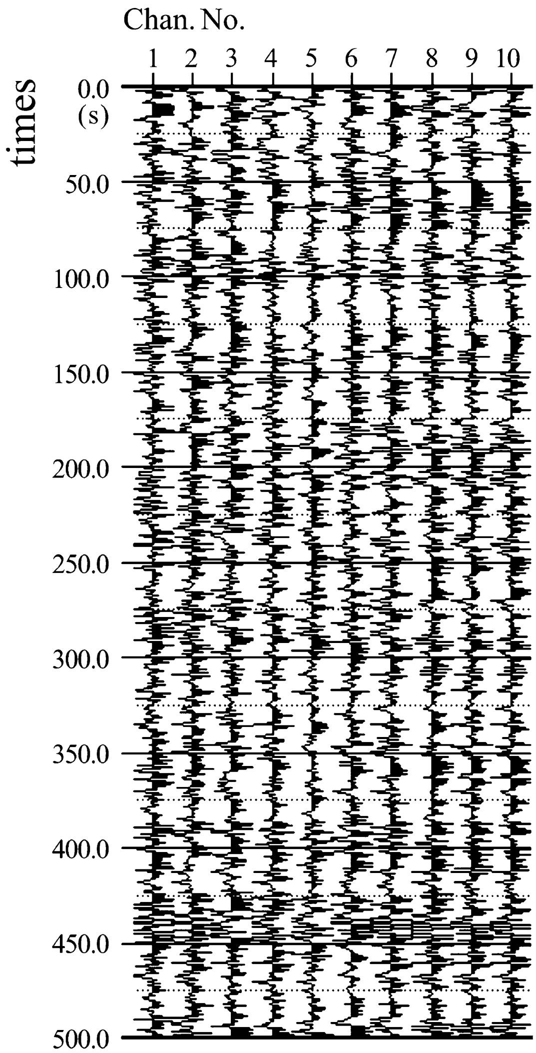

Fig. 2 Measured waveform

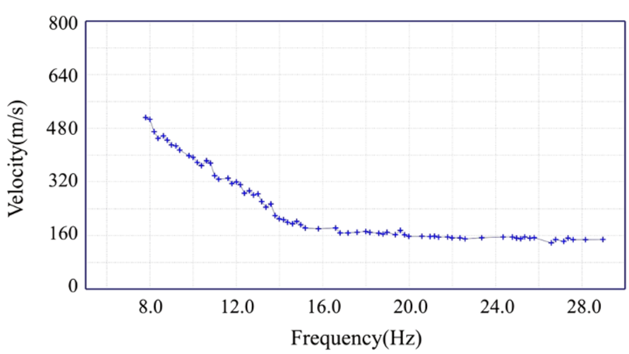

Fig. 3 Frequency dispersion curve

geophone in the work, the maximum observation radius of which is 11.55 m.

In the passive source surface-wave method, it is required that the record signal of the finite time is random in time and space and is a sample function of the homogeneous

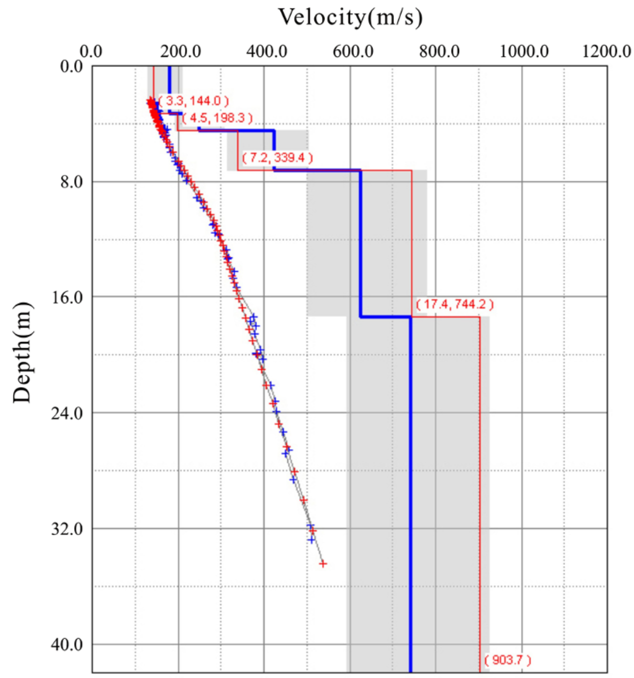

Fig. 4 Initial model and inversion result. (*Blue zigzag lines* in the figure indicate the velocity structure of initial model, while the *red* indicate the inversion results)

Table 1 Table of model parameters and inversion results

No.	Depth (m)	Model V_S (m/s)	Result V_S (m/s)
1	3.31	180.0	144.0
2	4.50	247.9	198.3
3	7.23	424.3	339.4
4	17.41	625.4	744.2
5	42.00	740.7	903.7

random process. On the basis of our studies, normally, the record length of 300–600 s can satisfy the demands. In this work we use the DAQLink III seismograph to record field data, with sampling frequency of 1 ms and record length of 500 s. Figure 2 shows the measured waveform. As Fig. 2 indicates, the waveform has abundant frequency components, and the data have good quality with few disturbance.

