Impact of Blasting Construction of Tunnel Crossing Expressway

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Abstract. In this study, we monitored the blasting process for constructing a water-conveying tunnel under an expressway and analyzed the dynamic response of the existing structures along the road resulting from the blasting process. The vibration comfort index of adjacent structures was evaluated. The results show that the amplitude of the vibration velocity of existing structures along the line resulting from the blasting process ranges from 0.4 to 71.8 mm/s, and the amplitude of the vibration frequency ranges from 22.7 to 166.7 Hz. More attention should be paid to structures with natural vibration frequency in this range. The maximum vibration velocity of the measuring points on the shoulder of the expressway and near rural roads was recorded in the vertical direction, whereas that of the measuring points on the slope protection and dam mainly appeared in the horizontal direction. The effect of vibration in different directions should be considered in different construction structures. The deformation of expressway pavement, slope protection, and reservoir dam caused by the blasting process is small, which meets the safety requirements. DIN4150-2 can be used for vibration comfort control in blasting construction, but the vibration comfort index determined by DIN4150-2 is inconsistent with personnel’s perception of horizontal vibration comfort. Therefore, it is necessary to further quantify the comfort evaluation index of adjacent structures in the tunnel blasting process.

1. Introduction
With the rapid development of China’s economy and the continuous expansion of the construction scale of basic transportation facilities, it has become more common for new railway lines to cross and merge with existing business lines and for more shallow-buried tunnel projects to cross expressways. The drilling and blasting method exhibits strong adaptability to geology and economic and efficient construction; hence, it is widely used in tunnel excavation in China. Approximately 90% of tunnels in China have been constructed using this method [1]. There is an increase in existing traffic line damage, leading to the key problem of ensuring the safety of tunnel construction and maintaining the stability of the original traffic line in the underpass tunnel blasting construction [2,3].

So far, these issues have been studied by many researchers. Zhang et al. [4] determined blasting parameters through theoretical calculations and studied the vibration response of existing tunnel support structures under the influence of the upper-crossing tunnel blasting construction combined with field monitoring data. According to the attenuation law of blasting vibration velocity, Cao et al. [5] fitted the monitoring data of tunnel blasting particle vibration velocity and proposed the vibration reduction scheme of vault-coring isolation belt and hollow holes in cutting areas. They further verified the vibration reduction effect. According to the statistical analysis results of blasting vibration monitoring data, Ye et al. [6] obtained the propagation trend of blasting vibration (Sadov’s formula) and the relationship between vibration velocities, distance from blasting center, and maximum section charge, providing a theoretical basis for effective reduction of blasting vibration velocity. Based on
these previous studies, the drilling and blasting construction method has a significant impact on the structures along the drilling and blasting lines. However, at present, there are few measured data on the dynamic response and vertical deformation of structures along lines resulting from drilling and blasting construction. Numerical methods have mainly been employed to study the impact of drilling and blasting construction on structures along the line, and the relevant numerical analysis results have not been verified.

Thus, in this study, the vibration velocity, main vibration frequency, and deformation of structures along a highway, adjacent to rural roads, slope protection, and adjacent to reservoir dams were monitored in real-time during the blasting construction of a water conveyance tunnel obliquely crossing a highway. The variation in the dynamic response of the first slope on the northeast side of the highway, the hard shoulder both on the northeast and southwest sides, the rural road on the southwest and northeast sides of a reservoir dam along the highway in the process of blasting construction was analyzed. The results provide a reference for the tunnel blasting construction development and influence control, as well as the evaluation index of blasting construction on highway driving comfort.

2. Project Profile

2.1. Project introduction

The water-conveying tunnel obliquely crosses an expressway at 81.5°, and the buried depth of the tunnel in the undercrossing section is 18.3 m. The surrounding rock includes types III and IV. It is mainly characterized by the development of fault structures, simple fold structures, and a monoclinic structure with a dip angle of 20°–30°. Figure 1 shows the tunnel section diagram. The project is supported by frame bolts. The slope-to-slope ratio is 1:0.75. The vertical spacing of the frame beam is 4 m, and the horizontal spacing is 4 m. In-situ-cast reinforced concrete is used, and high-strength precision-rolled threaded steel bars are used inside the anchor rod. The tunnel is constructed using the full-section drilling and blasting method. The tunnel blasting construction affects the construction along the highway pavement, highway slope protection (Figure 2), and reservoir dam adjacent to the tunnel. Thus, the dynamic response and deformation of adjacent structures during blasting were monitored in real-time. Figure 3 shows the relative position of the tunnel and expressway.

