Near-field directional seismic waves based on tunnel environment

Yongao Yue¹, Dongxu Ren¹, Yongqian Chen¹, Zhengfeng Li¹, Gaofeng Zhou¹, Lujun Cui¹, Chun Han²,*

¹School of mechanical and Electrical Engineering, Zhongyuan University of Technology Zhengzhou, China
²College of Civil Engineering, Xinxiang University Xinxiang, China

*Corresponding author e-mail: 371534123@qq.com

Abstract. In this paper, a near-field directional seismic wave (NFDSW) method based on near-field application environment is proposed. Different from the far-field directional seismic wave technique, the time-delay parameter of near-field directional seismic wave is not a single fixed value, but a variation value. In this paper, the accurate delay parameters of target signal are estimated by cross-correlation method, then the phase axis of target signal is leveled by delay parameters, and finally the final target signal is obtained by array element superposition and inverse correction. Numerical simulation shows that the near field directional seismic wave technology can separate the target signal well and improve the quality of target signals significantly in the near field environment.

1. Introduction

Directional seismic wave (DSW) technology originates from phase array radar, which can enhance the energy of directional signals by superposition of seismic wave fields [1]-[2]. Far field directional seismic wave (FFDSW) technology can significantly improve the quality of target signal has been applied in many fields [3]-[10]. However, there are not many researches on the near field directional seismic wave technology, mainly because the accuracy of time delay parameter estimation in the near field is higher. In recent years, DSW have been gradually applied in the medium and near field environment [11]-[12]. In 2019, Yue et al. proposed the random dislocation directional seismic wave (RDDSW) method to suppress false multiple wave interference and random interference, and achieved good results [13]. The characteristics of near field seismic waves in different environments are different, so the study of near-field directional seismic waves should be targeted at specific application environments. Tunnel seismic prediction is of great significance to tunnel construction and its seismic waves are mainly in the middle field and near field [14]-[15]. Based on the above research and present demand, this paper proposes the near-field directional seismic wave (NFDSW) technology based on tunnel environment.

In this paper, the difference between near field and far field of seismic wave is analyzed in detail, and DSW theory based on near field environment is studied according to the characteristics of near field. In addition, the effect of NFDSW on tunnel seismic prediction is studied. Finally, the feasibility and effectiveness of NFDSW technology are verified by through numerical simulation.
2. Principle of NFDSW

There are two ways to generate directional seismic waves through array, one is based on the source, and the other is based on the receivers. The essence of the two methods is the same, but the directional seismic wave method based on the receivers has a wider application range and better effect. Therefore, in this paper, we study the NFDSW technology based on the receivers in detail.

The schematic graph of an \( m \)-element NFDSW is shown in Figure 1. Shot array and geophone are maintained in a straight line, and the shots are labelled in ascending order. The records collected by the system are \( x_1(t), x_2(t), \ldots, x_m(t) \), and \( m \) is the number of sources. Considering the influence of environmental noise, the collected X component records can be expressed as

\[
\begin{align*}
x_1(t) &= s_1(t) + n_1(t) \\
x_2(t) &= s_2(t) + n_2(t) \\
&\vdots \\
x_m(t) &= s_m(t) + n_m(t)
\end{align*}
\]

Where \( s_i(t) \) and \( n_i(t) \) represent the signal and noise from \( i \)-th (\( 1 \leq i \leq m \)) shot record, respectively.

Suppose the geology is homogeneous and the wave velocity is \( v \), then the time corresponding to the \( i \)-th trace reflected wave is \( t_i \), which can be represented as

\[
t_i = \frac{r_i}{v},
\]

where \( r_i \) represents the total distance of the reflected wave from the \( i \)-th shot.

