Dynamic Effect of the Earth Fissure Sites in the Yuncheng Basin, China

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Abstract

Earth fissures are a type of major geological disaster that occurs worldwide. China has experienced some of the most serious earth fissure disasters in the world. The Yuncheng Basin is an important constituent basin of the Fenwei Basin in China where earth fissures are densely developed and caused severe damage. In particular, the impact of earth fissures on the seismic response of the site is still unknown and is an urgent problem that needs to be solved. Based on microtremor tests, three types of typical earth fissure sites in the Yuncheng Basin were selected for field testing. Through spectrum analysis, the dynamic response characteristics of the earth fissure sites were determined. The results show that the dynamic response of the site is significantly affected by the earth fissures. The dynamic response strength of the site is the largest on both sides of the earth fissures, and it decreases and gradually stabilizes with increasing distance from the fissures. The impact range of the earth fissures on the hanging side is slightly longer than the heading side.

1 Introduction

Earth fissures are linear tensile fissures with a certain extension length that develop on the earth surface and may be accompanied by vertical dislocations. They are affected by various complex factors such as internal and external forces and human activities (Carpenter 1980). Earth fissures are widely developed around the world and occur in the United States, Mexico, Africa, Europe, and throughout most of China. Thus, earth fissure disasters are an important geological disaster that restricts the development of the national economy and seriously affects infrastructure construction (Qiao et al. 2015). The existence and activity of earth fissures do not only cause direct damage to aboveground and underground structures, but when an earthquake occurs, the presence of earth fissures can change and even increase the seismic response of the site, causing the structures near the earth fissures to suffer severe damage or even be destroyed .

Humans have been studying earth fissures for a century. The first reported earth fissure was discovered in the Goose Creek oil field in the Houston-Galveston area in the United States in the 1920s. At this time, some scholars believed that it was caused by oil exploitation (Snider 1927; Minor 1925). Since then, earth fissures have been reported in many areas of the southwestern United States and have caused considerable economic losses. A series of scholars have launched intense discussions of the formation mechanisms of earth fissures, which have resulted in several relatively systematic understandings. The main cause hypothesis states that the causes of earth fissures include tectonic genesis (Leonard 1929), groundwater genesis (James, Langer and Kerr 1968; Fletcher et al. 1954), and structural and groundwater compound genesis (Holzer 1980a, b). Later, as amount of research, observations, and data on earth fissures increased, it was discovered that the formation mechanism of earth fissures is very complicated. Thus, the combined cause theory was generally developed. In addition to the United States, Mexico (Rojas, Arzate, and Arroyo 2002), Ethiopia (Laike 1998), and other countries have also carried out research on earth fissures.

Earth fissures are widely developed in China and cause severe damage. The earth fissures in the Fenwei Basin, the Hebei plain and Su-Xi-Chang area are most typical earth fissures (Fig. 1) (Wan et al. 2019). Among them, the earth fissures in the Xi'an area, which is located in the Fenwei Basin, are the earliest and most representative. Many scholars have studied the earth fissures in the Xi'an area and have proposed their own formation theories. The early theories mainly include the structural theory (Li et al. 1986), groundwater theory (Li 1994), and combined cause theory (Yang and Wu 1986). With further in-depth research, some scholars (Deng et al. 2007, 2013; Peng et al., 2007; Peng et al. 2016) proposed a formation model for the Xi'an earth fissures, which involved the internal and external dynamic coupling of the extensional fault activity and water action in a regional extensional environment. Other areas in the Fenwei Basin, such as the cities of Datong, Linfen, and Yuncheng, are also severely affected by earth fissure disasters. Many scholars have studied the distribution characteristics and formation mechanisms of earth fissures in the Yuncheng Basin (Wu, Jiang, and Li 2003; Peng et al. 2007; Song et al. 2007; Meng et al. 2010; Xu et al. 2010; Chen 2016; Qiao, Peng, and Lu 2017; Zhao et al. 2018; He et al. 2019).

