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Deformation Analysis of the Cable Reinforcement System of Large Section Box Culvert Roof Entry and Downward Penetration

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Abstract: For the underpass railway large-section box culvert jacking and pipe jacking project, the key to ensuring the normal operation of the existing railway is to maintain the smoothness and stability of the track, railway settlement monitoring and line reinforcement, and box culvert and pipe culvert attitude control are the keys to solving this problem. Taking the Beijing-Harbin high-speed railway project under a city road in Beijing as an example, the law of railway track settlement during the implementation of box culvert jacking was analyzed according to real-time monitoring data. The monitoring results show that accelerating the pouring of the bedding and grouting and strengthening the railway subgrade on both sides of the foundation pit can effectively control the settlement of the railway subgrade and reduce the impact of subsequent construction on the railway, and the line renovation and secondary grouting reinforcement can effectively improve the smoothness of the railway. Combined with the comparative analysis of numerical simulation results, the necessity of line refurbishment and rail fastening combination reinforcement in actual construction is verified.

With the advancement of railway and high-speed rail construction, later highways often need to cross existing cable railways, resulting in many level crossings between the two[1]. Proper selection of the intersection form of highway and railway intersection is very important for traffic safety and smoothness, and the jack-frame bridge has gradually been popularized and applied due to its advantages of low cost and low environmental impact on the surrounding environment.[2] During the construction of frame bridge jacking, each key stage of construction (such as excavation of work pits, line reinforcement, bridge body jacking, etc.) will affect the track smoothness of the operating railway. How to reduce the traffic interference to existing wires, make the frame bridge quickly and accurately in place without affecting the normal operation of the railway, and how to limit the displacement of railway subgrade and track during construction and ensure soil stability are the key issues and core objectives in construction control.[3]

In the process of jacking construction, the roadbed soil, the bridge body and the existing cable influence each other, Milligan[4], Attewell[5], Tao Lianjin [6], Fang Yingguang[7], Zhao Ning[8], Wang Feiqiu [9] has been extensively studied. Tao Lianjin summarized the construction method of underwear construction and the influence law of deformation internal force. Fang Yingguang analyzed and studied the mechanism and characteristics of the surrounding soil disturbance deformation caused by large-scale pipe jacking construction. Wang Feiqiu used ABAQUS finite element software to analyze the variation law of soil stress during the jacking process of the underpass box culvert. Lin Qingtao, Lu Dechun et al. [10] took the actual engineering as the background, designed the test model, carried out the model test of the shield under the pebble formation through the existing horseshoe-shaped tunnel and rectangular tunnel, monitored the surface settlement of the test model, as well as the strain of the existing tunnel and the earth pressure acting on it, and explained the reasons for the collapse failure of the pebble soil around the existing tunnel by using the change of the shield discharge amount during the shield underpenetration. Xiao Shiguo et al. [11-12] used the method of theoretical analysis to discuss the vertical deformation and bearing effect of the pipe curtain at the top of the box culvert. Acharya [13-14], Abdel-karim [15], Bennett [16] and others have conducted a lot of research on the structural response and load distribution of box culverts, which provides guidance and basis for the structural design and jacking implementation of box culverts in the future. Zhu Hehua et al. [17] analyzed the risks of tunnel construction by pipe curtain method and put forward corresponding preventive measures. Li Qing et al. [18] analyzed the deformation monitoring data and control measures of the high-speed rail piers in the key construction stages of the high-speed railway under the frame bridge (excavation of the working pit, jacking frame structure, excavation of the north side approach road), and proposed a pressure jacking frame scheme based on the concept of "unload-load balance". Yang Yanjun[19] dynamically monitored the pavement settlement, box culvert, and back wall stress and deformation during the construction of the taxiway under the box culvert through the airport. The project monitoring data was collected and the information feedback was provided to the construction process, and the engineering examples verified the reliability of the information-based construction.

