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Numerical Simulation and Effect Evaluation of Seismic Reinforcement Measures for Subsea Tunnels

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ABSTRACT

As a crucial component of modern transportation infrastructure, subsea tunnels play a vital role in cross-sea transportation and urban rail transit. However, due to their unique geographic locations and environmental conditions, subsea tunnels face significant safety risks under seismic loads. This study aims to enhance the seismic performance of subsea tunnels by systematically reviewing mainstream seismic reinforcement measures and using finite element numerical simulation techniques to evaluate the mechanical response and safety performance of different reinforcement methods under seismic actions. By establishing a three-dimensional finite element model, seismic responses of tunnels with no reinforcement, structural reinforcement, foundation reinforcement, and combinations of multiple measures are simulated. The analysis focuses on key indicators such as tunnel deformation, internal force distribution, and stress concentration. The results show that reasonable configuration of structural and foundation reinforcement measures can significantly improve the seismic resistance of subsea tunnels and reduce the safety hazards caused by earthquakes. The research findings provide a theoretical reference for the design and construction of subsea tunnels and lay a solid foundation for subsequent engineering optimization and technology promotion.

KEYWORDS

Subsea tunnel; Seismic reinforcement; Numerical simulation; Finite element method; Structural safety; Engineering application

1 Failure mechanism of subsea tunnels under seismic loads

As deep-buried and complex structures beneath the seabed, subsea tunnels are affected not only by the long-term actions of surrounding seawater and soil but are also particularly prone to unique stress characteristics during seismic events. The mechanism of seismic load action mainly lies in two aspects: first, the interaction between the tunnel structure and the surrounding soil causes significant relative displacement; second, the dynamic response inside the structure aggravates stress concentration.

From a structural perspective, subsea tunnels usually adopt circular, horseshoe, or rectangular cross-sections, with reinforced concrete as the main lining material. Under the excitation of seismic waves (such as P-waves, S-waves, and surface waves), different parts of the tunnel experience various degrees of deformation. P-waves can induce compression and tension of the structure, S-waves intensify lateral displacement and shear deformation, while surface waves result in complex structural oscillations and instability.

Moreover, the geological conditions where subsea tunnels are located are often complex, involving soft soil layers, high pore water pressure, and non-uniform strata. These factors make the tunnel more susceptible to local instability, joint dislocation, and lining cracking under seismic loads, thereby compromising the overall structural safety. In cases of strong seismic intensity or foundation liquefaction, tunnels are extremely vulnerable to structural damage or even total collapse. Thus, a thorough understanding of the failure mechanism of subsea tunnels under seismic action is the basis for formulating effective reinforcement measures.

According to domestic and international engineering accident records, common earthquake-induced damages to subsea tunnels include lining cracking, concrete spalling, steel yielding, structural dislocation, tunnel leakage, and foundation settlement. Additionally, seismic loads may cause certain areas of the tunnel to exceed stress limits, significantly reducing safety reserves. Therefore, it is essential to propose scientific and effective seismic reinforcement measures based on actual engineering conditions to improve the structure ' s adaptability to extreme situations.

It is also noteworthy that the propagation characteristics and incident angles of seismic waves greatly influence the dynamic response of the tunnel. For example, when the seismic wave direction aligns with the tunnel axis, significant longitudinal compression and tension occur, whereas perpendicular incidence mainly causes shear deformation. The reflection and refraction of seismic waves at the soil-structure interface create complex stress superposition, increasing stress heterogeneity. These factors must be fully considered in seismic analysis and reinforcement design.

2 Common seismic reinforcement measures and their principles

To address the structural failures of subsea tunnels under seismic loads, various reinforcement measures have been proposed in engineering practice, including structural reinforcement, foundation reinforcement, optimization of connection parts, and improvement of auxiliary facilities.

Firstly, structural reinforcement aims to enhance the overall stiffness and bearing capacity of the tunnel. The most common practices involve adding strengthening belts at critical lining sections, thickening the lining, and using high-performance concrete or fiber-reinforced materials. These measures effectively distribute seismic loads, reduce structural deformation, and improve seismic limits. In recent years, new composite materials such as carbon fiber sheets and basalt fibers have gradually been applied to tunnel reinforcement, further enhancing the structure's ductility and crack resistance.

Secondly, foundation reinforcement is crucial for the safety and stability of subsea tunnels. Techniques such as high-pressure grouting, deep mixing piles, and ground reinforcement significantly increase the bearing capacity and deformation modulus of the soil, improving the cooperative behavior between the tunnel structure and the foundation and effectively inhibiting settlement and slip risks induced by earthquakes. Soil reinforcement also prevents seismic soil liquefaction and reduces the probability of structural instability.

Furthermore, the installation of flexible joints and damping devices can relieve stress concentration between tunnel segments, reducing the risk of joint dislocation and lining cracking. Rubber pads and dampers enable the structure to better accommodate deformations under seismic loads, thereby improving the overall seismic performance of the tunnel.

