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Analysis and monitoring on jacking construction of continuous box girder bridge

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Abstract. It is hard to guarantee the strict synchronization of all the jacking-up points in the integral jacking of a large-span continuous box girder bridge. This paper took the Hengliaojing Bridge as background, which need jacking up as an object with 295m length and more than 10,000tons weight, adopted 3D software to calculate the unsynchronized jacking-up working conditions, and studied the relationships between the unsynchronized vertical difference and the girder's deformation behaviour. The aim is to verify the maximum value of the unsynchronized vertical difference, and guide the construction and ensure safety. The monitoring system with its contents is introduced corresponding to the analysis. The results of the deck relative elevations prove that it is difficult to avoid the deck torsional deformation for jacking different; especially the side span shows more deformations for its smaller stiffness. The maximum difference is smaller than the limited value with acceptable stresses in the sections. The jacking heights of the pier in each construction step are controlled regularly according to the design. The shifting of the whole bridge in longitudinal direction is smaller than in transverse direction. The several beginning steps are the key to adjust their support reactions. This study is one parts of the fundamental research for the code "Technical specification for bridge jacking-up and reposition of China". The whole synchronous jacking project of the main bridge set a world record by the World Record Association for the whole bridge jacking project with the longest span of the world.

Keywords: continuous box girder bridge; integral jacking; synchronized jacking; jacking control; construction monitoring

1. Introduction

The long-span continuous box girder bridge is one of the widely used bridge structures; this type of bridge has the advantages of small deformation, strong span ability, good structural stiffness, comfortable and stable driving conditions, strong seismic capacity, simple maintenance, etc. So it is favoured by the bridge designers and is an ordinary bridge type in the world. On the other hand, for the rapid development of the transportation industry, many large-span continuous box girder bridges need reformation for many complex reasons, for example: (1) the rise of waterway standards; (2) the clearance insufficient under the high-way cross line; (3) the diseases

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of the bridge foundation; (4) the replacement of the bearings; (5) the elevation difference between the old bridge abutment and the new bridge abutment; (6) the damages caused by the traffic loading. It is impractical and wasteful to reconstruct this kind of large bridges (Yuan *et al.* 2010, Sliuzas *et al.* 2010). One more economical and convenient way is jacking up, or dropping down, or translating. These methods achieve the goals of reformation, save the construction funds, extend the service life of the existing bridge; it matches the green environmental protection idea (Jin *et al.* 2012 and Zhang *et al.* 2012).

In the process of jacking construction, the force of the superstructure may change, even damage. If the design and construction are unreasonable, the problems mainly are reflected in the following three aspects: (1) The unsynchronized vertical difference between each jacking point will change the internal force condition of the girder; (2) the structural form will be changed if the difference jacking supports change their supporting location; (3) During the jacking construction, when the girder's longitudinal or transverse slope is changed, the internal force condition will change too (Sliuzas *et al.* 2010, Hongshan 2010 and Kim *et al.* 2001). In fact, these three aspects always occur in the same engineering, but the first aspect mentioned above has a greater impact.

The bridge jacking-up construction is a complicated process; it is hard to control the construction precision, to ensure the synchronized jacking of each jacking point during the process of integral jacking construction. If there is too much unsynchronized vertical difference between the jacking points for an indeterminate structure, it may lead to excessive deformation of the box girder, appearance of the cracks, occurrence of overturning displacement, even damage of the girder, which is harmful and dangerous to the bridge. Therefore, it is necessary to do some simulating calculation to determine the alarm value and guide the construction to control these dangers, which is the main reference for the monitoring of the construction (Bienen and Cassidy 2006). There are three different situations to explain the unsynchronized jacking: (1) asynchrony in both axial and transverse directions, in other words, unsynchronized jacking in space; (2) asynchrony in axial direction; (3) asynchrony in transverse direction (Van Lam *et al.* 2003, Yoo *et al.* 2010 and Zhang *et al.* 2012). In order to ensure the safety and lower the maintenance cost, different construction methods should be used for different structural forms. In the following, take the Hengliaojing Bridge as an example to study the relationship between unsynchronized vertical difference and the force condition, then to determine the control value of each jacking point's difference in height. This may provide the basis and experience for similar projects in the future.

