Study of non-uniform seismic response of intercity tunnels with defective shields

Abstract:

Based on the structural viscoelastic boundary theory, considering the geological changes of the soil layer and depth of tunnel crossing, the dynamic time course analysis is carried out for the defective lined tube sheet structure under non-uniform seismic excitation, to obtain the force and deformation law of the whole tunnel structure as well as the defective section. Analyze the dynamic response of shield tunnel structure under non-consistent seismic excitation under the influence of tube sheet misalignment factors, summarize the intrinsic mechanism of the dynamic response of defective tunnel tube lining structure, identify the phenomena affecting lining junction damage, and refine the seismic safety evaluation method of defective lining structure.

Keywords: shield tunnel; lining misalignment; non-uniform earthquake; disease; seismic performance.

Introduction

China is located between the Pacific Rim and the Eurasian seismic zone, and is squeezed by the Pacific Plate, the Indian Ocean Plate and the Philippine Plate, making it an earthquake-prone country [1]. Up to now, the total length of China's urban rail transit routes has reached 10,291.95 km, and Zhengzhou city is located in the eastern part of Henan province, with the Yellow River alluvial plain to the east and the weakly cut loess hills to the west, with a slightly undulating topography [2], and there are not many researches on the seismicity of shield tunnels under alluvial plain clays at present both at home and abroad, and the problem of tunnel damage is becoming more and more prominent, especially in the tunnel lining structure, can it maintain the stability of tunnel lining structure under the earthquake effect? It remains to be seen whether the tunnel lining structure can maintain stable performance, especially under seismic effects. When the size of the substructure is small, the spatial effect of ground shaking and the angle of incidence has less influence on the structural response due to the large propagation velocity of seismic waves in the soil and the limited size of the underground structure. However, when the size of the underground structure is large, the site soil traversed by the structure is more complicated, and the ground vibration inputs of different parts are different, so the spatial variation effect of ground vibration has a non-negligible influence on the seismic response of the underground structure at this time. At present, domestic and foreign experts have done some research on the diseases of shield tunnels under non-uniform ground vibration, but there are fewer studies on the vulnerability of shield tunnels under defects of non-uniform seismic excitation. The evaluation and excitation of seismic action of tunnels under defects need further in-depth research to realize the technical support for later operation and maintenance. Li Yue [3] relied on an example of a cross-river shield tunnel project, for the shield tunnel and other phases of the occurrence of the misalignment of the actual measurement, in the inclusion of the shield through the flood control wall to the crossing of important underground pipelines in 635 rings of pipe pieces in the misalignment of the proportion of about 14%, the proportion of the pipe pieces of the water leakage of about 26%. Xie and Jiang[4] through the observation of a tunnel in Beijing, found that the phenomenon of misplaced platforms is widespread, especially in the curve construction section, there are a number of misplaced platform values of more than 40mm, which greatly affects the use of the tunnel.

1. Principles and methods of calculating seismic vulnerability of tunnels

For the seismic vulnerability, is to analyze due to the emergence of earthquakes, the structure of the chance of damage.Vulnerability is a characteristic of the structure itself, that is, under the effect of earthquakes of different intensities, the chances of the structure exceeding the damage level, that is, from a probabilistic point of view to quantitatively assess the seismic performance of tunnels, a method. Its basic principle is to deeply analyze the strength of the tunnel through many seismic waves, and secondly, through probability theory, combined with the tunnel damage index, to establish an intrinsic connection between the ground shaking intensity and the damage level of the tunnel, so as to further analyze the seismic performance of the structure.

Seismic susceptibility can be expressed by the following equation (ground shaking intensity is expressed in PGA):

$$\mathrm{P}_{\mathrm{DV/IM}}(0/\mathrm{PGA}) = \sum \mathrm{P}_{\mathrm{DV/LS}}(0/\mathrm{c})\mathrm{P}_{\mathrm{DM/IM}}(\mathrm{Z} > c/PGA) \qquad (1\text{-}1)$$

In the above expression, DV is a dichotomous indicator variable, which is an expression of whether the structure is in a limit state or not, and a value of zero means that the structure is in a limit state; $\mathrm{P}_{\mathrm{DV/IM}}(0/\mathrm{PGA})$ represents the probability of the structure being in an ultimate condition when the seismic intensity is PGAfor LS, which represents the structural capacity index, $\mathrm{P}_{\mathrm{DV/LS}}(0/\mathrm{c})$ represents the probability of the structure being in an ultimate condition when the seismic capacity of the structure is c.

