Alignment Calculation Method of Double-Deck Frame Bridge Based on New Split Movable Scaffolding System

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Abstract. With the decrease of bridge site resources, double-deck frame bridges are more and more used in bridge construction. In order to solve the problem that the conventional movable scaffolding system is difficult to through the hole of the frame pier, a new type of split movable scaffolding system suitable for the double-deck frame bridge is developed in this paper based on the approach bridge of Maanshan Yangtze River Rail-cum-Road Bridge. A coupling analysis method of double-deck frame bridge structure-multi-leg movable scaffolding system based on iterative method is proposed, and the field preloading verification test is carried out. The results show that the new type of split movable scaffolding system with separated design and split support of flange formwork and bottom formwork can realize split through-hole and reset casting, which can effectively realize split through-hole of the frame pier and fast clamping casting, and provide a new idea for the construction of similar double-deck frame bridge. The test values of the preloading test are in good agreement with the simulated values, which indicates that the proposed iterative method can effectively simulate the coupling effect of double-deck frame bridge and multi-legged movable scaffolding system. The maximum deformation of the railway beam at the support leg of the movable scaffolding system is up to 21mm, which shows that the influence of the coupling effect of the structure and the formwork on the alignment of the upper highway beam cannot be ignored.

Keywords: New Split Movable Scaffolding System, Double-Deck Frame Bridge, Alignment Control, Coupling Effect, Multi-Leg Structure, Iterative Method.

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1 Introduction

At present, traffic engineering construction is advancing with unprecedented volume, speed and standard in China, which is increasingly prominent with the decreasing bridge resources. At the same time, it also puts forward higher requirements for the application and innovation of construction technology, specifications and equipment (Zhang et al. 2017). As a product of the development of modern bridges, double-deck bridges can not only make full and reasonable use of land, rivers and space, but also reduce infrastructure projects compared with single-deck bridges. They are gradually adopted in bridge construction and show an increasing trend year by year in China (Xu et al. 2022).

The movable scaffolding system has the advantages of unaffecting the traffic under the bridge, high quality of beam casting, saving labor and materials, fast construction speed, and safe operation. It is especially suitable for the cast-in-place construction of small and medium-span high-pier bridges with complex ground conditions such as canyons, tidal flats, and rivers (Dong et al. 2022). Some scholars are also committed to the transformation and upgrading of conventional movable scaffolding system for special structures and application scenarios, so that its scope of application is still expanding. Pacheco et al. (2009; 2011; 2021) introduced organic prestressing technology into the movable scaffolding system, increased its economic span from 60m to 90m, and successfully applied it to the Ankara-Sivas viaduct in Turkey and the Cabriel bridge in Spain. Wang et al. (2022) proposed a double-span parallel box girder movable scaffolding system, which avoids the problem that it is difficult to open and move in the double-span box girder with small space for the conventional single-span movable scaffolding system. Zhu (2017) introduced the prefabricated assembly technology of rebar parts on the basis of double-span parallel box girder movable scaffolding system to realize the synchronous operation of rebar production and concrete casting and curing, which greatly shortened the construction period of beam. Zhong et al. (2018) proposed the ground movable scaffolding system, which solves the problem that it is difficult to adapt to the ultra-wide beam surface and the low efficiency of the through-hole for the conventional movable scaffolding system.

Due to the limited space of the double-deck frame bridge, for the upward movable scaffolding system, it faces the problems of opening formwork, closing formwork and passing through the hole, and for the downward movable scaffolding system, the legs cannot take root on the pier and it is difficult to be used for the construction of the double-deck frame bridge (Liu et al. 2009; Däbritz, 2009; Kwak and Son 2006; Díaz de Terán et al. 2016). Therefore, based on the analysis of the structural characteristics of the double-deck frame bridge, this paper proposes a new type of split movable scaffolding system with separated design and split support of flange formwork and bottom formwork. The coupling effect of the complex system of the lower railway beam-multi-leg formwork-upper highway beam is mainly studied, and the alignment control method of the upper highway beam is proposed. The research results are intended to provide reference for similar engineering construction.

