Review Article

Review and Outlook on Seismic Vulnerability Analysis of Tunnel Engineering

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. The results indicate that the seismic vulnerability analysis of tunnels can reflect the performance of tunnels under seismic loads by considering relevant uncertainty factors, which is beneficial for future risk assessment and loss estimation, and is of great significance for the development of performance-based seismic design of tunnels.

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

Introduction

In recent years, frequent earthquakes both domestically and internationally have caused varying degrees of structural and functional damage to underground engineering such as tunnels. For example, tunnels in earthquake stricken areas such as the Hanshin earthquake in Japan, the Chiji earthquake in Taiwan, and the Wenchuan earthquake have all experienced different types of seismic damage, such as cave collapse and door cracking, lining and surrounding rock collapse, and bottom plate cracking and uplift[1],Seriously affecting transportation, economy, and safety. Therefore, it is of great significance to establish and continuously improve the tunnel earthquake risk assessment mechanism and earthquake damage assessment system.

Vulnerability analysis is an important component of risk assessment. Seismic vulnerability refers to the probability of different levels of structural damage occurring under the action of earthquakes of different magnitudes. It quantitatively reflects the seismic performance of engineering structures through probability indicators and macroscopically describes the relationship between seismic strength and structural damage degree[2][3].Therefore, conducting seismic vulnerability analysis research on tunnel engineering can not only predict the probability of structural damage at all levels before earthquakes, but also provide guidance for post earthquake structural and functional loss assessment.At present, seismic vulnerability analysis is widely used in the field of ground structures such as buildings and bridges, while the application and research progress in underground engineering such as tunnels are relatively slow. Existing research results cannot meet the needs of practical engineering. On the one hand, the engineering community traditionally believes that tunnels have weaker seismic damage to ground structures, resulting in insufficient research and scope on tunnel seismic vulnerability; On the other hand, previous research only introduced uncertainty factors for qualitative analysis, lacking quantitative description and comparison of various uncertainties.

This article systematically reviews the research status of seismic vulnerability in tunnel engineering at home and abroad, summarizes the characteristics and applicability of various analysis methods, and emphasizes the establishment and development of vulnerability curves. Finally, the existing problems in this field were pointed out, and the future development trends were discussed, laying the foundation for further promoting and advancing the development of tunnel engineering risk assessment theory.

Research status

The concept of seismic vulnerability analysis was first proposed by American scholar Comell in 1968, and this probability analysis method was first applied to seismic risk assessment of nuclear power plant infrastructure[4],Later, it gradually spread to the field of infrastructure such as houses and bridges, while earthquakes in underground structures such as tunnelsThe development time of vulnerability analysis is relatively late.Early seismic vulnerability analysis of foreign tunnels was mainly based on expert judgment and empirical vulnerability curvesLine, some scholars have collected the actual damage situation of past earthquake tunnels around the world through observation[5][6][7][8],Based on expert judgment, Rojahn used the revised MelCALI strength scale to establish failure probability matrices for alluvial layers, cover excavation methods, and rock tunnels[9];Alliance conducted regression analysis on the global tunnel earthquake disaster database and established empirical vulnerability curves based on ground peak acceleration (PGA) for both excavation and cover excavation tunnels. They also used attenuation models to backcalculate tunnel damage, taking into account the uncertainty of seismic motion 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; Based on a composite database of 120 tunnel related seismic damage cases[11], Corigliano replaced traditional PGA with PGV as the input parameter for seismic intensity and established a new seismic vulnerability empirical curve for shallow buried rock tunnels[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 tunnel structure types of earthquake vulnerability research objects are divided into shallow buried, deep buried tunnels, and tunnel shafts according to burial depth, hidden excavation and cover excavation tunnels according to construction methods, and circular and rectangular tunnels according to cross-sectional form.

Argyroudis considered uncertain parameters such as the geometric dimensions and lining strength of the tunnel, seismic input, and soil properties. A one-dimensional equivalent linear numerical analysis method was used to establish the seismic vulnerability curve of the shallow buried subway tunnel in the alluvial layer. The reliability of the numerical simulation was verified by comparing the numerical calculation solution with the fully enclosed analytical solution. Compared with the empirical vulnerability curve, the new vulnerability curve highlights the importance of local soil characteristics in seismic response[13];Andreotti proposed that deep buried tunnels are suitable for evaluating their seismic vulnerability using theoretical vulnerability curves, and derived the seismic vulnerability curve and cumulative damage model of deep buried tunnels using a two-dimensional nonlinear numerical model. This can reproduce the different failure mechanisms of the lining and quantify the cumulative damage of the entire system during earthquakes[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].