2. Background project

The Hengliaojing Bridge is one part of the A30 national road of China, which crosses the Hengliaojing River, upstream of Huangpu River. It is a three-span prestressed concrete continuous girder bridge with variable box cross-section. The span combination is two 85m side spans and one 125 m middle main span. The bridge is designed in the form of separated lanes for upstream and downstream vehicles with a 1.0m wide medial space. The total width of the bridge is 27.5 m with 3.5% longitudinal slope (See Fig. 1). For the same condition, only the east bridge's results are reported in this paper (Institute 2010).

Based on the research results for the waterway specification of the upstream of the Huangpu River, the navigational dimension of Hengliaojing Bridge cannot meet the third-grade requirements after the waterway was upgraded regulation; therefore, it is necessary to make jacking reformation. According to the third-grade waterway specification, 1.58 m jacking height is required with the same line shape of the road's vertical section.

3. Jacking-up construction design

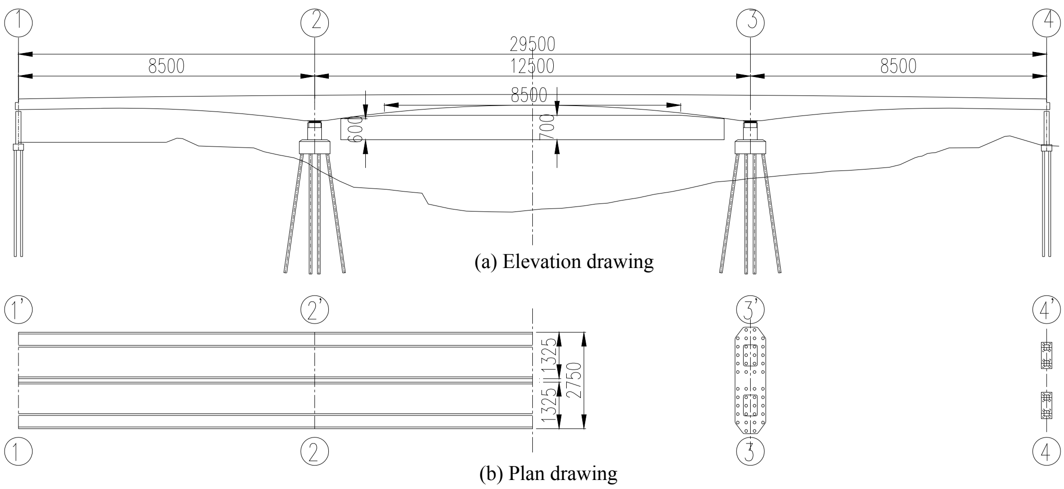
In this project, the researchers use the direct entire jacking method based on both the middle piers and the side piers which act as the reaction basement. Workers install the jacks between the pier and the girder, then jack up the box girder (the upper of the girder needs partial reinforcement) integrally with the synchronized control of Programmable Logic Controller (PLC), finally achieve the goal of elevation of the bridge deck. The advantage of this method is that it almost does not change the force system on the bridge with a clear mechanical performance.

The extraordinary modification for jacking of this project is cutting piers and strengthening for different requirement (Yan 2011), including

(1)The space between old middle piers and the girder's bottom is smaller than 400 mm, which is less than length to install the large jacks. The middle piers need to be cut 200 mm off partially, while the total section of the side piers will be cut 200mm off. The different construction step before and after cutting should be controlled. The simulation for the cutting state has been reported in reference.