2 Engineering background

The Maanshan Yangtze River Rail-cum-Road Bridge is located about 2.3km upstream of the built Maanshan Yangtze River Highway Bridge. It is a rail-cum-road bridge integrating urban expressway, high-speed railway and intercity railway. The lower layer of the bridge is the double-track Chaoma high-speed railway with design speed of 250km/h and the double-track reserved intercity railway with design speed of 200km/h. The upper layer is a double-track six-lane urban expressway with design speed of 80km/h. Among them, double prestressed concrete continuous box girder with the span of 3×42m+36×40.7m+(34+48+34)m+72×40.7m is adopted in the upper highway, and double prestressed concrete simply supported and continuous box girder with the same span is adopted in the lower railway of Jiangxinzhou approach bridge. The box girders adopt one-way single-chamber equal section, and the concrete grade is C50. The substructures are frame piers as shown in Figure 1.

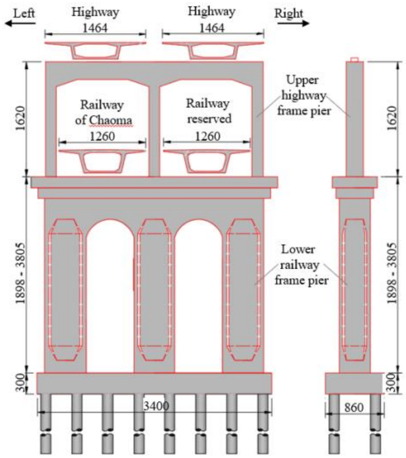

Fig. 1. Typical section of Jiangxinzhou approach bridge of the Maanshan Yangtze River Rail-cum-Road Bridge (unit: cm).

3 Design of new-type split movable scaffolding system

Aiming at the problem that it is difficult for the conventional upward and downward movable scaffolding system to cross the frame pier, a new split movable scaffolding system suitable for the double-deck frame bridge is proposed for the first time on the basis of making full use of the existing lower railway bridge deck. The formwork support system for upper highway box girder is divided into two parts to realize the separation design and split support of the flange formwork and the bottom formwork. The flange formwork is supported on the top of the frame pier, and the bottom formwork is supported on the existing lower railway bridge deck.

The flange formwork is composed of small main beams, front and rear guide beams, outer formworks and upper longitudinal moving mechanism. The bottom formwork is composed of big main beams, cross beam, supporting legs, lifting columns and lower longitudinal moving mechanism. Under the casting condition as shown in Fig.2 (a), in order to optimize the force of the leg and reduce the influence on the lower railway girder, the multi-leg cooperative support design is adopted, and a total of 5 pairs of legs are set. Under the hole passing condition as shown in Fig.2 (b), the connecting bolt between the bottom frame and the flange frame is removed, and the legs of the bottom frame is folded through the hydraulic system. The bottom frame is converted from the legs support to the lifting columns support, and descends along the lifting columns until the longitudinal sliding seat and the roller box fall on the longitudinal rails set at the railway bridge deck. Finally, the flange frame and the bottom frame pass the hole independently through the upper and lower longitudinal moving mechanisms, respectively.

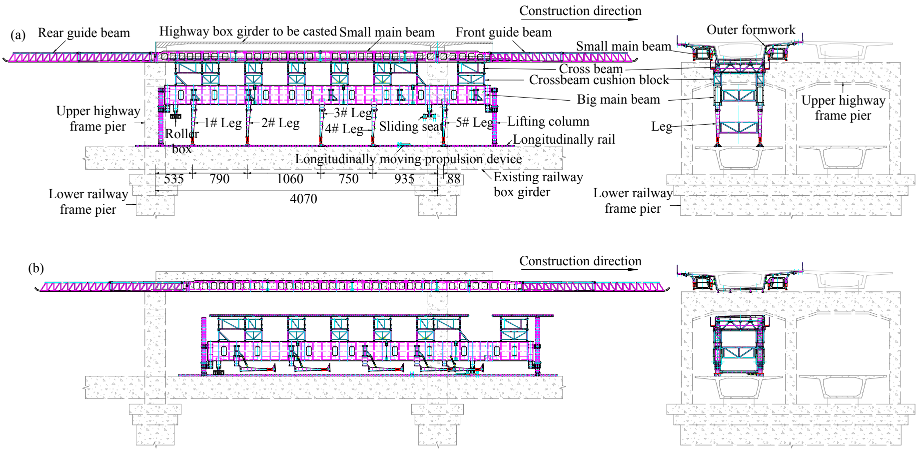

Fig. 2. Design of the new split movable scaffolding system (unit: cm): (a) casting condition; (b) hole passing condition.

