Shaking table test on the characteristics of seismic acceleration responses at the portal section of the loess tunnel

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Abstract. A large-scale shaking table test was conducted to study the dynamic response at the portal section of a tunnel based on the loess tunnel of the Baoji–Lanzhou high-speed railway as an engineering background. A wavelet packet transform method was applied to analyze seismic acceleration responses. The pattern of changes in energy in the loess tunnel under the seismic load was obtained. Results reveal that (1) the acceleration amplification factor of the slope surface increases with elevation, but a turn exists at the inverted arch of the tunnel because the stiffness of the tunnel is greater than that of the slope soil. As such, the tunnel elicits a certain protective effect on the slope soil below it. (2) The amplification effect of the internal slope soil decreases gradually outward, and the tunnel portal is affected by the amplification effect of the slope surface. The peak ground acceleration (PGA) of the tunnel vault is greater than that of the inverted arch of the tunnel. Thus, the vicinity of the tunnel vault should be the key seismic fortification area. (3) The loess layer causes an amplification effect on low-frequency-band seismic waves (0–12.51 Hz) and a filtering effect on the high-frequency-band seismic waves. The changes in the energy of the slope surface and the inside tunnel gradually stabilize as the seismic load increases. This study can provide a reference for the seismic fortification of the tunnel portal section of the loess slope–tunnel system under a seismic action.

Key words: Loess tunnel; Shaking table test; Peak Ground Acceleration; Wavelet packet transform; Deformation failure characteristics
1. Introduction

Earthquakes are one of the main causes of slope failure. With the implementation of China’s “One Belt and One Road” initiative and the continuous improvement of the national economy, numerous tunnels have been and will be built in the Western earthquake zone. Among them, Baoji–Lanzhou high-speed railway and Lanzhou–Chongqing railway are open to traffic, and Yinchuan–Xi’an high-speed railway and Chengdu–Lanzhou railway are under construction; they traverse the seismic zone of the loess area. The tunnel portal is the key to seismic fortification, so the dynamic response of the loess tunnel portal is a hot research topic. After the earthquake in Wenchuan on May 12, 2008, investigations revealed the damage to mountain tunnels, and the tunnel portal section, the shallow buried section, and the weak surrounding rock section located in the fracture zone had the most serious damage and the highest probability of damage during the earthquake. The failure mechanism at the portal section of the mountain tunnel under the action of a strong earthquake, the repair technology, and the seismic fortification length of the portal section have been widely explored, and studies have shown that the dynamic response at the portal section of the mountain tunnel is influenced by many factors, such as the buried depth of a tunnel, slope gradient, and slope height. The stability of a slope is also essential for the seismic fortification of the tunnel portal section. Furthermore, the earthquake resistance of loess tunnels has been comprehensively studied. Liang et al. obtained the pattern of variation in the acceleration amplification effect and seismic fortification length at the portal section of loess tunnels through large-scale shaking table tests and numerical simulation studies. Sun et al., Wang et al., and Tao et al. studied the dynamic responses of the tunnel portal section under different portal elevations and slopes through numerical simulation. They showed that the greater the portal elevation is, the greater the displacement response and internal force response of the lining of the portal section will be. The greater the slope is, the weaker the magnifying effect will be.

Previous studies mainly focused on the amplification effect of a slope on a seismic wave. Wang et al. and Bian et al. analyzed the acceleration response through Fourier transform and found that the soil body causes a certain amplification effect on low-frequency waves and a certain filtering effect on waves greater than 20 Hz. However, Fourier transform, which can only achieve transformation from a time domain signal to a frequency domain signal, is a global transformation that fails to express the local nature of the time frequency of a nonstationary signal. Wavelet packet analysis is a typical method for examining nonstationary signals. In comparison with wavelet analysis, wavelet packet analysis can be applied to divide signals more finely by using time–frequency characteristics and improve the analysis rate of high-frequency bands.

