Seismic Vulnerability Assessment in Tunnels: A Review

Abstract: Vulnerability analysis is an important method for earthquake prevention and disaster reduction research in the field of tunnel engineering. Firstly, a detailed overview of the research history and current status of tunnel seismic vulnerability at home and abroad was provided; Secondly, the main methods for analyzing the seismic vulnerability of tunnels at home and abroad were summarized, and the practical applicability of various methods was summarized; Subsequently, the steps for evaluating the seismic vulnerability of tunnels were proposed, and three key contents in establishing theoretical vulnerability curves using numerical simulation as the main method were discussed:(1) Input parameter determination; (2) Classification of destructive states; (3) Calculation of relevant uncertainty parameters; Finally, point out some urgent problems and future research directions in this field. By summarizing the existing studies on the seismic vulnerability of tunnels at home and abroad, the results show that the seismic vulnerability analysis of tunnels can reflect the performance of tunnels under seismic loading by considering the relevant uncertainty factors, which is conducive to the future risk assessment and loss estimation, and is of great significance to the development of performance-based seismic design of tunnels.

Keywords: Tunnel engineering; Earthquake; Vulnerability analysis; Uncertainty; numerical simulation

Introduction

In recent years, frequent earthquakes at home and abroad have caused different degrees of structural and functional damage to tunnels and other underground works, such as the Hanshin Earthquake in Japan, the Jiji Earthquake in Taiwan, the Wenchuan Earthquake and other earthquake zones of the tunnels have occurred in different types of seismic damages, such as cave-in and door cracking, lining and surrounding rock collapse, cracking and rumbling of the base plate and so on[1].These earthquakes have serious negative impacts on transportation, the economy, and safety.Therefore, the establishment and continuous improvement of the tunnel seismic risk evaluation mechanism and seismic damage assessment system have far-reaching significance for the maintenance of the harmonious and healthy development of the society.

Vulnerability analysis is an important part of risk evaluation. Seismic vulnerability refers to the probability of different levels of structural damage under the action of earthquakes of different magnitudes. It quantitatively reflects the seismic performance of engineering structures through probability indexes, and macroscopically describes the relationship between seismic intensity and the degree of structural damage. The relationship between seismic intensity and the degree of structural damage is described macroscopically[2][3].Therefore, the seismic vulnerability analysis study of tunnel engineering can not only predict the probability of damage at all levels of the structure before the earthquake, but also provide guidance for the post-earthquake structural and functional loss assessment. The seismic vulnerability analysis of tunnels has been widely used in the field of ground structures such as houses and bridges. Currently, seismic vulnerability analysis is widely used in the field of ground structures such as houses and bridges. The existing research results cannot meet the needs of actual projects: on the one hand, the engineering community traditionally believes that the seismic hazard of tunnels is much higher than that of above-ground structures. On the one hand, the engineering community traditionally believes that tunnels are weaker than above-ground structures, which leadsto insufficient research on the seismic vulnerability of tunnels; On the other hand, previous studies have only introduced uncertainty factors for qualitative analysis and lacked quantitative descriptions and comparisons of various uncertainties.

In this paper, the current status of seismic vulnerability research in tunnel engineering at home and abroad is systematically sorted out, and the characteristics and scope of application of various analytical methods are summarized. It also emphasizes the establishment and development of vulnerability curves, and finally points out the problems that still exist in this field and discusses the future development trend. Finally, it points out the remaining problems and discusses the future development trend in this field, so as to lay the foundation for further promoting and advancing the theoretical development of tunnel engineering risk assessment.

