

The Application of Rayleigh Wave Exploration in Subway Construction

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Abstract

The method of Rayleigh wave exploration was selected and used in this paper to detect the location of underground cavity areas in subway tunnel construction. The change rule of Rayleigh dispersion curves in the underground cavity areas was studied by using Fourier transform, filtering, wavelet analysis, etc. The result showed that: through the analysis of Rayleigh dispersion curves and the assessment of engineering geological properties of foundation soil in the whole site, the dispersion curves of different strata in underground normal and underground cavity were selected and compared, and the inflection point in the dispersion curves of underground cavity areas was fairly obvious. Thus, Rayleigh wave exploration has good application effects and development prospects.

Keywords - Rayleigh wave, dispersion curve, subway, underground, tunnel

I. INTRODUCTION

A section of the Shijiazhuang subway Line 1 is located in the central part of the city. Hand excavation is adopted. The ground transportation is very busy and there are lots of surrounding buildings. In addition, above the section there are 5 brick sanitary sewers, which are only about 3m away from the tunnel vault, and they have poor structural integrity and even have the problem of leakage of water. So, it is of great difficulty to control ground settlement and building settlement. During construction, the disturbance of soil outside the tunnel must be minimized and the monitoring measurement should be strengthened. In order to ensure the safety of surrounding buildings and pipelines, special geological conditions of the site must be ascertained before excavation, such as water-enriched regions including cave, pipeline leakage, perched groundwater, etc.

Since geological conditions of the subway tunnel construction region are very

complicated, some errors between prospective design and geological reality are unavoidable, especially for the accurate location of underground cavity, ponding and unfavorable geological zone, and this is an important reason why geologic engineering investigation forecast is needed. In terms of geologic condition analysis, the problems existed in the strata such as leakage, fissure, chipping, disengagement and corrosion as well as in the waterproofing and drainage facilities, especially the separation of secondary lining, tunnel leakage and cavity, can bring various kinds of hidden danger and barrier to the engineering construction of subway tunnel.

II. RAYLEIGH WAVE EXPLORATION PRINCIPLES AND FIELD TESTS

Rayleigh wave exploration mainly utilizes the unique properties of Rayleigh wave: due to the dispersion characteristics of Rayleigh wave propagated in the stratified media, when surface wave is transmitted in the multilayered media, the propagation speed of surface wave will have some changes with different frequencies[1]. So, the curve of Rayleigh wave velocity with the change of depth at the measuring point can be calculated by digital signal analysis, thus realizing the goal of exploration. The greatest advantage of Rayleigh wave exploration is high shallow layer resolution, low requirement for operating conditions, high efficiency, low cost and no influence on construction processes. In recent years, many domestic and overseas scholars have done a lot of research work on subway engineering exploration and accumulated a great deal of experience in subway engineering test data and image analysis, making Rayleigh wave exploration more applicable to engineering practice[2].

SE2404EP engineering seismograph with hammer excitation was used in the actual test. The integrated engineering seismograph had 24 reception channels; the instrument dynamic range $\geq 126\text{dB}$; the equivalent input noise $\leq 1\mu\text{v}$; the range of frequency acceptance band was $0.1\sim 5000\text{Hz}$; the low cutoff frequency of detector was 4.5Hz ; the sampling length was $512\sim 4096$ byte/channel; the sampling frequency was $0.005\sim 30\text{ms}$; and the total harmonic distortion was less than 0.05% .

The trace header file could record the point coordinate in the test process, and the hammer was adopted for the seismic origin. In order to acquire observing system parameters of each measuring line, unilateral excitation was mainly performed. It was hard to distinguish reflected wave and direct wave, surface wave and noise in the near seismic channel, so a certain offset was needed to clearly distinguish them from interference wave. According to the test, the minimum and maximum offsets were chosen as 2m and 6m, respectively.

A total of 4 measuring lines were arranged in this paper for test, and they were: 2 lines were located at the inside wall of subway tunnel outside away from 30cm, recorded as A and B; and 2 lines were located at the north and south side wall of subway tunnel outside away from 50cm, recorded as C and D. There were 12 measuring points in each line, with the interval of 2m. Hammer was used to impact the ground, and the wave was stimulated and produced in the foundation soil. A thick iron plate was placed at the stimulation point as a pallet to improve the stimulation effect. Several

stimulations should be conducted in each stimulation point to make sure that good recorded data could be obtained. Whether the record of several stimulations on the same measuring point had fine repetition was an important indicator to measure the reliability of Rayleigh wave test results. On the one hand, the fine repetition indicated that the instrument system was normal and reliable; on the other hand, it also showed that each record basically reflected the real characteristics of engineering rock and soil mass. The seismic wave of A was shown in Fig. 1.