Currently, the pattern of the variation in the energy of the dynamic response to a slope–tunnel system under an earthquake load is important for studying the dynamic security and stability of a tunnel structure. However, the wavelet packet transform is seldom used to explore of the dynamic response of the loess tunnel portal section. Therefore, this study analyzed the slope acceleration amplification effect based on the loess tunnel of the Baoji–Lanzhou high-speed railway and a shaking table test, achieved a local decomposition via a wavelet packet transform to time frequency, and obtained the pattern of variation in the dynamic response of the energy of the slope–tunnel system through a quantitative analysis of the energy ratio of each frequency band. This study could provide a new perspective for related research on seismic fortification.

2. Overview of the shaking table test

2.1. Test equipment and model box
The model of the shaking table test is based on the large electric servo shaking table of the Key Laboratory of Loess Earthquake Engineering of China Earthquake Administration, as shown in Figure 1. The size of the vibration table is 4 m × 6 m and driven by 28 servo motors. The maximum accelerations in the X and Y directions are 1.7 and 1.2 g, respectively. The frequency range is 0.1–50 Hz. The model box has a length of 2.8 m, a width of 1.4 m, and a height of 1.8 m, as shown in Figure 2. The sliding surface and the side of the slope body and plexiglass plates with a thickness of 30 mm were longitudinally provided on both sides to observe the deformation of the tunnel. A flexible material, i.e., a polyethylene closed-cell foam board, was placed inside the model box before the test model was filled to weaken the “boundary effect” of the model box. This material could effectively absorb seismic waves to reduce the influence of the boundary effect. In addition, in accordance with the test method of Li et al. [23], pebbles with a thickness of 3–5 cm were laid on the bottom of the model box and bonded with a cement mortar to prevent relative slippage during vibration and simulate the bedrock environment under the slope, thereby achieving the actual project.

Figure 1. Large electric servo shaking table. Figure 2. Test model box and boundary treatment.

2.2. Model material parameters

According to the background of the loess tunnel of the Baoji–Lanzhou high-speed railway, the physical and mechanical parameters and similarity of the loose Q3 undisturbed loess require indoor tests combined with the size of the model box. The main parameters of the model test were as follows: a geometric similarity coefficient of 1:80 and a similar density coefficient of 1; other parameters were derived in accordance with Buckingham’s theorem [24–25]. After several attempts, the final test fill was composed of undisturbed Q3 loess, with more than 0.5 mm sawdust, barite powder, water, and other components. Their mix ratio was 0.835:0.015:0.04:0.11. The test model was prepared via layered filling. The physical and mechanical parameters of the model test soil are shown in Table 1.

Table 1. Physical and mechanical parameters of the loess.

| Soil type | Water content (%) | Dry density (g cm\(^{-3}\)) | Soil specific gravity | Cohesion (kPa) | Internal friction angle (°) |
|-----------|-------------------|-----------------------------|----------------------|---------------|---------------------------|
| loess     | 11                | 1.5                         | 2.73                 | 23.5          | 28.9                      |

2.3. Model preparation and acceleration sensor layout

The test model slope was 60°, the slope height H was 1,440 mm, and the tunnel was located in the 1/3H of the slope height. The experimental research focused on the instability and failure of the slope
on the side of the loess tunnel and the dynamic response of the tunnel portal section. A total of 26 acceleration sensors were arranged, i.e., 12 of them were uniformly arranged along the tunnel lining, the slope direction, and the interior of the soil, and 3 were arranged on the top of the slope surfaces. The arrangement of the test accelerometer measurement points is shown in Figure 3.

Figure 3. Layout of the acceleration sensors (unit: mm).

2.4. Input seismic waveform and loading conditions

In this experiment, the typical Wenchuan Tangyu wave and the EL-Centro wave were selected as loading waveforms. Their acceleration time history and fast Fourier transform (FFT) curves are shown in Figure 4. The X-directional loading and the X and Z coupling loading were used to obtain the dynamic response of the slope–tunnel model under different ground motions. A total of 13 sets of loading conditions were included, and the seismic intensity gradually increased from seven onward. The specific loading conditions are presented in Table 2.