Research status

The concept of seismic vulnerability analysis was firstly proposed by the American scholar Comell in 1968, and this probabilistic analysis method was firstly applied to the seismic risk assessment of the infrastructure of nuclear power plants[4], and then gradually extended to the infrastructure fields such as houses and bridges, while the development of seismic vulnerability analysis of underground structures such as tunnels is relatively late.Early seismic vulnerability analysis of foreign tunnels was mainly based on expert judgment and empirical vulnerability curves, and some scholars collected actual damage conditions of tunnels in previous earthquakes around the world through observation[5],Rojahn established damage probability matrices for alluvial, cap-and-cut, and rock tunnels based on expert judgment using a modified MelCALI strength scale[9];Alliance established empirical peak ground acceleration (PGA)-based susceptibility curves for concealed and covered tunnels based on regression analyses of the Global Tunnel Seismic Hazard Database and back-calculated the tunnel damage using an attenuation model, which also took into account the uncertainties in ground shaking and tunnel performance[10];On the basis of Rojahn[9], Hazus established seismic empirical vulnerability curves for underground excavation and cover excavation tunnels at different PGA levels based on expert opinions[11];Corigliano established a new empirical seismic susceptibility curve for shallow rocky tunnels based on a composite database of 120 tunnel-related seismic examples, replacing the traditional PGA with PGV as the input parameter for ground shaking intensity[12].

With the promotion of computer software simulation analysis in the field of civil engineering, numerical calculation methods are gradually being applied to construct tunnel seismic vulnerability analysis models, which can overcome the shortcomings of insufficient seismic records in the research area. The types of tunnel structures subject to seismic vulnerability studies are categorized by depth of burial into shallow and deep tunnels and tunnel shafts, by construction method into tunnels with concealed excavation and covered tunnels, and by cross-section form into circular and rectangular tunnels.Argyroudisconsidered the tunnel geometry and lining strength, ground vibration input and soil properties and other uncertain parameters, and used a one-dimensional equivalent linear numerical analysis method to establish the seismic susceptibility curve of alluvial shallow subway tunnels, and verified the reliability of the numerical simulation by comparing the numerical solution with the fully closed analytical solution, and the new susceptibility curve compared with the empirical susceptibility curve highlights the importance of the localized soil properties on the seismic response[13].Andreotti proposed that deep-buried tunnels are suitable for evaluating their seismic susceptibility using theoretical analysis of susceptibility curves and derived seismic susceptibility curves and a cumulative damage model for deep-buried tunnels using a two-dimensional nonlinear numerical model, which is capable of reproducing the different damage mechanisms of the lining and quantifying the cumulative damage of the whole system during an earthquake[14].On the basis of Argyroudis[13], Le considered the soil structure interaction (SSI) effect and adopted the quasi-static ground response acceleration method for tunnel deep buried structures (GRAMBS). Finally, the seismic vulnerability curve of the tunnel was obtained by applying the mathematical method of maximum likelihood estimation (MLE)[15];Kim conducted seismic performance evaluation on the classification of Jinfu high-speed railway tunnels and established a seismic vulnerability curve for probabilistic risk assessment. The comparison showed that the seismic performance of the hidden excavation method tunnel was better than that of the cover excavation method tunnel, and the probability of each damage level was relatively low[16];Mayoral conducted three-dimensional finite difference nonlinear analysis using FLAC3D to obtain the seismic response of tunnel shafts under increasing seismic intensity, and established their seismic vulnerability curves[17];Andreotti proposed a new cumulative damage index for deep buried tunnels to evaluate the degradation failure behavior of reinforced concrete under cyclic loading, and based on plastic concentration theory and multiple two-dimensional incremental dynamic analyses, simulated the seismic cumulative damage of tunnel lining[18].

