Journal of Civil Engineering and Urban Planning (2024) DOI: 10.23977/jceup.2024.060304
Clausius Scientific Press, Canada ISSN 2616-3969 Vol. 6 Num. 3

Safety Risks and Control Technologies for Highway Bridges Crossing Existing Rail Transit

Yuge Du*

Northeast Forestry University, Harbin, China
**Corresponding author: 13021257775@163.com*

Keywords: Rail transit; Bridges; Security hazards; finite element

Abstract: With the ongoing increase of urban traffic, the problem of highway crossing existing rail transit bridges is developing. This crossing project not only requires complicated building technology, but also faces enormous security challenges. Bridge project not only contains sophisticated building technology, but also faces considerable security risks. In this paper, Midas GTS NX software is used to calculate the additional displacement and track deviation caused by construction through finite element model, aiming at discussing the safety risk of highway crossing the existing rail transit bridge and putting forward the corresponding control scheme.

1. Introduction

With the rapid development of urbanization in China, the problem of traffic congestion is becoming more and more serious, and the interweaving and integration of highway transportation and rail transportation as the two main trunks of urban transportation has become an important trend in the development of urban transportation. However, this expansion trend also presents new concerns, particularly the safety risks of highway crossing the existing rail transit bridges. These dangers are not only related to the smoothness of transportation, but also directly related to the lives and property safety of the people. Therefore, it is of considerable theoretical value and practical significance to undertake an in-depth study on the safety concerns of highway crossing existing train bridges and put forward appropriate control technology. The safety risk of highway crossing existing rail transit bridges mainly comes from two aspects: one is the impact of highway traffic on rail transit bridges, including vehicle vibration, impact, etc.; the other is the impact of rail transit bridges on highway traffic, such as the stability of bridge structure, deformation, etc. [1]. These collisions may lead to damage and deformation of the bridge structure, or possibly cause safety mishaps. Therefore, how to effectively identify these hazards and apply relevant control measures is the key to ensure the safety of urban transportation. At present, academics at home and abroad have undertaken some studies on the safety concerns and control strategies of highway bridges crossing existing rail transportation. These investigations mainly focus on the dynamic response analysis of bridge structures, risk assessment methods, control strategies and so on. However, due to the complexity of highway traffic and rail transit, as well as the diversity of bridge structures, the present study results can not fully match the needs of actual projects. Therefore, it is required to carry out a more in-depth investigation on this subject in order to provide more effective risk control approaches. The goal of this study is to analyze in depth the safety risk and control technology of highway crossing current rail transit bridges by theoretical analysis and experimental investigation, as follows.

2. Security Risk Assessment and Control

In the process of urban rail transit building, the construction of bridges across existing lines is surely an exceedingly difficult and challenging operation. Given that the construction process involves the stability of the bridge structure, the control of construction precision, and the safety of the surrounding environment, ensuring the safety of existing bridges in service and the smooth progress of the rail transit construction process has become a key scientific issue to be solved in this field. For this reason, this project proposes to conduct out a safety risk evaluation research of rail transportation bridges.

2.1 Pre-work inspection

The main aim of the pre-work inspection is to get a full understanding of the current operating condition of the bridge and appurtenant structures within the scope of the examination. This includes, but is not limited to, the bridge's primary structure, bearings, expansion joints, waterproofing system, drainage facilities, and so on. Through professional inspection tools and procedures, every element of the bridge is painstakingly inspected to guarantee that no prospective faults are missed. Making an objective and reasonable appraisal of the bridge's service condition is the primary activity of the pre-construction inspection. This includes merging the bridge's historical maintenance records, frequency of usage, load-bearing conditions and other information, and using expert analysis software and procedures to make a full assessment of the bridge's overall performance. The evaluation not only focuses on the existing condition of the bridge, but also predicts the pattern of its change in the future period of time, providing solid empirical support for the building. Providing a basis for the pre-construction evaluation of rail transit tunnel crossing bridges is another key role of pre-construction inspection [2]. Based on the comprehensive testing and evaluation of the bridge in the early stage, combined with the characteristics and requirements of the rail transit tunnel construction, the bridge's bearing capacity, deformation performance, seismic performance, etc. are comprehensively evaluated to ensure that the bridge can remain stable during the tunnel construction process. In the pre-construction inspection, it is also required to put forward matters and suggestions that should be noticed. This includes, but is not limited to, reinforcing measures before bridge construction, monitoring points during construction, and maintenance recommendations after construction. These guidelines are meant to assure the safety of the bridge during construction, as well as provide for long-term operation following completion.