A lot of research has been done on the theory of inlet soil disturbance, the response of box culvert structure and the influence of jacking construction on the deformation of adjacent buildings (structures). However, there are few studies on railway deformation and control methods caused by the jack-fed box culvert of the underpass railway. Jia Peng [20] used the three-dimensional numerical simulation method to analyze and compare the changes of key parameters such as surface settlement and internal forces of the structural system during the construction of the underpass expressway from the perspective of the transformation of the structural system in the whole excavation process and the spatial effect of the construction process. Ramirez Chasco [21] and Wang H [22] et al. conducted case studies of the railway and expressway under the box culvert, analyzed the reasons for the large deformation and proposed control measures. This paper takes the project of a Beijing-Harbin railway node under a city road in Beijing as an example, briefly introduces the construction process of key nodes of the large-section box culvert, small box culvert and pipe jacking project at the same time through the railway jacking construction, and analyzes the settlement law according to the measured data, and verifies the feasibility of deformation control measures.

1. Engineering background

1.1 Project overview

The existing Beijing-Harbin railway is a dual-line electrified railway for passenger and cargo use, with a maximum operating speed of 200km/h. The underpass project is located between Tongzhou and Yanjiao, the railway embankment at the intersection is 2.5m above the ground, and the lines at the bridge site are all in a straight section, with a line spacing of 4.5m. The electrified railway is 60kg/m steel rail, seamless line, reinforced concrete pillows. The construction content of the project includes the main body of the road frame (7m+13m+13m+7m), the comprehensive pipe culvert (4.9m), and the sewage protection culvert (inner diameter 1.55m). Among them, the net height of the frame main structure is 7.7m, the total length of the main body is 24.7m, the top distance is 36.4m, and the angle of intersection with the existing Beijing-Harbin left line is θ=96.2°; The net height of the comprehensive pipe culvert structure is 5.6m, the total length of the main body is 24.7m, the top distance is 33.4m, and the angle of intersection with the existing Beijing-Harbin left line is θ=90.0°; The pipe jacking adopts 1550Ti-S-T12 type with a length of 99.64m, and the angle between the center of the jacking pipe and the existing Beijing-Harbin left line is θ=90.0°. The overhead plane intersection relationship is shown in Figure 1. The lower penetration is mainly filled soil, silt sand, silty clay, silty clay, fine sand, and the bearing capacity is 120~300kPa. The soil layer parameters are shown in figure 1.

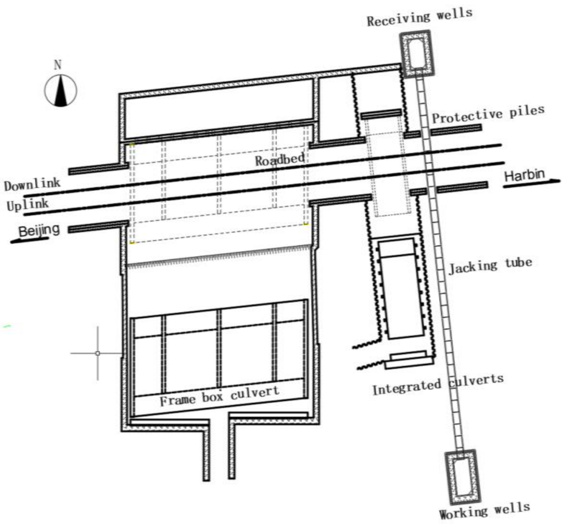

Figure 1: Schematic diagram of the jacking plane

1.2 Geological conditions

Table 1: Geological soil formation parameters of the lower cross-section

The name of the soil layer	Thickness /m	Compression modulus /MPa	Severe /kN m^3	Cohesion /kPa	Angle of frictionφ/°
Miscellaneous fill soil	2.1	5	16	8	10
Silt	12.6	Dense, saturated			
Silty clay	8.8	5.9	19.8	26.8	15.2
Silt earth	2.2	9.5	20.2	23.2	17.2
Sand	9.2	Dense, saturated			

The lower penetration is mainly filled soil, silt sand, silty clay, silty clay, fine sand, and the bearing capacity is 120~300kPa. The groundwater level is buried at a depth of 6.9~7.1m, which is located above the bottom of the foundation pit. The terrain of this section is flat, the water level is high, and the foundation pit support and precipitation measures should be strengthened when excavating the foundation pit. The soil layer parameters are shown in Table 1.

2. Both wired settlement change law and control measures

According to the national specification of "Technical Regulations for Construction Safety Monitoring of Adjacent Railway Business Lines" (TB 10314-2021), the scope of the impact area of this project is calculated. The main influence area range: 86.09m, the general influence area range on both sides: 6.23m, and the slightly affected area on both sides: 9.86m. In the main affected area of construction, the maximum allowable spacing of 5m is taken to arrange the monitoring points, and there are 19 measurement points on one side of the rail, and the range and distribution location of the affected area are shown in Figure 2.