Compared with foreign countries, China's research on seismic vulnerability started late and mainly focused on bridges and building frame structures, while the research on seismic vulnerability of tunnels is less and not deep enough and comprehensive enough.However, the tunnels and underground pipeline structures of some recent mega-earthquakes in China have suffered different forms of damage, and the analysis of the seismic vulnerability of shallow and deeply buried tunnels has attracted the attention of some scholars.In 2002, Professor Liu Jingbo of Tsinghua University first introduced the theoretical fragility analysis method based on numerical simulation into China[19]; In 2007, Zhou Jian from Tongji University established a dynamic numerical model for seismic vulnerability analysis of underground buildings in soft soil and applied it to the risk assessment of the Chongming Crossing Tunnel Project in Shanghai, where the probability of liquefaction of soft ground was analyzed and the vulnerability of the tunnel structure was evaluated[20];In 2008, Wei Pingping of Nanjing University of Technology introduced the holistic analysis method for the first time into the vulnerability assessment of tunnel engineering under seismic loading, and selected seven key parameters, such as seismic intensity, engineering geological conditions, lining thickness, lining type, cross-section shape, tunnel width, and tunnel life as the evaluation factors taking into account the relevant uncertainties, which significantly provided the assessment accuracy[21].In 2012, Fan Gang of Southwest Jiaotong University established the probabilistic susceptibility models for the cave-in section, the fault fragmentation zone and the ordinary section respectively based on the seismic damage investigation data of Wenchuanearthquake[22].Subsequently, in 2015, Zhao Xiaoyong of Southwest Jiaotong University proposed a rapid assessment method for tunnel seismic loss on this basis, where the seismic loss of each tunnel on a certain line can be added up to get the tunnel seismic loss of the whole line[23].In 2017, Wenge Qiu and Huang from Southwest Jiaotong University obtained seismic susceptibility analysis curves for rock tunnels considering multiple uncertainties based on the uniform design-dynamic numerical simulation-support vector machine approach (UDM-DNS-SVM)[24];Liu Lirong considered the uncertainty of the surrounding rock and lining, and proposed a model for efficiently calculating the seismic susceptibility of mountain tunnels, and obtained a susceptibility calculation curve for calculating the structure of rocky mountain tunnels[26];In 2018, Zhiguang Zhou of Tongji University established a finite element model to analyze the dynamic time course of the soft soil railway tunnel in Shanghai, and used a one-dimensional equivalent linear method to consider the nonlinear characteristics of the soil layer to obtain the analytical susceptibility curve of the soft soil tunnel in Shanghai[27].In 2020, Huang Zhongkai used IDA analysis method to analyze the seismic vulnerability of shallow buried tunnels in soft ground layer and derived the corresponding vulnerability curve[28];In 2021, Dong Zhengfang used the modified IDA analysis method to analyze the susceptibility of tunnels in soft ground layers and derived the modified susceptibility curves[29].

2 Seismic vulnerability analysis method for tunnels

Structural susceptibility is usually described as the probability of different degrees of damage to a structure under a given ground shaking action, and is expressed in the form of seismic susceptibility indices, damage probability matrices, and susceptibility curves, all of which can be referred to as the damage-motion relationship.The Damage Probability Matrix (DPM) expresses in discrete form the probability of the damage level $\boldsymbol{j}$ obtained by the structure under a given ground motion intensity $\boldsymbol{i}$, expressed as $\boldsymbol{P} = [\boldsymbol{j}/\boldsymbol{i}]$; The vulnerability function is a continuous function of the probability of exceeding a given damage state under a given seismic intensity.Seismic vulnerability analysis of tunnels in the form of damage probability matrices usually requires a large amount of seismic data and is not intuitive enough to be understood by non-specialists. Therefore, the vulnerability assessment of tunnels is mainly based on vulnerability curves.

According to the literature review, it can be concluded that existing methods for tunnel seismic vulnerability can be divided into three categories based on different sources and principles of data analysis: (1) vulnerability analysis based on seismic damage data investigation; (2) Vulnerability analysis based on mechanical analysis and numerical simulation; (3) Vulnerability analysis based on overall risk analysis method.

2.1 Vulnerability analysis based on earthquake damage investigation

The seismic survey mainly includes the historical seismic survey data of the tunnels in the same area and the corresponding ground vibration intensity information, and then according to the data of the seismic survey, the parameters of the probabilistic susceptibility model are obtained by using mathematical and statistical methods such as logistic regression analysis, great likelihood estimation and analysis of variance, etc. Finally, the empirical susceptibility analysis curve of the tunnels is established through the calculation of the susceptibility distribution function, which is mainly suitable for the areas where there are relatively complete seismic survey data and ground vibration record data.In Corigliano's research[12], a total of 121 cases of damaged tunnels were reported based on the 1952 Kern County earthquake (United States), 1989 Loma Prita earthquake (United States), 1994 Northridge earthquake (United States), 1995 Kobe earthquake (Japan), 1999 Chiji earthquake (Taiwan), and 2004 Niger Tata earthquake (Japan),The shortest distance from the seismic source to the damaged rupture surface was calculated, and combined with the magnitude of the site area, the estimated peak ground velocity (PGV) for quantifying seismic motion intensity was obtained.Fan Gang and Zhao Xiaoyong extensively investigated the seismic damage phenomena of some highway tunnels located in the extremely severe and severely affected areas of the Wenchuan earthquake,Analyzing the seismic damage characteristics of 56 tunnels along 18 railway lines, the tunnel structures are divided into three categories: ordinary section, entrance section, and fault fracture zone. Based on the 15 different forms of tunnel damage, the tunnel damage states are classified from light to heavy into four types: slight damage, moderate damage, severe damage, and complete damage. The seismic vulnerability curves at different locations are obtained[28][29].