A total of 4 sets of the new split movable scaffolding system were put into the Jiangxinzhou approach bridge, with 2 sets of left and right frames respectively. The left and right frames were staggered for two-span synchronous construction (Fig. 3).

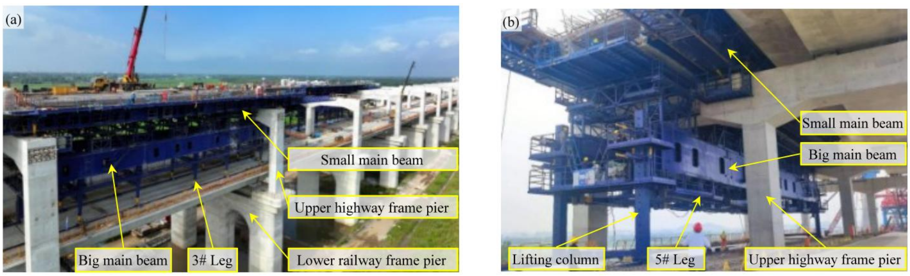

Fig. 3. Pictures of the new split movable scaffolding system during construction: (a) casting condition; (b) hole passing condition.

4 Alignment control technology of upper highway box girder considering coupling effect

4.1 Establishment of finite element model

The simulation of the new split movable scaffolding system and the lower railway box girder is carried out by using the ANSYS platform. Among them, the box structure such as big main beam, small main beam, leg, lifting column and outer formwork are simulated by the shell element of SHELL 181, and the nose beam, the cross beam and the cushion block of cross beam are simulated by the 3D beam element of BEAM 189. The lower railway box girder is simulated by the solid element of SOLID 65, and the prestressed reinforcement is established by the solid force reinforcement method (Zhang et al. 2017; He et al. 2015). The finite element model is shown in Figure 4. The material properties of each part are summarized in Table 1.

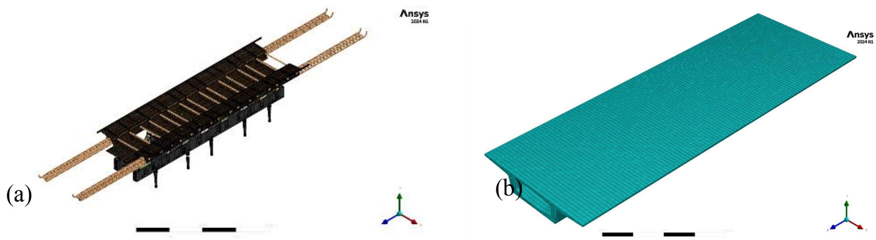

Fig. 4. Refined finite element model: (a) the new split movable scaffolding system; (b) the lower railway box girder.

Table 1 Material parameters used in finite element model.

Type of materials	Elastic modulus/GPa	Poisson ratio	Density /(kg/m^3)	Position
Steel Q355B	206	0.3	7850	main beam, leg, lifting column and so on
Steel Q235B	206	0.3	7850	Cross beam, guide beam and so on
C50	34.5	0.2	2650	railway box girder
Prestressed rebar	195	0.3	7850	railway box girder

4.2 Coupling analysis of structure-formwork based on iterative method

Different from the conventional movable scaffolding system supported by bridge piers, the bottom formwork of the new split movable scaffolding system is directly supported on the existing railway box girder. During the concrete casting process, the lower railway box girder will undergo bending deformation, which will affect the reaction force distribution of the bottom formwork legs and the alignment of the upper highway box girder. In turn, the reaction force distribution of the bottom formwork legs will affect the bending deformation of the lower railway box girder.