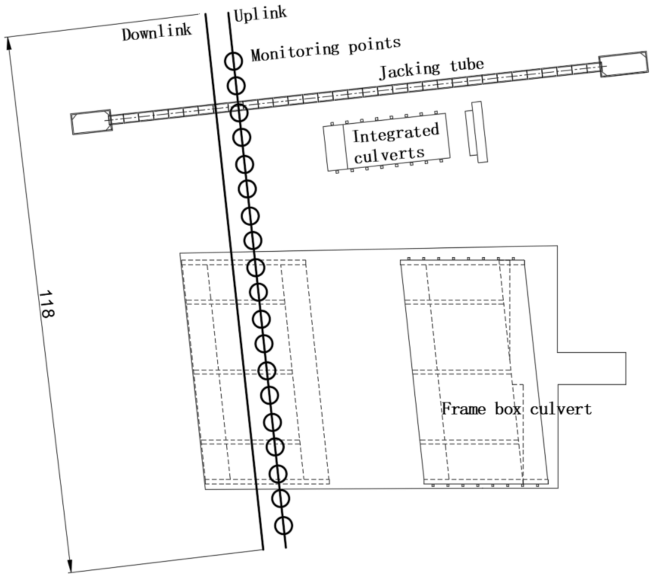

Figure 2: Point layout drawing

Based on the position relationship between the frame bridge and the Beijing-Harbin railway line, two key stages were selected for analysis, focusing on the cumulative change of track settlement of the Beijing-Harbin railway. The first stage is the middle position of the upper and lower lines of the frame bridge, at which time the line reinforcement and partial ballast cleaning have been completed. The second stage is after the top of the bridge in the frame is in place, before the wall backfilling and secondary grouting reinforcement.

2.1 Deformation monitoring during the excavation phase of the working pit

With the excavation of the foundation pit, the settlement curve of the Beijing-Harbin railway on the north side of the foundation pit is shown in Figure 3. During the excavation of the jacking work pit, the subgrade of the Beijing-Harbin railway was settled, and the maximum settlement value was 7.4mm, which occurred at the No. 12 monitoring point between the frame bridge working pit and the pipe culvert working pit. With the increase of excavation depth, the settlement value of each monitoring point generally showed an increasing trend, and the differential settlement at both ends of the railway within the monitoring range gradually increased, and the maximum differential settlement occurred after the completion of the fourth layer excavation, which was 8.1 mm.

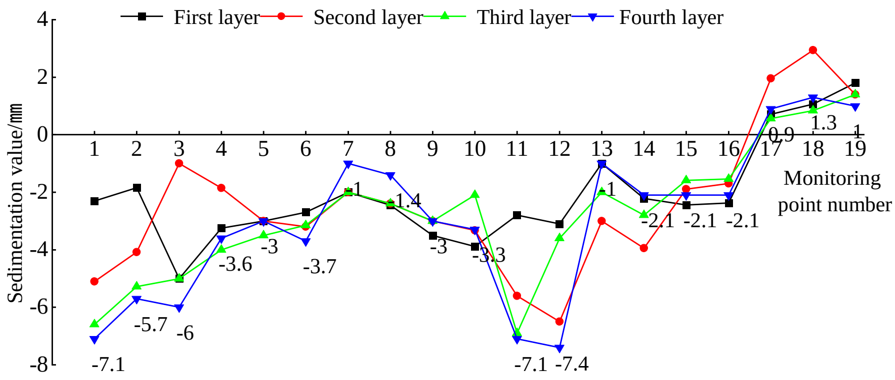

Figure 3: Settlement change diagram of excavation of foundation pit

2.2 Deformation control measures during the excavation stage of the working pit

After the excavation of the working pit and the precipitation of the foundation pit, the settlement value of the railway subgrade was greater than expected, and the method of accelerating the bedding pouring was used to "press" the quicksand and reinforce the railway subgrade on both sides of the foundation pit for the first time, which can control the settlement of the surface and subgrade and reduce the impact of subsequent construction on the railway [23]. The grouting curing depth starts from 2m below the shoulder to 1.5m (frame bridge) and 3.3m (integrated culvert) below the bottom of the floor. After the completion of grouting reinforcement, the settlement state of Beijing-Harbin railway is shown in Figure 4.