2.2 Security assessment

Safety evaluation is a vital component in assuring the safety and stability of bridges during operation. In carrying out such an evaluation, we first need to rely on the results of the pre-work inspection, which is the basis of the assessment task. Pre-construction inspection can offer the actual status data of the bridge, such as structural deformation, material characteristics and other critical information. These data can be compared and examined with the original design specifications of the bridge, and it can be first determined whether the bridge is deformed or damaged beyond the design expectation. The original design specifications of the bridge are a crucial basis for assessment. These factors include the bridge's structural form, material strength, design load and other critical data [3]. By comparing the actual inspection data with the design specifications, we may comprehend the force state of the bridge under the influence of extra differential settlement. Differential settlement may be caused by changes in geological conditions, faulty construction, or long-term operation. Such settlement will modify the force state of the bridge, which in turn may impair the safety of the bridge. In the assessment process, we must also incorporate appropriate technical regulations and standards. These rules outline in detail the safety standards of bridges in different elements of design, construction and operation. By comparing the actual test data and technical specifications, we can assess whether the safety of the bridge matches the requirements. At the same time, we also need to evaluate the actual structural form of the bridge. Different structural forms correspond to different stress characteristics and safety assessment methodologies. Finally, we need to identify the control indexes and control standard values of existing bridges. These indicators are precise criteria for measuring the safety of bridges, such as the maximum permissible values of critical characteristics such as displacement, stress and deformation. By comparing the actual inspection data and the control standard values, we may assess whether the safety of the bridge satisfies the standards, and then recommend an effective reinforcement program. The proposed reinforcing scheme is based on the analysis of the damage form and adverse deformation location of the existing bridge structure. Through the analysis, we can understand the weak links and potential safety dangers of the bridge. In response to these problems, we can recommend equivalent reinforcement solutions, such as expanding the support structure, reinforcing the girders, fixing the damage, and so on. These improvements aim to improve the bearing capacity and safety of the bridge and assure the stability of the bridge during operation [4]. At the same time, the determination of the reinforcing program also needs to consider the aspects of construction and monitoring programs. The construction program needs to plan the exact steps and procedures of the reinforcement work in detail to ensure the safety and efficacy of the reinforcing process. The monitoring software needs to set up appropriate monitoring points to monitor the main parameters in the reinforcement process in real time to ensure that the reinforcement effect fulfills expectations.

2.3 Work-in-progress control

During the construction process, it is necessary to closely monitor and manage the deformation of the bridge structure. Such monitoring is not only related to the safety of construction, but also an important assurance for the safety of the existing bridge structure. In order to ensure the construction safety, we established a vital index - the displacement ratio F, which is the ratio of the actual displacement occurred in the construction to the allowable value of the bridge control index. During the construction phase, we will regularly compare and analyze the monitoring results with the goal values of the defined control program stages. When the value of the displacement ratio F falls between 0.6 and 0.8, it signifies that the displacement of the bridge is near to the warning value. At this moment, we will immediately issue an early warning and report it to the proper authorities in a timely way. Our engineers will quickly assess the safety of the existing bridge structure and, depending on the actual situation, will take appropriate precautions and make adjustments to the construction program if necessary, in order to ensure that the construction can continue to be carried out safely and achieve the desired goals as much as possible. However, the issue becomes more problematic when the value of the dislocation ratio F approaches 0.8 [5]. At this moment, we will instantly raise an alarm and notify the constructor to cease construction. At the same time, we will rapidly disclose this scenario to the operating and construction units so that they can respond quickly. In this circumstance, greater monitoring becomes extremely vital, and we need to inspect the structural condition of the bridge more frequently to ensure the safety of the bridge.