Until now, research on the development, distribution characteristics, and formation mechanisms of earth fissures all over the world has produced very rich results, but our understanding of the dynamic effects of earth fissure sites is insufficient. Several studies have investigated the dynamic effects of earth fissures under earthquake loads based on numerical simulations (Liu et al. 2012; Fan et al. 2014), and others have used indoor simulation experiments to explore the influence of earth fissures on the dynamic response of a site (Liu et al. 2014; Huang et al. 2018; Xiong et al. 2018; Mu et al. 2019; Xiong, Zhang, and Chen 2019), but the existing results are few and unsystematic and are not sufficient to guide engineering practice. Therefore, in terms of seismic fortification, the Specification for site investigation and engineering design on Xi'an ground fractures (DBJ61-6-2006) only regards the seismic effects of earth fissure sites as a general site threat in accordance with the Code for seismic design of buildings (GB50011-2010). Furthermore, because there is no systematic measurement data on the seismic response of earth fissure sites, in order to study this problem, it is necessary to develop new ideas and appropriate methods.

Microtremor is a kind of constant micro-movement that has no specific seismic source and can be observed at any time, and its amplitude is generally only a few microns. The Microtremor studies originated in the 1950s. The Japanese scholars (Kanai and Tamaka 1954) quantitatively analyzed the nature of microtremor surface waves. After this, a series of scholars investigated the in-situ microtremor sources, formation mechanisms, and waveforms of microtremors (Aki 1957; Ohta et al. 1978; Kagami et al. 1986, 1982). In the late 1960s, Toksoz and Lacoss used a seismic network to separate, extract, and analyze the various periodic components of microtremor (Lacoss, Kelly, and Toksoz 1969; Toksoz and Richard 1968) and reported on the components of the different bands of the microtremor and their possible causes. In the 1990s, Nakamura proposed a new microtremor method (Nakamura 1989). This horizontal-to-vertical spectral ratio (H/V) method has gradually become the focus of the analysis of site dynamics around the world. Many scholars try to explain the theoretical basis of this method from different angles (Bard 1998; Konno and Ohmachi 1998). In 1994, Lermo and Chavez-Garcia (1994) summarized the three main types of microtremor analysis methods and concluded that the H/V method can effectively eliminate the source effect. Since then, the H/V method has been widely used in the field

of engineering. Many scholars in China have also contributed to the microtremor theory and practical engineering applications (Guo and Song 2000; Guo, Xie and Yu 2002; Guo and Ren 2005). A large number of studies have shown that microtremor movement is an efficient, economical, and convenient method for testing the dynamic characteristics of a site, which contain a large amount of site soil structure information that can be used as field measurement data. Some scholars (Zhang et al. 2017; Chang et al. 2020) studied the dynamic effects of earth fissures on sites using microtremor measurement data and found that the existence of earth fissures does indeed aggravate the vibration intensity of the site.

The Yuncheng Basin is an important part of the Fenwei Basin and contains with the most well-developed earth fissures in China. The earth fissures in the Yuncheng Basin have caused serious disasters. earth fissures have become the most important geological disaster in this area. Furthermore, the basin has a large population, developed agriculture, and industry, and the earth fissures not only cause direct damage to local roads and houses but also severely restrict the construction of urban infrastructure, and thus they restrict the economic and social development in the Yuncheng basin. Therefore, in this study, three types of typical earth fissure sites in the Yuncheng basin were selected, based on microtremor testing and analysis, the influence of the earth fissures on the dynamic response of the site was determined, and the amplification effect and influence range of the earth fissures on the dynamic response of the site were preliminarily determined. The results of this study provide theoretical support for the development of seismic fortification and avoidance measures for the earth fissure sites in this area.

2 Regional Structure

From north to south, the Fenwei graben system consists of the Datong Basin, the Xinding Basin, the Taiyuan Basin, the Linfen Basin, the Yuncheng Basin, the Weihe Basin, and several other large fault basins (Fig. 1). The Yuncheng Basin is located in the southwestern part of Shanxi Province and has a total area of 4885 km².

The Yuncheng basin is a Cenozoic faulted basin superimposed on the multi-cyclic superimposed Ordos Basin. The sedimentary strata have been deformed by multiple tectonic movements and have experienced multiple tectonic periods, such as the Yanshanian and Himalayan movements. A representative large rift basin formed later (Zhao et al. 2018). The basic framework of the Zhongtiao mountain uplift area and the Emei platform uplift area in the basin was laid by the strong tectonic movement in the Yanshanian period, and it was mainly affected by the Himalayan movement during the Paleogene. Large-scale fault block tectonic movement occurred in this area. The tectonic setting of the basin has changed from a compressive and twisting thrust fault to a tension and twisting normal fault, and the embryonic form of the basin has been modified since then. The main structural deformations preserved today include a fault system in the Himalayan strike-slip extensional background (Qiao et al. 2015).