After grouting reinforcement, the settlement state of Beijing-Harbin Railway was alleviated, the maximum settlement value was reduced to 2.6mm, especially the two ends of the affected zone and the middle position were raised, the left end was raised by 5.6mm, the middle was raised by 4.8mm, and the differential settlement at both ends was reduced to 1.7mm.

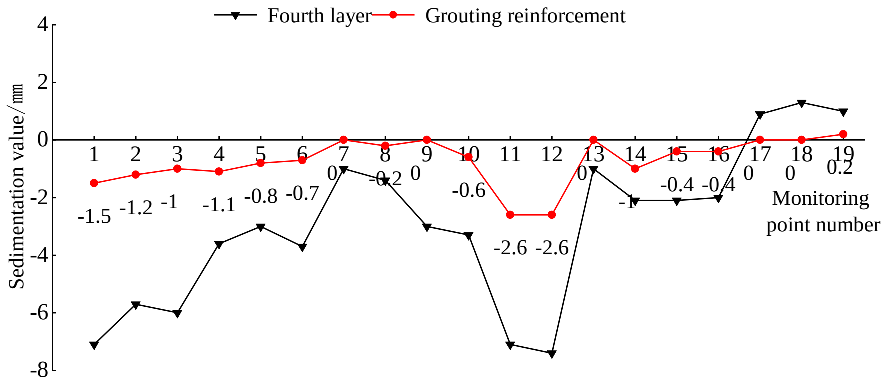

Figure 4: Grouting reinforcement settlement change diagram

The self-weight of the frame middle bridge is 6435t, when the pouring of the frame bridge and pipe culvert is completed, the foundation pit converts the compressive load of 48kPa, and the railway subgrade further undergoes a small lift, the maximum settlement value is 2.1mm, and the maximum difference settlement at both ends is 1.5mm.

2.3 Deformation monitoring in the first stage of jacking

According to the actual measurement on site, after the completion of the first stage of jacking, the maximum settlement value of the Beijing-Harbin railway was 92.8mm, and the maximum value occurred at the No. 9 monitoring point above the frame middle bridge, an increase of 92.8mm compared with the previous stage. The increase in differential settlement at both ends of the railway was not obvious, but the differential settlement at the middle points increased significantly, and the maximum differential settlement was 39 mm, which occurred at monitoring points 12 and 13. The deformation curve is shown in Figure 5.

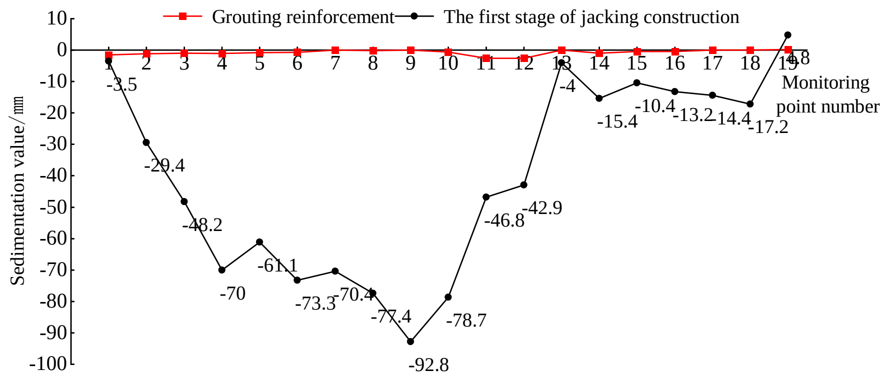

Figure 5: Settlement change diagram of the first stage of jacking

2.4 Deformation control measures for the first stage of jacking

The top distance of the first stage of jacking is large, and a large amount of soil on the railway subgrade is unloaded, resulting in a large sinking of the Beijing-Harbin railway. In order to avoid affecting the normal operation of the train, the site suspended the jacking construction, and the line was renovated for the first time, the specific method was to use small jacks, sleeper piers, wooden wedges to lift the rails and pad them.

