High-resolution reflected P- and SH-wave imaging for the shallow subsurface in the thick Quaternary area

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Abstract. For the construction of urban underground space, the shallow stratum structure from surface to 200 meters needs to be high-precision investigated. As limited in the theoretical level, the normal reflection P-wave can’t image in the very shallow subsurface especially in a thick Quaternary area. The SH-wave survey has a higher resolution in the theoretical level because the SH-wave has a lower velocity and shorter wavelength. The aim of this paper is to present a combined seismic reflection survey of P- and SH-wave in a thick Quaternary area where is close to Xiong’an New Area. By using the ($\lambda/4$) criterion, we obtain a resolution around 1.4m and 2.4 m for the SH-wave section in 9 m ($v=169$ m/s and $f=30$ Hz) and 50 m ($v=209$ m/s and $f=22$ Hz) depth separately and a resolution around 3.8m for the P-wave section in 200 meters depth ($v=1878$ m/s and $f=125$ Hz).

1. Introduction

The structure of shallow or even ultra-shallow subsurface is often concerned by engineers, hydrogeologists, and geo-technicians for some economic construction of the city. They prefer some low costs geophysical methods, such as seismic refraction and surface wave methods [8] or electrical resistivity and electromagnetic methods. Usually, the resolution of these methods is not satisfaction. Both reflection P-wave and SH-wave have proven to be very useful in engineering, shallow geo-hazard and environmental studies [1,2,5,10,11]. Many geophysicists focus on increasing the resolution of reflection seismic from sources [6,7,13], receivers [9], geometry [4,12] and processing methods [3,5]. Also, some SH-wave seismic reflection work integrated with P-wave had been done to apply to the landslide geo-hazard [11]. He obtained a resolution around 2.5m for the SH-wave section ($v=280$ m/s and $f=30$ Hz) and around 9m for the P-wave section ($v=1800$ m/s and $f=50$ Hz) at the expected shallowest slip surface (12-19 m of depth from topography).

What we concern about is how to increase the resolution of reflection seismic exploration in Xiong’an New Area where the subsurface is covered with thick unconsolidated Quaternary sediments. For the development and construction of the underground space in Xiong’an New Area, we focus on
the geological structure of depth less than 200 meters. The thickness of the Quaternary sediments differs between north and south of Xiong’an New Area. In the north, the thickness ranges from 300 m to 500 m, and in the south, the thickness is around 800-900 m.

As we all know, wavelet with high and broad frequency corresponds to high resolution. In this article, we use the broadband vibrator as the P-wave source to increase the resolution of the reflection P-wave method. Also, we research the reflection SH-wave method along the P-wave survey line. Then, we combined P- and SH-wave reflection field data to characterize the structure of the subsurface shallower than 200 meters. Joining P- and SH-wave method to image the structure of shallow or ultra-shallow subsurface can balance the relations to resolution and depth of investigation.

2. Field data acquisition
The survey line is located in the district of Gaoyang County which is next to the Xiong’an New Area in the north (Figure 1a). The depth of the basement in this area is between 3 km to 4 km (Figure 1b). According to the borehole data, the thickness of the Quaternary strata in this area is about 430 m. The main lithology interpreted from borehole information of this area is clay, silty clay, silty sand, and fine sand. Also, there are several thin aquifers between silty sand and fine sand layers. The length of P- and SH-wave survey lines is 2 km and 1 km separately. They are coincident with each other in the middle of the P-wave line. The survey line runs along the road which is unpaved with soil on the surface. This condition benefits the coupling between geophones and the ground. To improve the signal-to-noise ratio, data acquisition is performed when there is no traffic.

The BV260 vibrator is used as a seismic source to activate P-wave (Figure 2). Its weight is 14 tons and the scanning frequency can be from 1 Hz to 400 Hz. The rated vibration output is 118.2 kN. We compared the seismic record acquired by 60 Hz and 100 Hz geophones simultaneously in one shot. Focusing on the high-frequency information, we chose the 100 Hz geophones as the P-wave receiver, and the scanning frequency starts from 10 Hz to 300 Hz. The analysis of the output signal is shown in Figure 3. The energy of the output signal increases gradually from 0 to 20 Hz and stabilizes till 200 Hz, and then it increases gradually till stabilizes between 210 Hz and 250 Hz. Although the highest scanning frequency is 300 Hz, there is no energy when the frequency is higher than 255 Hz (Figure 3a). The phase of the output signal stabilizes around zero degree from 10 Hz to 255 Hz (Figure 3b). After correlation, the output signal is zero-phase Ricker wavelet (Figure 3c). In order to generate more high-frequency energy, we enlarge the scanning length to 20 seconds to increase the high-frequency scanning time.