For the complex coupling system of the lower railway box girder-new split movable scaffolding system-upper highway box girder, the alignment of highway box girder is composed by three parts: (1) deformation of the lower railway box girder; (2) deformation of the new split movable scaffolding system and (3) pre-camber of the upper highway box girder. Among them, the deformation of the lower railway box girder and the deformation of the new split movable scaffolding system are the core of the control, and it is basically determined by the reaction force distribution of the bottom formwork legs. Therefore, the coupling effect is considered by iterative method. The specific process is as follows (Figure 5):

Step1: the finite element models of the new split movable scaffolding system and the railway box girder are established respectively, and the initial reaction force value, $F_i^0 (i = 1,2,3,4,5)$, of the bottom formwork legs and the initial deformation value, D_i^0, of the railway box girder at the legs under the action of self-weight and prestress are obtained.

Step2: the initial reaction force value, F_i^0, is applied to the box girder, and the deformation, D_i^1, of the railway box girder at the leg after the first iteration is obtained.

Step3: the difference value, Δ_i^1, between the deformation value, D_i^1, after the first iteration and the initial deformation value, D_i^0, is applied as a displacement load to the corresponding bottom formwork leg, and the reaction force value, F_i^1, after the first iteration is obtained.

Step4: the reaction force value, F_i^1, after the first iteration is applied to the railway box girder, and the deformation value, D_i^2, of the railway box girder at the leg after the second iteration is extracted.

Step5: the difference value, Δ_i^j, between the deformation value, D_i^j, after the j iteration and the initial deformation value, D_i^0, is applied as a displacement load to the corresponding bottom formwork leg, and the reaction force value, F_i^j, after the j iteration is extracted. When $|\sum_{i=1}^{5} (\Delta_i^j - \Delta_i^{j-1})| / \sum_{i=1}^{5} \Delta_i^j \le 0.01$, the iteration is stopped, and the reaction force value, F_i^j, is taken as the final reaction force value, and the deformation of the railway box girder and the new split movable scaffolding system under the final reaction force value are calculated.