The main tectonic movement of the Yuncheng basin are faults. It was controlled by the Yanshan movement in the Mesozoic, the Himalayan movement in the Cenozoic, and especially the tectonic

movement since the Late Cenozoic. The fault structure in the basin is developed. The main active fault in the basin is the large fault on the northwest side of Zhongtiao mountain, which is also the main controlling boundary fault in the Yuncheng basin (Chen 2016). There are eight active faults in the basin, with NE, NEE, and NNE strikes. They enclose the boundaries of the Yuncheng basin and the secondary structural units inside the basin, and they mutually restrict and control the structural framework of the basin (Zhao et al. 2018). The Yuncheng basin is bordered by the Emei Platform to the west, and the Zhongtiao mountains to the southeast. The NE-trending Mingtiaogang in the middle of the basin divides the Yuncheng basin into the Sushui river plain and the Qinglong river plain. The basin is an asymmetrical sag basin that is deep in the south and shallow in the north.

The basin contains a large amount of Cenozoic strata, accounting for about 80% of the total area, and the thickness of the strata increases from the northeast to the southwest. The thickness of the Cenozoic strata in the basin is generally greater than 1000 m, and the Quaternary sediments are also more than 300m thick. This loose, thick sedimentary layer provided the material basis for the extensive development of earth fissures.

In general, factors such as the uplift of the horst in the Yuncheng basin, the faulted basement, the over-exploitation of groundwater, and the loose, thick sedimentary layer have laid the foundation for the development of earth fissures in the basin.

3 Characteristics Of The Earth Fissures In The Yuncheng Basin

The development of earth fissures is controlled by tectonic movement. The earth fissures in the basin are mainly affected by the secondary structural units. The Yuncheng basin has been affected by the Himalayan tectonic movement since the Cenozoic. Due to the control of the faults at the northern foot of the Zhongtiao mountain, the basement has been in a faulted extensional environment. Under the strong tectonic activity of the Zhongtiao mountain fault, the secondary structural unit in the basin was controlled, which intensified the uplift of the block and caused the formation of the Mingtiaogang earth fissures. The dip slip extension of the hanging wall normal fault in the basin caused the tension shear cracking of the surface soil layer, which laid the structural foundation for the development of earth fissures in the basin. In addition, since the 1980s, the over-exploitation of groundwater has been severe in this area, causing the groundwater level to continuously fall and the falling funnel to expand year by year, which induced a large number of earth fissures in the Yuncheng basin. Thus, the Yuncheng basin has become the faulted basin with the largest number of earth fissures in Shanxi.

The earth fissures in the basin are mainly distributed on top of and on both sides of the Mingtiaogang uplift within the basin, in the Zhongtiao mountain uplift to the southeast, and in the Emei platform front edge to the north (Fig. 2). The earth fissures in the Yuncheng basin are distributed along the boundaries of the geomorphology, are concentrated along the fault zone, and are associated with land subsidence. The earth fissures predominantly have NE strikes. According to the survey, the earth fissure disasters in the basin mainly occurred before 1980 and between 1995 and 2005. A total of 119 earth fissures (belts)

have been developed in the study area. They mainly strike NE-NEE and are generally 100–2000 m long. The longest fissures are up to 5000 m. They are generally 0.05–0.5 m wide, and the widest can reach up to 2 m wide. The small earth fissures account for 45% of the earth fissures (length less than 500 meters); the medium earth fissures account for 28% (length between 500–1000 meters); and the large earth fissures account for 17% (length between 1000–5000 meters). There is only one giant earth fissure in the basin. It is located in the salt lake district and is 10 km long and 0.3–1 m wide.

Figure 3 shows six typical earth fissures in the Yuncheng basin and the damage they have caused to the ground and buildings. Earth fissure F_1 (Pleistocene earth fissure on the southern margin of the Mingtiaogang uplift) is located in the salt lake district of Yuncheng. It is the only giant earth fissure in the Yuncheng basin. Earth fissure F_1 appeared in 1975. It has a long extension, large scale, and strong continuity, and is not controlled by the pavement, buildings, and roads along the route. It is 10 km long and crosses Taocun-Banpo-Wucaoxincao and other villages, and it is very destructive along strike (Fig. 2(a), (b)). Earth fissure F_1 strikes NE, which is consistent with the active fault in the underlying bedrock. In plane view, earth fissure F_1 is longer, its overall shape is linear. In cross-section, a smaller number of secondary fissures on both sides of the main fissure can be seen, the vertical dislocation of the two discs near the surface of the main fissure is small, and the deep dislocation is large, showing the characteristic of a synsedimentary fault (Fig. 3(a)).