2.4 Post-construction evaluation

After the completion of the construction project, it is necessary to conduct a full post-evaluation of the safety of existing bridges. This process not only concerns the safety of the bridge itself, but is also directly tied to the safety of people's lives and properties as well as the smooth flow of traffic. Therefore, we must pay significant emphasis to the post-construction evaluation to guarantee that the bridge meets the safety standards before it is put into operation. As shown in Figure 1.Safety Risk Assessment and Control Process for Railway Tunnel Crossing Existing Bridges .Specifically, the main substance of the post-construction evaluation includes a detailed examination and assessment of the structural integrity, stability and load-bearing capability of the bridge. By collecting and evaluating monitoring data during the construction phase, we can determine the affects that the bridge has undergone during the construction process, and whether these impacts will have a detrimental influence on the long-term functioning of the bridge. These data contain crucial indicators such as the displacement, stress distribution, and crack formation of the bridge, which can directly represent the safety state of the bridge. After receiving this monitoring data, we need to apply professional assessment methodologies and standards to statistically evaluate the safety of the bridge. This process not only requires the assessors to have significant professional knowledge and expertise, but also demands the use of advanced computation and analysis tools to assure the correctness and reliability of the assessment results. Through the assessment, we can understand the reality of the predicted control effect, i.e. if the various control mechanisms during the construction process have effectively maintained the safety of the bridge structure. At the same time, we need to perform an in-depth investigation of the existing safety status of the bridge. This includes detecting probable safety concerns and weaknesses in the bridge structure, as well as forecasting the difficulties that these hazards may generate during future use. Based on these evaluations, specific rehabilitation programs and measures can be devised. These projects not only need to examine the requirement and extent of rehabilitation, but also need to foresee the settlement and deformation that may occur after the work, and establish corresponding preventive measures [6].

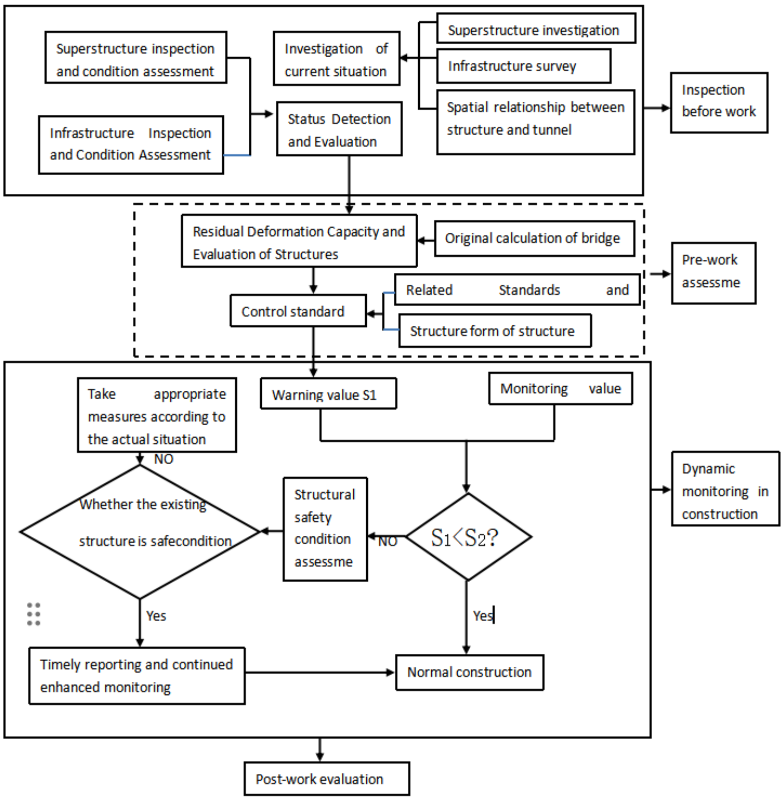

Figure 1: Safety Risk Assessment and Control Process for Railway Tunnel Crossing Existing Bridges

3. Project Overview

3.1 Geological profile

The project is located in an economically prosperous metropolis on the east coast of China, which features flat landscape, crisscrossed rivers and sophisticated rail transit network. The rail transit bridge involved in the project is an important transportation hub in the central area of the city and carries substantial transportation tasks. Geologically, the area is a sedimentary plain, mostly consisting of Quaternary alluvial flood deposits, with a significant thickness of soil layer, but uneven distribution. At the location of the bridge, the geological study shows that the soil layer is predominantly formed of medium-coarse sand, powdery clay and clayey silt, of which the sand layer accounts for a larger share, offering a certain challenge to the stability of the bridge foundation. In terms of groundwater, the area is rich in groundwater, the major type of which is submersible, and the water level fluctuates substantially with seasonal fluctuations. Underneath the bridge, the scouring effect of diving on the bridge foundation cannot be ignored, and the long-term effect may produce uneven settlement of the foundation. In addition, the seismic activity in this area is more frequent, while the magnitude is usually small and medium earthquakes, but considering the importance of the bridge, the impact of earthquakes on the safety of the bridge should not be overlooked. In the geological examination, it is found that there exists an active fracture zone near the bridge, although the distance is far away, but it offers a potential threat to the long-term safety of the bridge.

