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## Opinion Article

# Research Progress and Overview on Seismic Performance of Highway Tunnels

**Abstract:** As a crucial component of transportation infrastructure, the seismic safety of highway tunnels is of utmost importance. This paper presents a comprehensive review of the current research status of the seismic response of highway tunnels, covering aspects such as the failure modes of highway tunnels under seismic action, the factors influencing the seismic response of tunnels, and the commonly used research methods. By summarizing the existing research, the paper points out the deficiencies in the current research and provides an outlook on future research directions, aiming to offer references for the seismic design and research of highway tunnels.

**Keywords:** Highway tunnel; Seismic response; Seismic damage mechanism; Analysis methods

## 1 Introduction

Tunnels and underground structures were once regarded as having excellent seismic performance. However, major seismic damage events such as the 1995 Great Hanshin - Awaji Earthquake in Japan, the 2008 Wenchuan Earthquake in China, and the 2023 Turkey Earthquake have indicated that tunnel structures can also suffer severe damage under seismic action, leading to traffic disruptions, difficult repairs, and potentially triggering secondary disasters<sup>[1]</sup>. Different from ground structures, the dynamic response of tunnel structures is mainly controlled by the displacement field of the surrounding rock and soil mass, and there are significant differences in their failure modes, mechanisms, and analysis methods. Therefore, in - depth research on the seismic response laws of highway tunnels and the development of advanced seismic analysis theories and design methods have become the core topics in the field of earthquake resistance of underground engineering. This paper aims to sort out relevant research results at home and abroad, summarize existing knowledge, and look forward to future trends, so as to provide ideas for promoting the further development of this field.

**Table 1 Cases of Highway Tunnel Affected by Earthquake Disasters**

Location	Time	Magnitude	Typical Case
WenChuan earthquake	2008	8.0	The lining of Longxi Tunnel and Zhipingpu Tunnel has cracked and there has been partial collapse.
The Great East Japan Earthquake	2011	9.0	Cracking and water leakage of the tunnel linings along the Northeast Shinkansen line
Nepal earthquake	2015	7.8	The tunnel lining has cracked and there has been a cave-in at the entrance section.
Turkish earthquake	2023	7.8	Cracking, misalignment and collapse of the lining of the transportation tunnels in the southeastern mountainous area

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## 2 Main forms and characteristics of seismic damage in highway

### tunnels

The study of historical earthquake-induced damage offers the most straightforward approach for comprehending tunnel behavior under seismic loading. In general, the seismic damage observed in highway tunnels can be categorized into the following primary types<sup>[2, 3]</sup>:

(1) Destruction of the entrance section: Damage to the tunnel portal section: Due to its distinctive topographic and geological features, the portal is frequently the most seismically vulnerable area of a tunnel. Typical failure modes include portal collapse, slope instability, as well as cracking and spalling of the lining. In regions of high seismic intensity, ground shaking often leads to loosening and landsliding of the rock and soil mass around the portal. This increases lateral pressure on the lining, resulting in its deformation and failure. For instance, during one earthquake, a major landslide occurred on the portal slope of a highway tunnel, partially burying the entrance. Simultaneously, extensive cracking was observed in the portal lining, significantly impairing the tunnel's operational safety.

(2) Destruction of the shaft section: Damage to the main tunnel structure primarily presents as lining cracks, spalling, localized blockage, and overall deformation. As seismic waves propagate, the lining is subjected to complex stress conditions. Once the induced stress surpasses the material's ultimate strength, cracking occurs. Progressive development of these cracks can lead to spalling and blockage of the lining, compromising the structural integrity of the tunnel. Furthermore, in soft soil strata or geologically complex areas, the tunnel may undergo differential settlement or uplift, resulting in extensive deformation and failure of the lining structure. For instance, following an earthquake, a highway tunnel located in soft soil exhibited significant settlement, with extensive cracking observed in the lining and even misalignment in certain sections.

(3) Damage during crossing of fault sections: When a highway tunnel crosses a fault zone, seismic-induced fault displacement can severely impact the tunnel structure. The relative movement across the fault may cause significant deformation, cracking, or even rupture of the tunnel. The surrounding rock and soil in fault-affected areas typically exhibit poorer engineering properties, rendering them more susceptible to damage during earthquakes, which in turn aggravates the extent of tunnel failure. For instance, in one case where a highway tunnel traversed a previously identified inactive fault, seismic activity triggered relative displacement of the rock masses on both sides of the fault. This resulted in multiple through-thickness cracks in the lining at the fault crossing location, bringing the tunnel structure to the verge of collapse.