After the completion of the line renovation, the maximum settlement value of 11.4mm occurred at the No. 14 monitoring point, and the settlement of the No. 9 monitoring point of the railway increased from 92.8mm to 4.6mm. The differential settlement change at both ends was not obvious, and the differential settlement of the middle points was greatly reduced, and the maximum differential settlement occurred at the monitoring points of No. 13 and No. 14, which was 12mm, which was 27mm lower than the previous stage. The sedimentation curve is shown in Figure 6.

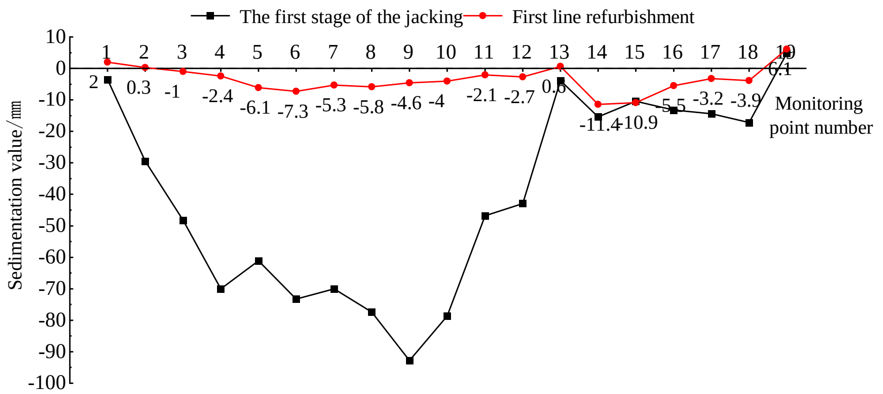

Figure 6: Settlement change diagram of the first line renovation

2.5 Deformation monitoring in the second stage of jacking

The second stage of the jacking was completed, and the Beijing-Harbin railway once again experienced a large settlement, with a maximum settlement value of 101.2mm of the No. 9 monitoring point, an increase of 96.6mm compared with the completion of the first renovation. The difference settlement change at both ends of the railway is still not obvious, and the maximum differential settlement at the middle points is 59.6mm, which still occurs at the 12th and 13th monitoring points. The deformation curve is shown in Figure 7.

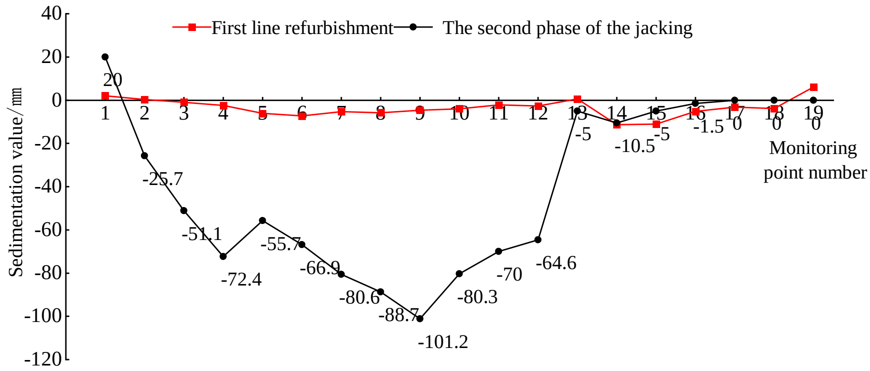

Figure 7: Settlement change diagram of the second stage of jacking

2.6 Ejection stage deformation control measures

After the frame jacking is in place, the roadbed soil within the jacking area is completely unloaded, and the railway load and the dynamic load during driving are all borne by the reinforcement system and transmitted to the frame bridge, and the stability of the reinforcement system determines the smoothness of the railway and the safety of driving. After the second line renovation, the bridge body was backfilled with graded gravel, and the second grouting was carried out within 2m on both sides of the back of the wall. Ensure the integrity of the roadbed on both sides of the frame to prevent the train from sinking on both sides of the roadbed caused by the vibration of crushing.

After the completion of the second line renovation and secondary grouting reinforcement, the maximum deformation is 2.2mm and the maximum difference settlement is 4.1mm, which is lower than the control value required by the specification. The settlement change curve after the completion of the control measures is shown in Figure 8.