3.2 Risk point identification

It is 26.94 kilometers long, with a design speed of 90 kilometers per hour, and is a trunk road with six lanes. As shown in Figure 2. Plan picture of risk points in relation to each other. Echoing it is the completed third segment of rail transit line 2, which together construct the city's transportation skeleton. Particularly noteworthy is the recently completed Huayuanqiao Station, which sits under the main segment of the West Third Ring Road's Huayuanqiao Bridge and reaches a total length of 1,629.37 meters. The station not only has a unique form, but also an exceedingly high level of craftsmanship. However, like with any large-scale initiatives, this one also confronts significant hazards. As shown in Figure 1. Safety Risk Assessment and Control Process for Railway Tunnel Crossing Existing Bridges .The major danger is that the mainline and ramps A, B, C and E of this segment need to cross the existing Line 2. The building process and safety management standards for this sort of crossing are exceedingly high. Specifically, the left and right lanes of the mainline as well as Ramps A, B and C are elevated, producing an angle of nearly 75 °with the current Line 2, which obviously increases the difficulties of construction. Ramp E, as an underground route, has an extraordinarily intricate relationship with the elevated segment of the rail system. In terms of foundation construction, the minimum lateral distance from Ramp A to the existing Line 2 was 9.64 meters, the minimum lateral distance from Ramp B to the existing Line 2 was 3.02 meters, the minimum horizontal distance between Ramp C and the pile foundation of the existing Line 2 was 4.36 meters, and the minimum horizontal spacing between Ramp E and the bearing platform of the existing Railway Transit Line 2 was only 2.43 meters. Similarly, the minimum horizontal distance between the pile foundation of the left lane of the road section and the pile foundation of the existing Line 2 is 5.0 meters, and the minimum horizontal distance between the pile foundation of the right lane of the main line and the pile foundation of the existing Line 2 is 5.22 meters.

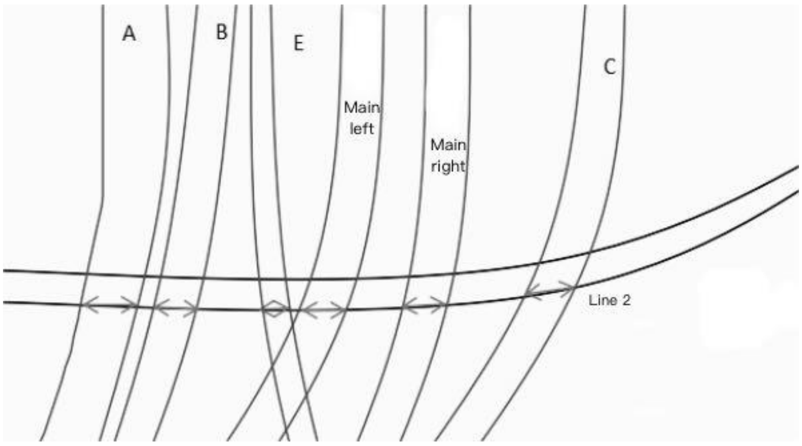

Figure 2: Plan picture of risk points in relation to each other

3.3 Risk point characterization

Two main lines and its linked Ramps A, B and C will intersect the current Rail Transit Line 2. The minimum lateral unobstructed distance between the pile foundation of the new roadway and the pile foundation of the existing Railway Line 2 reaches 2.43 meters. Considering the limited impact on the surrounding environment, the project aims to employ hand-dug piles as foundations for the highway bridge foundations. Since the elevation of the bottom of the pile foundations of the track structure is set outside the transfer range of the stiffness angle of the pile foundations of the highway abutments, this can effectively prevent the additional load from adversely affecting the track structure. Ramp E of the project is a highway underpass tunnel, and only the nodes of the line protection and control area will be closed during the construction period. For this crossing, we will use open cut excavation with an excavation width of 12.6 meters and a depth of 11 meters. In order to assure the stability of the pit, this project is proposed to use a pile-slab composite enclosure structure, i.e., two steel pipe supports, each 5 meters wide, will be erected on the interior. The minimum net horizontal gap between the enclosing piles of the crossover bridge and the ceiling of the existing Railway Transit Line 2 is 3.17 m. In the existing Railway Transit Line 2, the minimum horizontal space between the enclosing piles of the crossing bridge and the ceiling of the existing Railway Transit Line 2 is 3.17 m. During the deep foundation construction, the foundation soil on the piling side of the railroad bridge will be unloaded, which may cause additional deformation to the existing line. Additional computations and rigorous verification of the actual magnitude of this effect are consequently required.