Figure 4. Acceleration time history and FFT amplitude curves of the loading seismic waves.
Table 2. Test loading conditions.

| Loading conditions | Seismic waveform          | Loading direction | Peak ground acceleration (PGA; gal) |
|--------------------|---------------------------|-------------------|-------------------------------------|
| gk-1               | Wenchuan Tangyu wave      | X                 | 116                                 |
| gk-2               | Wenchuan Tangyu wave      | X and Z           | 116 and 78                          |
| gk-3               | EL-Centro wave            | X                 | 117                                 |
| gk-4               | EL-Centro wave            | X and Z           | 117 and 54                          |
| gk-5               | Wenchuan Tangyu wave      | X                 | 233                                 |
| gk-6               | Wenchuan Tangyu wave      | X and Z           | 233 and 156                         |
| gk-7               | EL-Centro wave            | X                 | 235                                 |
| gk-8               | EL-Centro wave            | X and Z           | 235 and 107                         |
| gk-9               | Wenchuan Tangyu wave      | X                 | 465                                 |
| gk-10              | Wenchuan Tangyu wave      | X and Z           | 465 and 312                         |
| gk-11              | EL-Centro wave            | X                 | 470                                 |
| gk-12              | EL-Centro wave            | X and Z           | 470 and 215                         |
| gk-13              | Wenchuan Tangyu wave      | X                 | 698                                 |

3. Analysis of test results

3.1. Acceleration response analysis of slope surface

The acceleration time history curve and FFT curve were employed to characterize their basic patterns of variation and study the dynamic response characteristics of the slope surface under the seismic action. The space is limited, so this article only presented the acceleration time history and frequency spectrum curves of the following: point A9 along the X and Z directions under working conditions 6, as shown in Figures 5 (a) and (b), and 8, as shown in Figures 5 (c) and (d). The maximum values on the acceleration time history curve were extracted for the follow-up study on the pattern of change in the peak ground acceleration (PGA) and their acceleration amplification factors.
(a) Time history of the Wenchuan Tangyu wave. (b) FFT curve of the Wenchuan Tangyu wave.

(c) Time history of the EL-Centro wave. (d) FFT curve of the EL-Centro wave.

**Figure 5.** Acceleration time history and FFT amplitude curves of seismic waves at point A9.

The acceleration amplification factor is defined as the ratio of the peak acceleration at the monitoring point to the peak acceleration input on the table. The X-axis acceleration amplification factor along the slope under various working conditions is plotted in **Figure 6** by using the acceleration amplification factor as the abscissa and the ratio of the slope height $h$ and the slope height $H$ as the ordinate. The measuring points along the slope foot to the slope surface include A4 (slope foot), A5, A9 (inverted arch), A17 (vault), A21, A22, and A26. In **Figure 6**, the overall trend of the acceleration amplification factor along the slope surface under various working conditions is listed as follows. The acceleration amplification factor from the slope foot to the inverted arch decreased. This result indicated that the existence of the tunnel suppressed the acceleration amplification factor and that the slope surface elicited a certain protective effect below the tunnel. The acceleration amplification factor from the inverted arch to the vault experienced a relatively large turn until the acceleration amplification factor gradually peaked at the top of the slope. This observation was basically consistent with the deformation and failure phenomenon of the test model. The model with a smaller peak acceleration in the first eight working conditions did not cause an obvious damage; thereafter, the model gradually showed an evident damage. From the measurement points gk9–gk10, the acceleration amplification factor gradually increased, lateral cracks first appeared at the top of the slope, and arc cracks formed on the slope surface. From gk11–gk12, the acceleration amplification factor continued to increase, and the acceleration amplification effect was significant. At this time, the cracks at the early stage gradually deepened, widened, and linked up. Radial cracks began to appear around the tunnel, and the slope bulged outward. The trend of the gk13 fold line was inconsistent with that under the previous working conditions possibly because the model was damaged, the suppression of the tunnel to the lower part weakened, and the acceleration amplification effect on the upper part of the tunnel was even more obvious. Consequently, the model was completely destroyed.
3.2. Analysis of the PGA characteristics of the tunnel

The measuring points are shown in Figures 7 and 8 to study the dynamic response characteristics of the inverted arch of the tunnel and the tunnel vault under seismic action. The curves of the acceleration amplification factors varying with the loading conditions are also drawn.