For vulnerability analysis, it is mainly divided into probabilistic capacity analysis and probabilistic seismic demand analysis. For the capacity analysis, it is the determination of a certain damage limit or the determination of its performance level limit. Therefore, the seismic capacity of the structure is considered as deterministic. In combination with the different limit states, there is a corresponding threshold value C. If the structural response reaches this threshold value, it can be judged that the structure is damaged, i.e., the expression $\mathrm{P}_{\mathrm{DV/LS}}(0/\mathrm{c}) = 1$. In this case, the seismic demand analysis structure $P_{DM/IM}(Z > c/PGA)$ and $P_{DV/IM}(0/PGA)$ are equal.

2. Structural seismic susceptibility curves

The seismic vulnerability [5] can be represented by a curve. The curve can be treated as a graphical example of seismic hazard, and it can also be used to quantify the seismic capacity of the structure from a probabilistic point of view. At present, researchers in many countries have begun to pay more attention to the vulnerability of building structures, which can analyze the probability of damage caused by different types of disasters. It has four calculation methods: traditional judgment method, empirical method, seismic intensity table method, analytical method, and more widely used. In recent years, due to the continuous development of computers, the analytical method has been widely used, which analyzes the structure through DHA analysis, then extracts the obtained performance parameters and analyzes the susceptibility curve. In the process of structural susceptibility analysis, the analytical method is applied and its main calculation process is as follows:

Firstly, an elastic-plastic structural model is constructed to simplify the ideal model, which is used to replace the previous building structures to analyze the seismic response of the structure under the influence of earthquakes.

After that, construct the motion expression of the model;

Then, scientifically selecting the number of seismic waves;

At the end, calculate the equation of motion through appropriate calculation methods to obtain the seismic response of the structure under the effect of ground shaking.

3. Research on dynamic response of tunnel structure under seismic action

Foreign scholars Lopes et al [6-7] on the Madrid metro along the dynamic response of the buildings near the test element method to establish a numerical computation model, integrated consideration of the vibration wave generation, propagation and acceptance of the process results of comparative analysis to verify the reliability of the numerical calculation results.

S.Gharehdash [8] and others compared the dynamic response characteristics of shield tunnels in soft ground with and without considering the joint effect, and the results show that there is a large gap between the assumption of not considering the joint effect and the actual situation, but the numerical model does not consider the tube piece modeling, and does not consider the bolts and reinforcement structure, and for the joint of the tension and misalignment of the deformation state cannot be embodied.

U. Nicolas Mos [9] proposed an improvement of a new technique for modeling cracks in a finite element framework. The standard displacement-based approximation is enriched by a unit decomposition method that incorporates both discontinuous and near-tip asymptotic fields near the crack. A method for constructing enriched approximations from the interaction of the crack geometry with the mesh is developed.

T. Real et al [10] developed two-dimensional and three-dimensional numerical computational models to predict the dynamic response of tunnel lining induced by railroad train operation, respectively.

Some domestic scholars Wang Wei [11] comprehensive use of theoretical analysis, numerical simulation and other research methods, and relying on the JiuMian high-speed flat spiral tunnel bias straight line tunnel opening section project, from the bias of the mountain tunnel opening section lining structure of the seismic damage mechanism, seismic response characteristics, seismic mitigation technology and other directions to carry out research.

Yan Longqi [12] sorted out the numerical method of calculating the lateral non-consistent seismic response of underground structure, and verified the validity of the method; the numerical simulation method was used to analyze the lateral seismic response of the circular tunnel structure and the horseshoe tunnel structure through the fault fracture zone under the non-consistent seismic wave under the conditions of plane strain in the layered foundation, respectively.