4. Finite Element Modeling

In order to assure the quality and reliability of the calculation results, this project proposes to employ Midas GTS NX software to construct a 2D finite element model based on the stratigraphy and structure, and combine it with enhanced numerical simulation [7]. The fundamental purpose of the project is to completely examine the interaction between the entry and exit section lines and the entrance/exit ramps in order to provide scientific and acceptable guidelines for engineering practice. In the modeling procedure, St. Venant's principle was followed and the scale of the model was carefully determined to assure the correctness of the model. For the surrounding rock, its plastic deformation characteristics were addressed in depth, and numerical modeling was carried out based on the Moore-Culombe criterion [8]. For structures such as bridge piers, bearing platforms, piling foundations and roadway decks, they are believed to have elastic qualities and a linear primary model is employed to describe their mechanical behavior. In setting the model boundary conditions, transverse restrictions were put on the left and right directions of the model, and a novel structural system was innovatively developed with longitudinal constraints. Such a setup makes the model more capable of imitating the constraints in the actual project, hence closer to the actual situation. From the loading point of view, the major loads on the bridge abutment are the self-weight of the bridge, constant loads such as road surface and live loads such as automotive. In order to simplify the computation, these loads are simplified into vertical homogenous loads according to the design value, and the influence of the pier superstructure is ignored. This strategy not only simplifies the model, but also better portrays the link between the ramp and the viaduct. In addition, the relationship between the inlet ramp and the existing viaduct is also investigated in depth. Compared with the planar model, the 3D model can reflect the spatial distribution and force condition of the structure more accurately. Meanwhile, a new calculation approach is proposed by combining the plastic deformation of the surrounding rock and the elastic working performance of the structure with St. Venant's concept. In order to ensure the comparability between the 2D and 3D models, it is ensured that the parameters such as boundary conditions and load settings are similar in both models during the computation process. By combining planar and 3D numerical simulations, a comprehensive and in-depth examination of the interaction between the entry and exit section lines and the entrance/exit ramps is carried out.

5. Calculation results

5.1 Control standards

When conducting deformation assessment of rail transit structures and expressway bridges, certain control criteria need to be followed in order to assure the safety and stability of the structures. These requirements are based on applicable engineering specifications and experience to ensure that the deformation of bridges and rails under typical use conditions will not exceed the permitted range. For the current rail transit line 2, the deformation control criteria of the bridge structure essentially include the differential settlement of the bridge abutment, the horizontal displacement of the top of the bridge abutment in the direction of the bridge and the direction of the cross bridge. Specifically, the differential settlement of bridge abutment shall not exceed 10mm, which is to assure the overall stability of the bridge. The horizontal displacement of the top of the bridge abutment pier in the direction of the crossing bridge and the direction of the transverse bridge should also not exceed 10mm correspondingly, which helps to maintain the straightness of the bridge and the smoothness of the track. In addition to the bridge structure, the smoothness of the track is also an important part of the assessment. Under the "regular maintenance" condition, the allowed height and rail deviation of the track shall be controlled within 6mm. This serves to ensure train stability and passenger comfort during transit. For highway bridges, the control standards differ depending to their structural kinds. For continuous girder bridges, the absolute settlement should not exceed 10mm, differential settlement should not exceed 5mm, the inclination of the bridge should not exceed 1/1000, and the horizontal displacement should not exceed 5mm. These standards aim to ensure the overall stability and load carrying capacity of continuous girder bridges. For simple girder bridges, the control standards are relatively loose due to their structural properties. Absolute settlement should not exceed 20mm, differential settlement should not exceed 10mm, inclination of the bridge should not exceed 2/1000, and horizontal displacement should not exceed 10mm. These standards are designed to ensure the safety and durability of simply girder bridges under normal conditions of use.