Figure 1 Cracks at the entrance



Figure 2 Concrete has fallen off

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### 3 Factors Affecting the Seismic Response of Highway Tunnels

The seismic behavior of highway tunnels involves a complex dynamic interaction process, governed not by a single factor but by the combined influence of several critical elements. First, the characteristics of seismic ground motion act as the external excitation source, defining the intensity and pattern of energy input. Second, the structural properties of the tunnel directly influence its inertial resistance and deformation mechanisms. Finally, local geological conditions, serving as the medium for energy transmission, significantly modify the propagation path and impact of seismic waves.<sup>[4]</sup> The coupling effect of these three types of factors jointly governs the dynamic behavior and potential failure mode of the tunnel structure.

#### 3.1 Seismic motion characteristics

Different types of seismic waves, such as compressional waves (P waves), shear waves (S waves), and surface waves, have different effects on highway tunnels. The compressional waves travel at a high speed and mainly cause vertical vibrations of the tunnel structure; the shear waves travel at a lower speed and cause horizontal shear deformation of the tunnel; the surface waves have high energy and a long propagation distance, and have a more significant impact on the tunnel entrance section and shallow-buried sections.<sup>[5-8]</sup> In actual earthquakes, it is often the combined effect of multiple seismic waves that makes the stress state of the tunnel structure complex.

The peak acceleration of seismic waves is an important indicator for measuring the intensity of an earthquake, as it directly affects the magnitude of the seismic force exerted on the tunnel structure. Generally speaking, the greater the peak acceleration of seismic waves, the stronger the seismic effect on the tunnel structure will be, and the more likely it is to cause damage. Studies have shown that when the peak acceleration of seismic waves exceeds a certain threshold, the stress and deformation of the tunnel lining will increase sharply, which may lead to cracks and other damages in the lining.

The duration of seismic waves refers to the time during which the seismic activity persists. A longer duration of seismic waves will cause the tunnel structure to undergo multiple cycles of loading, which is likely to lead to fatigue damage to the structure. In cases where the duration of seismic waves is long, even if the peak acceleration of the seismic waves is not particularly high, the tunnel structure may still suffer damage due to cumulative damage. For example, in some earthquakes of higher magnitudes and shallower epicenters, due to the long duration of seismic waves, some highway tunnels have experienced phenomena such as degradation of the lining material properties and expansion of cracks.

#### 3.2 Tunnel structural characteristics

The form of the tunnel section has a significant impact on its seismic response. Common tunnel section forms include circular, horseshoe-shaped, and rectangular, etc. Different section forms of tunnels have differences in their mechanical properties. The circular section has an advantage in resisting uniform pressure, while the horseshoe-shaped section is more suitable for use in conditions with better rock and soil properties. Generally speaking, section forms with regular shapes and good symmetry have more uniform stress distribution under seismic action and have relatively better seismic performance. For example, under the same seismic conditions, the lining stress distribution of a circular tunnel is more uniform compared to that of a rectangular tunnel, and the possibility of cracks is relatively smaller.

The thickness of the lining is one of the key parameters affecting the seismic performance of a

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tunnel structure. Increasing the lining thickness can enhance the stiffness and load-bearing capacity of the tunnel structure, thereby strengthening its ability to resist seismic forces<sup>[9-11]</sup>. However, an increase in lining thickness also leads to an increase in engineering costs. Therefore, it is necessary to determine the optimal lining thickness through reasonable design while ensuring the seismic safety of the tunnel. Studies have shown that within a certain range, appropriately increasing the lining thickness can effectively reduce the stress and deformation of the tunnel lining under seismic action.

The material properties of the tunnel lining, such as elastic modulus and strength, also have a significant impact on its seismic response. Using high-strength and high-elastic modulus materials can enhance the seismic resistance of the tunnel structure. At the same time, the damping properties of the material will also affect the energy dissipation of the tunnel during an earthquake. For example, some new composite materials or lining with damping materials can better absorb and dissipate energy during an earthquake, reducing the vibration response of the structure.