Taking the reflected wave signal in the first trace record as the reference signal, the delay time between the other trace and the reference trace is calculated by the method of maximum cross correlation, and denoted as

\[
\begin{align*}
\tau_{11} &= t_1 - t_1 \\
\tau_{12} &= t_1 - t_2 \\
&\vdots \\
\tau_{1m} &= t_1 - t_m
\end{align*}
\]

According to the calculated delay parameters, the phase axis of the target signal is leveled, denoted as

\[
\begin{align*}
y_1(t) &= x_1(t - \tau_{11}) \\
y_2(t) &= x_2(t - \tau_{12}) \\
&\vdots \\
y_m(t) &= x_m(t - \tau_{1m})
\end{align*}
\]

The result of \( n \)-element superposition of \( y_1(t), y_2(t), \ldots, y_m(t) \) is recorded as
Where \( n \) represents the number of array elements, which is an odd number greater than 1 and less than \( m \).

Reverse correction is performed for \( z_i(t) \) to obtain the target signal recorded as

\[
z_i(t) = \begin{cases} 
\frac{z_{\frac{n-1}{2}}(t)}{(1 \leq i < \frac{n-1}{2})} \\
\sum_{j=\frac{n-1}{2}}^{\frac{n-1}{2}} y_j(t - \tau_{ij}), (\frac{n-1}{2} \leq i \leq m - \frac{n-1}{2}), \\
\frac{z_{\frac{n-1}{2}}(t)}{(m - \frac{n-1}{2} < i \leq m)} 
\end{cases}
\]  

(5)

Next, we analyse the effect of NFDSW on the recorded SNR. The SNR of the original record \( x_1(t), x_2(t), \ldots, x_n(t) \) is

\[
\text{SNR}_1 = \frac{E_s}{E_n}.
\]  

(7)

Suppose that the random noise is Gaussian noise and that the SNR of \( d_1(t), d_2(t), \ldots, d_m(t) \) can be expressed as

\[
\text{SNR}_2 = \frac{n^2 \cdot E_s}{(n \cdot E_n)}
\]  

(8)

\[
\frac{\text{SNR}_2}{\text{SNR}_1} = \frac{(n^2 \cdot E_s)}{(n \cdot E_n)}/(E_s/E_n) = n
\]  

(9)

Therefore, the SNR of seismic records processed by \( n \) element NFDSW technology is improved \( n \) times.
3. Numerical simulation analysis

In this part, we will study the application effect of NFDSW technology through numerical simulation. Firstly, the theory of tunnel seismic prediction technology and the characteristics of corresponding record are introduced in detail. Then, the near field records of TSP synthesis will be quantitatively analyzed by the NFDSW technique.

3.1. Tunnel seismic prediction (TSP)

The TSP method constitutes one of the main non-destructive methods used for geological prediction during tunnel construction, which can be used to predict the location and morphology of unfavorable geological condition [16]. However, when environmental noise and other sources interference are strong, it is difficult to obtain high quality effective signals, which seriously affects the accuracy and reliability of geological prediction. Therefore, suppressing noise and improving the effective signal quality are essential not only for recognizing and predicting the geological conditions in front of the tunnel face but also for reducing both the drilling time and the safety risks in the tunnelling operation [17]. TSP is multi-wave, multi-component seismic reflection data processing method that provides geological information about tunnel construction by accurately detecting changes in the rock.

3.2. Numerical simulation analysis of NFDSW

The observation system of TSP-203 is shown in Figure 2(a), which mainly consists of shot points array and three-component geophones are arranged in a straight line [18]-[19]. When the space angle \( \theta \) of the tunnel is small, the in-phase axis of the reflected wave signal is approximately linear, and the corresponding seismic wave field can be treated as far field. When the space angle \( \theta \) of the tunnel is large, the in-phase axis of the reflected wave signal is a curve, and the corresponding seismic wave field needs to be treated as the near field. In order to facilitate the numerical simulation analysis, it is usually used to carry out the research in the form of shot-receiver interchangeable. The space angle in this example is 60 degree, and the offset and shot spacing are 20 m and 1.5 m, respectively. The S-wave and P-wave velocities are 1700 m/s and 3000 m/s, respectively. The Riker wavelet with a primary frequency of 100 Hz is used as the excitation source, and the sampling interval is 0.0625 ms. The records collected by three component seismic geophone are divided into X, Y and Z components, and the records of the X-component with Gaussian noise are shown in Figure 2(b). Due to the larger incident Angle of seismic waves, the synthesized seismic records produce a large number of Ps converted waves. Because of the strong random noise, the effective signals (R_p, R_s, P) are difficult to be recognized (~10.641 dB), which affects the later data processing and analysis. In order to improve the quality of effective signals, far-field...