The dispersion curve obtained by analyzing and processing the collected data by the SPAC method is shown in Fig. 3. In which, the small blue crosses denote the dispersion points calculated depending on the field data. As Fig. 3 illustrates, the frequency of extracted dispersion curve is 7–29 Hz and the phase velocity is 120–560 m/s.

According to the adjacent borehole data and characteristics of dispersion curve, we build an initial model and calculate inversely by the genetic algorithm. The inversion results are shown in Fig. 4 and Table 1. The blue zigzag lines shown in Fig. 4 indicate the velocity structure of initial models, the red is the inversion results, numbers in the bracket are the interface depth and shear-wave velocity from inversion results, and the gray areas indicate the velocity range searched in inversion calculation by the genetic algorithm. The small blue crosses indicate the dispersion curves with depth that converted from the frequency as illustrated in Fig. 3, while the small red crosses indicate the calculated dispersion curve from the inversion results.

Table 1 shows the model parameters and inversion results. Although the genetic algorithm does not require an accurate initial model, the inversion results may be greatly biased from the true values if we invert the depth and velocity at the same time. In this work, we determined the interface depth of soil first according to the stratigraphic distribution and characteristic points of dispersion curve, then divided the models into five layers with the interface depth of 3.31, 4.50, 7.23, 17.41, and 42.00 m, respectively. Based on the characteristics of the dispersion curve and the empiric value of near site, the shear-wave velocity of the initial mode is 180.0, 247.9, 424.3, 625.4, and 740.7 m/s, respectively. Using the genetic algorithm developed by Shi and Jin (1995) for dispersion inversion of surface wave, the inversion results of layers are 144.0, 198.3, 339.4, 744.2, and 903.7 m/s, respectively, which corresponds with the known information. On the basis of the inversion results of wave velocity, we inferred that the layers are miscellaneous fill, silty clay, pebbly sand, and weathered base rock successively downward from the ground surface.

3.1 Site classification

Site classification is the characterization of site conditions, and the class of site is mainly used for seismic design as the basis of selecting design response spectrum. The basis of site classification is the shear-wave velocity of soil and the overburden thickness of site.

Generally, the overburden thickness of building site is the distance from the ground surface to the top of layer whose shear-wave velocity is larger than 500 m/s and the shear-wave velocity of each of its underlying strata is not less than 500 m/s. The equivalent shear-wave velocity of soil is calculated as follows:

$$v_{se} = d_0/t \quad (7)$$

$$t = \sum_{i=1}^{n} (d_i/v_{si}) \quad (8)$$

where,

v_{se}—the equivalent shear-wave velocity of soil;
d_0—the calculation depth (m), taking the smaller value between the covering thickness and 20 m;
t—the travel time of shear wave between the ground surface and calculation depth;
d_i—thickness (m) of the ith soil within the calculation depth;
v_{si}—shear-wave velocity of the ith soil within the calculation depth;
n—number of soil within the calculation depth.

According to the inversion results of passive source surface-wave method and the regulation above, the overburden thickness in the site is 7.23 m and the equivalent shear-wave velocity of soil is 195.2 m/s. In accordance with the *Code for Seismic Design of Building*, the site classification of studying site is Class II.

3.2 Determining the maximum shear modulus of soil

In seismic effect analysis of soil, it is usual to use the equivalent linear model to simulate the nonlinearity of soil and build the constitutive relation of site soil. In building the constitutive relation of site soil, first determine the maximum shear modulus based on the shear-wave velocity of soil. There are many factors affecting the maximum shear modulus; not only by the soil component, sedimentary environment, and history, but also by the testing method and instrumentation. From the wave theory, the in situ wave velocity can reflect the true general condition of soil more accurately.

Based on the shear-wave velocity determined by the passive source surface method and the mass density of soil, the maximum shear-wave modulus of soil can be calculated as follows (Feng et al. 2007):

$$G_{\max i} = \rho_i \cdot v_{si}^2 \quad (9)$$

where,

$G_{\max i}$—dynamic shear modulus of the ith soil;
v_{si}—shear-wave velocity of the ith soil;
ρ_i—mass density of the ith soil.

The calculation result of the maximum shear modulus ($G_{\max}$) of each soil in the site is shown in Table 2. Based on the drilling data of site, there are three soil in this engineering site, and the natural mass density is 1.68, 1.92, and 2.23 g/cm^3 respectively. The shear-wave velocity of

Table 2 Maximum shear modulus ($G_{\max}$) determined by the shear-wave velocity

No.	ρ (g/cm^3)	V_S (m/s)	$G_{\max}$ (MPa)
1	1.68	144.0	34.8
2	1.92	198.3	75.5
3	2.23	339.4	256.9

each soil, obtained by passive source surface-wave method described above, is 144.0, 198.3, and 339.4 m/s, respectively. The calculated maximum shear modulus of each soil is 34.8, 75.5, and 256.9 MPa, respectively.