The methodology based on seismic damage survey requires the statistics of tunnel damage in the earthquake affected areas, and the seismic susceptibility curves established from this data are of great practical value in the statistical regions. However, the lack or insufficiency of historical damage statistics or information on the spatial distribution of ground shaking in tunnels in most regions of the world affects the reliability of the vulnerability analysis results, thus limiting the use and popularization of the method to a certain extent.

2.2 Vulnerability analysis based on numerical simulation

The vulnerability analysis data based on numerical simulation comes from numerical simulation calculations. Researchers establish different models by changing the number and type of seismic waves to achieve controllability and reliability of the analysis data. Currently, this method has been widely used. In seismic vulnerability analysis, the standard logarithmic normal cumulative distribution function is used to describe the relationship between the seismic capacity of a structure and seismic demand:

$$p_f\left(d_s \geq d_{si} \middle| S = \phi[\frac{1}{\beta_{tot}}\square\ln(\frac{S}{S_{ml}})]\right)^{[13]} \tag{1}$$

In the formula: $p_f()$ is the probability of being in or exceeding a specific damage state d_{si}; S represents the given peak acceleration (PGA); ϕ It is a standard cumulative probability function; S_{mi} is the median threshold of the seismic parameter S required to cause its damage state; β_{tot} is the standard deviation of the logarithmic normal population.Lognormal standard deviation β_{tot} describes the total variability associated with each vulnerability curve;reference [11] considers three main sources of uncertainty, namely the definition of damage state β_{DS} ,response and bearing capacity (capacity) of tunnels β_C ,earthquake input motion (demand) β_D .The total variability is composed of a combination of three sources, assuming they are statistically independent and lognormal distributed random variables, as shown in equation (2):

$$\beta_{tot} = \sqrt{\beta_{DS}^2 + \beta_C^2 + \beta_D^2}^{[13]} \tag{2}$$

According to equation (1), relevant scholars have established the seismic theoretical vulnerability curve of tunnels using different analysis methods. Among them, numerical simulation is one of the most commonly used methods, whose main purpose is to obtain the response of tunnels under a given seismic input, that is, the parameters of the distribution function β .Due to the fact that tunnels can be numerically analyzed using different methods (such as finite element method, finite difference method, and discrete element method), and can use different dimensional models (such as 1D, 2D, and 3D), different methods have been developed, which can be mainly divided into the following types:

(1) Quasi static 1D plane strain analysis: Quasi static analysis essentially means that real-time processes are simulated infinitely slowly, allowing the equilibrium equation to be satisfied at each step and inertia, while momentum effects are ignored,

and the calculation time cycle is minimized as much as possible. Therefore, dynamic problems can be solved as static problems.

(2)Ground Response Acceleration Method (GRAMBS): The simplified dynamic analysis method GRAMBS is applied to the two-dimensional seismic soil structure interaction (SSI) analysis of tunnel structures. Firstly, the surrounding soil of the tunnel structure is subdivided into several layers; Secondly, based on software such as SHAKE and M-SHAKE, the equivalent linear method is used to analyze the free field response without considering the tunnel structure, and the corresponding displacement and acceleration responses of each soil layer at the corresponding time are calculated; Finally, search for the moment when the maximum displacement difference occurs between the top and bottom of the tunnel.

