Research on seismic exploration techniques and methods in urban environment of loess plateau

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Abstract. Seismic wave energy being absorbed strongly in thick loose loess stratum is a major problem that seismic exploration has to face. In the urban environment, this problem is particularly prominent due to the inability to use explosives, borehole explosion, and large-scale 3D observation methods to increase fold number. To solve this difficult problem, a series of seismic exploration effect tests were carried out in Shaoling Plateau, a southern suburb of Xi’an City. A large-tonnage vibroseis, 28-ton vibrator vehicle, was selected as seismic source. By comparing and analyzing the effects of various vibrating parameters of vibrator vehicle, cooperating with different model geophones acquisition, and using appropriate observation system, we had figured out the feasible parameters for the source excitation and data acquisition in the field working area. Based on the results of above test, a nearly 7 km long seismic survey line was completed with pretty good data acquisition, and the expected exploration aims were well achieved.

1. Introduction

The loess region of China is mainly distributed in the central and eastern parts of Gansu Province, southern parts of Ningxia Autonomous Region, northwestern and central parts of Shaanxi Province, and western parts of Shanxi and Henan Provinces. In this loess-covered area, there are abundant resources such as coal, oil, and natural gas. Many cities are also located in the region, including provincial capitals such as Xi’an, Lanzhou, and Taiyuan.

The climate in this loess region is very dry and causes the loess being generally dry and loose. In thick loess area, seismic wave energy is absorbed severely, particularly for high-frequency wave, in its propagation. In order to cope with this problem, the engineers have carried out a large number of experimental researches in petroleum and coal prospecting, hoping to acquire high signal-to-noise ratio information of target stratum. The research work has made a series of achievements on the aspects of blasthole depth, blasthole combination, the amount of excited explosives, the combination of geophones, and the fold number of observation system [1,5,6]. In urban engineering seismic exploration, unfortunately, the previous research achievements cannot be simply promoted and easily generalized because of restricted using of explosive, limited working site, less working expense, and strong urban traffic interference. At present, study on strong attenuation of seismic wave energy in thick loess is scarce, almost blank, in the urban environment.

In this article, relying on a scientific research project we have carried out a series of tests on the Shaoling Plateau, a thick loess plateau located in the southern suburbs of Xi’an City, Shaanxi Province.
The goal was to break through the bottleneck of severe energy attenuation during seismic wave propagating in thick loose loess stratum. The tests successfully determined various acquisition parameters which were employed in following seismic exploration to probe geological structure of Lintong-Chang'an Fault Zone (LCFZ hereinafter). The final nearly 7 km long seismic profile shows clear geological structures with high quality.

2. Geological and geophysical setting

LCFZ starts from Lintong to the Fengyu Valley of Qinling Mountains, and generally runs 35-45° northeast with total length of about 50 km and width of 5-7 km. The fault zone is composed of three parallel normal faults dipping to northwest and passes through the northern half of Shaoling Plateau, as shown in Fig. 1 [2].

Shaoling Plateau is a loess depositional platform located in the southeastern of Xi'an City. The upper stratum of the plateau is covered by Quaternary loess with a thickness of over 100 m. The basement of the loess is Lower Pleistocene formation. It is estimated that the thickness of the Quaternary System in the plateau area is 500-600 m.

According to the first arrival wave information in the following experimental data, it can be clearly seen that there are two refractive layers near the ground surface. The stratum structure around the experimental site might be mapped by refraction calculation. The top loose loess is of 280-330 m/s wave velocity with thickness 15-17 m. And the next down stratum is consolidated loess with wave velocity above and below water table are 580-640 m/s and 1680-1890 m/s, respectively. The depth of water table ranges from 29 to 41 m.

3. Excitation and acquisition parameter tests

For the purpose of fully probe geological structure of Quaternary system in LCFZ within Shaoling Plateau, we made a plan to conduct a seismic survey line. The survey line run south-north direction with almost 7 km length crossing LCFZ, as shown in Fig. 1. The maximum depth of the exploration target is about 1000 ms, two-way reflection time, and corresponding about 800 m depth.

In order to overcome severe absorption of thick loess stratum for seismic wave propagation, we tried to improve acquired data quality from aspects of source and geophone. Therefore, a series of tests were designed based on previous work experiences and achievements. The tests involved selection of different tonnage of vibroseis, comparison of different parameters of vibrating, testing different model geophones, and setting suitable observation system.