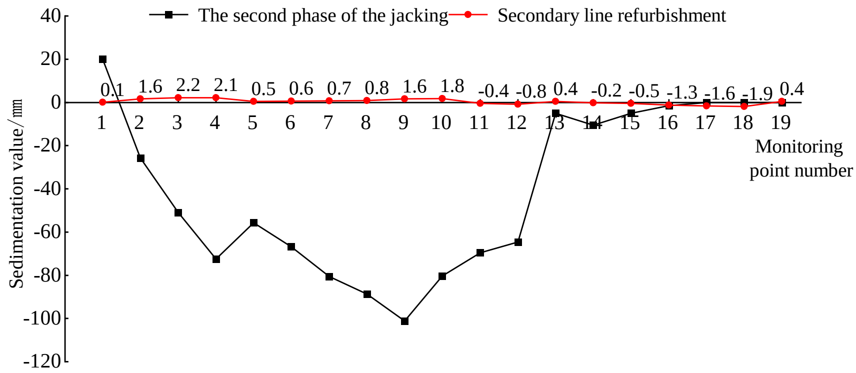

Figure 8: Settlement change diagram of secondary grouting and secondary refurbishment

One month after the completion of the project, the settlement deformation of the Beijing-Harbin railway tends to be stable, and the cumulative settlement value within the monitoring range does not exceed 1.8mm, which meets the requirements of the specification, and through the rail inspection

inspection, the track smoothness meets the operation requirements. During the whole construction process, through deformation monitoring and timely repair of the line, backfilling of gravel, grouting reinforcement and other measures, the development of railway uplift deformation was effectively controlled, and the deformation control effect was remarkable.

3. Finite element analysis of reinforcement system under train load

After the longitudinal beam reinforcement system is used to empty the line, the main bearing structure of the train load above the track is changed from the roadbed to the reinforcement system, so the deformation control of the reinforcement system is the key to maintaining the smoothness of the track during the jacking period, and the study of the deformation of the reinforcement system is particularly important. A BAQUS was used to analyze the finite element analysis of the deformation of the reinforcement system under train loading.

3.1 Basic assumptions

In order to reflect the deformation characteristics of the system as much as possible, and to ensure that the calculation is fully in line with the reality and facilitate the calculation, the calculation model makes the following basic assumptions:

(1) The line rail is reliably connected by fasteners and beams of the reinforcement system, and the beams are reliably connected by fasteners and longitudinal beams, which are considered rigid joints.

(2) The boundary condition of the truncated section of the longitudinal beam adopts a fixed end to constrain the displacement in three directions on both sides of the longitudinal beam section.

(3) Both ends of the beam are placed on the anti-migration pile, and the displacement of the pile top is ignored in the analysis. The two ends of the beam are hinged in a support mode, one side constrains the displacement in the X and Y directions and allows it to rotate in the Y-Z plane, and the other side restricts the displacement in three directions and allows it to rotate in the Y-Z plane.

3.2 Model parameters

The length of the longitudinal beam and track is 45.9m, the length of the beam is 25.5m, the actual spacing of the beam is 1.2m/0.6m space, and the modeling is uniformly taken 0.9m. The longitudinal beam adopts I40b I-beam, the cross beam adopts I45b I-beam, and the longitudinal beam, beam and track are established according to the actual cross-sectional size and are all simulated as elastomers. The material structure parameters are shown in Table 2:

Table 2: Material structure parameters

Name	Model	E(Pa)	v	ρ(t/m^3)
Track	60	2.1×10^{11}	0.3	7.83
Longitudinal beam	I40b	2.1×10^{11}	0.3	7.85
Crossbeam	I45b	2.1×10^{11}	0.3	7.85

3.3 Load application

During the jacking process, the speed limit of the lower section of the train runs at the speed, the Beijing-Harbin railway is a passenger and freight co-linear railway, and the vertical load of the track is selected according to the ZKH load pattern in the "Railway Train Load Pattern", and the four concentrated loads represent the axle load effect, wheelbase and adjacent wheelbase effect of the rolling stock, and the uniform load on both sides represents the linear meter weight effect of the vehicle. During construction, the speed limit of the train is 45km/h, and the load is evenly distributed on the two rails when loading, and the load distribution is shown in Figure 9.