(3)Completely nonlinear 2D dynamic analysis: The characteristic of dynamic time history analysis is that the output of each dynamic analysis can be directly used as input for further dynamic analysis until reaching a severely damaged state (DS3) and the calculation stops.The use of dynamic analysis to evaluate seismic vulnerability requires a high computational workload, as large numerical models are required to perform extensive calculations to avoid boundary effects, and mesh refinement is required to accurately calculate the correct transmission of seismic waves and soil structure interactions,the complexity of numerical simulations considering relevant uncertainties has been increased, but it can reproduce the nonlinear behavior of materials and the most important failure mechanisms (i.e. tensile, compressive, bending, and shear failure),and the established two-dimensional nonlinear dynamic time history analysis numerical model can quantify the cumulative damage of rock, soil, and structure in deep tunnels in earthquake sequences, used to derive state independent (traditional methods) and state dependent vulnerability functions.

2.3 Vulnerability analysis based on overall risk analysis method

The holistic approach to risk analysis considers the components of a system and also integrates the factors that affect the whole. The term "whole", as opposed to parts, is defined as relating to the whole or complete system, rather than to analyzing, treating or dissecting the parts.Under the guidance of this method, the risk evaluation model of the tunnel is constructed. Among them, the hierarchical analysis method (AHP) is the core of the overall analysis method, using the AHP method as a screening tool for the causal factors[30], considering the uncertainty of seismic vulnerability of tunnels, and then obtaining the probability statistics of seismic damages of tunnels through the collection of historical data to establish the tunnel risk assessment diagrams, so as to obtain the discriminative values of the vulnerability of tunnels to earthquakes, and ultimately to assess the vulnerability of the tunnels under seismic effects.This method is not only able to accurately evaluate the actual functional losses of tunnels at risk from earthquakes, but also provides decision makers with detailed information for predicting economic losses from disasters.

3 Tunnel seismic vulnerability assessment program

Due to the widespread application of numerical simulation based tunnel seismic vulnerability analysis, the main steps and key contents of this method are discussed in detail. The steps to obtain a numerical simulation based method for evaluating the seismic vulnerability of tunnels are shown in Fig 1.Among them, three key steps are related to the form and accuracy of the seismic vulnerability curve, which are:(1) determination of input parameters;(2)Classification of destructive states;(3) Calculation of related uncertainty parameters.