2 Seismic vulnerability analysis method for tunnels

Structural vulnerability is usually described as the probability of different degrees of damage to a structure under a given seismic action. Its representation mainly includes seismic vulnerability index, damage probability matrix, and vulnerability curve, all of which can be referred to as 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.The seismic vulnerability analysis of tunnels in the form of damage probability matrix usually requires obtaining a large amount of seismic damage data, and the performance is not intuitive enough to be understood by non professionals. So far, the vulnerability assessment of tunnels has mainly been based on the vulnerability curve.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 damage investigation mainly includes historical seismic damage investigation data of tunnels in the same area and corresponding seismic intensity information. Then, based on the seismic damage investigation data, mathematical statistical methods such as logistic regression analysis, maximum likelihood estimation, and analysis of variance are used to obtain the parameters of the probability vulnerability model. Finally, the empirical vulnerability analysis curve of tunnels is established by calculating the vulnerability distribution function, Mainly suitable for areas with relatively complete seismic damage investigation data and seismic motion 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[19][20].

The method based on earthquake damage investigation requires statistical data on tunnel damage in earthquakestricken areas, and the seismic vulnerability curve established through this data has significant practical value in its statistical area. However, the historical seismic damage statistics or spatial distribution information of tunnels in most regions of the world are still lacking or insufficient, which affects the reliability of vulnerability analysis results, thus limiting the use and promotion of this 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:

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

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):

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

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 overall risk analysis method considers the components of the system and also comprehensively considers the factors that affect the overall situation. Compared to parts, the term "whole" is defined as being related to the whole or a complete system, rather than to analyzing, processing, or dissecting parts. Under the guidance of this method, construct a risk assessment model for tunnels. The Analytic Hierarchy Process (AHP) is the core of the holistic analysis method[21],using the AHP method as a disaster causing factor screening tool, considering the uncertainty of tunnel seismic vulnerability, and collecting historical data of tunnel seismic damage to obtain its probability statistics, a tunnel risk assessment map is established to obtain the discriminant value of tunnel vulnerability under earthquake action, and finally evaluate the vulnerability of the tunnel under earthquake action.This method can not only accurately evaluate the actual functional loss of tunnel risk under earthquake action, but also provide decision-makers with detailed information on predicting disaster economic losses.

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.