(2)For the reduction of support area of the piers after cutting, and there are more than eight jacks on the middle piers and four jacks on the side piers, the old piers need to be reinforced with surround steel hoop plates. The girder's bottom plates above the middle piers need to be reinforced locally at the exchange place of the jacks.

In this paper, the main target is the mechanical characterizes with monitoring results in construction stages. All this modification with mechanical analysis can consult the reference. To ensure the jack construction quality and safety, the designer specified the criterion as following precision



(a) Elevation drawing

(b) Plan drawing

Fig. 1 Profile of the Hengliaojing bridge (Unit: cm)

- The relative elevation difference of the deck above any support point should be less than ±5 mm.
- The longitudinal shifting at the horizontal plane should be less than ±15 mm; while the transverse shifting should be less than ±10 mm.
- The vertical height error of different support point should be less than ±10 mm.
- The increase of tensile stress in girder section should be less than 1.0 MPa, while the compressive stress should be less than 2.0 MPa.

4. Mechanical analysis on unsynchronized jacking construction

4.1 FEM simulation

It is prone to happen that there is unsynchronized jacking in the construction. The researchers use the 3D Finite Element software to simulate the process of jacking for all above mentioned specified criterion, to study the relationship between the unsynchronized jacking and the box girder’s force, which respectively was divided into three different kinds:

- Asynchrony in longitudinal direction;
- Asynchrony in transverse direction;
- Asynchrony in space.

All these results will guide to determine the maximum value and guide the construction.

The box girder is established by grillage analytical method, and the prestressed tendons are input into the model according to the design drawings, and then the boundary conditions and construction step are simulated according to the real conditions (Li *et al.* 2003). The model is built without the considerations of the transverse slope of the bridge and the substructure’s deformation, and the bearings are consolidated in the piers, because the process of unsynchronized jacking will be simulated using the bearing’s displacement. The whole model includes 360 spatial elements, 290 nodes, and 13 construction stages (shown in Fig. 2).

The concrete of the girder is C50 grade with diameter 15.24 mm high-strength and low-relaxation steel strand (CCCC Highway consultants Co. 2004). According to the standard, the normal stress at the edge of the section for the prestressed concrete bending structure under the prestress and the dead weight should meet the requirements as the following. In fact, these stresses are the criterion to get the unsynchronized jacking error, which will help the control of the jacking construction.

- Compressive stress: $\sigma^{t}_{cc} \leq 0.7 f_{ck}' = 22.68$MPa,
- Tensile stress: $\sigma^{t}_{ct} \leq 0.7 f_{tk}' = 1.855$MPa.

Where f_{ck}' and f_{tk}' respectively stands for the actual compressive and tensile strength, for C50 grade concrete, f_{ck}' =32.4MPa and f_{tk}'=2.65MPa.

4.2 Analysis of calculation results

This paper shows the calculation results of all the possible working conditions, which will exist in the transverse, axial, spatial direction, corresponding to the above mentioned three kind differences. The simulation gives the variational relationship between the box girder’s stress and the unsynchronized vertical difference.

Fig. 2 The grillage FE model of the Hengliaojing bridge

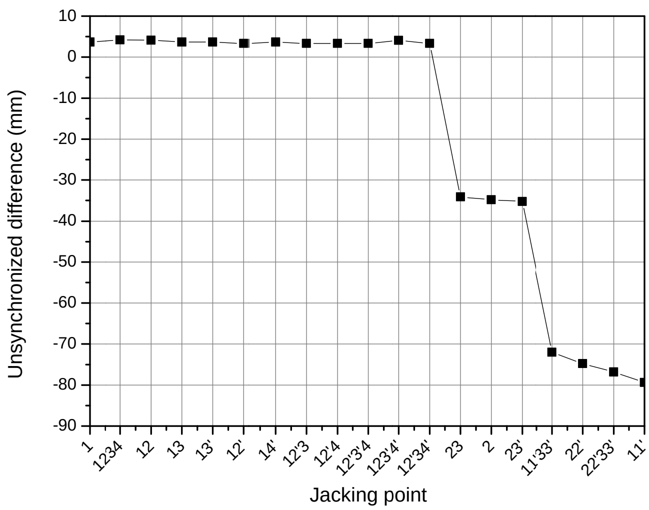


Fig. 3 Critical unsynchronized vertical difference under different working condition