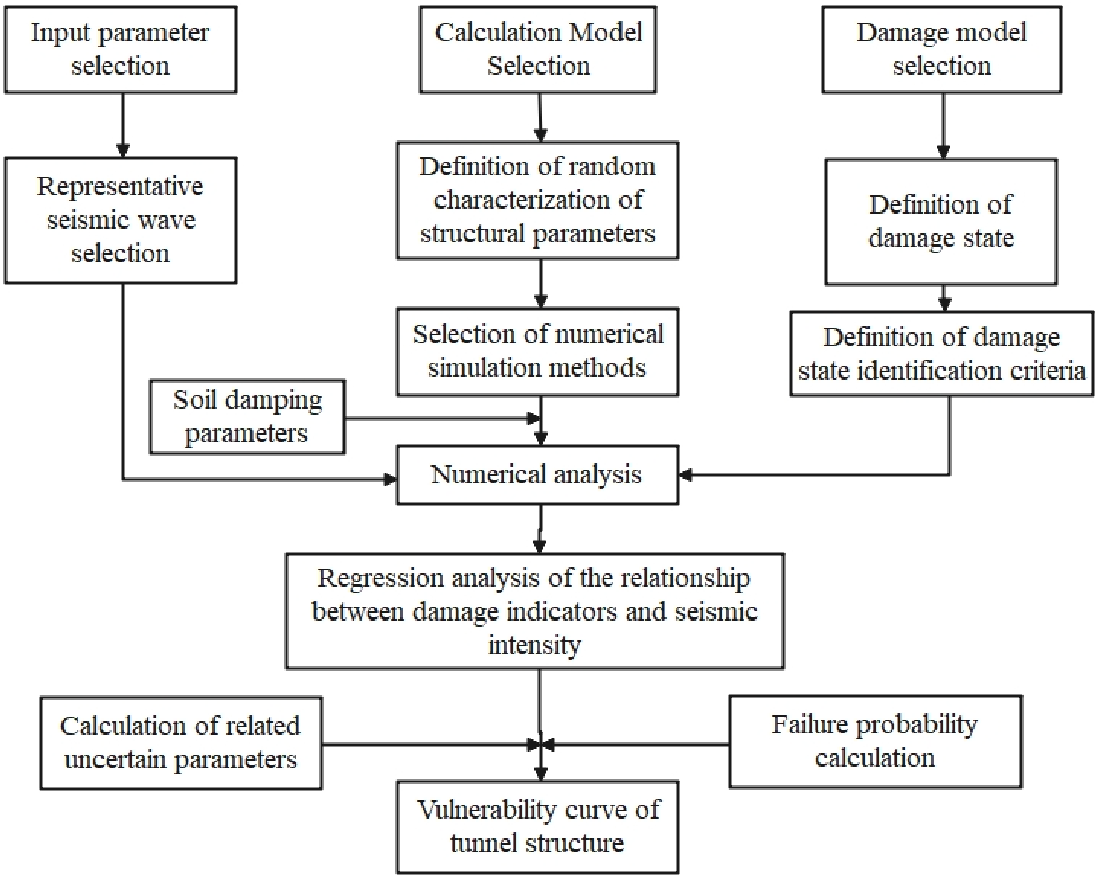

Fig 1 Steps for seismic fragility analysis of tunnels

3.1 Input parameter

The seismic vulnerability function indicates the probability that the seismic demand of a structure under seismic action reaches or exceeds the specified damage limit state. In general, various physical quantities (IM) that represent the magnitude of seismic intensity can be used as independent variables of the seismic vulnerability function,overall, these physical quantities can be divided into three categories: the first category is macroscopic physical quantities, such as earthquake intensity;The second type is the simple seismic parameters obtained through measuring and processing seismic information, such as peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD)[12];The third type is the parameters obtained by calculating the seismic response of the structure, usually the response spectrum parameters, such as spectral acceleration (Sa), spectral velocity (Sv), and spectral displacement (Sd).Due to the strong randomness of seismic input, the results of structural vulnerability analysis heavily rely on seismic input. Using only one physical quantity as the input of seismic motion cannot fully describe the strong randomness of seismic motion. Therefore, using multiple physical quantities to represent the input of seismic motion can better solve this problem.

3.2 Destructive state

The tunnel undergoes various types of damage under seismic action, such as lining cracking and concrete peeling as shown in Fig 2,In the process of analyzing and evaluating the vulnerability of tunnels to earthquakes, the selection of the failure state and failure indicators under tunnel earthquakes is very important.By reviewing the existing damage classification criteria, two approaches can be used to determine the damage status. The first one is strictly based on structural damage; The second one is related to its function after an earthquake.

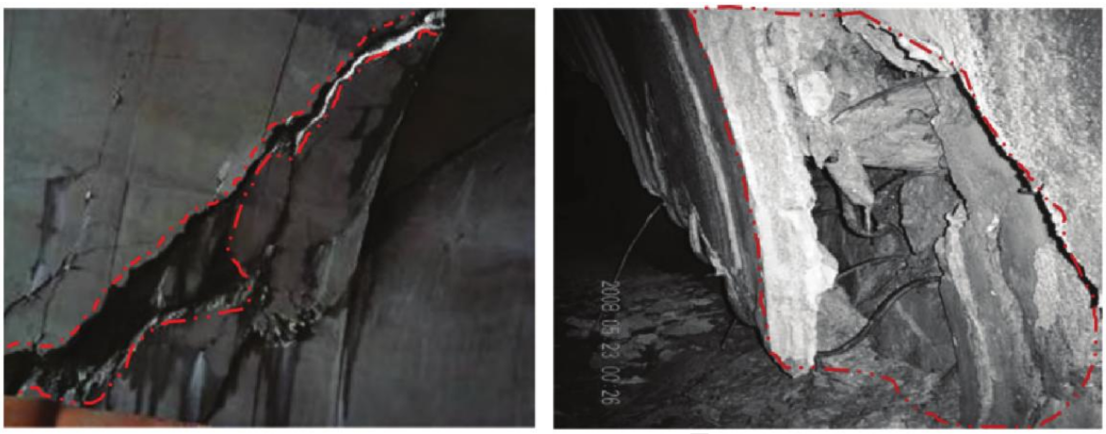

Fig 2 Seismic damage characteristics of tunnels

Corigliano qualitatively and quantitatively classifies tunnel failure states, taking into account four levels of failure (none, minor, moderate, and severe), divided into three categories: A, B, and C[12],see table 1.