2.2. Measuring point arrangement and working conditions

Five vibration monitoring points are arranged during the blasting process (Figure 3). Measuring point \( V_1 \) is positioned on the first slope on the northeast side of the highway. Measuring point \( V_2 \) is on the hard shoulder of the northeast side of the highway, measuring point \( V_3 \) is on the hard shoulder of the southwest side of the highway. Measuring point \( V_4 \) is placed on the rural road southwest of the highway, and measuring point \( V_5 \) is placed on the northeast side of the reservoir dam. According to actual tunnel excavation, vibration monitoring is divided into three stages (Figure 2). In the first stage, three vibration testers are arranged at \( V_1, V_2, \) and \( V_5 \), respectively. In the second stage, they are arranged at \( V_2, V_3, V_4, \) and in the third stage, they are arranged at \( V_3, V_4, \) and \( V_5 \).

For deformation monitoring, the monitoring points are arranged in positions with good visual conditions and representativeness (significant deformation or great influence on engineering safety): three horizontal displacement monitoring points \( P_1, P_2, \) and \( P_3 \) are arranged on the high-slope northeast
side of the highway, and one horizontal displacement monitoring point \( P_4 \) is placed on the low-slope southwest side of the highway, with a total of four horizontal displacement monitoring points (Figure 4). Two vertical displacement monitoring points \( G_1 \) and \( G_2 \) are arranged on the southwest side of the highway, one point \( G_3 \) on the northeast side of the highway, and three points \( B_1 \), \( B_2 \), and \( B_3 \) on the reservoir dam. The six vertical displacement-monitoring points are shown in Figure 3.

![Figure 3. Relative position of the tunnel and highway](image)

![Figure 4. Position of horizontal displacement measuring points](image)

3. Vibration monitoring results and analysis

In this project, electronic detonators are used for near-end blasting, with an explosive volume of 3 kg. The vibration velocity of surface engineering-structure-mass points resulting from blasting vibration has three components, one vertical direction and two horizontal directions. The vibration velocity and main frequency of each measuring point in three directions are recorded during vibration monitoring, where the X direction is the horizontal direction along the tunnel axis, the Y direction is the horizontal direction perpendicular to the tunnel axis, and the Z direction is the vertical direction perpendicular to the tunnel axis.

The distribution of the amplitude of blasting response at each measuring point is shown in Table 1. In the first stage of blasting, in the six measurements at measuring point \( V_1 \), the maximum vibration velocity occurs zero times in the vertical direction, five times in the radial direction, and once in the tangential direction. The maximum dominant frequency occurs six times in the vertical direction, and there are situations where the dominant frequency is the same in both directions. In the six measurements at measuring point \( V_2 \), the maximum vibration velocity appears four times in the vertical direction, once in the radial direction, and once in the tangential direction. The maximum dominant frequency occurs five times in the vertical direction and once in the radial direction. The dominant frequency is the same in the two directions (X direction and Y direction). In the six measurements at measuring point \( V_3 \), the maximum vibration velocity is recorded five times in the vertical direction and once in the radial direction. The maximum main frequency occurs six times in the vertical direction. The main frequency is the same in the two directions. For the measurement points of the first-order slope, the maximum vibration velocity is recorded in the radial direction. For the measurement points of the highway hard shoulder, the maximum vibration velocity is recorded in the vertical direction, and the maximum dominant frequency of all the measurement points appears in the vertical direction. The blasting trends of the second and third stages are shown in Table 1.

| Measurement points | First-stage vibration velocity | dominant frequency | Measurament points | Second-stage vibration velocity | dominant frequency | Measurament points | Third-stage vibration velocity | dominant frequency |
|--------------------|-------------------------------|-------------------|--------------------|-------------------------------|-------------------|--------------------|-------------------------------|-------------------|
| \( V_1 \)         | 5                             | 1                 | \( V_2 \)          | 1                             | 0                 | \( V_3 \)          | 0                             | 0                 |
| \( V_2 \)         | 1                             | 1                 | \( V_3 \)          | 1                             | 0                 | \( V_4 \)          | 0                             | 0                 |
| \( V_3 \)         | 1                             | 0                 | \( V_4 \)          | 0                             | 0                 | \( V_5 \)          | 1                             | 0                 |

In summary, in the blasting construction process, the amplitude of the vibration velocity of the highway pavement varies from 1.9 to 71.8 mm/s, and the main frequency of vibration varies from 25.6 to 166.7 Hz. The amplitude of the vibration velocity of highway slope protection varies from 1.3 to 7.7 mm/s.
mm/s, and the main frequency of vibration varies from 62.5 to 111.1 Hz. The amplitude of the vibration velocity of the reservoir dam varies from 0.4 to 1.4 mm/s, and the main frequency of vibration changes from 22.7 to 76.9 Hz. Special attention should be paid to building structures whose natural frequency is in this range.