**Fig 1.** The schematic diagram of m-element NFDSW.
directional seismic wave technology and near-field directional seismic wave technology are used to process and analyze them respectively. Figure 2(c) shows the results of Rs signal processed by 9-element array FFDSW technology with $\tau_s = 0.2\ ms$. It can be seen from the results that only part of the trace recording energy of target signal Rs is improved, while the rest of the trace recording energy becomes worse or even completely disappears. This is mainly due to the influence of approximation error in the FFDSW technique, which results in only some trace records can be effectively superimposed with the same phase, while the rest of trace records are seriously distorted when superimposed. The delay parameter ($\tau_s$) of the Rs is estimated by equation (3) and the maximum cross-correlation method. The results of

![Diagram](image)

**Fig 2.** Effect analysis of target signals extraction by NFDSW. Where Dp, Ds, Rp, Rs and Ps denote the direct P-wave, direct S-wave, reflected P-wave, reflected S-wave and Ps converted wave respectively. (a) Schematic graph of the DSW technique in TSP; (b) The records of the X-component with Gaussian noise; (c) The recordings of a 9-element array with $\tau_s = 0.2\ ms$ by FFDSW; (d) Shot recordings of a 9-element array with $\tau_s$ by NFDSW.

NFDSW processing by 9-element array with $\tau_s$ are shown in Figure 2(d). It is clear that the quality of the target signal Rs is significantly improved (-3.982 dB), while other signals are well suppressed. Numerical simulation further verifies the effectiveness of NFDSW technique.
In order to further study the influence of NFDSW technology on tunnel detection distance, a simulation example is used for analysis, as shown in Figure 3. There are two reflection interfaces in the tunnel model. The first reflection interface is 200 m away from the tunnel face, and the second reflection interface is 400 m away from the tunnel face. The P wave velocity at the first reflective interface is 2000 m/s, and the S wave velocity is 1155 m/s. The second reflection interface P wave velocity is 3000 m/s, and the S wave velocity is 1732 m/s. The X component record of the random noise is shown in Figure 3(a). In Figure 3(a), we can only observe Ds, Dp and Rp1 waves, and the signal quality of Rp1 wave is very poor. In addition, the Rp signal is completely submerged by noise. To improve the target signal quality and increase the tunnel detection distance, NFDSW technology was used to process and analyze the target signal. The results of NFDSW processing by 5-element array with $\tau_p$ are shown in Figure 2(d).

It is clear that the signal quality of Rp1 has been significantly improved, and we can clearly identify the first reflection interface. In addition, we were also able to effectively identify the Rp2 signal, and the second reflection interface at a greater distance can also be detected. Therefore, we can conclude that the adoption of NFDSW technology can significantly increase the tunnel detection distance.

4. Conclusion
In this paper, NFDSW method based on tunnel environment is proposed, and the method can extract target signals in the near field and suppress random noise in the environment. Time delay estimation and stacking are used to improve the quality of near-field target signals. In the numerical simulation part, the NFDSW and NFDSW methods were tested on synthetic TSP records, and the comparative results showed the method of NFDSW can effectively separate the whole target signal from that mixed with strong random interference. In addition, the signal-to-noise ratio of the effective signal is increased from -10.641 dB to -3.982 dB, which further verifies the feasibility and effectiveness of near-field directional
seismic waves. In addition, we also studied the influence of NFDSW technology on the tunnel detection distance. The research results show that this method can significantly increase the tunnel detection distance theoretically. The application of NFDSW technology is not only limited to tunnel seismic advanced detection, but also has important significance for other fields.

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