Table 1Classification of macroscopic failure states[[12][31]

Damage level	Damage description	Post earthquake function
No A	Visual inspection shows no damage	normal
Slight A	Visual inspectionrevealed minor damage, concrete lining cracking and cracking (crack width<3mm, crack length<5m); Hole blockage and deformation	Not strictly requiring interruption of operations
Moderate B	The top plate or side wall of the tunnel lining or unlined section is damaged, collapsed, or falls; Concrete lining cracking (crack width>3mm, crack length>5m), fragmentation, and peeling; Exposed lining steel bars	Operation interruption for 2 or 3 days
Serious C	Tunnel collapse caused by instability	Prolonged interruption of

	of the tunnel portal and slope; Lining misalignment; Elevated road surface, inverted arch, tunnel flooding, or damage to tunnel ventilation or lighting systems	its operational use

The most commonly used method for classifying tunnel failure states is based on the failure index (DI), which is defined as the ratio of the actual bending moment (M) of the tunnel lining to the bearing bending moment (M_{RD})[32],The actual bending moment (M) is calculated as a combination of static and seismic loads, taking into account the resulting static and seismic axial forces (N) and bending moment (M). Based on the experience of tunnel diseases in the past and the judgment of application engineering, four different seismic damage states were considered, which are divided into mild, moderate, extensive, and complete damage states of tunnel lining.According to existing literature, there are two main types of DI based on the different ranges of divided states, as shown in Tables 2-3.

Table 2 Classification of failure statesbased on failure indices[32]

Damage level (d_{si})	Destruction index range (DI)	Median disruption index
Not	$M/M_{RD} \leq 1.0$	-
Minor damage	$1.0 < M/M_{RD} \leqslant 1.5$	1.25
Moderate damage	$1.5 < M/M_{RD} \leqslant 2.5$	2.00
Widespread destruction	$2.5 < M/M_{RD} \leqslant 3.5$	3.00
Complete destruction	$M/M_{RD} > 3.5$	-

Table 3 Relationship between failure indexand failure state[33]

Destruction index DI	Destructive state
$DI \leqslant 0.7$	Not
$0.7 < DI \leqslant 1.0$	Minor damage
$1.0 < DI \leqslant 1.3$	Moderate damage
$1.3 < DI \leqslant 1.8$	Complete destruction

3.3 Uncertainty calculation

In the establishment of tunnel seismic vulnerability functions and curves, there are many uncertainty issues that need to be considered, including various sources of uncertainty. Through literature review, it has been found that the uncertainty in seismic vulnerability analysis is mainly based on probability analysis methods, which consider factors such as soil characteristics, soil structure interaction, tunnel depth, and lining strength. Various mathematical statistical methods have been introduced to increase the reliability of the analysis.On the basis of deriving the vulnerability curve of underground tunnels based on SSI, Le used static elastic-plastic pushover analysis to generate information on different damage states[34].On the basis of Argyroudis[13], Osmi focused on considering the uncertainty of tunnel lining types and used three-dimensional nonlinear time-history dynamic analysis to obtain the seismic dynamic effects of shallow buried rock tunnels. The seismic vulnerability curve ignoring soil structure interaction was applied to evaluate the seismic performance of tunnel lining[35].Subsequently, Osmi established seismic vulnerability curves for shallow buried circular tunnels in four soil types: dense sand, loose sand, hard clay, and soft clay, taking into account the influence of soil characteristics on tunnel seismic vulnerability. There are significant differences between these curves; To explore the influence of overlying rock stress on the seismic vulnerability of deep tunnels in soft rock[36].Andreotti obtained numerical results and seismic vulnerability curves for corresponding parameters by using advanced fully nonlinear incremental dynamic analysis on soft rock tunnels located at 100m, 300m, and 500m[[37].Han conducted a probabilistic site response analysis based on the shear wave generated by Monte Carlo simulation in order to consider the soil response with fixed uncertainty in the tunnel susceptibility analysis, and the results showed that the seismic susceptibility of tunnels using the probabilistic site response analysis was weaker than that of the fixed condition[38].The susceptibility function curves of shallow segmental tunnels in alluvial normal faults were developed by Kiani through centrifugal experiments, and the curves were constructed with permanent ground displacement (PGD) as the independent variable, and then compared with the empirical susceptibility curves of rocky tunnels, and concluded that alluvial tunnels are more susceptible to damage[39].Argyroudis proposed a numerical calculation method for seismic susceptibility curves of shallow subway tunnels taking into account soil-structure interaction (SSI) and aging effects due to corrosion of lining reinforcement, and compared it with existing empirical and analytical susceptibility models, highlighting the importance of soil conditions and corrosion effects on the structural susceptibility of tunnels[40].