### **3.3 Geological conditions**

Different types of rock and soil materials have significant differences in their physical and mechanical properties, which have different effects on the propagation of seismic waves and the seismic response of tunnel structures. For instance, soft soil layers have lower stiffness, and seismic waves will experience significant attenuation when propagating through them<sup>[12]</sup>, but at the same time, they make the tunnel structure more prone to larger deformations; while hard rock layers have higher stiffness, seismic waves travel faster, and the seismic forces acting on the tunnel structure are relatively more intense. In practical engineering, corresponding seismic design measures need to be taken based on different types of rock and soil materials.

The mechanical parameters of the rock and soil mass, such as density, shear modulus, Poisson's ratio, etc., directly affect the propagation characteristics of seismic waves and the interaction between the rock and soil mass and the tunnel structure. Accurately obtaining the mechanical parameters of the rock and soil mass is crucial for accurately analyzing the seismic response of the tunnel. For instance, the shear modulus of the rock and soil mass determines its ability to resist shear deformation. Under seismic action, the magnitude of the shear modulus will affect the constraint effect of the surrounding rock and soil mass on the lining structure of the tunnel, thereby influencing the stress state of the tunnel.

Geological structures, such as faults and folds, can alter the propagation path and intensity of seismic waves, exerting a significant influence on the seismic response of highway tunnels. When a tunnel passes through a fault, the presence of the fault causes the seismic waves to undergo phenomena such as reflection and refraction during propagation, resulting in extremely complex forces acting on the tunnel structure.<sup>[13]</sup> Moreover, the properties of the rock and soil on both sides of the fault often differ significantly, and during an earthquake, this can easily lead to uneven deformation of the tunnel structure. Fold structures can also cause changes in the distribution and mechanical properties of the rock and soil, thereby affecting the seismic response of the tunnel.

## **4 Analysis Method for Seismic Response of Highway Tunnels**

Currently, three primary approaches serve as the main basis for analyzing the seismic responses of highway tunnels: prototype observation paired with damage investigation, experimental research, and theoretical analysis. The sections that follow will elaborate on the existing research status of tunnel structure seismic response analysis—encompassing both domestic and global contexts—by

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focusing on these three methodological perspectives.

#### **4.1 Prototype observation and seismic damage investigation**

The seismic performance of underground structures has been extensively studied through post-earthquake damage observations by researchers globally. For example, following the Hanshin-Awaji Earthquake, the Japan Society of Civil Engineers systematically investigated damaged infrastructure such as subway stations and tunnel sections, recording typical failure mechanisms and identifying major contributing factors to seismic damage. In a separate effort, Dowding et al.<sup>[14]</sup> analyzed multiple tunnel cases, with particular emphasis on structural seismic responses, deformations, and ground motion parameters. Wang Wenli et al.<sup>[15]</sup> focused on mountain tunnels affected by the Chi-Chi Earthquake in Taiwan, examining relationships among damage patterns, seismic intensity, site conditions, and structural anti-seismic capabilities. Additionally, Qian Qihu et al.<sup>[16]</sup> evaluated tunnel damage from the Wenchuan Earthquake and integrated worldwide case studies to derive dynamic response characteristics of tunnels; their findings led to practical recommendations for improving seismic resistance and ensuring the safety of underground transportation systems.

#### **4.2 Experiment research**

Experimental research entails constructing models that roughly replicate real-world engineering conditions, with the goal of investigating how underground structures dynamically respond to seismic forces. Yuan Yong et al.<sup>[17]</sup> conducted a multi-point shaking test using a 1:60 scaled model. By adopting a segmented model container and applying a stiffness equivalence approach, they analyzed the influence of the traveling wave effect on the longitudinal seismic performance of shield tunnels. Their results indicated that non-uniform seismic input significantly increases lining acceleration and ring joint deformation, underscoring the importance of considering spatial variation in ground motion during seismic design. In another study, Shao Genda et al.<sup>[18]</sup> integrated physical modeling with finite element simulations to explore the coupled response of underground structures and surrounding soil under seismic action. They demonstrated that soil vibration properties—especially shear-type deformation under horizontal excitation—govern the interactive response. The study also elucidated the mechanisms of seismic force transmission to linings, evaluated the contribution of anchor bolts to seismic performance, and emphasized the need to reconcile flexibility with static capacity in anti-seismic lining design, while identifying vulnerabilities in conventional lining systems. Liu et al.<sup>[19]</sup> carried out a series of centrifuge tests on soil–structure systems at different burial depths, focusing specifically on acceleration and displacement responses under seismic loading.