5.2 Two-dimensional finite element calculations

(1) Detailed investigation of the initial stress field of the site strata. This includes the distribution

of the strata, the physical properties of the strata (e.g., modulus of elasticity, Poisson's ratio, etc.), and the initial stress state (e.g., vertical and horizontal stress). By precisely characterizing the initial state site stratum stress field, we can provide an acceptable starting point for further simulations;

(2) Introduce the railroad bridge structure and its comparable load into the simulation. As shown in Figure 3. Two-dimensional finite element numerical modeling of danger points .The estimate of equivalent load needs to be based on the bridge structure, traffic flow, vehicle type and other criteria in the actual project. At the same time, in order to assure the correctness of the simulation, it is required to zero the displacement value created by the bridge structure and its load, so that the displacement changes in the succeeding steps can truly reflect the actual situation in the construction process;

(3) The construction process of perimeter piles for road underpasses will be simulated. This comprises the arrangement of the perimeter piles, the determination of parameters such as pile diameter, pile length, and pile spacing, as well as the analysis of the influence of the perimeter piles on the ground stress field and displacement field. Through this step of simulation, we can forecast the stability and safety of the perimeter piles during the construction process;

(4) Construction technicians simulates the process of step-by-step excavation via the foundation pit, and apply the corresponding internal support in each excavation stage. The layout and selection of internal support need to be evaluated according to the ground conditions, excavation depth, building conditions and other considerations. Through step-by-step excavation and application of internal support, we can simulate the changes of stress and displacement fields during the excavation process of the foundation pit, so as to evaluate the stability of the foundation pit;

(5) Construction technicians simulates the step-by-step procedure of placing structural bedding, underpass structures and upper backfill. This comprises the selection of bedding materials, the determination of bedding thickness, the building order of the underpass structure and the selection of backfill materials. At the same time, as the construction proceeds, we need to gradually remove the matching place of the support. Through this simulation process, we can analyze the stability and deformation of the structure after the building is completed, offering direction and reference for the actual construction.

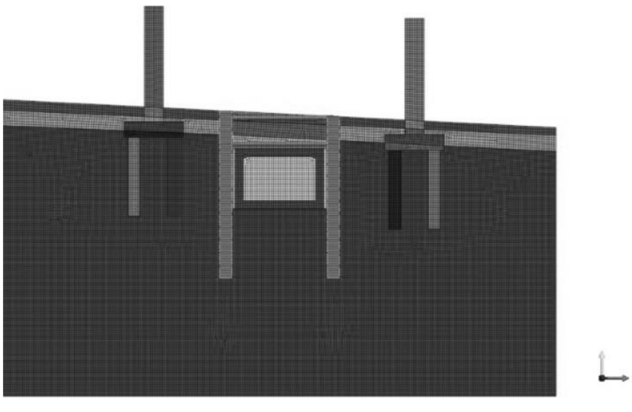

Figure 3: Two-dimensional finite element numerical modeling of danger points

After fine 2D finite element calculations, the maximum horizontal displacement of the top of the railroad bridge piers during the entire construction process was only 3.28mm, which is much lower than the current specification of 10mm, fully proving that the bridge has excellent stability in the horizontal direction. In addition, the analytical findings also show that the maximum settlement of the bridge is only 1.07mm, which is also significantly lower than the standard of 10mm, further demonstrating that the bridge also works effectively in the vertical direction. In terms of the comfort of train operation, the analysis shows that the track surface unevenness experienced by the train is just 1.22mm, which accounts for only 1.54% of the static rail rate and is substantially lower than the design specification of 6mm. In addition, although the bridge's height unevenness value of 2.79mm is significantly greater than the rail surface unevenness, it is still far from the 6mm standard, accounting for only 1.98% of the static height difference. These analysis results suggest that the scheme can effectively preserve the geometry of the line and has no substantial effect on the smoothness of train operation.

5.3 Three-dimensional finite element calculation

(1) As above (1);
(2) As above (2);
(3) As above (2);
(4) In the design and study of railroad bridge constructions, the road equivalent load on the abutment faces is a significant concern. Road equivalent load refers to the comprehensive effect of various loads borne by the bridge in the course of use. As shown in Figure 4. 3D Finite Element Numerical Modeling of Risk Points. Through three-dimensional finite element calculation, the road equivalent load can be applied on the abutment face and its influence on the bridge structure may be simulated. This helps to assess the load carrying capability and service life of the bridge structure and offers a basis for later structural optimization.