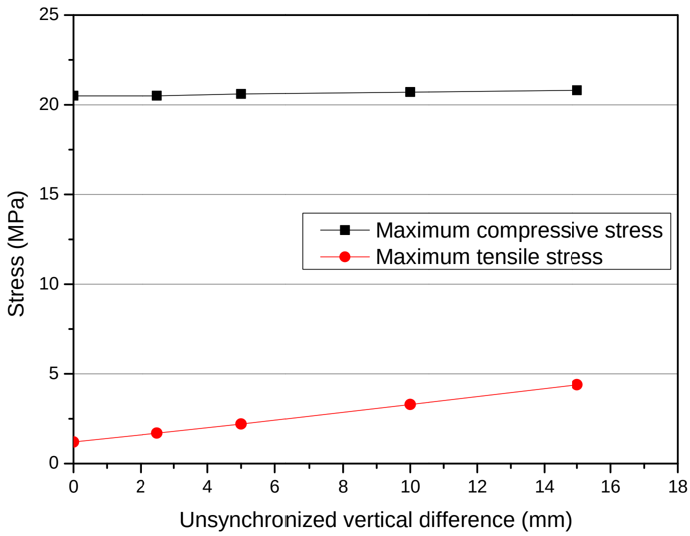


Fig. 4 Relationship between stresses with unsynchronized differences in woking condition12’3’4

Table 1 Critical value of the unsynchronized difference in each possible working condition

Working condition	Jacking point	Control item	Critical stress	Critical unsynchronized difference /mm	Remark
Transverse direction	1	1	$0.7f_{tk}'$	3.69	Control value
	2	1	$0.7f_{tk}'$	-34.79	——
	1234	1	$0.7f_{tk}'$	4.21	——
Axial direction	11'	2	$0.7f_{ck}'$	-79.39	——
	22'	2	$0.7f_{ck}'$	-74.79	——
	11'33'	2	$0.7f_{ck}'$	-72.01	Control value
	22'33'	2	$0.7f_{ck}'$	-76.85	——
Two direction (In space)	12	1	$0.7f_{tk}'$	4.11	——
	13	1	$0.7f_{tk}'$	3.69	——
	23	1	$0.7f_{tk}'$	-34.09	——
	13'	1	$0.7f_{tk}'$	3.68	——
	12'	1	$0.7f_{tk}'$	3.34	——
	14'	1	$0.7f_{tk}'$	3.68	——
	23'	1	$0.7f_{tk}'$	-35.21	——
	12'3	1	$0.7f_{tk}'$	3.35	——
	12'4	1	$0.7f_{tk}'$	3.34	——
	12'3'4	1	$0.7f_{tk}'$	3.33	Control value
	123'4'	1	$0.7f_{tk}'$	4.10	——
	12'34'	1	$0.7f_{tk}'$	3.35	——

[Note]
1) The numbers in the second columns stand for the jacking positions (shown in Fig. 1).
2) Each working condition stands for the difference of the jacking height with other positions, and the positive value means that the jacking height is higher than other positions.
3) Control item 1 means the tensile stress at the apical margin of the end-beam section.
4) Control item 2 means compressive stress at the hemline of middle cross section of the side span.