#### **4.3 theoretical analysis**

Theoretical investigations in this field are primarily divided into two categories: analytical approaches and numerical simulation techniques. Analytical methods include, among others, the seismic coefficient approach, free-field deformation analysis, reaction displacement technique, foundation resistance coefficient method, and the surrounding rock strain transmission method.<sup>[20, 21]</sup>

Derived from static theory simulation, the seismic coefficient method converts dynamic seismic actions into equivalent static loads for estimating the forces imposed on underground structures. This technique has been extensively adopted in the seismic design of highway and railway tunnels throughout China. On the other hand, the free-field deformation approach assumes that the seismic behavior of underground structures is predominantly controlled by the deformation

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of the surrounding rock, neglecting the dynamic soil-structure interaction. Using the free-field strain of the rock mass as the input for structural strain, this method relies on elastic wave theory to predict structural responses under seismic events. Based on assumptions of either full bonding or complete sliding at the interface, Wang et al.<sup>[22]</sup> derived and examined the force distribution in underground structures during earthquakes. Subsequently, Hashash et al.<sup>[20]</sup> confirmed that under the no-slip condition, their computational results were consistent with those of Wang et al. Under full-slip conditions, although axial forces were higher, the overall computational outcomes remained in agreement with the earlier study.

Numerical simulation methods serve as a critical tool for predicting and evaluating the dynamic response of tunnel structures under seismic loading. Researchers have employed various advanced computational techniques to investigate complex soil-structure interaction mechanisms during earthquakes. Shen et al.<sup>[23]</sup> utilized OpenSees to develop finite element models examining how interlayer liquefaction affects shield tunnels under different frequency contents, adopting a fully coupled solid-fluid effective stress approach. Similarly, Wang et al.<sup>[24]</sup> established 3D finite element models to analyze fault effects on underground caverns, identifying the most critical instability condition at approximately 40° between fault trend and cavern axis. Studies using discrete element methods, such as those by Chen Yongming et al.<sup>[25]</sup> on jointed rock slopes and Ou Erfeng et al.<sup>[26]</sup> on layered surrounding rock, consistently demonstrate that geological discontinuities significantly amplify principal stresses and induce relative displacements while reducing acceleration responses. Complementing these findings, Sui Bin et al.<sup>[27]</sup> used FLAC3D software to simulate the dynamic response of surrounding rock in an underground cave cluster under seismic loads, conducting dynamic calculations for two distinct conditions. They applied a new splitting failure criterion to predict the potential range of splitting damage zones post-earthquake, and also analyzed in detail the changes in stress, displacement, and energy of the surrounding rock—comparing these post-earthquake metrics with those measured before the earthquake.

## 5 Conclusion

At present, significant achievements have been made in the research on the seismic response of highway tunnels. In terms of the types of damage, a clearer understanding has been gained of the damage characteristics of different sections such as the entrance section, the main body section, and the section crossing faults; in the study of influencing factors, the important influences of factors such as seismic motion characteristics, tunnel structure characteristics, and geological conditions on the seismic response of tunnels have been clarified; in terms of research methods, theoretical analysis, numerical simulation, and experimental research complement each other, providing powerful means for in-depth exploration of the laws of tunnel seismic response. However, the existing research still has some shortcomings:

(1) Research under complex geological conditions needs to be strengthened: In actual engineering projects, highway tunnels often pass through areas with various complex geological conditions, such as karst regions and deep soft soil areas. Currently, the research on the seismic response of tunnels under these complex geological conditions is not deep enough, and the related theories and methods are not yet mature, making it difficult to accurately predict the behavior of the tunnels during earthquakes.

(2) Studies on multi-factor coupling effects are scarce: The seismic motion characteristics, tunnel structural characteristics, and geological conditions all interact with each other in actual

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earthquakes. However, most current studies only consider the influence of a single or a few factors. Research on the seismic response of tunnels under multi-factor coupling effects is relatively limited, and it is unable to comprehensively and accurately reflect the forces and deformations of tunnels in real earthquake environments.

(3) Insufficient long-term performance research: Current studies mainly focus on the short-term responses of tunnels during earthquakes. There is relatively little research on the long-term performance changes of tunnel structures after earthquakes, such as the long-term development of lining cracks, the degradation of material properties, and the impact on the durability of the structure. This is not conducive to the long-term safe operation and maintenance of tunnels.

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