Additionally, the rational arrangement of drainage systems and the enhancement of waterproof layers are vital. Proper drainage reduces pore water pressure and mitigates the risks of leakage and structural damage triggered by earthquakes. Strengthening waterproof layers using composite materials further improves the structure's impermeability.

In recent years, intelligent reinforcement technologies have gradually been applied to subsea tunnel projects. For example, health monitoring systems based on smart sensors and data feedback can achieve real-time detection and reinforcement warnings, providing technical support for operation and maintenance as well as post-disaster repairs.

It should be emphasized that all reinforcement measures must be selected scientifically according to the specific engineering environment, design parameters, and seismic zoning of the tunnel, to avoid a one-size-fits-all approach and resource waste. Meanwhile, the constructability and economic viability of reinforcement measures should be considered to ensure smooth project implementation.

3 Numerical simulation method and parameter settings

To scientifically evaluate the seismic effects of various reinforcement measures, this study establishes a three-dimensional finite element numerical simulation model based on the finite element method. This model incorporates not only the mechanical properties of the tunnel structure, surrounding soil, and foundation but also simulates the complex conditions under actual seismic loads.

During model construction, a typical subsea tunnel cross-section is selected, including reinforced concrete linings, strengthening belts, and flexible joints. The parameters of surrounding rock and foundation soils are assigned based on actual investigation data, including soil density, elastic modulus, Poisson's ratio, internal friction angle, and pore water pressure. The structural material adopts an ideal elastoplastic constitutive model, fully considering the nonlinear response triggered by seismic action.

For seismic input, multiple sets of typical strong ground motion records are loaded, combining both horizontal and vertical seismic components to simulate the tunnel's dynamic response under different seismic intensities. Seismic waveform parameters are selected according to the national seismic ground motion parameter zoning map, and loading duration matches earthquake duration, ensuring simulation realism and scientific rigor.

Model boundary conditions combine absorbing and fixed boundaries to avoid interference from boundary-reflected waves. Nonlinear connection elements are used at joints to simulate the mechanical behavior of flexible joints.

Simulation conditions are set for the original (unreinforced) structure, structural reinforcement, foundation reinforcement, flexible joint optimization, and combined measures. Key outputs include maximum deformation, internal force distribution, stress concentration areas, joint displacement, and foundation settlement, comprehensively evaluating the effectiveness of each reinforcement measure.

It is worth mentioning that to ensure the accuracy and representativeness of simulation results, sensitivity analyses are performed on critical parameters such as material properties and seismic input. For instance, by adjusting soil elastic modulus and structural damping coefficients under different geological and seismic conditions, the applicability and effectiveness of reinforcement measures are assessed. Furthermore, considering initial defects and uncertainties in real projects, random disturbances and error analyses are introduced to broaden the model's applicability and reliability.

4 Numerical simulation results and effect evaluation of reinforcement measures

Through finite element numerical simulations, the seismic response characteristics of subsea tunnels under different reinforcement measures are systematically compared. Results indicate that in the unreinforced state, the tunnel undergoes extensive deformation and severe stress concentration under strong seismic action, with lining cracking, dislocation, and other failures. Seismic motion causes significant displacement in the tunnel's roof, sidewalls, and floor, with stress at some nodes exceeding material limits, posing considerable safety risks.

After installing lining strengthening belts, the overall stiffness of the tunnel is significantly increased, and the seismic load transfer path becomes more rational. Stress concentration at critical sections is greatly reduced. Strengthening belts effectively disperse seismic energy, suppress excessive deformation, and enhance structural safety reserves.

The use of high-performance concrete and fiber-reinforced materials further improves ductility and crack resistance. Fiber materials show outstanding crack suppression, significantly reducing the damage area under repeated seismic loads.

Foundation reinforcement measures such as high-pressure grouting and ground reinforcement substantially improve the bearing capacity of the tunnel's bottom and surrounding soil. Settlement and slippage are significantly reduced, greatly enhancing overall tunnel stability. Simulation results indicate that foundation reinforcement not only mitigates structural deformation due to earthquakes but also effectively lowers the relative displacement between the tunnel and foundation, improving the cooperative performance of the structure and ground.

Optimized flexible joints alleviate stress transfer between tunnel segments, minimizing the risk of joint dislocation and crack development. Stress peaks in the flexible joint area are noticeably reduced, and the overall ductility and adaptive deformation capacity of the structure are further improved.

With multiple reinforcement measures working together, the tunnel achieves optimal seismic performance. All indicators—maximum deformation, stress peak, foundation settlement, joint displacement—are superior to those of single-measure reinforcement, and overall seismic resistance is greatly enhanced.

It should be noted that comprehensive reinforcement measures, though having higher initial investment, provide more significant safety assurance and long-term operation benefits. In practice, reinforcement measures should be balanced according to project funding and actual needs to ensure both economic and reliability considerations.