Gu Jun [13] used the finite element software ADINA to establish a three-dimensional finite element model of the subway tunnel, performed nonlinear dynamic characterization, and input three different seismic waves. The calculation results show that the seismic dynamic response of the subway tunnel structure inputting different seismic waves is obviously different.

Yan Qixiang [14] and other studies show that: the results of the equivalent stiffness proposed static method are on the safe side, the formula is simple, and it is closer to the reality when considering the interface slip, so the equivalent stiffness proposed static method considering the slip condition can be recommended as the seismic design method for deeply buried circular shield tunnels.

Wang Peng [15] conducted some research on the seismic performance of curved tunnels,constructed soil and curved tunnel dynamic models from the basic principles of dynamic analysis of tunnels. The seismic response characteristics of curved tunnels are discussed and the seismic response law is summarized.

Li layer [16] used numerical simulation to analyze the force characteristics of the tunnel buried depth of 4d, 6d, 8d, 10d, 12d, 14d (D is the diameter of the tunnel 6.253m) under the seismic action of the tunnel under six cases in the top of the arch, the left arch waist, the right arch waist, the left elevation arch foot, the right elevation arch foot, the elevation arch bottom force, and get the dynamic response law of the tunnel lining structure.

Wu Yue [17] and others analyzed the acceleration and stress response characteristics of the tube lining structure affected by seismic waves based on the local staggered-seam assembled tube piece refinement model of the lining stiffness equivalent numerical test, and revealed the cracking process and damage mechanism of the tube piece lining under the strong seismic action by the extended finite element method.

Wang Guobo [18-19] and others proposed a method to consider the misalignment, assuming the amount of misalignment of 1mm, 10mm, and 20mm at four positions of the arch top, arch shoulder, arch waist, and arch bottom, respectively, and the influence of the amount of misalignment of the shield tunnel tubular sheet and the misalignment site on its seismic response through the reaction displacement method; numerical simulation was adopted to study the seismic response of the soil ¬-tunnel system under the non-consistent excitation. It is investigated by numerical simulation to explore the response law of the grown-up shield tunnel model through refinement under the excitations of consistent wave, traveling wave, coherent wave and coherent traveling wave and the difference between its response and the response under consistent excitation.

Wang Ziwei [20] established a three-dimensional numerical model to analyze the seismic dynamic response of the tunnel vault lining insufficiency, according to the different depths of burial as the upper boundary of the model, the tunnel depth was set to 8D, 10D, 12D,and 14D (D is the tunnel span 6m) four cases, the normal thickness of the lining h is 50cm, respectively, the vault thickness of 20cm, 30cm, 20cm and 10cm. situation simulation. The horizontal displacement of different positions of the lining under different degrees of under-thickness of the vault lining is studied, so as to derive the seismic dynamic response law of the lining.

4. Characteristics and statistical analysis of defects of large diameter shield tunnel misplaced platforms

With the development of cities, the shield method construction has become the mainstream constructionmethod for urban rail tunnels because of its economy, safety,fast construction speed and good protection of the surrounding environment. However, the shield tunnel tube sheet itself has more or less quality defects such as cracks, missing edges and corners, concrete tube sheet pockmarks, honeycomb and so on[21]. Due to the cumulative damage during the construction and operation phase, tube sheet diseases such as tube sheet misalignment, insufficient lining strength, insufficient thickness, and tube sheet cracks have become the most common types of defects, which will affect the safety of tunnel operation if not effectively treated in time [22].

Tunnel cracks are categorized into the following three main groups: edge, corner, and local cracks; tunnel circumferential cracks; and tunnel longitudinal cracks. The main reasons for the cracks in the tube sheet are the excessive thrust of the shield machine, the influence of curve construction, the longitudinal joints appearing at the place of maximum force, and the protrusion of sealing strips at the top of the roof. [23]

Zhang Danfeng [24] found that through numerical simulation for the tunnel lining hollowing, concrete is not compact and lining thickness is insufficient defects mainly due to the tunnel construction of over-under-excavation, large deformation of the weak surrounding rock and the construction of the improper reasons, concrete is not compact and lining hollowing phenomenon is mainly due to the shrinkage and creep of the concrete.

