A Review on the Dynamic Response Characteristics of Tunnels under Rayleigh Wave Excitation

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Abstract

As a significant component of seismic waves, Rayleigh waves exhibit strong surface energy concentration, wide propagation range, and high destructive potential, which pose critical threats to the safety and stability of shallow-buried tunnels. This paper reviews the dynamic response characteristics of tunnels subjected to Rayleigh waves. The formation mechanism, motion pattern, and energy distribution of Rayleigh waves are first introduced, followed by a systematic summary of their influence on tunnel structures. Existing studies reveal that the multi-directional particle motions induced by Rayleigh waves, coupled with the complex soil–structure interaction, can lead to bending, torsion, and non-uniform stress states in tunnel linings. Key influencing factors include burial depth, soil properties, and lining stiffness. While considerable progress has been achieved through theoretical analysis, numerical simulation, and shaking table tests, challenges remain in addressing complex geological conditions, three-dimensional irregular wave fields, and nonlinear soil–structure coupling. Future research should emphasize multi-scale experimental validation, the development of advanced numerical models, and the exploration of active control and seismic isolation measures, with the goal of enhancing tunnel safety and resilience under strong seismic events.

Keywords

Rayleigh Waves; Tunnel Engineering; Dynamic Response; Soil–Structure Interaction; Seismic Performance.

1. Introduction

In recent years, the scale of underground space development has expanded rapidly, with subways, water conveyance tunnels, and municipal utility corridors playing increasingly important roles in modern cities [1-4]. However, underground structures are not inherently safe; under strong seismic loading, their seismic performance is as critical as that of surface buildings. Numerous seismic damage investigations have shown that the failure mechanisms of underground structures differ significantly from those of aboveground structures, with the effects of surface waves being particularly important [5-6]. Compared with body waves such as P-waves and S-waves, Rayleigh waves-one of the dominant components of surface waves-are characterized by concentrated energy, long duration, and long propagation distance. Their destructive effects are especially pronounced for shallow-buried tunnels and large-span underground projects. In many strong earthquakes, the energy carried by Rayleigh waves accounted for more than 50% of the total seismic energy, making them one of the primary causes of widespread damage. Since tunnels are usually located tens of meters below the surface-precisely within the depth range significantly affected by Rayleigh waves-studying the dynamic response characteristics of tunnels under Rayleigh wave excitation is of great academic and engineering value[7-8]. Such research helps refine seismic theories for underground structures, optimize design codes, and enhance urban disaster prevention and mitigation.

2. Interaction Mechanism between Rayleigh Waves and Tunnel Dynamics

Rayleigh waves are generated by the coherent coupling of P-waves and SV-waves at the free surface. The particle motion exhibits an approximate elliptical trajectory near the ground surface, producing significant displacement and velocity components in both vertical and horizontal directions. Their propagation velocity is slightly lower than that of shear waves, with energy mainly concentrated within one wavelength beneath the surface, decaying exponentially with depth. Consequently, when tunnel burial depth falls within this influence zone, the structure inevitably experiences strong dynamic disturbances.

From the perspective of wave effects, Rayleigh-induced particle motion combines vertical oscillation with horizontal shear, subjecting tunnel linings to multi-directional dynamic loads. Compared with body waves, the coupled characteristics of Rayleigh waves more easily induce bending and torsional responses, and may also generate circumferentially non-uniform stresses, leading to complex stress states and localized damage.

With respect to burial depth, shallow-buried tunnels generally lie within the energy-concentrated zone, where vertical accelerations and horizontal shear deformations are greatly amplified, resulting in increased circumferential stresses and additional longitudinal bending moments in the lining. As burial depth increases, Rayleigh wave energy attenuates significantly, and tunnel response amplitudes decrease accordingly, suggesting that depth provides a natural seismic isolation effect.

From the soil–structure interaction perspective, the dynamic coupling between tunnel linings and surrounding soils is a decisive factor in determining response patterns. If the lining stiffness is much greater than that of the soil, wave reflection and scattering occur at the interface, causing local strain concentration. Conversely, weak bonding at the interface may result in sliding or cracking, amplifying structural damage risks. When the lining and soil form a well-bonded system, part of the seismic energy can dissipate through the soil medium, thereby reducing stress concentrations in the structure.

Overall, the dynamic interaction between Rayleigh waves and tunnels exhibits strong nonlinearity and multi-factor coupling, influenced by the wavelength-to-tunnel size ratio, burial depth, soil properties, interface conditions, and lining stiffness. Its mechanisms are complex and cannot be fully captured by a single theoretical framework.

3. Research Progress

3.1 Theoretical Studies

Early theoretical studies originated from elastic dynamics, assuming the soil as a homogeneous half-space, and derived tunnel responses under Rayleigh wave excitation through wave equations. Wave function expansion methods have been employed to describe the propagation, scattering, and diffraction of Rayleigh waves, while boundary element methods (BEM) have been widely applied due to their efficiency in unbounded domain problems. These studies clarified the displacement and stress distributions in tunnels and analyzed the influences of wavelength, incidence angle, and tunnel radius. Later developments incorporated layered foundations, anisotropic media, and poroelastic theories, extending theoretical models toward more realistic geological conditions. However, analytical solutions generally rely on strong idealizations such as homogeneous soils and regular tunnel cross-sections, limiting their applicability to real projects. Nonetheless, they provide a solid foundation for numerical and experimental research.