Furthermore, simulation reveals that the seismic response of tunnel structures varies significantly with different seismic inputs, highlighting the importance of seismic ground motion characteristics on reinforcement effectiveness. Therefore, it is recommended that personalized reinforcement designs be carried out in accordance with regional seismic characteristics to enhance engineering adaptability.

5 Engineering recommendations for seismic reinforcement of subsea tunnels

Based on the simulation and evaluation results, seismic reinforcement of subsea tunnels should adhere to principles of scientific, systematic, economic, and practical implementation. It is recommended to conduct geological risk assessment and seismic analysis during the design phase, reasonably configure structural and foundation reinforcement measures, and apply measures according to specific conditions.

When selecting reinforcement schemes, priority should be given to the collaborative application of structural and foundation reinforcement. Strengthening belts, high-performance materials, and optimized flexible joints significantly improve comprehensive seismic performance. In areas with complex geology or high seismic intensity, high-pressure grouting and deep mixing piles are recommended to enhance soil bearing capacity and deformation modulus.

During construction, strict quality control is essential, following design requirements and process specifications. Digital monitoring can be used for key areas to monitor structural deformation and stress changes in real time, enabling timely adjustment of construction processes and parameters to ensure reinforcement effectiveness.

In the operation phase, it is advisable to establish a tunnel structure safety monitoring system for dynamic monitoring of lining cracks, joint displacement, foundation settlement, and surrounding water pressure. Upon detection of abnormal data, timely repair and reinforcement measures should be taken to prevent further structural damage.

Additionally, to prevent secondary earthquake disasters, internal drainage systems should be improved to reduce pore water pressure and avoid exacerbated structural damage from hydrodynamic coupling. Comprehensive emergency plans should be developed for earthquake contingencies, enhancing management and rescue capabilities.

In terms of new materials and technologies, it is recommended to promote innovative technologies such as fiber-reinforced materials, self-healing concrete, and smart damping devices, continuously optimizing reinforcement schemes and improving the intelligence and sustainability of structures.

Attention should also be paid to seismic design and construction lifecycle management, ensuring seismic requirements are fully considered at all project stages.

Future work may involve promoting structural health monitoring and diagnosis using big data and artificial intelligence, improving disaster warning and emergency response. Multidisciplinary collaboration in dynamics, earthquake engineering, soil mechanics, and intelligent construction is encouraged to address structural uncertainties under extreme seismic conditions.

Personnel training and experience sharing should be enhanced to improve disaster prevention and control capabilities, including regular seismic drills and technical exchanges. Stronger collaboration between management, research institutions, and universities should be fostered for joint technical breakthroughs and the deep integration of industry, academia, and research.

Besides technical measures, daily management should include minimizing crowd and vehicle congregation, improving emergency escape routes and signage, and raising public awareness of earthquake disaster prevention.

For tunnel operation management, strenuous labor and intense physical activity should be strictly limited, and prolonged sitting, standing, and exposure of the lower back to drafts or cold should be avoided to reduce the risk of lumbar injuries, providing scientific guidance for managers and operators.

6 Conclusion

This paper systematically analyzes the failure mechanisms of subsea tunnels under seismic loads, reviews mainstream seismic reinforcement measures, and comprehensively evaluates the seismic performance of structural reinforcement, foundation reinforcement, flexible joint optimization, and the collaborative application of multiple measures using finite element numerical simulation. The results show that while single reinforcement measures can improve the seismic performance of tunnel structures to a certain extent, the comprehensive application of multiple measures is most effective in reducing the risk of structural failure and increasing safety reserves. Rational selection of reinforcement measures, optimized structural design, and enhanced foundation treatment are crucial for improving the seismic resistance of subsea tunnels.

In practice, reinforcement schemes should be formulated based on actual geological and structural characteristics, safety monitoring during construction and operation should be strengthened, and new materials and technologies should be promoted to continuously optimize and improve tunnel seismic safety. With the development of earthquake engineering theory and intelligent construction technology, seismic design and safety management of subsea tunnels will become more scientific and efficient, providing strong support for urban transportation and regional economic development.

It is also recommended to further conduct multi-scale and multi-condition experimental research and numerical simulations for tunnel structural performance under different conditions, promoting seismic reinforcement technology toward more refined, intelligent, and efficient directions, and contributing to the safe operation and sustainable development of subsea tunnel projects in China and worldwide.

Future work should also deepen research into the application of new materials and technologies to improve the durability and economy of reinforcement measures. Project personnel should strengthen their understanding of the concept of full-lifecycle management for subsea tunnels, paying close attention to structural safety and seismic performance at every stage from design and construction to operation and maintenance. In addition, international cooperation and experience sharing are crucial for absorbing advanced global seismic reinforcement concepts and methods, advancing China's subsea tunnel technology.

It is important to enhance public awareness and stakeholder engagement, fostering a social atmosphere of collective attention and participation in engineering safety. Through the coordinated development of technological and managerial innovation, seismic safety levels of subsea tunnels will continue to rise, making a greater contribution to the secure and stable operation of national infrastructure.

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