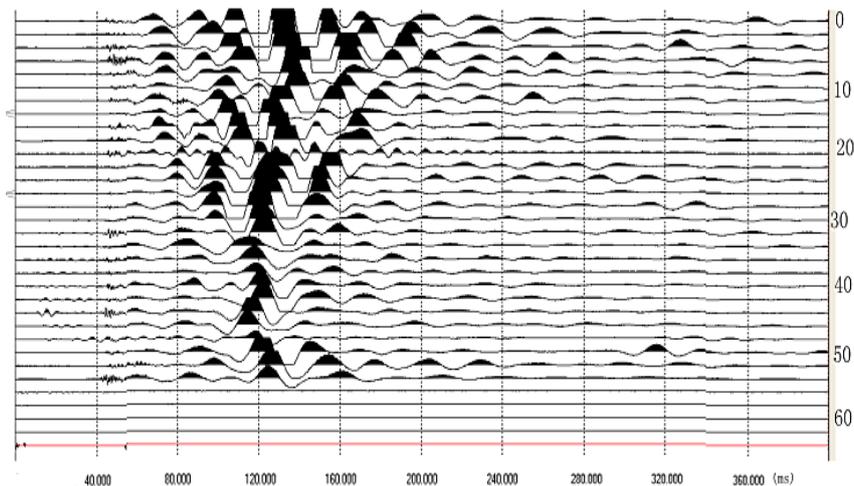


Fig. 1 Seismic wave of A (actual measurement)

III. TEST DATA PROCESSING METHODS AND PROGRAM IMPLEMENTATION

Matlab, developed by MathWorks, is an advanced interactive software package specially designed for scientific and engineering calculation. It has been proven that Matlab is a very flexible and useful tool used to solve the complicated numerical calculation in the application fields of mathematics, physics, chemistry, engineering, medicine, finance, etc. It has a friendly interface, is easy to operate, and can be used to completely achieve programming.

(1) Digital Filtering

In the Rayleigh wave exploration, when seismic apparatus was used to record Rayleigh wave, broadband was usually adopted for the record in order to increase the resolution. Therefore, not only various effective waves but also various interference waves were recorded within the broadband range [3]. Effective waves and interference waves were often mixed together, and filtering was an important means to highlight the effective waves and suppress the interference waves [4]. The purpose of filtering was to obtain the amplitude spectrum of seismic record through the spectral analysis of seismic trace, and select proper parameters for filtering according to the spectrum difference between the signal and the noise in the seismic record, thus eliminating the noise, highlighting the effective signal, and improving the signal-to-noise ratio in the seismic record. Based on the test data, the corresponding Matlab

filtering program was written as follows:

```
x=[-20 -24 -44];
```

The cut-off frequency is 60Hz

The specifications of filter were designed as follows:

```
fs (sampling frequency)=5000Hz;
```

```
wp (passband cut-off frequency)=4Hz;
```

```
ws (stopband cut-off frequency)=60Hz;
```

```
rp (the maximum attenuation within passband)=0.3db;
```

```
rs (the minimum attenuation within stopband)=200db;
```

```
wp=2*pi*4;
```

```
ws=2*pi*60;
```

```
rp=0.3;
```

```
rs=200;
```

```
fs=5000;
```

The minimum order of filter was selected

```
[N,wn]=buttord(wp,ws,rp,rs,'s');
```

```
[b,a]=butter(N,60/2500);
```

```
% Establish the prototype of Butterworth low-pass filter
```

```
[h,f]=freqz(b,a,2048,fs);
```

```
% Calculate the frequency response
```

```
sf=filter(b,a,x);
```

```
SF=fft(sf,2048);
```

```
m=abs(SF);
```

```
f=5000*(0:2047)/2048;
```

```
plot(f,m);
```

```
grid;
```

```
xlabel(' frequency (Hz) ');
```

```
ylabel(' amplitude (db)');
```

```
title(' the filtered waveform ');
```