As for the SH-wave source, we made a basement with a block of wood that weighs about 40 kg, in the middle of which we insert rebar to penetrate to the soil to increase its coupling with the soil surface. We use a sledgehammer which weighs 16 kg to strike the side of the basement to generate the SH-
wave. A vertical stack of 5 blows was applied for each SH-source point. Considering the low frequency of SH-wave, we apply 4Hz geophones for acquisition.

Table 1. Acquisition parameters of the P- and SH-wave seismic reflection profile

| P-wave acquisition parameters | SH-wave acquisition parameters |
|-------------------------------|--------------------------------|
| Number of receivers in one spread | 120 | Number of receivers in one spread | 96 |
| Total number of receivers | 668 | Total number of receivers | 501 |
| Total number of sources | 334 | Total number of sources | 251 |
| The total length of the line | 2km | The total length of the line | 1km |
| Source space | 6m | Source space | 4m |
| Receiver space | 3m | Receiver space | 2m |
| Minimum offset | 0m | Minimum offset | 0m |
| Maximum offset | 180m | Maximum offset | 96m |
| Maximum fold | 45 | Maximum fold | 36 |
| Sample rate | 0.5ms | Sample rate | 0.5ms |
| Sample length | 2s | Sample length | 2s |
| Scanning frequency of the vibrator | 10-300Hz | Number of shots on one source point | 5 |
| Length of scanning | 20s | The natural frequency of geophones | 4Hz |
| Vibrator output | 50% | |
| The natural frequency of geophones | 100Hz | |

The parameters of the P- and SH-wave acquisition are listed in Table 1. The geometry of P- and SH-wave is shown in Figure 4. Due to the bad condition of the soil surface, there are some places that the vibrator cannot reach. So we change the original shot point to the adjacent receiver point where the vibrator can reach. The geometry for the P-wave survey is irregular and regular for SH-wave. The folds of P- and SH-wave reach up to 45 and 36 on both sides of the survey line separately. The normal folds for P- and SH-wave are 30 and 24 separately.

Figure 2. BV260 Vibrator working on the survey line

Figure 3. Signal output of BV260.
(a) correlation force of the signal.
(b) correlation phase of the signal.
(c) wavelet after correlation

Figure 4. Field data acquisition geometry. (a) P-wave geometry. (b) SH-wave geometry.

There are two typical shot records with an AGC process (window length 100ms) for the P- and SH-wave survey in the thick Quaternary area shown in Figure 5. There is a loose loess layer which is a few meters depth below the surface, so the first arrival for the P-wave shot record consists of direct wave (about 11 channels around source point) and refracted wave (channels with a far offset) (Figure
5a). The reflected P-waves shows a good hyperbolic characteristic in the far offset part. The energy of the Raleigh wave is so strong that contaminates the near offset channel. In the SH-wave record (Figure 5b), it is obvious that the first arrival is the sound wave. It means that in the shallow subsurface, the SH-wave velocity is lower than 340m/s. The SH-wave and Love wave have a similar velocity in the shallow subsurface so that they mix together in the far offset. Cause the SH geophone has a low natural frequency of 4Hz, the record of SH-wave contains some low-frequency noise with strong energy.

Figure 5. Shot records after AGC (window length 100 ms) of P- and SH-wave. (a) P-wave record (FFID 3182) with a vibrator source, the time length is cut to 1s. (b) SH-wave record (FFID 4180) with a sledgehammer source, the time length is 2s.

3. Data processing

All the raw data were processed on a work station with FOCUS seismic processing software. As both the P- and SH-waves are pure-wave, the P- and SH-wave data processing flow is basically the same, and only the module parameters are different from each other. The main processing flow and parameters are shown in Table 2.

The strong surface wave and sound wave are the main noise for the P-wave raw data, while surface wave and low-frequency are noise for the SH-wave raw data (Figure 5). The surface is so flat that we didn’t do the geometry static correction. First, we use a bandpass filter to suppress the low-frequency and ultra-high-frequency noise. Then we use the F-K filter combined with KL transformation to suppress the surface wave (Figure 6).

Table 2. Data processing flow of P- and SH-wave

| Pre-process | Data decompilation and add geometry to the data. Edit the dead traces manually. |
|-------------|--------------------------------------------------------------------------------|
| Bandpass filter | For the P-wave: 30-40-200-210. For the SH-wave: 10-20-120-130. Denoise the 100 Hz noise. |
| 2D filter | Suppressing the surface wave and linear noise |
| Suppress sound wave | Calculate the statistic average amplitude of a sliding window, suppress the high amplitude to be consistent with the average amplitude. |
| Suppress multi-wave | Surface consistent prediction deconvolution. For P-wave: operator length: 200 ms, prediction step: 15 ms. For SH-wave: operator length: 300 ms, prediction step: 15 ms. |
| Seismic frequency expanding | For SH-wave, expanding the frequency to increase the resolution. |
| Velocity analysis | In conjunction with residual static correction. |
| Stack | After NMO with a mute of 45% stretch. |
| Post-stack denoising | Structure-oriented filter and dip filter. |
| Time-depth conversion | With the average velocity transformed from stack velocity by DIX formula. |
Figure 6. Denoising of P- and SH-wave shot data. (a) P-wave raw data with AGC. (b) Suppressing the surface wave. (c) SH-wave raw data with AGC. (d) Suppressing the surface wave, linear noise, and expanding the frequency.