The maximum shear modulus is a key parameter to determine the dynamic shear modulus ratio and damping ratio of soil. The change of the maximum shear modulus will greatly influence the acceleration distribution of soil and peak acceleration of ground surface.

4 Conclusions

In the site engineering seismic survey in Shijingshan District, Beijing, China, we obtained the shear-wave velocity structure of soil by passive source surface-wave method. Over the depth of 42 m underground, it totally consists of five layers with interface depth of 3.31, 4.50, 7.23, 17.41, and 42.00 m, and shear-wave velocity of 144.0, 198.3, 339.4, 744.2, and 903.7 m/s, respectively. Based on the inversion results of wave velocity, it is inferred that the layers are miscellaneous fill, silty clay, pebbly sand, and weathered base rock successively downward from the ground surface. In accordance with the *Code for Seismic Design of Buildings*, the site classification is Type-II; as the overburden thickness in the site is 7.23 m and the equivalent shear-wave velocity of soil is 195.2 m/s. Combined with the mass density of soil, the maximum shear modulus of each soil calculated according to the shear-wave velocity is 34.8, 75.5, and 256.9 MPa, respectively.

Application of passive source surface-wave method in the site engineering seismic survey can obtain the shear-wave velocity structure of soil which has a great significance to the seismic effect analysis of site. This method can be used for site classification and determining the maximum shear modulus of soil, and provide basis for further seismic hazard analysis, site evaluation, site zoning, etc.

Acknowledgments This work was supported by National Natural Science Foundation of China (No. 41174085), Chinese Academy of Sciences (KZZD-EW-TZ-19), and China Geological Survey (12120113101400).

References

Aki K (1957) Space and time spectra of stationary stochastic waves, with special reference to microtremor. Bull Earthq Res Inst 35:415–456

Capon J (1969) High resolution frequency-wavenumber spectrum analysis. Proc IEEE 57:1408–1418

Feng ZR, Guo DC, Liu HS, Chen XL (2007) Influence of maximum shear modulus on dynamic parameters and seismic response of soil layer. J Nat Disasters 16:90–95 (in Chinese with English abstract)

He ZQ, Ding ZF, Jia H, Ye TL (2007) To determine the velocity structure of shallow crust with surface wave information in microtremors. Chin J Geophys 50:492–498 (in Chinese with English abstract)

Jiang P, Dai LS (1993) Introduction to engineering seismology. Seismological Press, Beijing, pp 1–10 (in Chinese)

Ling SQ (1994) Research on the estimation of phase velocities of surface waves in microtremors. Hokkaido University, Sapporo (in Japanese)

Okada H (2003) The microtremor survey method (translated by Koya Suto): geophysical monograph series, No. 12. Society of Exploration Geophysicists

Okada H (2006) Theory of efficient array observations of microtremors with special reference to the SPAC method. Explor Geophys 37:73–85

Park CB, Miller RD, Ryden N, Xia J, Ivanov (2005) Combined use of active and passive surface waves. J Environ Eng Geophys 10:323–334

Peng CG, Li YG (2004) Base of investigation of site effect in earthquake. Seismological Press, Beijing, pp 189–219 (in Chinese)

Ran WY, Wang ZD (1994) The long wave microtremors method and its advances. Geophys Geochem Explor 18:28–34 (in Chinese with English abstract)

Shi YL, Jin W (1995) Genetic algorithms inversion of lithospheric structure from surface wave dispersion. Chin J Geophys 38:189–198 (in Chinese with English abstract)

Song XH, Li DY, Gu HM, Tang L (2010) Rayleigh waves theory and applications. China Water and Power Press, Beijing, pp 67–113 (in Chinese)

Stoffa P, Sen M (1991) Nonlinear multiparameter optimization using genetic algorithms: inversion of plane-wave seismograms. Geophysics 56:1794–1810

Sun YJ, Xu PF, Ling SQ, Li CJ (2009) Microtremor survey method and its progress. Prog Geophys 24:326–334 (in Chinese with English abstract)

Wang ZD (1986) The micromotional spatial autocorrelation method and its practical technique. Geophys Geochem Expl 10:123–133 (in Chinese with English abstract)

Xu PF, Shi W, Ling SQ, Guo HL, Li ZH (2012) Mapping spherically weathered "Boulders" using 2D microtremor profiling method: a case study along subway line 7 in Shenzhen. Chin J Geophys 55:2120–2128 (in Chinese with English abstract)

Xu PF, Li CJ, Ling SQ, Zhang YB, Hou C, Sun YJ (2009) Mapping collapsed columns in coal mines utilizing microtremor survey methods. Chin J Geophys 52:1923–1930 (in Chinese with English abstract)

Ye TL (2004) The exploration technique for microtremor array and its application. Earthq Res China 20:47–52 (in Chinese with English abstract)

Zhao D (2010) Passive surface waves: methods and applications. Geophys Geochem Expl 34:759–764 (in Chinese with English abstract)

Zhao D, Wang GJ, Wang XT, Sun RG (1995) The application of genetic algorithm to Rayleigh wave inversion. Geophys Geochem Expl 19:178–185 (in Chinese with English abstract)