(2) Fourier Transform Analysis

A kind of global time domain or frequency domain transform was used in the Fourier

transform analysis to establish a relationship from time domain to frequency domain or from frequency domain to time domain [5]. The seismic record was discrete series with a limited length and a given sampling interval [6]. Supposing the seismic record of discrete-time series was $f(n\Delta t)$, the sampling interval was Δt , and there were totally N discrete values in the seismic record, then $n=1,2,3,4,\dots,N$; supposing the function of frequency domain was $F(m\Delta f)$ the sampling interval of frequency domain was Δf , the frequency range of seismic wave was limited, and there were totally M discrete values, then the real part and imaginary part of amplitude spectrum could be obtained according to the discrete Fourier transform formula [7]. Firstly, the real part and imaginary part of forward transform were calculated according to the following formulas:

The real part:

$$\text{Re}F(m\Delta f) = \Delta t \sum_{n=0}^{N-1} f(n\Delta t) \quad (1)$$

The imaginary part:

$$I_m F(m\Delta f) = \Delta t \sum_{n=0}^{N-1} f(n\Delta t) \quad (2)$$

The spectral analysis of Fourier transform was performed for the Rayleigh wave measured in the field according to the discrete Fourier transform formula and amplitude spectrum formula, and the Matlab program for spectral analysis was shown as follows:

```
x=[-20 -24 -44];
```

```
The sampling frequency was set as 5,000Hz
```

```
N=2048
```

```
FFT (fast Fourier transform) was performed
```

```
The amplitude value was calculated
```

```
f=5000*(0:2047)/2048;
```

```
The corresponding frequency conversion was performed
```

```
The amplitude waveform of frequency domain was performed for the Rayleigh wave grid;
```

```
xlabel(' frequency ( Hz ) ');
```

```
ylabel(' amplitude (db)');
```

```
title(' spectral analysis');
```

According to the Matlab program used for spectral analysis, the spectral analysis was conducted for the Rayleigh wave, and a Butterworth filter with the cut-off frequency

of 60Hz was designed. Fig. 2 The amplitude characteristic of Butterworth filter was: flatten passband and the monotonic decrease of stopband. Through comparison, it can be found that the interference wave was effectively suppressed and the effective wave was highlighted before and after filtering. The frequency higher than 60Hz was eliminated by the filter since the frequency of surface wave was relatively low (10-40Hz). It could be seen that the effect of filtering was very good, with the interference wave being removed and the effective wave being retained, as shown in Fig. 3.

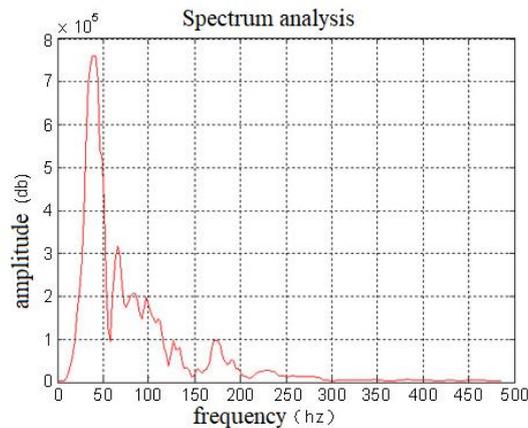


Fig. 2 Seismic of b (1) in the time domain

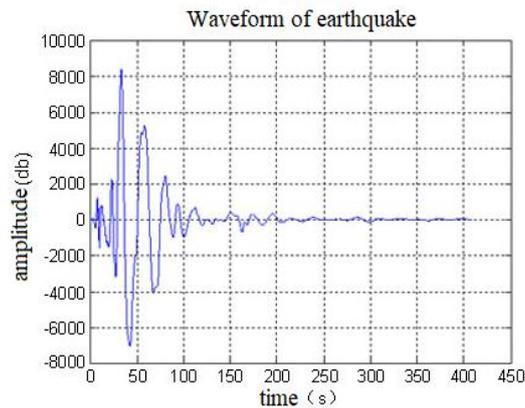


Fig. 3 Spectrum analysis of b in the frequency domain

(3) Wavelet Analysis

Wavelet analysis is currently a new field of mathematics, and its basic knowledge involves functional analysis, Fourier transform, signals and systems, digital signal processing, etc. It is of vital significance in both theory and application [8]. Wavelet analysis belongs to harmonic analysis and is a kind of time domain and frequency domain analysis, with the feature of multiresolution. It utilizes the resolution on

heterogeneous distribution to observe the unsteady signal through translational zoomed windows. The narrow window is used in the transient signal change, while the wide window is used in the slow signal change, thus effectively extracting the features of signal waveform [9].

As for the one-dimensional Rayleigh wave signal, there are usually 3 steps in the filtering processing of seismic wave signal by wavelet transform:

Step1: The wavelet decomposition of one-dimensional signal. Select a wavelet and determine a decomposition level N, and then the N level decomposition is performed for the signal.