Table 2 Variation of box girder's normal stress in working condition 12'3'4

Unsynchronized vertical difference (mm)	Maximum compressive stress		Maximum tensile stress	
	Value(MPa)	Location	Value(MPa)	Location
0.0	20.47	Bottom surface at the middle section of the side span	1.18	Top surface of the end beam section
2.5	20.51		1.68	
5.0	20.56		2.20	
10.0	20.65		3.31	
15.0	20.81		4.42	

In order to apparently show the influence degree of each working condition on the box girder's stress, it is easy to calculate the critical value of the unsynchronized vertical difference in different working conditions. The possible adverse working conditions and the critical values of the unsynchronized vertical difference are listed in Table 1 and shown in Fig. 3. In Table 1, the numbers of the jacking point stand for the jacking positions on the piers as shown in Fig. 1).

For the limitation of this paper's capacity, it just lists the data of the worst working condition (No.12'3'4), which has the highest jacking position than others, the variational relationship between the maximum stress and the unsynchronized difference in different working conditions are listed in Table 2, and the curve is shown in Fig. 4.

Fig. 4 showed the critical compressive stress and tensile stress changing with the unsynchronized vertical difference. They are the main references to decide the construction control factor at each construction step.

Apparently, the box girder’s maximum compressive and tensile stresses both have a linear relationship with the unsynchronized vertical difference; the maximum compressive stress exists at the hemline of middle cross-section of the side span, and the maximum tensile stress occurs at the apical margin of end-beam section.

The calculation results indicate that the minimum unsynchronized vertical difference in the transverse, axial, and spatial direction is respectively 3.69 mm, 72.01 mm, 3.33 mm, so the 3.33 mm in space is the overall controlling value. In order to show the influence degree of each working condition on the box girder’s stress, the calculation values are listed in Fig. 4 from the smallest to the biggest in the form of absolute value.

This curve is shown in a step shape; all the working conditions can be classified as three types on the basis of the unsynchronized vertical difference. The working condition, that the asynchrony of these two jacking positions at the end beam in the transverse direction (1 and 1’ or 4 and 4’), has the smallest unsynchronized vertical difference, which determines the final critical value. The working conditions like this have greater influence on the stress at the apical margin of the end beam section. On the other hand, whether other positions have unsynchronized vertical difference or not, it has few influences on the final critical values.

Firstly, the controlling value 3.33 mm in 12’3’4 situation indicates that if the girder torsion for the side support and middle support did not unsynchronized jack up, the tensile stress at the top surface is the critical stress. To give the construction controller reference, Table 1 list the different unsynchronized vertical difference for this situation.

Secondly, two working conditions which stand for the asynchrony of the two jacking positions (2 and 2’ or 3 and 3’) in the transverse direction have big values, for the minimum value is 34.09mm, which is about ten times of the critical value, it has no control function.

Thirdly, four working conditions which stand for the asynchrony in the axial direction have bigger unsynchronized vertical differences, the minimum value is 72.01 mm which is nearly 21 times of the critical value, and it mainly has great influence on the stress at the bottom surface of middle cross section of the side span.

During the construction, some measures should be taken to ensure that the unsynchronized vertical difference is in safety range. According the analysis, the asynchrony of jacking positions at the end beam in the transverse direction has a control of 3.33 mm; however, the asynchrony in the axial direction has the smallest influence, which has a controlling value of 72.01 mm.

4.3 Controlling measures of synchronized jacking

As mentioned above, for the Hengliaojing Bridge’s long span and great weight, too much unsynchronized vertical difference does harm to the force of the box girder, even threaten the construction safety. The engineers should take some effective measures to ensure that the unsynchronized vertical difference in the safety range and the construction safe.

(1) There must be precise synchronicity for the jacking device, whether in the transverse direction or in the axial direction, precise synchronicity should be ensured among each jacking point. For example, the large-structure hydraulic synchronized jacking device and the PLC

hydraulic integral synchronized jacking device are widely used during the construction (Gaddy 2001, Yoo *et al.* 2010 and Li 2012).