The Zhongtiao mountain piedmont fault zone is located in the southern part of Xia County. Affected by tectonic movement, the five earth fissures (F_2 – F_6) developed in the Xia County area are all distributed on the northwestern side of the Zhongtiao mountain fault zone. The earth fissures are distributed in parallel rows at nearly equal intervals from southeast to northwest. Earth fissure F_2 is farthest from (i.e., ~9.5 km) the Zhongtiao mountains in Xia County. It has the most significant vertical surface dislocation among the 5 earth fissures in Xia County. The largest surface vertical dislocation occurs in the playground of Xinmiao primary school in Yuwang where the surface dislocation reaches 30 cm (Fig. 2(d)). Earth fissure F_2 appeared in 1998 and developed rapidly from 2007 to 2008. It strikes NE35°, which is consistent with the trend of the Zhongtiao mountains, and extends for 3.9 km. Its scale is relatively large. Earth fissure F_2 passes through Xinzhuang-Yuwang-Lizhuang and other places, and it is more destructive along strike. As can be seen from the cross-section shown in Figure 3, the formation is composed of interbedded loess and silty clay, and the vertical dislocation increases with increasing depth (Fig. 3(c)).

Earth fissure F_5 is 5 km from the Zhongtiao mountain fault zone, making it closest of the five earth fissures to the fault zone. Earth fissure F_5 starts in Yuguo and ends in Zhongwei. Its overall trend is NE55°, which is consistent with the trend of the Zhongtiao mountains. It extends for about 2.3 km, and the vertical dislocation of the ground surface is 8–20 cm. Earth fissure F_5 appeared in 2000, and it entered a period of rapid development after 2007. It is active and destructive along strike (Fig. 2(c)), and it is still developing. The earth fissure is a tilt-slip tension crack with obvious horizontal extensional movement and vertical differential movement. The differential settlement on both sides of the earth fissure is obvious, and the maximum vertical dislocation is 25 cm. As can be seen from the cross-section

shown in Fig. 3, the formation is composed of sandy soil and silty clay. The stratum is relatively weak, and there are associated secondary fissures around the main fissure, which mainly appear in the heading side (Fig. 3(b)).

4 Microtremor Tests And Analysis

4.1 Survey Line and Data Point Layout

Survey lines were laid along the previously described earth fissures (F_1 , F_2 , and F_5). Two survey lines (S1 and S2) were laid in Banpo and Wucao for earth fissure F_1 , only one survey line (S3) was laid in Yuwang for earth fissure F_2 , and one survey line each was laid in Yuguo and Zhongwei (lines S4 and S5, respectively) for earth fissure F_5 . The sketch map of survey line layout as shown in Fig. 5. The survey lines were laid perpendicular to the earth fissures. Each survey line contained 18 data acquisition points, and 9 measurement points were set on either side of the earth fissure, where A represents the hanging side, and B represents the heading side. The survey lines were about 60 m long (Fig. 4).

4.2 Equipment and Methodology

The testing instrument for used for the microtremor was a high-sensitivity servo-type velocity network seismograph (CV-374AV) manufactured by Tokyo Sokushin Co., Ltd. (Fig. 5). The sampling frequency of the instrument is 0.1–100 Hz. It can monitor in three orthogonal directions of microtremor data at the same time. The testing instrument meets the requirements of the microtremor test.

The tests were carried out at night when it was quiet and in good weather in order to avoid obvious vibration sources. The microtremor in the X, Y, and Z directions were measured at each measurement point, and each measurement point was monitored for more than 10 minutes. If pedestrians or vehicles passed by during the test, these details were recorded, and the affected time period was avoided as much as possible when selecting the data. According to the above requirements, the microtremor signal after the observation was a stable random process.

The collected speed-time history curve from the reliable signal was intercepted and converted it into the acceleration time-history curve. The intercepted data were imported into the SeismoSignal program. After the preprocessing, including filtering and baseline corrections, was completed, Fourier spectrum, response spectrum, and Arias intensity analyses were performed.