In Figures 7 and 8, the trend of the PGA of the measuring points under each working condition of the lower part of the tunnel was consistent, i.e., from a decreasing trend to an increasing trend: $\text{PGA}_{A6} > \text{PGA}_{A7} > \text{PGA}_{A9}$ (tunnel portal) $> \text{PGA}_{A8}$. This result showed that the acceleration amplification effect inside the slope body gradually decreased outward, and the increase at the measuring point A9 was caused by the amplification effect near the slope. The PGA curves were slightly depressed under working conditions 8, 10, and 12. The X and Z coupling loading conditions of these three working conditions indicated that the degree of the inhibitory effect of coupling loading on PGA was lower than that of the X-unidirectional loading. The Z direction loading also slightly affected the PGA, and this observation was consistent with the experimental results of Zhang [26]. The degree of changes in the PGA under the first eight working conditions was low, and the PGA during the loadings remarkably increased from gk8 to gk9. These findings were consistent with the characteristic phenomenon of the crack failure starting at gk9. The comparison of Figures 7 and 8 revealed that the PGA in the upper part of the tunnel was larger than that in the lower part of the tunnel. The measurement point A17 near the portal of the tunnel was more obvious than A9 because of the increase in elevation. The changes in the PGA along the axis of tunnel, the inverted arch of the tunnel, and the tunnel vault differed. Hence, the seismic fortification of the tunnel vault should be emphasized.
Figure 7. Curves of the PGA of the inverted arch of the tunnel with loading conditions. Figure 8. Curves of the PGA of the tunnel vault with loading conditions.

3.3. Wavelet packet analysis

Traditional Fourier transform is insufficient for processing nonstationary signals because it fails to represent the local transform in the time–frequency domain. However, the wavelet transform makes up for the defect of Fourier transform, thereby allowing it to keep a constant resolution in time–frequency analysis. Wavelet packet analysis is based on wavelet transform and has been developed and extended to provide a more detailed analysis and reconstruction method. According to the characteristics of signal analysis and through a set of orthogonal filters (high-pass H and low-pass L), it can decompose signals into high- and low-frequency parts in multilevels. Thus, the problems of low-frequency resolution in the high-frequency band and the low-time resolution in the low-frequency band are solved. In addition, wavelet packet transform can subdivide and decompose the high-frequency part into a set number of layers.\[^{[27-28]}\]

3.3.1. Selection of wavelet basis function.

The selection of the wavelet basis function is the core of wavelet packet analysis. The effect of signal processing varies in terms of the difference in wavelet basis functions. Therefore, the rational selection of a wavelet basis is crucial to the analysis of practical problems. According to the principle of optimal wavelet basis mentioned by Liu\[^{[29]}\] and the nature of the db wavelet basis function (Table 3), the db 5 wavelet function was used in this study.

| Orthogonal | Biorthogonal | Tight support property | Symmetry | Support length | Filter length | Vanishing moment order | Continuous wavelet transform | Discrete wavelet transform |
|------------|--------------|------------------------|----------|----------------|---------------|------------------------|-----------------------------|---------------------------|
| ○          | ○            | ○                      | 2N−1     | 2N             | N             | ○                     | ○                           |                           |

Note: ○ represents this property, ≈ represents approximately this property.

3.3.2. Decomposition layers.

In addition to selecting the appropriate wavelet basis function, choosing the appropriate number of decomposition layers is critical to the results of wavelet packet analysis. The number of decomposition layers is usually chosen in accordance with Equation (1)\[^{[30]}\].

\[
0 < j \leq \log_2 \left( L_S \right),
\]

where \( j \) is the number of wavelet packet decomposition layers, and \( L_S \) is the length of the signal input. For a typical nonstationary signal such as an earthquake, if the sampling frequency is 50 Hz, then the signal length is about \( 2^9 \) to \( 2^{10} \), and the duration is generally 10 s to 20 s. Therefore, frequency domain was considered comprehensively to meet the requirements of the time domain resolution, the number of decomposition layers was set to 3, and the test frequency of 0.1–50 Hz was divided into eight equal parts (\( 2^3=8 \)), i.e., eight frequency bands, to ensure the accuracy of the result of the frequency domain energy. Wavelet packet decomposition was implemented in the MATLAB program. The specific
frequency band of the wavelet packet decomposition and the number of each frequency band are presented in Table 4.