The field tests were carried out in the southern section of Jingdong Avenue on Shaoling Plateau. The elevation of survey line varies gently. Traffic interference was not heavy because of fewer...
vehicles in suburb than in city center. French instrument Serce l 408XL was employed to record data with 1 ms sample time, 2 s recording length, and 250-300 channels by 3 m interval.

3.1. Selection of vibroseis
In the urban environment of Xi'an City, previous seismic explorations had achieved excellent results. The employed source was vibrator vehicle with a tonnage of 18 tons [4]. The locations of these successful seismic surveys were all in Zao River and Feng River terraces, located in the southwestern of Xi'an, where the water table was shallow and there was no loess. Meanwhile, some seismic surveys on loess plateau were not satisfactory. In order to minimize impact of seismic wave energy attenuation in thick loess stratum, the tonnage of vibrator vehicle must be as large as possible. For this purpose, we selected 28-ton vibrator vehicle, model AHV4C, as shown in Fig. 2. By judging from the raw records of subsequent field test, utilizing this type of vibroseis could achieve good excitation effects.

3.2. Sweep frequency tests
In order to determine the best sweep frequency parameters of vibroseis, different initial and termination frequencies tests were conducted. The initial frequencies to be tested were selected as 10, 15 and 20 Hz, respectively. Meanwhile, the termination frequencies were 100, 120 and 140 Hz, respectively. During the testing, employed geophone was single 4.5 Hz broadband model for one channel. At the beginning, the initial frequency was 10 Hz, and the termination frequencies were 100, 120 and 140 Hz, respectively. The records are shown in Fig. 3a, 3b and 3c. It can be seen that the differences among the three records are not obvious, especially the interference of random passing vehicles on road reduces the detailed contrast effects. Even so, there is slightly better first arrival energy at far end of array for the 100 Hz than 120 and 140 Hz. It should be that wave energy attenuation of high frequency in loess stratum is stronger than that of low frequency.

![Figure 3. Comparison of effects of different sweep initial and termination frequencies of vibroseis](image)

Based on the above result, the next step was to fix the termination frequency to 100 Hz, and to vary the initial frequencies to 15, 20 Hz, respectively. The records are shown in Fig. 3d and 3e. Comparing with Fig. 3a, 3b and 3c, it can be seen that the main frequency are obvious different among three records. In the record of 20 Hz initial frequency, the proportion of high frequency component is obvious higher than those of 10 and 15 Hz, and the surface wave energy is the weakest. In contrast, 10 Hz initial frequency record shows much lower frequency component, and the surface wave energy is significantly more prominent than other two records. In general, the reflection events in the vicinity of
1000 ms can be recognized in all three records. Relatively, the initial frequency of 15 Hz shows clearest reflection. Therefore, the sweep initial and termination frequencies of excitation were determined to be 15-100 Hz eventually.

3.3. Sweep duration tests
The sweep duration determines the energy of single vibration excitation. Because vibrator vehicle may increase excitation energy by multiple repeated excitations, the sweep duration is mostly set to be 10-20 s generally. During the sweep duration testing, the number of repeated excitation was set to be 10, the initial and termination frequencies were determined to be 15-100 Hz. The sweep duration was set to be 8 s (Fig. 4a), 10 s, 12 s (Fig. 4b), 14 s, and 16 s (Fig. 4c) successively. It can be seen from the records that reflection waves could be identified in less than 1000 ms of travel time, and the signal-to-noise ratio improves with the increase of the sweep duration. In the record of 16 s, reflection information of 600-800 ms is most clear among these records. Considering the field working efficiency and other factors, the sweep duration was finally set to be 12 s.

![Figure 4. Comparison of the effects for different sweep duration](image)

3.4. Repeated excitations tests
In order to enhance excitation energy, vibroseis may repeatedly vibrate multiple times at same point. For this test, the number of repeated excitations was set to be 1 (Fig. 5a), 2, 4 (Fig. 5b), 6, 8 (Fig. 5c), 10, 12 (Fig. 5d), 14, 16 (Fig. 5e), 18, 20 (Fig. 5f), successively. The related parameters during testing were designed as follows: the sweep duration was set to be 10 s, the initial and termination frequencies were determined to be 15-100 Hz. The contrast among above records shows that the signal-to-noise ratio raise obviously with the increase of excitation repeated times. Great than 8 times, however, the signal-to-noise ratio improves slowly. In overall consideration, the number of repeated excitations finally was determined to be 10 in principle.
3.5. Different model geophones tests

Considering the strong absorption property of thick loess for seismic waves, particularly for the high frequency waves, we designed the test to compare two sets of different model geophones, a single 4.5 Hz broadband geophone and 60 Hz geophone (3 in signal channel), as shown Fig. 2.