3.2 Numerical Simulation Studies

Numerical methods such as the finite element method (FEM), finite difference method (FDM), boundary element method (BEM), and meshfree methods have been extensively employed to investigate Rayleigh wave–tunnel interactions. Findings indicate that the ratio of Rayleigh wavelength to tunnel characteristic size is a key parameter governing response amplitudes. When the wavelength is comparable to the tunnel diameter, dynamic amplification effects are often observed. Burial depth and incidence angle also significantly influence lining stresses and displacement patterns.

More recently, nonlinear constitutive models and interface elements have been introduced to account for soil plasticity, cracking, and lining–soil sliding, yielding more realistic results. The development of three-dimensional numerical models has further enabled investigations of topographic effects, tunnel group interactions, and groundwater coupling. Through large-scale parametric analyses, numerical simulations not only reveal systematic response characteristics but also provide quantitative indices for seismic design.

3.3 Experimental Studies

Experimental studies provide direct evidence of Rayleigh wave–tunnel interactions. Centrifuge model tests, which satisfy stress similitude, have been widely used to investigate tunnel responses under varying depths and soil conditions. Shaking table tests reproduce system-level tunnel–soil dynamics and are frequently used to validate theoretical and numerical findings. Specialized wave excitation devices have also been developed to simulate Rayleigh wave propagation in soils. Results consistently indicate that when Rayleigh wavelengths are comparable to tunnel dimensions, lining stresses are greatly amplified, with crowns and inverts particularly vulnerable to cracking and localized damage. Although experimental studies face limitations due to scaling effects and boundary conditions, making it difficult to fully reproduce realistic wave fields, they remain indispensable for mechanism exploration and model validation.

3.4 Engineering Case Studies

Seismic damage cases provide practical evidence for Rayleigh wave effects. During the 1995 Kobe earthquake in Japan, subway tunnels exhibited longitudinal cracks and lining spalling, widely attributed to strong surface wave effects. In the 2008 Wenchuan earthquake, numerous mountain tunnels experienced lining dislocations, crown cracking, and even partial collapses, suggesting that Rayleigh wave energy significantly contributed to tunnel damage at burial depths. Similarly, during the 2016 Kumamoto earthquake, underground transportation facilities reported comparable failures. Comparative analyses indicate that Rayleigh wave–induced tunnel damage typically manifests as a combination of longitudinal vibrations and localized stress concentrations, offering valuable insights for seismic-resistant tunnel design.

4. Existing Problems and Limitations

Despite considerable progress, several limitations remain. In theoretical studies, overly idealized assumptions fail to represent complex geological conditions such as stratified deposits, fault zones, and groundwater saturation, all of which can alter Rayleigh wave propagation. Experimental studies are constrained by facility and scaling limitations: Rayleigh waves have long wavelengths, whereas model sizes are small, making it difficult to satisfy similitude requirements. As a result, experimental results may not fully replicate real wave effects. Numerical simulations, although flexible, strongly depend on constitutive models and soil parameters, which are often difficult to obtain accurately, introducing uncertainties. Moreover, most existing studies focus on single factors, while coupled effects involving topography, groundwater, tunnel groups, and multi-wavefield interactions remain insufficiently addressed. This limits the transfer of research outcomes to engineering practice.

5. Future Development Trends

Future research should focus on several directions. First, multi-scale modeling frameworks should be developed to integrate analytical solutions, numerical simulations, and experimental observations, achieving both computational efficiency and engineering applicability. Second, advanced monitoring and sensing technologies-such as piezoelectric smart aggregates, distributed fiber optic sensing, and real-time seismic inversion-should be applied to tunnels for real-time monitoring and early warning of Rayleigh wave–induced responses. Third, more attention should be given to complex geological conditions, including interbedded strata, fault zones, groundwater, and topographic effects, by establishing multi-factor coupling models. Fourth, from the engineering design perspective, new protective measures should be proposed, such as seismic isolation layers, high-ductility composite linings, or localized reinforcement for shallow-buried tunnels, to mitigate adverse surface wave effects. Finally, artificial intelligence and machine learning techniques can be applied to extract patterns from large-scale simulation and monitoring datasets, enabling rapid identification and prediction of tunnel response modes and supporting intelligent seismic design and operation.

6. Conclusion

In summary, Rayleigh waves, as one of the most energy-intensive seismic waveforms, exert significant impacts on the dynamic responses and failure modes of tunnels. Through theoretical analysis, numerical simulation, experimental studies, and damage investigations, researchers have progressively revealed their mechanisms and response characteristics. However, limitations remain in understanding coupled effects under complex geological conditions and in translating findings into engineering applications. Future research should emphasize interdisciplinary approaches and technological integration, shifting from qualitative descriptions to quantitative predictions, and from laboratory-scale studies to engineering practice. Such efforts will provide more scientific and systematic theoretical foundations and technical support for ensuring the seismic safety of underground structures.

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