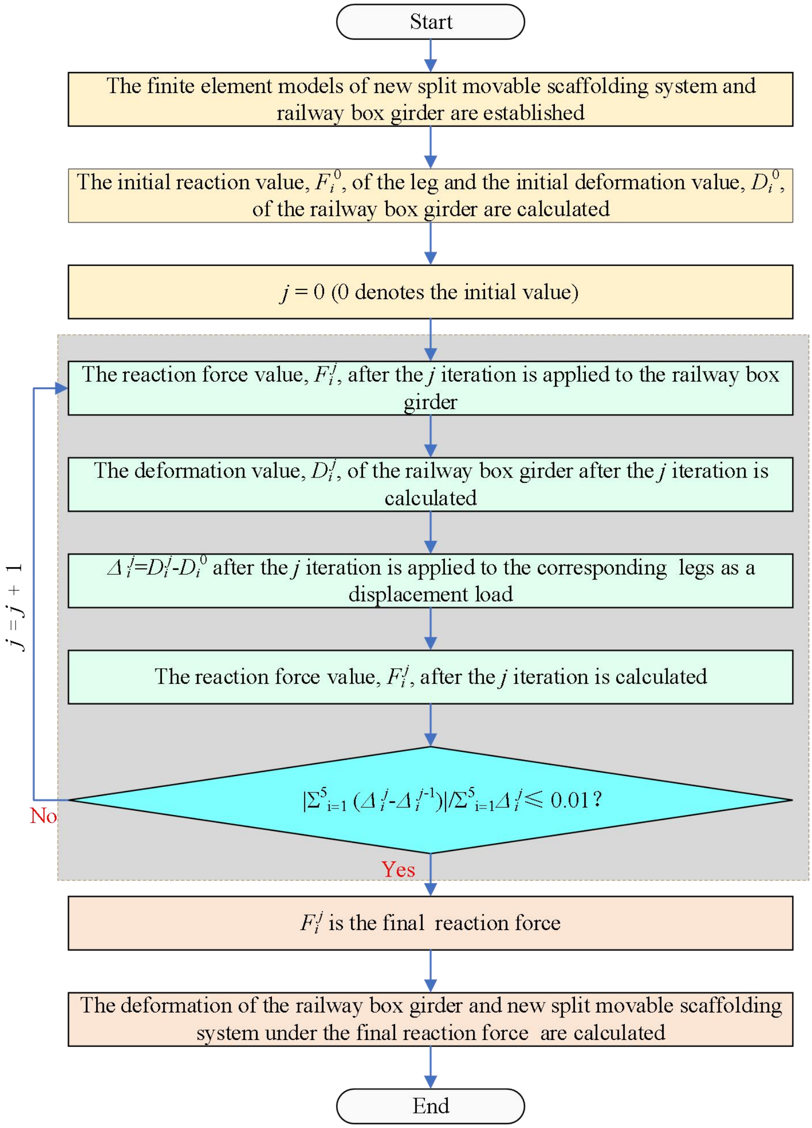

Fig. 5. The process of iterative calculation.

Based on the proposed iterative method, the coupling analysis of the railway box girder- new split movable scaffolding system are carried out. After 6 iterations, the convergence requirements are met. The results of the reaction force of the bottom formwork leg and the deformation of the railway box girder at the bottom formwork leg are shown in Figure 6.

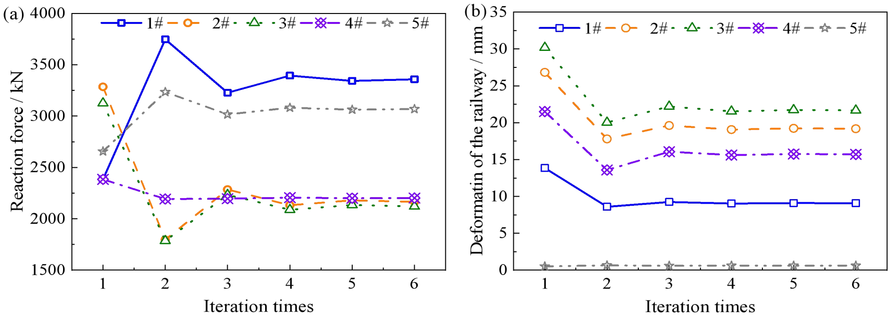

Fig. 6. The results of iterative calculation: (a) the reaction force of the bottom formwork leg; (b) the deformation of the railway box girder at the bottom formwork leg.

It can be seen from Figure 6(a) that: (1) the reaction force distribution trend of the bottom formwork legs before and after the iteration is completely opposite. Before the iteration, the reaction force of the side legs near the bridge pier is small, and after the iteration, the reaction force of the middle legs away from the bridge pier is small. (2) After the iteration, the reaction force of the side legs (1#, 5#) increases, and the reaction force of the middle legs (2#, 3#, 4#) decreases. Among them, the 1# leg with the largest increase is 40.86%, and the 2# leg with the largest decrease is 34.11%. The main reason for the change of the reaction force of the legs is that the deformation of the railway box girder gradually decreases from the middle of the span to both ends under the load of the reaction force, so that the reaction force of the legs is redistributed, and the reaction force of the middle legs in the large deformation zone is transferred to the side legs in the small deformation zone.

It can be seen from Figure 6(b) that: (1) the deformation trend of railway box girder before and after iteration is consistent, both of which are large in mid-span deformation and small in both ends. (2) After the iteration, the deformation of the railway box girder at all legs is reduced. Among them, the 3# leg with the largest reduction is 28.18%. This is because the fact that the total reaction force of the legs before and after the iteration remains unchanged, that is, the weight of the highway box girder and the self-weight of the new split movable scaffolding system are borne by the bottom formwork. After the iteration, the reaction force of the middle legs is transferred to the side legs. The closer the action position is to the end of the railway box girder, the smaller the deformation of the railway box girder is undoubtedly caused under the same size reaction force. (3) It is worth noting that except for the 5# leg closest to the bridge pier, the average deformation of the railway box girder at the other four pairs of leg is 16.41mm, and the deformation of the railway box girder at the 3# leg is 21.68mm, indicating that the influence of the coupling effect on the alignment of the upper highway box girder cannot be ignored.

4.3 Preloading test verification

In order to verify the rationality of the above analysis and the design and manufacturing quality of the new split movable scaffolding system, the preloading test was carried out on site after the new split movable scaffolding system was assembled to ensure that it can work smoothly and safely after being put into use, and eliminate the inelastic deformation.