3.1. Vertical deformation
The vertical displacement monitoring points were observed for the first time before blasting, and the initial vertical displacement was recorded. Then, the vertical displacement monitoring points were observed once every five days for 30 days after blasting was completed. Figure 5 shows the cumulative settlement curve of typical section-monitoring points. The cumulative settlement rate gradually decreases and stabilizes, and the cumulative settlement is approximately 3.54 mm. The vertical displacement of the monitoring points above the tunnel (G1–G3) is high, whereas the vertical displacement of the monitoring points beside the reservoir dam (B1–B3) is low. That is, with an increase in the distance from the tunnel axis, the settlement of the monitoring points decreases.

3.2. Horizontal deformation
The horizontal displacement monitoring point was observed for the first time before blasting, and the initial horizontal displacement was recorded. Then, the horizontal displacement monitoring points were observed once every 10 days for 30 days after the blasting construction was completed. Figure 6 shows the horizontal displacement curve for different monitoring points, where the X direction is along the tunnel horizontal direction, and Y direction is perpendicular to the tunnel horizontal direction. The maximum horizontal cumulative deformation at each monitoring point in the X and Y directions is 3 mm. The horizontal cumulative deformation at P1 and P4 on the four-level slope protection on the northeast and southwest sides of the expressway, respectively, is larger than that at other points.

In summary, vertical and horizontal deformation of the highway pavement, slope protection, and reservoir dam caused by blasting are small. However, the horizontal deformation of adjacent structures resulting from blasting can reach the same level of vertical deformation. On the one hand, blasting may cause vertical differential settlement and horizontal tilting of adjacent structures. The horizontal and vertical deformations affected by blasting should be monitored simultaneously for structures with high design safety levels along the blasting process.

4. Comfort analysis for adjacent structures in blasting construction
The vibration response of adjacent structures during blasting is very significant. The dynamic response of nearby buildings significantly affects driving and pedestrian comfort. To provide a basis for the formulation of traffic management measures for crossing expressways in the blasting process in the future, as well as the evaluation of driving safety and pedestrian comfort, this section analyzes the vibration comfort of nearby structures during blasting.
There are three commonly used comfort evaluation methods: maximum weighted vibration-intensity evaluation \([7-9]\), blasting vibration-peak-intensity evaluation \([10]\), and vibration acceleration evaluation methods \([11,12]\). Among them, the maximum weighted vibration-intensity evaluation method defines the impact of periodic and nonperiodic vibration caused by transient blasting on personnel comfort. \(K_{BF_{max}}\) is calculated using the peak vibration velocity and the corresponding main vibration frequency obtained through monitoring. When \(K_{BF_{max}} < [K]\), the environmental vibration meets the comfort requirements of people in structures, where \([K]\) is the limit value specified by DIN 4150-2.

\[
K_{BF_{max}} = c_F \frac{1}{\sqrt{2}} \frac{v_{PPV}}{\sqrt{1 + (f_0 / f)^2}}.
\]  

In the equation, \(f_0\) is the cut-off frequency of the high-pass filter (Hz). Generally, \(f_0 = 5.6\) Hz. \(c_F\) is a constant (0.6–0.8). Table 2 shows the vibration comfort evaluation parameters of the highway shoulder during blasting.