| Frequency band number | Frequency band range (Hz) | Frequency band number | Frequency band range (Hz) |
|-----------------------|---------------------------|-----------------------|---------------------------|
| 1                     | 0.10–6.26                | 5                     | 25.01–31.26              |
| 2                     | 6.26–12.51               | 6                     | 31.26–37.51              |
| 3                     | 12.51–18.76              | 7                     | 37.51–43.76              |
| 4                     | 18.76–25.01              | 8                     | 43.76–50.00              |

3.3.3. Wavelet packet transform process analysis.

The amplification factors of the PGA along the slope surface, the inverted arch of the tunnel, and the tunnel vault were analyzed in the preceding sections. In this section, the wavelet packet transform was used to analyze the measurement points along the slope surface, the vault, and the inverted arch. In particular, wavelet packet transform was conducted as follows. First, Fourier transform was performed on the acceleration of each measurement point to obtain its spectrum map. Second, the wavelet packet transform was utilized to decompose and reconstruct the seismic signals that were divided into eight frequency bands. Lastly, the energy proportion of each frequency band was obtained.

In Figure 9, E1 dominated the energy proportion of the first frequency band (0–6.25 Hz). E1 under all the working conditions occupied more than 85%, and the sum of the energy of the first frequency band and the energy of the second frequency band (E1 + E2) reached approximately 95%. This finding was consistent with that of Men et al.\textsuperscript{31} who concluded that the slope body causes an amplification effect on the low-frequency part of the seismic wave and a filtering effect on the energy in the high-frequency band.

(a) Slope surface energy analysis. The changes in E1 and E2 with elevation under various working conditions in Figure 9 indicated that a sag phenomenon occurred at the energy of the first frequency band of the measuring point A5 under the invert, combined with the test failure process and the trend of PGA, the tunnel suppressed deformation on the slope below it, so the amplification effect of the slope body on the low frequency band was slightly reduced. The energy E1 in the first frequency band increased from the inverted arch to the vault, whereas the energy E2 in the second frequency band decreased. The trend of E1 was consistent with the conclusion that the overall PGA in the upper tunnel was larger than that in the lower tunnel. Among them, the change in gk13 E1 was relatively great because of the destruction of the internal structure of the soil body under the cumulative vibration of the previous working condition and the small shear stiffness. In general, as the seismic load and elevation increased, the changes in E1 and E2 at each measuring point stabilized and became concentrated gradually.
Figure 9. Curves of the energy ratio (E1 and E2) with relative elevation under different working conditions.

(b) Energy analysis of the inverted arch and vault. The curves of the energy ratio (E1 and E2) with the distance between the inverted arch, the tunnel vault, and the portal under different working conditions are shown in Figure 10. E1 and E2 of the inverted arch of the tunnel under various working conditions indicated that the E1 graph gradually stabilized from the “sag,” and the E2 graph gradually increased from the “bulge.” When the “depression point” and the “protrusion point” were 350 mm away from the portal of the tunnel, and these points were also the very point where the PGA turned, as was described above. When being 750 mm away from the portal of the tunnel, which was 4.68 times the tunnel span, E1 and E2 stabilized above 85% and below 10%, respectively. The section of the tunnel portal with a change in energy should be explored in seismic fortification. Five times the diameter of the tunnel should be taken as the seismic fortification length of the tunnel section, considering the structural particularity of the tunnel portal section; this condition was consistent with the conclusion mentioned by Liang et al.\cite{12}

Compared with E1 and E2 of the inverted arch, the energy change of the vault was smaller, but the “sag” and “protrusion” points still existed and were just opposite to the vault, which was consistent with the trend turning position of the PGA in Figure 7. E1 and E2 stabilized above 90% and below 5%, respectively. Compared with the increase in E1 and the decrease in E2 of the inverted arch, the overall PGA of the tunnel vault was larger than that of the inverted arch. This result showed that the first frequency band of E1 played a dominant role in the amplification effect and destruction of the loess.
Figure 10. Curves of the energy ratio (E1 and E2) with the distance between the inverted arch, the vault, and the tunnel portal under different working conditions.