5 Microtremor Analysis Of The Earth Fissure Sites

Figures 6–10 show the results of the microtremor spectrum analysis of the five survey lines. As can be seen from the figures, The Fourier spectral results show that the Fourier spectrum patterns of the same earth fissure sites are basically the same, while there are differences in the spectra from different fissure sites. The Fourier spectrum patterns of the F_1 earth fissure site are all single peaks spectra, with prominent main peaks, small spectral areas, and concentrated predominant frequencies (Figs. 6 and 7).

The Fourier spectrum patterns of the F_2 and F_3 fissures are both multi-modal, with many secondary peaks and large spectral areas (Fig. 8–10). The Fourier spectra are consistent with the characteristics of the earth fissure sites, the soil layer of the F_1 earth fissure site is relatively hard, and the secondary fissures are less developed, while the F_2 and F_5 earth fissure cross-sections reveal that their soil layers are weak, and the secondary fissures are densely developed on both sides of earth fissure F_5 . Further analysis of the predominant frequencies derived from the Fourier spectra shows that the earth fissures have less effect on the predominant frequencies of the sites, meaning that the predominant frequencies of the same survey line do not change significantly with increasing distance from the earth fissures, and the ranges of the predominant frequencies on the hanging and heading sides are basically the same. From the results of the spectral analysis, it can be concluded that the predominant frequency of the F_1 earth fissure site is 6–7 Hz, that of F_2 is 3–5 Hz, and that of F_5 is 3–5 Hz. However, because of the different soil structures of different earth fissure sites, the predominant frequencies of the different sites are different. The predominant frequency of the F_1 earth fissure site is the largest, and the predominant frequencies of the F_2 and F_5 earth fissure sites are similar. The predominant frequency of the site is mainly determined by the soil structure of the site and the physical and mechanical properties of the soil, and the earth fissures have little effect on the frequency.

The response spectra of the same earth fissure sites are basically the same. The response spectrum of earth fissure F_1 has a main single peak, with few or almost no secondary peaks. The main peak is prominent, and the predominant period is concentrated. The response spectrum of earth fissure F_2 also has secondary peaks, its spectrum area is larger, the predominant period is more concentrated, and the response spectrum characteristics are consistent with the characteristics of the sites. The response spectrum of earth fissure F_5 exhibits multi-peak development, with many secondary peaks and a large spectrum area.

The Arias intensity is the curve of the energy accumulation at the measurement point over time. The difference between the energy of the different measurement points can be seen better from the final accumulated energy. Based on the Arias intensity of the three earth fissure sites, the closer the measurement point to the earth fissure, the greater the energy accumulated at the measurement point. The accumulated energies of each site reached the extreme values at measurement points A1 and B1; and as the distance increased, the energy gradually decreased and finally stabilized.

6 Analysis Of Dynamic Effects Of The Earth Fissures

6.1 Amplification Effect

The Fourier spectrum, the amplitude of the response spectrum, and the relationship between the Arias intensity and the distance from the earth fissure of each survey line are shown in Fig. 11. Although the response intensities of the different sites are different, the measurement points near the earth fissures all

exhibit a significant amplification effect, which gradually attenuates and stabilizes with increasing distance from the earth fissure.

In order to more intuitively reveal the degree and scope of the impact of the earth fissures on the dynamic response of the site, the concept of the amplification factor is introduced here. Figure 11 shows that the amplitudes of the three measurement points on both sides of the earth fissure on each survey line are basically the same and tend to be stable. Therefore, the stable amplitude is defined as the average of the amplitudes of these three measurement points, and the amplification factor is defined as the average amplitude of each measurement point divided by the stationary amplitude. Figure 11 shows the attenuation curve and fitting curve of the amplification factor with distance. As can be seen from the figure, the amplification effect of the earth fissure is significant in the area near the earth fissure. The amplification factor decreases and gradually becomes stable with increasing distance from the earth fissure. The amplification factor tends to 1, which also indicates that the influence of the earth fissure on the dynamic response of the site has a limited range.

Table 1 shows the extreme values of the amplification factors derived from the Fourier spectrum, response spectrum, and Arias intensity. As can be seen from the table, the extreme values of the hanging side amplification factor are 1.8–2.9, and the extreme values of the heading side amplification factor are 1.7–2.9. Using the same analysis method, the extreme value of the hanging side is slightly greater than or equal to that of the heading side, and the amplification effect of the hanging side is slightly greater.