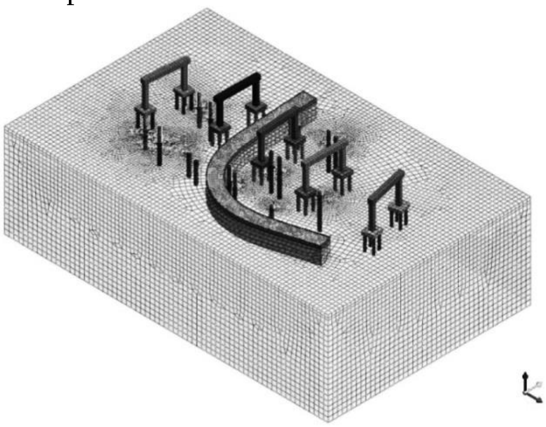

Figure 4: 3D Finite Element Numerical Modeling of Risk Points

After three-dimensional finite element calculations, the maximum horizontal displacement of the top of the pier of the railroad bridge during the entire construction process is only 1.48 mm, which is substantially lower than the present specification of 10 mm. In terms of the comfort of the train operation, following analysis, we found that the track surface irregularity experienced by the train is only 0.72 mm, which accounts for 1.64% of the static rail rate, and is substantially lower than the design standard of 6 mm. 6mm design specification. This shows that the implementation of the road project will not produce too much influence on the bridge, therefore achieving the requirements of the design index. By assessing the project example paired with 2D finite element analysis, the project is within the safety range.

6. Control program

6.1 Bridge Strengthening and Structural Evaluation

Before the highway crossing, a full structural assessment and reinforcement of the existing train bridges is first carried out. Through a professional bridge inspection organization, the bridge's bearing capacity, deformation, crack distribution, etc. are studied in detail, and appropriate reinforcement measures are formulated based on the results. Reinforcement procedures may include the addition of support structures, strengthening of bridge piers, and restoration of bridge deck pavement layers. evaluation process ensures the safety and stability of the bridge during and after the highway crossing construction [9].

6.2 Traffic organization and management during construction

Builder implements stringent traffic organization and management procedures during the road crossing construction process. The traffic upstream and downstream of the railroad bridge will be redirected, obvious construction warning signs will be set up, heavy trucks will be limited, and special people will be arranged to guide the traffic. At the same time, according to the construction progress and weather circumstances, prompt modification of traffic control measures to ensure the normal usage and safety of the rail transit bridge during construction.

6.3 Construction Monitoring and Emergency Response

During the construction of the highway crossing, 24-hour uninterrupted construction monitoring is undertaken. The deformation, stress and other essential characteristics of the bridge are monitored in real time by placing monitoring cameras, displacement sensors, stress-strain monitoring equipment, etc. [10]. Once abnormal conditions are found, the emergency response mechanism is immediately engaged, and professional professionals are mobilized to carry out on-site disposal to ensure the safety of the bridge.

6.4 Adoption of advanced construction technology and equipment

In the process of highway crossing construction, innovative construction technology and equipment, such as shield method, pipe jacking method and other non-excavation technology, are actively used to reduce the impact on existing train bridges. At the same time, high-precision construction equipment, such as laser rangefinders and intelligent excavators, are employed to improve construction accuracy and efficiency and reduce construction risks.

6.5 Establishment of long-term monitoring and maintenance mechanisms

Establish a long-term monitoring and maintenance method after the road crossing construction is done. Regular structural inspections and safety assessments of railroad bridges are carried out to identify and deal with possible safety issues in a timely way. At the same time, a detailed emergency plan is established, and frequent drills are performed to increase the ability to respond to emergencies.

7. Conclusion

A rigorous safety examination of the principal entrances and exits of the roadway and its crossing of the existing line led to the conclusion that the E-ramp would have a substantial impact on the existing line. In order to more accurately assess this impact, 2D and 3D finite element modeling of key sections was performed using MidasGTSNX software, a methodology designed to quantify the additional displacements and offsets generated by the construction of the new works on the existing line in order to ensure the safety of the line during operation. After in-depth calculations, we decided that the risk to the current line from this new construction is generally controllable, which gives solid support for ensuring the safe operation of the transportation line.

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