Two pairs of different sweep parameters were selected for different model geophones comparison. One pair of the initial and termination frequencies were 15-100 Hz, and the other 20-100 Hz, both with 12 times repeated excitations by 10 s sweep duration. Two working conditions for geophones test were designed. One is to use single 4.5 Hz broadband geophone for every channel in whole array. The other was that 4.5 Hz broadband geophones between 61st and 121st channels were replaced by three 60 Hz combined geophones one by one. Fig. 6a and 6b are the records of using 60 Hz geophone between 61st and 121st channels with two pairs of different sweep frequencies, 15-100 Hz and 20-100 Hz, respectively.

Comparing Fig. 3d with Fig. 6a, Fig. 3e with Fig. 6b, and Fig. 6a with Fig. 6b, the following several opinions may be inferred. ① The reflection signal acquired by 60 Hz geophone has higher frequency and resolution. ② The reflection energy acquired by 60 Hz geophone is weaker, especially for the deeper information. Compared with the clear reflection events in 600-800 ms picked up by 4.5 Hz broadband geophone, the reflection events of more than 700 ms could hardly be distinguished for the array section picked up by 60 Hz geophone. ③ For 60 Hz geophone, the deep reflection energy is more attenuated on the record of sweep bandwidth of 20-100 Hz than that of 15-100 Hz. ④ The comparison results of the two sets of geophones come from one 4.5 Hz broadband geophone versus
three 60 Hz geophones. If 4.5 Hz geophone were also used three for combination, the contrast of deep reflection would be more obvious. In summary, the quality of the data acquired by low-frequency (broadband preferred) geophone is better than that of 60 Hz.

3.6. Determination of final acquisition parameters

Based on target depth, utilizing the selected parameters via above tests and also referring to previous seismic exploration experience in Xi'an area [3,4], the parameters of seismic exploration in Shaoling Plateau were finally determined as follows.

The source: sweep initial and termination frequencies were 15-100 Hz, sweep duration was 12 s, and the number of repeated excitation was 12.

The geophone: single 4.5 Hz broadband geophone was adopted.

The observation system: trace spacing was 3 m, the number of receiving trace was 240, spacing of shoot point was 15 m, the number of fold was 24, and the offset was 0 m.

The instrument parameter: the sampling time was 1 ms, and the length of record was 2 s.

3.7. Final seismic exploration effects

With the acquisition parameters determined above, a seismic survey line with length of nearly 7 km had been completed along Jingdong Avenue, Shenzhou Avenue, and Gongtian Second Road from south to north. Fig. 7 is the final stack profile. In order to judge the quality of original information on profile, no additional explanatory is added to the profile.

It can be seen in Fig.7 that the main reflection information is about 200-800 ms. The reflection events are clear with well continuity. The geological structures are revealed clearly and obviously. The seismic exploration overall achieved expected goals.

4. Conclusions

Through the above tests and analysis, it can be known that seismic exploration under urban environment in loess plateau area might mitigate the strong absorption impact of thick loess during seismic wave propagating by means of reasonable selecting source, correctly setting excitation parameters, utilizing suitable acquisition equipment, and designing feasible observation system. The following conclusions can be summarized:

(1) Selecting large tonnage, such as 28 tons, vibrator vehicle as vibroseis source can not only suppress urban traffic interference, but also achieve high quality excitation effects by flexibly changing sweep parameters and repeated excitation times.
(2) The initial and termination frequencies should be determined through field tests. On the premise that the resolution is satisfied, the initial and termination frequencies should be set as low as possible to minimize impact of seismic wave energy attenuation in thick loose loess stratum, especially for high-frequency waves.

(3) The selected geophone should have low frequency, preferably with broadband characteristics. The 60 Hz geophone commonly used in coal seismic prospecting is not suitable for reflection acquisition of hundreds of meters deep in loess plateau under urban environment.

(4) Due to strong attenuation of seismic wave energy in loose loess and uninterrupted urban traffic interference, the signal-to-noise ratio of the single shot reflection data is generally not high. The higher number fold observation system is required to achieve better results.

(5) Engineering prospecting in urban environments generally requires high accuracy, and the trace spacing is preferably 3-4 m. The array length should be determined based on both field tests and the depth of exploration target stratum.

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