Step2: The threshold quantization of high frequency coefficient in the wavelet decomposition. As for the high frequency coefficient from the first level to the Nth level, select a threshold and perform the softening of threshold quantization processing.

Step3: The reconstruction of one-dimensional wavelet. Perform the reconstruction of one-dimensional signal according to the coefficient of the Nth level of wavelet decomposition and the high frequency coefficient from the first level to the Nth level after the quantization processing.

The seismic data from the measuring line A were selected in this paper to conduct the filtering and noise reduction. The seismic signal with the sampling frequency $S=0.2\text{ms}$ and a total of 2,048 data was used. The original graph was as follows. Dmey wavelet was used to carry out the simulation. After 7 level wavelet decomposition, the high-frequency wave was filtered out, and then the reconstruction was performed, as shown in Fig. 4.

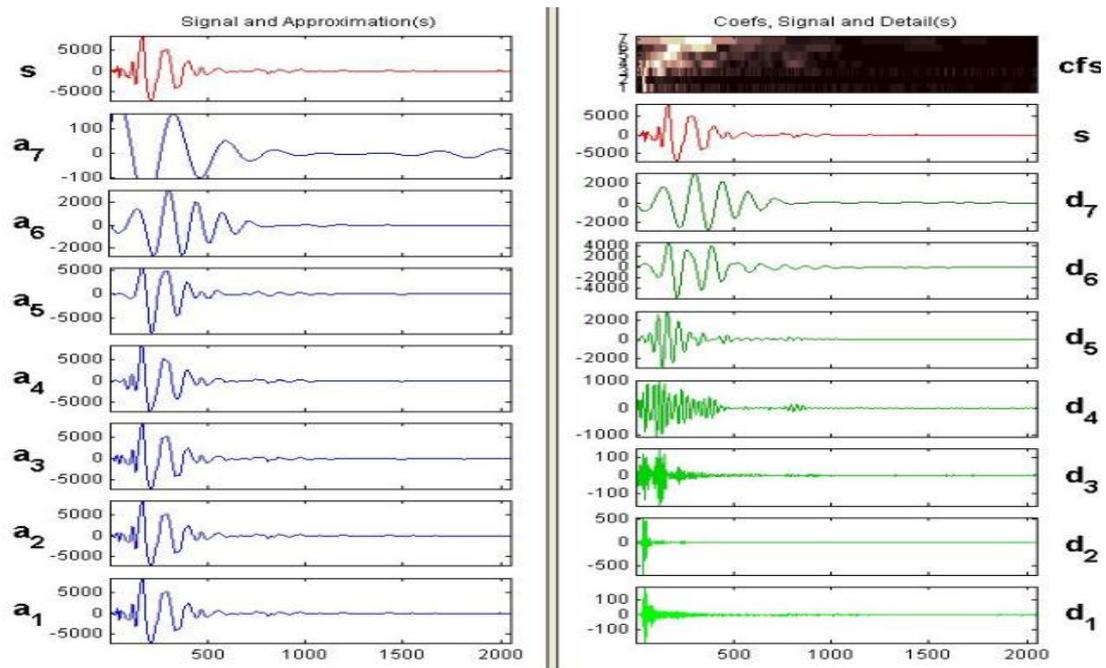


Fig.4 The seismic of wavelet decomposition

IV. ANALYSIS OF PHASE VELOCITY –DEPTH DISPERSION CURVE

(1) The exploration result of measuring line C

The table of calculating phase velocity was obtained through the Fourier transform of Rayleigh wave, filtering analysis and processing, as well as wavelet analysis, as shown in Table 1. The dispersion curves between each two waveforms were extracted, and the depth of subsurface formation interface was determined according to the feature of dispersion curves. The burial depth of underground cavity areas was interpreted by these curves. In order to verify the feasibility and accuracy of Rayleigh wave phase velocity obtained, a comparison of dispersion curves and drillhole data was performed by using the two special circumstances of underground normal and underground cavity.