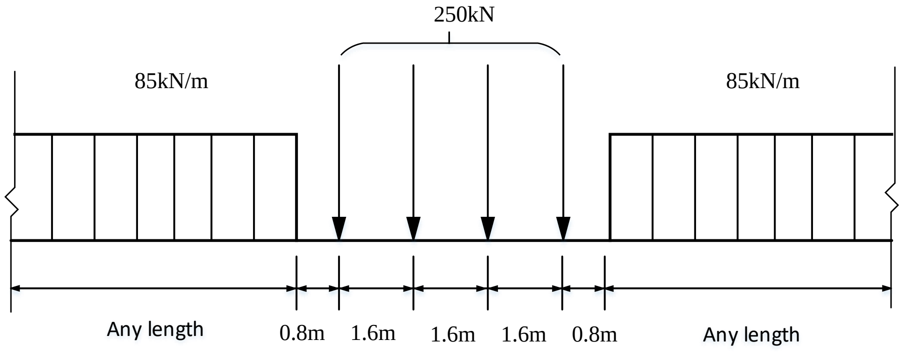

Figure 9: Load distribution diagram

3.4 The mechanical response of the track

When the train passes through the longitudinal beam reinforcement system, the train load first acts on the track, causing the settlement deformation of the track. Figure 10 shows the deformation of the track when the maximum vertical settlement displacement is generated on the track by the longitudinal beam reinforcement structure, and it can be seen from the figure that the maximum settlement of the track occurs in the middle part of the overhead reinforcement structure when the train passes, and the maximum settlement value is 101mm.

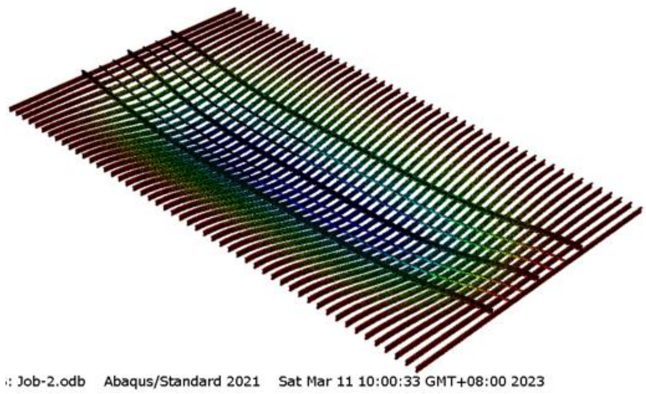

Figure 10: Schematic diagram of the displacement of the reinforcement system

According to the numerical analysis results, the track bending moment distribution map is plotted, and Figure 11 is the bending moment distribution diagram of the track when the train passes through the reinforcement system, the abscissa is the distance along the X direction, and the ordinate is the track bending moment value. It can be seen from the figure that due to the restraining effect of the longitudinal beam and the beam on the track, the track bending moment is distributed in an M shape along the track, and the middle track as a whole is shown as the lower part is pulled, and the two sides are shown as the upper tension. The maximum positive bending moment of the track occurs at 15m on both sides of the middle point, 9.8kNm and 9.9kNm, respectively, and the maximum negative bending moment value occurs at 10m distance to the left and right sections, 33.2kNm and 33.3kNm, respectively. During construction, the track and beam are rigidly connected with bolts and hoops, and attention should be paid to the working condition of the bolts of the overhead system.

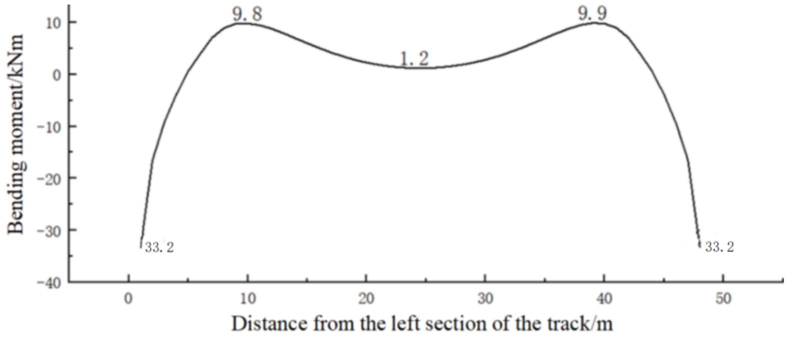

Figure 11: Distribution of orbital bending moments at the most unfavorable time

3.5 Comparative analysis of monitoring results

The deformation monitoring results of the track surface of the upward line of the track were extracted after the completion of the first stage of jacking, and the monitoring results showed that the maximum settlement value of the side rail surface of the upward line was 92.8mm. The numerical analysis results show that the maximum settlement value of the track surface when the train passes is 101mm. The results are similar, and the monitoring results of the settlement value in the middle of the reinforcement system are lower than the simulation results, and the results are compared in Figure 12. The main reasons for this are:

(1) With the jacking of box culvert and jacking pipe, the load of railway track and train gradually changes from the bearing of railway subgrade to the joint burden of subgrade and line reinforcement system, and then to be borne by the reinforcement system alone, and finally the line reinforcement and removal after the jacking is in place, and the load is finally borne by the frame middle bridge and the comprehensive pipe culvert. When the face of the jacking construction is excavated between the upper and lower rows, the dynamic load of the track and train is borne by the roadbed, the reinforcement system and the frame bridge. However, the mutual transformation of the force system during the jacking process makes the load transmission unstable, so the large deformation begins to occur in the middle of the jacking process, and the construction unit takes corresponding measures in time to repair the line and reinforcement system. The use of jacks and wooden pier wedges to raise the railway track elevation led to an upward trend in the monitoring data on 3 April.

(2) The modeling only considers the displacement limiting effect of longitudinal beams and beams on the track in the reinforcement system, and does not consider the role of 3-5-3 fasteners in the reinforcement system. In the actual construction, the rail fastener, the track and the longitudinal beam form an overall force system, and jointly bear the load of the train.

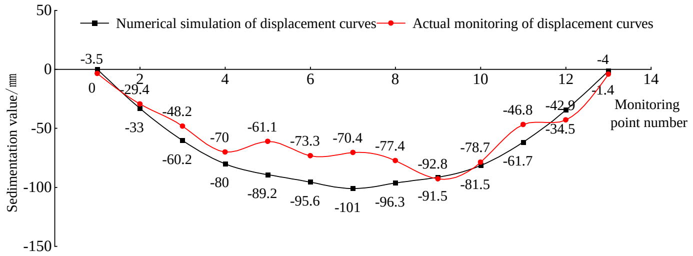

Figure 12: Numerical simulation and actual monitoring of deformation comparison char

4. Conclusion

Taking the Beijing-Harbin railway project under a city road in Beijing as an example, the law of railway track settlement change during the implementation of box culvert jacking was analyzed, and corresponding engineering treatment measures were proposed. The main conclusions are as follows:

1) Combined with the on-site measured data, methods such as accelerated cushion pouring, grouting reinforcement and timely repair of the line are adopted during construction, which can effectively limit the settlement deformation of the railway in each construction stage. When the excavation of the working pit is completed, the maximum settlement of the railway is 7.4mm, and the maximum difference settlement between the two ends of the railway within the monitoring range is 8.1mm; when the project is completed one month later, the settlement deformation of the Beijing-Harbin railway tends to be stable, and the cumulative settlement value within the monitoring range is stable within 1.8mm, which meets the requirements of the specification, and through the rail inspection inspection, the track smoothness meets the operational requirements, and the settlement control effect is obvious.

2) Based on the on-site monitoring data, the maximum settlement position of the railway track should be located directly above the largest section box culvert during the joint construction of the box culvert jacking and pipe jacking project, and the small box culvert jacking and pipe jacking project will generally not cause excessive deformation of the upper track, and the large section box culvert jacking construction may produce settlement beyond the early warning value or even beyond the control value during the entire jacking process, and the dangerous position should be reinforced and repaired in time during construction.

3) Through numerical analysis, it is calculated that the maximum settlement displacement of the track when the train passes occurs in the middle position of the overhead reinforcement structure; The track bending moment is distributed in an M shape along the track, and the overall performance of the track is that the middle lower part is pulled and the upper part of the two ends is pulled. The maximum positive bending moment of the track occurs 15m on both sides of the middle point when the train passes; The maximum settlement displacement of the beam when the train passes occurs in the middle of the beam in the middle of the longitudinal beam, the upper part of both ends of the beam is pulled, and the middle lower part is pulled, and the firmness of the connecting bolts of the beam and the longitudinal beam should be noted; The overall settlement deformation of the longitudinal beam is approximately parabolic, and the maximum vertical displacement occurs in the middle of the stringer. Combined with the comparative analysis of actual monitoring results, the necessity of line refurbishment and rail combination reinforcement in actual construction is verified.

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