4 Outlook on Seismic Vulnerability Analysis of Tunnels

The seismic vulnerability analysis of tunnels has evolved from traditional empirical vulnerability analysis to theoretical vulnerability analysis mainly based on numerical simulation. At the same time, different mathematical probability and statistical methods have been combined to consider relevant uncertainties, greatly promoting the scientific research and practical development of tunnel seismic damage assessment and prevention. However, there are still some shortcomings that need to be further explored, and new methods and programs need to be developed to make up for these shortcomings.

In the seismic vulnerability analysis of tunnels, scholars have not formed a unified standard for selecting input parameters, failure criteria, analysis types, and analysis methods, and there are significant differences in the degree of reliability evaluation. Most of the input parameters are based solely on seismic motion parameters, without selecting multiple physical quantities. In addition, the differences in the destruction criteria also lead to significant differences in the calculation and analysis results.

To address the above issues, research on tunnel seismic vulnerability can be improved and developed in the following areas:

(1)To synthesize the characteristics of various previous analysis methods and establish a set of seismic vulnerability analysis methods for tunnel engineering that can systematically consider multiple uncertainties. The effects of uncertainty factors related to tunnel structural design, construction quality, maintenance conditions, experimental data, structural modeling, engineering site hazards, and seismic wave spectral characteristics are further investigated. Based on probabilistic statistical analysis methods to quantify the relative magnitude of each type of uncertainty and to study the linkage effects between the various uncertainties, which can directly guide the performance-based seismic design of tunnels.

(2)Tunnels are usually used in harsh environments with poor maintenance conditions. As the service time of the structure grows, the effects of chloride erosion in the atmospheric environment and the carbonization of concrete will lead to the gradual degradation of the seismic performance of the structure. In future research, it is necessary to combine the concept of whole-life tunnel design with the concept of performance-based seismic design to further explore the time-varying seismic performance of tunnel structures during service life, and to establish the time-varying seismic susceptibility curves of tunnel structures.

(3)The steps and contents of vulnerability analysis are complex and take into account a wide range of factors, and the geological environment and engineering profiles of tunnels in different regions are usually different, so the seismic vulnerability of each tunnel has to be recalculated and analyzed, which increases the workload. Therefore, there is an urgent need to develop a set of software and system for seismic vulnerability assessment of tunnels, embedded with a global seismic database and a tunnel damage information database, introducing a mathematical analysis language for factor variability and a module for selecting the analysis method, and providing a fast seismic economic loss calculation program.

5 Conclusion

Tunnel earthquake prediction and prevention technology has been a difficult problem for the engineering community. Seismic vulnerability analysis, as a kind of risk probability analysis method, is mainly applied to the pre-earthquake estimation and post-earthquake economic impact assessment of tunnels. At present, there are still many deficiencies in the seismic vulnerability analysis of tunnels in China. Tunnel seismic vulnerability analysis is an important part of tunnel disaster prevention (control) technology, which can be combined with big data, artificial intelligence analysis and other cutting-edge fields to promote the development of tunnel disaster prevention (control) technology in many ways.

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