Li Jie [25] established a three-dimensional stratigraphic-structural model through ABAQUS, considering the nonlinear situation of lining materials, it was concluded that during the operation period, the cross-sectional deformation of the tunnel tube sheet is characterized by horizontal outward expansion and vertical phase compression. The axial pressure at the top of the arch of the tube ring is the smallest, the axial pressure at the arch waist is the largest, and the damaged areas of the tube ring under tension and compression are all concentrated at the bottom of the arch, and the rest of the damage is not obvious.

Wang Shimin [26] explored through modeling tests, the tunnel by the increase in water pressure will make the tube lining structure into the plastic phase event lag, the bearing capacity increased. The existence of a certain range of water pressure increases the level of axial force of the lining structure, effectively improving the stress state of the tube sheet lining structure, but once the damage occurs, the tube sheet lining structure destabilizes and destabilizes resulting in the development of a shorter process and faster time.

At present, the shield method of tunnel construction is the main way of urban subway tunnels, which is very likely to cause longitudinal displacement between tube sheets due to uneven jacking force when assembling tube sheets, dimensional errors in manufacturing tube sheets, non-standardization of assembling tube sheets, and uneven grouting and so on[27]. At the same time, the tunnel surrounding rock, soil thickness, slurry solidification time, slurry density, shield tunneling speed and shield tail clearance during the construction period will also exacerbate the generation of lining misalignment [28].

Synchronized grouting is the main factor causing tube sheet misalignment. Define the uplift force F dynamic with the change of stratigraphic conditions and tunnel depth and the buoyancy force F static under the slurry package, f dynamic in a long time after the tube sheet assembly on the tube sheet, f static in the tube sheet ring out of the shield tail with the increase of synchronous grouting volume increases first, and then after the transition section gradually decreases and eventually tends to be stabilized. [29]

Ji Chang [30] et al. found through field tests that when the lower half of the grouting pressure is higher than the upper half of the grouting pressure, the amount of uplift of the pipe sheet increases. On the basis of the total amount of synchronous grouting cementitious materials remains unchanged, and the dosage of non-cementitious materials remains unchanged, with the reduction of the powder-cement ratio and water-cement ratio, the compressive strength of the slurry and the cohesive forceincreased, the initial consolidation time is reduced, and the amount of pipe sheet uplift is reduced.

Xiao Mingqing [31] and other analytical models found that the slurry setting time will significantly affect the generation of pipe sheet misalignment during the construction period, shortening the slurry setting time can effectively reduce the misalignment between the rings of pipe sheet.

Liu Shubin [32] found that through on-site measurements in the actual small radius curve section and large variable slope point section construction, the synchronized grouting volume is not synchronized to increase the lining misalignment phenomenon will also be caused by the increase of the phenomenon.

Zhu Ling [33] established the ANSYS longitudinal model based on the theory of elastic foundation beam, and analyzed that when the slurry is unevenly filled, the maximum amount of uplift of the pipe sheet and the amount of misplaced platforms is larger than that of the slurry completely filled, and the uplift of the pipe sheet disease is aggravated. When the grouting pressure dissipates, the difference between the water and soil pressure above and below the pipe sheet becomes the main factor in maintaining the uplift of the pipe sheet. In addition, the maximum amount of ring seam opening caused by post-wall grouting is also affected by the number of ring seam connecting bolts and the ring width of the pipe sheet.

5. Conclusion

This paper reviewed a large number of literature and information related to the research content of this paper, sorted out the prevalent seismic damage patterns in tunnels, and at the same time, deeply explored its damage mechanism, according to the current relevant standards and information, to determine the damage indexes of the tunnel seismic damage, and then to determine the damage level, formulated the performance indexes that can be used in the tunnel susceptibility analysis, and determined the level of its performance. After that, a finite element numerical model will be constructed, the PGA index will be taken as the ground vibration strength index, the inter-ring tension will be used as the tunnel performance index, and the incremental dynamic analysis will be performed on the tunnel. In addition, the tunnel's susceptibility was analyzed in depth using the principle of susceptibility analysis in conjunction with the conclusions of the incremental dynamic analysis.

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