The characteristics of sound waves in seismic records are broadband in frequency and strong in amplitude. Both of the bandpass filter and F-K filter aren’t suitable for suppressing the sound wave. For the sound wave denoising, we create a sliding window along the sound wave slope, calculate the statistic average amplitude of the window and suppress the high amplitude to be consistent with the average amplitude. Surface consistent prediction deconvolution and seismic frequency expanding were applied to the denoised shot data for increasing the resolution of seismic events. By conjunction with residual static correction, high-precise velocity analysis was performed on supergathers formed by adjacent CMP gathers (Figure 7). It is obvious that the SH-wave has a very low velocity which is about one-eighth of the P-wave’s velocity in the shallow subsurface.

Besides the classical steps of NMO corrections, residual static correction and stack, a structure-oriented filter method was applied to the stack profile to suppress the random noise. The structure in this area is simple and flat, we don’t apply the migration method to the stack profile for the high-resolution purpose. The time domain profile was converted to depth domain profile with the average velocity transformed from stack velocity obtained by velocity analysis with DIX formula.

The P- and SH-wave stack profiles of the time domain are shown in Figure 8. Aiming to combine P- and SH-wave to analyze, we select the overlaid part of the two surveys line which is 1 km long. For the SH-wave profile, we choose three seismic events to analyze the frequency spectrum, which is 0.12 s, 0.48 s and 1s corresponding to 9 m, 50 m, and 150 m in depth separately (Figure 8a, b, c). For the P-wave profile, we choose two seismic events to analyze the frequency spectrum, which is 0.12 s and 0.25 s correspond to 50 m and 200 m in depth separately (Figure 8d, e).

Figure 7. Velocity analysis. (a) P-wave velocity analysis. (b) SH-wave velocity analysis.
Figure 8. SH- and P-wave stack profile in the time domain of the coincident part on the survey line. The left corresponds to the SH-wave profile, and the right corresponds to the P-wave profile. The bottom graphs of both profiles are the spectrogram of the red rectangle area separately.

Figure 9. SH- and P-wave profile in the depth domain. (a) Ultra-shallow SH-wave profile with a depth of 100 m. (b) Ultra-shallow P-wave profile with a depth of 100 m. (c)(d) Profiles with a depth of 300 m. The interval SH- and P-velocities transformed from stack velocity by DIX formula is over-imposed to the profile separately.

Our concern depth of subsurface is shallower than 200 m, so in the depth domain of the two profiles, we extract the seismic data to a depth of 300 m. A translucent interval velocity section obtained from stack velocity was over-imposed to the seismic profile (Figure 9c, d). An obvious higher resolution can be obtained from the SH-wave profile than the P-wave profile especially in the ultra-shallow (less than 60 m) subsurface (Figure 9a, b).

4. Discussion and Conclusion

The vertical resolution of seismic exploration is considered to be a quarter of the wavelength of the elastic wave by the $\lambda/4$ criterion. According to the wavelength calculation formula ($\lambda=v/f$), increasing and broadening the frequency of elastic waves will decrease the wavelength and improve the resolution. We obtained a higher resolution of the P-wave profile by increasing the wavelet frequency and broadening the band of wavelet frequency with a broadband frequency vibrator as the compressional source. In the thick Quaternary area, the SH-wave has a lower velocity which is about one-seventh of P-wave, and its frequency is about one-fifth of P-wave. So the SH-wave has a higher resolution than P-wave at the theoretical level.

In the ultra-shallow subsurface (less than 60 m), there isn’t a continuous seismic event in the P-wave profile (Figure 9b). In the SH-wave profile, there are three continuous seismic events in the depth less than 60 m. The depth of the shallowest seismic event is about 9m (Figure 9a). The seismic events in the SH-wave profile are thinner than those in the P-wave profile. Comparing the two profiles of SH- and P-wave, in the position of 3718 m, there is a fault we call F1 which is more obvious in the SH-wave profile than that in the P-wave profile. F1 is a normal fault with a 1m fault throw (Figure 9c).
According to the Figure 8 and Figure 9c, d, we obtain a resolution around 1.4 m and 2.4 m for the SH-wave section in 9 meters (v=169 m/s and f=30 Hz) and 50 meters (v=209 m/s and f=22 Hz) depth separately and a resolution around 3.8 m for the P-wave section in 200 meters depth (v=1878 m/s and f=125 Hz).

As a result, combining reflected SH- and P-wave in the thick Quaternary area is a high-precise method to explore the structure of shallow or ultra-shallow subsurface.

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