Table 1
The extreme value of the amplification factor of each analysis method

	Hanging Side	Heading Side
Fourier	2.1	1.8
Response	1.8	1.7
Arias	2.9	2.9

6.2 Range of Influence

As can be seen from the previously described attenuation pattern of the amplification effect, the earth fissure has a certain range of influence on the amplification effect of the site. When the amplification factor attenuates to 1, it can be said that the site is no longer affected by the amplification effect of the earth fissure, and thus, a dynamic response zone can be delineated.

Based on Figure 12, the influence range of the earth fissure amplification effect was obtained (Table 2). As can be seen from Table 2, the impact range is about 20 m, and the ranges provided by the different methods are slightly different. Furthermore, for the same analysis method, the scope of the influence of the hanging side is slightly larger than that of the heading side. From the perspective of seismic fortification in actual engineering, buildings should not be constructed in areas affected by earth fissures.

If they must be constructed in these areas, the seismic fortification intensity of the building should be appropriately increased according to the corresponding amplification factor.

Table 2
The influence range of each analysis method

	Hanging Side	Heading Side
Fourier	21.2	20.0
Response	20.0	19.5
Arias	21.5	17.0

7 Discussion And Conclusions

Earth fissures are distributed around the world, causing serious disasters, affecting the safety and stability of the surrounding buildings on the earth fissure sites. However, until today, there are very few studies about the dynamic response of earth fissures. The current seismic fortification standards do not take into account the impact of the dynamic response of earth fissures. Therefore, this study based on the typical earth fissure sites in the Yuncheng Basin, and demonstrated the effect of fissures on the dynamic response of a site through spectral analysis of microtremors.

(1) The predominant frequencies of three typical earth fissure sites in the Yuncheng Basin are not significantly different with the distance of the earth fissures. The frequency is only determined by the site. The earth fissures have no significant influence on the predominant frequency.

(2) The earth fissures have a significant amplification effect on the dynamic responses of the sites. For all of the different sites, the strongest dynamic response occurred at the earth fissures, and the amplification factor is the most significant near the earth fissures. Both the response and the amplification factor decrease and finally stabilizes with increasing distance from the earth fissures. The extreme values of the amplification factor in the Yuncheng Basin are 1.8–2.9 on the hanging side and 1.7–2.9 on the heading side. The dynamic response of the hanging side is slightly larger or almost equal to that of the heading side.

(3) The dynamic response of the site is only affected by the earth fissures within a certain range. The impact ranges of the hanging and heading sides in the Yuncheng Basin are slightly different, but the overall impact range is about 20 m.

(4) In the actual seismic fortification of an engineering project, building in the area affected by the earth fissures should be avoided as much as possible. If it cannot be avoided, the seismic fortification intensity of the buildings in the area affected by the earth fissures should be increased according to the corresponding amplification factor.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Yahong Deng contributed to the study conception and design. Field investigation, data collection were performed by Ge Cao, Jiang Chang, You Xuan, and Nainan He. And the data analysis by Ge Cao. The first draft of the manuscript was written by Ge Cao, and Huandong Mu is responsible for the final revision of the manuscript. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Geographical location of the Yuncheng Basin

Figure 2

Structure and earth fissures distribution map of Yuncheng Basin

Figure 3

The locations of six typical earth fissures in the Yuncheng Basin and the damage to the ground and buildings caused by them

Figure 4

Cross-sections for three typical earth fissure sites

(a) earth fissure F₁, (b) earth fissure F₅, and (c) earth fissure F₂

Figure 5

Schematic diagram of the survey line layout and testing instrument

Figure 6

Fourier spectrum, response spectrum, and Arias intensity analysis results for line S1

Figure 7

Fourier spectrum, response spectrum, and Arias intensity analysis results for line S2

Figure 8

Fourier spectrum, response spectrum, and Arias intensity analysis results for line S3

Figure 9

Fourier spectrum, response spectrum, and Arias intensity analysis results for line S4

Figure 10

Fourier spectrum, response spectrum, and Arias intensity analysis results for line S5

Figure 11

The amplitude attenuation curves of each site

Figure 12

Amplification factor diagrams of the different analyses

(a) Fourier amplification factor and fitting curve, (b) Response spectrum amplification factor and fitting curve, and (c) Arias intensity amplification factor and fitting curve