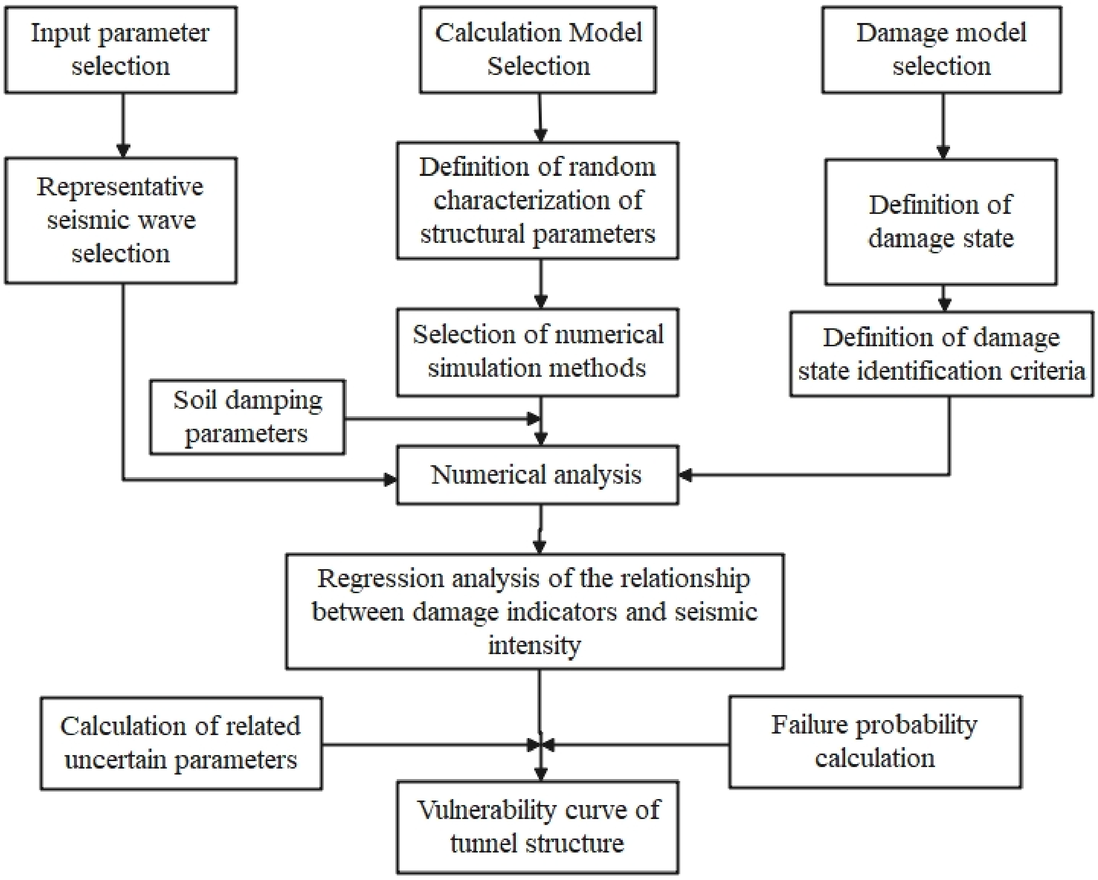

Fig 1 Steps for seismic fragility analysis of tunnels

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.

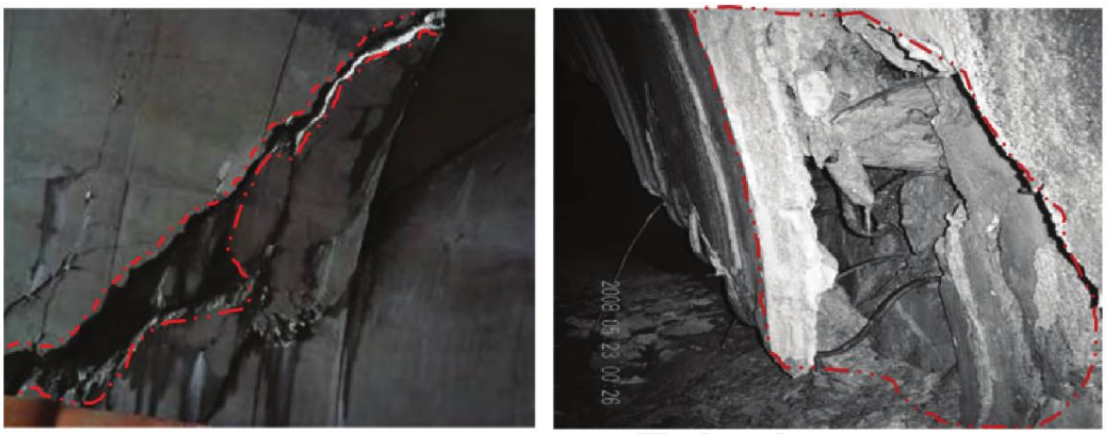

Fig 2 Seismic damage characteristics of tunnels

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][22]

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 of the tunnel portal and slope; Lining	Prolonged interruption of its operational use

	misalignment; Elevated road surface, inverted arch, tunnel flooding, or damage to tunnel ventilation or lighting systems	

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})[23],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[23]

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	$M/M_{RD} > 1.5$	-

Table 3 Relationship between failure indexand failure state[24]

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[25].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[26].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[27].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[[28].

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) Based on the characteristics of various analysis methods in the past, establish a seismic vulnerability analysis method for tunnel engineering that can systematically consider various uncertainties.Further study the impact of uncertainty factors related to tunnel structure design, construction quality, maintenance conditions, experimental data, structural modeling, engineering site hazards, and seismic wave spectrum characteristics.Using probability and statistical analysis methods to quantify the relative magnitude of each type of uncertainty, and studying the linkage effects between various uncertainties, can directly guide performance-based tunnel seismic design.

(2)The usage environment of tunnel engineering is usually harsh, and the maintenance conditions are also poor. As the service life of the structure increases, the corrosion effect of chloride ions in the atmospheric environment and the carbonation effect of concrete will gradually degrade the seismic performance of the structure. In future research, it is necessary to combine the concept of full life tunnel design with performance-based seismic design, further explore the time-varying seismic performance of tunnel structures during their service life, and establish a time-varying seismic vulnerability curve for tunnel structures.

(3)The steps and content of vulnerability analysis are complex, and a wide range of factors are considered. Generally, there are differences in the geological environment and engineering overview of tunnel engineering in different regions. Therefore, the seismic vulnerability of each tunnel needs to be recalculated and analyzed, which increases the workload.A simple method is needed to evaluate the vulnerability of tunnels.

5 Conclusion

Tunnel earthquake prediction and prevention technology has always been a difficult problem in the engineering industry. As a risk probability analysis method, earthquake vulnerability analysis is applied to pre earthquake estimation and post earthquake economic impact assessment of tunnels. Currently, there are still many shortcomings in tunnel earthquake vulnerability analysis in China. It can be combined with cutting-edge fields such as big data and artificial intelligence analysis to promote the development of tunnel disaster prevention (control) technology in various aspects.

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