4. Analysis of the destruction characteristics of the test model

The deformation and failure of the slope–tunnel structure system were selected to analyze the seismic failure process of the test model under the action of seismic loads (Figure 11). The results revealed that no obvious damage phenomena occurred under the eight working conditions before the test. When \( X_a = 465 \) gal, two vertical microcracks appeared 80 cm away from the top of the slope along the tunnel axis, as shown in Figure 11(a). When \( X_a = 465 \) gal and \( Z_a = 312 \) gal, obvious transverse cracks appeared on the lower right side of the tunnel, and arc-shaped microcracks, which were tensile cracks caused by the bulging of the slope, formed on the left and right sides of the slope. The characteristic phenomena are shown in Figures 11(b) and (c). When \( X_a = 470 \) gal, these small cracks continued to lengthen and widen, the arc-shaped cracks along the slope surface were completely linked up, and the lateral cracks on the top surface of the slope were linked up, as shown in Figure 11(d). When \( X_a = 470 \) gal and \( Z_a = 215 \) gal, two vertical cracks appeared on the surface of the slope top, and severe seismic subsidence occurred. Several horizontal cracks formed on the slope surface, and a linking-up phenomenon was observed. Radial cracks appeared around the tunnel, and the whole slope surface bulged outward, as shown in Figures 11(e), (f), and (g). When \( X_a = 698 \) gal, the whole slope was destroyed, as shown in Figure 11(h).

After the deformation characteristics of the test model under the above seismic loads were summarized, the model failure process could be divided into three stages:

(1) At the microdeformation stage (working conditions 1–8), micro cracks appeared in the model, as shown in Figures 11(a)–(c).

(2) At the small deformation stage (working conditions 9–12), microcracks continued to expand, and several long cracks appeared, as shown in Figures 11(d)–(e).

(3) At the large deformation stage (working condition 13), long cracks continued to develop, and through cracks appeared until the model was completely destroyed, as shown in Figures 11(f)–(h).
5. Conclusions

Based on the results of the large-scale shaking table test and the wavelet packet transform method, the main conclusions can be drawn as follows:

(1) Under the action of a seismic load, the acceleration amplification effect of the slope surface increases as the slope height elevates, but turning occurs at the inverted arch of the tunnel. The stiffness of the tunnel is greater than that of the slope soil, so energy dissipation changes largely at the inverted arch of the tunnel. This result indicates that the tunnel structure elicits a certain inhibitory effect on the acceleration amplification effect below it.

(2) As the distance from the acceleration monitoring point to the tunnel portal increases, its PGA increases gradually. At the portal, the PGA increases because of the amplification effect of the slope. Overall, the PGA of the tunnel vault is greater than that of the inverted arch of the tunnel. Hence, the tunnel vault should be the key area of seismic fortification.

(3) The seismic acceleration time history is transformed via wavelet packet transform. This result suggests that soil causes an amplification effect on the low-frequency seismic wave of 0–12.51 Hz and a filtering effect on the high-frequency band. The energy ratio of the first frequency band (0.1–6.25 Hz) is mainly E1, and the ratio of E2 is relatively small in the second frequency band (6.25–12.51 Hz). As seismic intensity increases, the energy ratio at the slope, tunnel vault, and inverted arch likely becomes stable. Under the horizontal loading of the Wenchuan wave, the energy of the soil surrounding the tunnel exhibits an evident “accumulation effect.”

Acknowledgments

This study is financially supported by the National Natural Science Foundation of China (Nos. 51968041 and 41562013), the Young Talent Fund of the University Association for Science and Technology in Shaanxi, China (No. 20190706), and the Middle-aged & Young Talent of Science and Technology Innovation for Shaanxi Railway Institute, China (No. KJRC201902). The authors of this paper also appreciate the help of some of the colleagues, especially Prof. Zhijian Wu, Dr. Fuxiu Li, Miss Dan Zhang, and Mr. Xiangjin Qiao, in the preparation of this paper.

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