**Table 2. Evaluation parameters for vibration comfort of expressway pavement during blasting**

| Serial Number |  |  |  | Feelings of Testers |
|---------------|---|---|---|---------------------|
|               | Z Direction | Y Direction | X Direction |                      |
| 1             | 21.6         | 3.7          | 3.9          | Obvious vertical abnormal seismicity |
| 2             | 24.0         | 10.4         | 9.3          | Obvious vertical abnormal seismicity |
| 3             | 33.8         | 8.4          | 13.2         | Obvious vertical abnormal seismicity |
| 4             | 31.2         | 13.6         | 33.9         | Obvious vertical and horizontal anomalies |
| 5             | 40.5         | 39.0         | 13.0         | Obvious vertical abnormal seismicity |
| 6             | 22.1         | 11.5         | 8.6          | Obvious vertical abnormal seismicity |
| 7             | 11.7         | 5.0          | 6.4          | Obvious vertical abnormal seismicity |
| 8             | 22.0         | 12.6         | 11.9         | Obvious vertical abnormal seismicity |
| 9             | 11.3         | 6.1          | 8.9          | Obvious vertical abnormal seismicity |
| 10            | 6.3          | 3.9          | 3.9          | Obvious vertical abnormal seismicity |
| 11            | 5.7          | 2.6          | 2.5          | slight vertical abnormal seismicity |
| 12            | 4.4          | 2.2          | 3.4          | slight vertical abnormal seismicity |
| 13            | 7.0          | 4.6          | 3.4          | Obvious vertical abnormal seismicity |
| 14            | 6.3          | 4.3          | 2.6          | Obvious vertical abnormal seismicity |
| 15            | 5.4          | 2.2          | 2.3          | No obvious abnormal seismicity |
| 16            | 4.6          | 1.6          | 1.5          | No obvious abnormal seismicity |
| 17            | 6.4          | 4.9          | 1.9          | Obvious vertical abnormal seismicity |
| 18            | 4.7          | 2.7          | 2.9          | No obvious abnormal seismicity |
| 19            | 6.4          | 3.2          | 4.6          | Obvious vertical abnormal seismicity |
| 20            | 6.0          | 2.2          | 2.8          | Obvious vertical abnormal seismicity |
| 21            | 9.4          | 3.0          | 3.7          | Obvious vertical abnormal seismicity |
| 22            | 5.2          | 1.9          | 2.5          | slight vertical abnormal seismicity |
| 23            | 9.0          | 3.8          | 4.3          | Obvious vertical abnormal seismicity |
| 24            | 5.5          | 2.9          | 3.0          | slight vertical abnormal seismicity |
| 25            | 5.4          | 3.7          | 3.7          | slight vertical abnormal seismicity |
DIN4150-2 can give the vibration comfort indexes of different blasting processes in three stages (Table 2). When the vertical limit of \(K_{H\text{Bfmax}}\) is greater than 6, people can feel vertical vibration discomfort. When the standard \(K_{H\text{Bfmax}}\) level limit is greater than 30, people can feel obvious horizontal vibration discomfort. Personnel’s perception of vertical vibration comfort is in good agreement with the specification parameters, whereas personnel’s perception of horizontal vibration comfort does not agree well with the specification parameters. The control index of personnel comfort in the existing specifications is not suitable for the comfort evaluation of adjacent structures during the blasting construction of underground tunnels, and it is necessary to further quantify the comfort evaluation index in the environment.

5. Conclusion
To ensure the safety of existing traffic lines and clarify the influence of tunnel blasting on the dynamic response and deformation of structures along the line, we monitored the blasting process for a water conveyance tunnel obliquely crossing the expressway. The following results were obtained.

1. The dynamic response of structures along the line resulting from blasting is correlated to the vertical distance between the structure and the blasting surface. The vertical distance decreases (highway pavement < slope protection < horizontal dam) while the vibration velocity amplitude of the structures increases. However, the vibration response of important structures in the distance can also reach the same level as adjacent structures. In the blasting process, attention should be paid to the response monitoring of important structures. The main vibration frequency of adjacent structures along the line ranges from 22 to 166 Hz, and structures whose natural vibration frequency is in this range should be focused on.

2. The vertical and horizontal deformations of highway pavement, slope protection, and reservoir dam caused by the blasting process are small, whereas the horizontal deformation of adjacent structures can reach the same level as the vertical deformation. Blasting may cause vertical differential settlement of adjacent structures, and at the same time, it may cause horizontal tilting of adjacent structures. The horizontal and vertical deformation affected by the blasting process should be monitored simultaneously for structures with high design safety levels along the blasting path.

3. DIN4150-2 can be used to control the vibration comfort of blasting. When the vertical limit \(K_{H\text{Bfmax}}\) is greater than 6, people can feel vertical vibration discomfort. When the standard \(K_{H\text{Bfmax}}\) level limit is greater than 30, people can feel horizontal vibration discomfort. The vibration comfort index determined by this specification is in good agreement with the perception of vertical vibration comfort of personnel, whereas it does not agree well with the perception of horizontal vibration comfort of personnel. It is necessary to further quantify the comfort evaluation index of adjacent structures in the process of tunnel blasting.

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