The concrete blocks with weights of 2t, 1.5t and 1.3t were used for loading, and the total loading amount was equal to the weight of 1348t of the highway box girder to be constructed. In order to monitor the reaction force of the legs, the deformation of the railway box girder and the deformation of the new split movable scaffolding system during the loading process, 5 groups of 10 pressure measuring points were arranged at the bottom of the leg, and 5 groups of 15 displacement measuring points were arranged at the bottom of the railway box girder and the top of the bottom formwork, respectively, as shown in Figure 7.

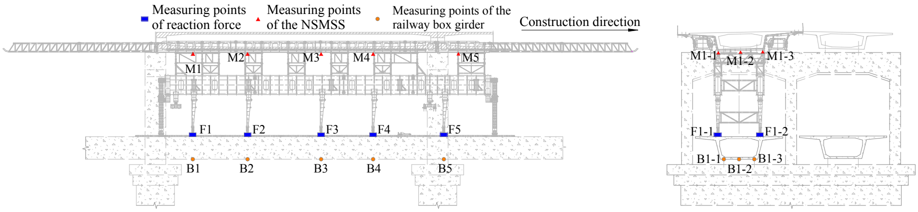

Fig. 7. Layout of measuring points.

The comparison between the preloading value and the simulated value before and after the iteration is shown in Figure 8. It can be seen that: (1) the simulated values of the reaction force and the deformation of the railway box girder after iteration are in good agreement with the preloading values, which effectively verifies the rationality of the coupling analysis based on the iteration method. (2) Before and after the iteration, the deformation difference between the simulated value and the preloading value of the new split movable scaffolding system is limited, which is due to the large stiffness of the formwork and the small deformation caused by the change of the reaction force.

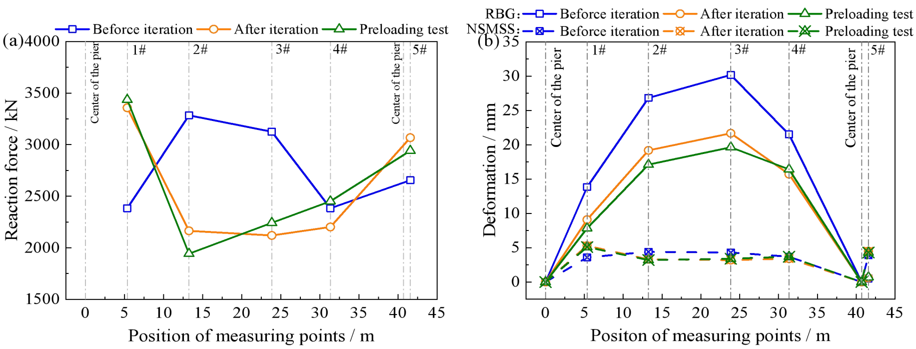

Fig. 8. Comparison of preloading value and simulated value: (a) the reaction force of the legs; (b) the deformation of railway box girder (RBG) and the new split movable scaffolding system (NSMSS).

5 Conclusions

Based on the approach bridge of Maanshan Yangtze River Rail-cum-Road Bridge, this paper studies the box girder construction equipment and its alignment control method suitable for the double-deck frame bridge. The main conclusions are as follows:

(1) The new split movable scaffolding system proposed in this paper can realize split through-hole and reset casting, which can effectively solve the problems of difficult through-hole in narrow space and complicated opening and closing process of conventional movable scaffolding system. It is especially suitable for the construction of upper bridge of double-deck frame bridge, and has great market application value.

(2) For the complex coupling system of the lower railway box girder-new split movable scaffolding system-upper highway box girder, the alignment of the upper highway box girder is composed of three parts: the deformation of the lower railway box girder, the deformation of the new split movable scaffolding system and the pre-camber of the upper highway box girder. The reaction force of the new split movable scaffolding system is the core for the alignment control.

(3) The preloading test is in good agreement with the simulated value, which indicates that the iterative method proposed in this paper can effectively simulate the coupling effect of the lower railway box girder-new split movable scaffolding system-upper highway box girder. The maximum deformation of the railway box girder is up to 21mm, indicating that this coupling effect cannot be ignored.

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