Table 1 The phase velocity of b (1-3)

Serial No.	Frequency (Hz)	Phase	Track pitch (m)	Phase velocity (m/s)	Wavelength (m)	Depth (m)
1	12.21	1.5202	2	213	16	8
2	14.66	1.9348	2	197	13.4	6.7
3	17.10	1.1499	2	187	10.9	5.45
4	19.54	1.4420	2	170	8.7	4.35
5	21.98	1.6131	2	171	7.8	3.9
6	24.43	1.8365	2	167	6.8	3.4
7	26.87	2.2555	2	150	5.6	2.8
8	29.31	2.8575	2	129	4.4	2.2

The conditions of engineering geology and underground water of measuring line A were: the strata of this section in order from top to bottom were: miscellaneous filling stratum, clay stratum, silty-fine sand stratum, medium-coarse sand stratum, gravel stratum, gravelly sand stratum, and gravel stratum; and according to the drillhole data, there was no underground cavity area, and the groundwater type was pore phreatic water, with the buried depth of stable water level of 4.6 m -5.7 m, good permeability of the aquifer, and sufficient groundwater recharge. The buried depth of tunnel was 6.3 m -6.6 m, and the whole tunnel was located below the underground water level.

Through the exploration of measuring line A-A, it was found that the dispersion curves of measuring line A (1-3) did not have an abrupt change, Fig. 5 and there was stratification at about 2m, but it was not very obvious. This section could roughly be divided into two layers within the range of investigation depth: the top layer was miscellaneous filling stratum and the under layer was sand stratum. At each measuring point, the thickness was different in different locations. There was no

phase velocity anomaly within this section and no zigzag change in each section of the measuring line, so there was no cavity area, which accorded with the geological exploration and drillhole data after practical verification.

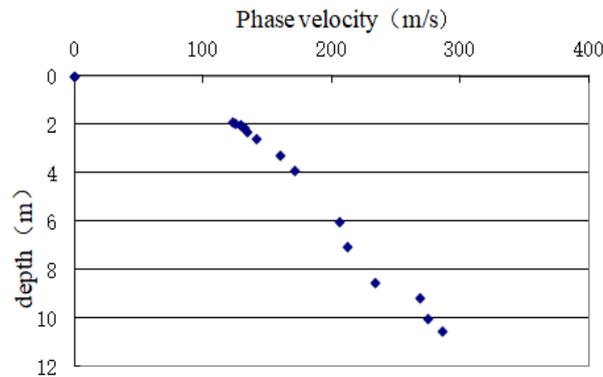


Fig. 5 The dispersion curves of measuring line A (1-3)

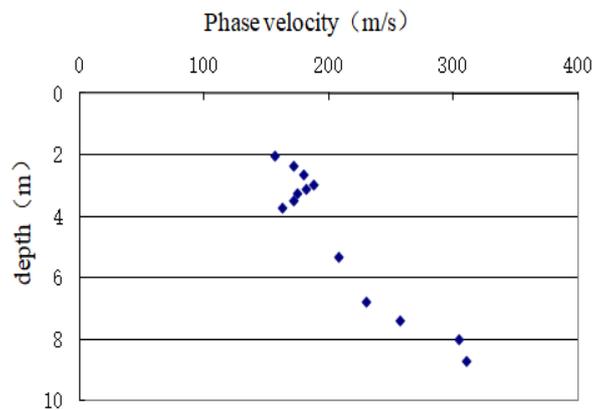


Fig. 6 The dispersion curves of measuring line C' (5-7)

(2)The exploration result of measuring line C

The engineering geology and underground water of measuring line C were the same with that of measuring line A. It could be clearly seen from Fig. 6 that there was geological stratification: the top layer was miscellaneous filling stratum with a low wave speed and the under layer was sand stratum with a high wave speed. There was Rayleigh wave anomaly between the horizontal distance of 35-41m and the depth of 3-4 m, and the speed of Rayleigh wave suddenly decreased, showing a zigzag change. It could be speculated that there was an underground cavity area. The comparison between Rayleigh wave speed profile map and drillhole data showed that the stratum situation reflected by the wave speed profile map was very consistent with the drillhole data.

V. CONCLUSION

(1) The method of Rayleigh wave exploration has a good effect on the discovery of underground cavity during subway construction. The inflection point in the dispersion curve of underground cavity area is very obvious, and it can make comprehensive evaluation for the engineering geological properties of foundation soil in the whole site.

(2) The effect of overburden failure caused by underground cavity areas makes the propagation speed of Rayleigh wave decrease, so there is a significant change in the characteristic of dispersion curves. The range of underground cavity areas can be delineated according to the change of phase velocity, and the detection result can meet the engineering demand.

(3) The comparison between Rayleigh wave exploration and interpretation and geotechnical engineering investigation data shows that Rayleigh wave exploration is an effective nondestructive survey method, which provides a basis for the replacement of traditional survey methods in the future.

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