(2) There must be some structural reformations for the bridge deck system before construction. For example, removing the original expansion joint, can avoid the damage to the expansion joint and neighbouring girder body in case of unsynchronized jacking. After removing the expansion joint, the concrete coarse aggregate of the girder should be high-visible to ensure the connection between the old concrete and the new one can satisfy the requirements of construction. There should be enough assurance about the girder's structural safety during the process of reformation.

(3) Some weak parts or stress concentration areas of the box girder should need some reinforcement and reconstruction, for improving the stress performance of these areas. For instance, put a thick steel plate at the jacking position or have some reinforcement and reconstruction at the apical margin of the end beam section.

(4) It is better to use the double-control method for the stress and displacement in the process of jacking construction. In most cases, monitor is required for the jacking force and the girder's integral posture. If any abnormality happened, it can stop the construction and do some adjustment after examinations.

(5) The other measure is to get the weigh of the bridge before construction to verify the hydraulic system and analysis results with the emergency preplan.

5. Construction monitoring execution

5.1 Monitoring system and hydraulic system monitoring

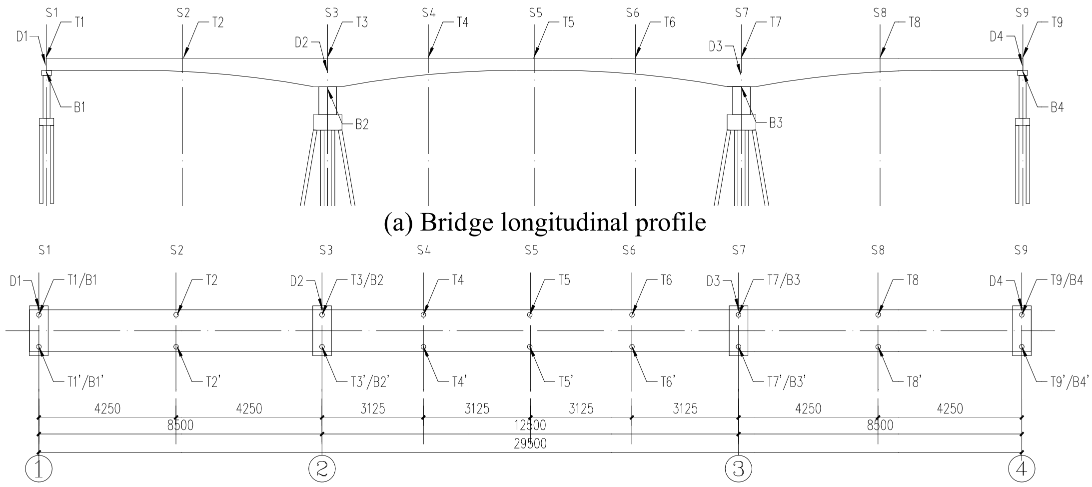
Jacking construction monitoring of a bridge in the process is to ensure that the bridge's pose in control as anticipation for the last objectives state, and guarantee no unexpected adverse effects during construction.

Both jacking and moving construction, the entire monitoring and control are completed in the central control room. In this room, the controller can monitor various parameters and can adjust them in real time to achieve the purpose of dynamic optimization and dynamic control. The control computer with monitoring software can collect all data with three-dimensional space status displays. Monitor software includes two modules, state monitoring management module and control management module (Yang *et al.* 2012, Zhang *et al.* 2012).

For its real-time performance, the monitoring module consists of hardware management, communication, real-time monitoring and data processing. The hardware management is to ensure them working properly thorough self-test before use. Communication modules complete the communication between the master computer and each PLC with high real time performance. Real-time monitoring module can monitor each hydro cylinder oil pressure and shifting length, display real-time dynamic curve of their state. Data processing module can store the initial parameters and real-time data for database with report forms output function.

The control management module implements the control operation through a human-computer interactive system. Interface provides parameter settings before the system running, including hydraulic cylinder selection, displacement sensor grouping, connecting the pumping station with displacement sensors, as well as synchronization accuracy settings. All these parameters can be fixed and saved into the database.

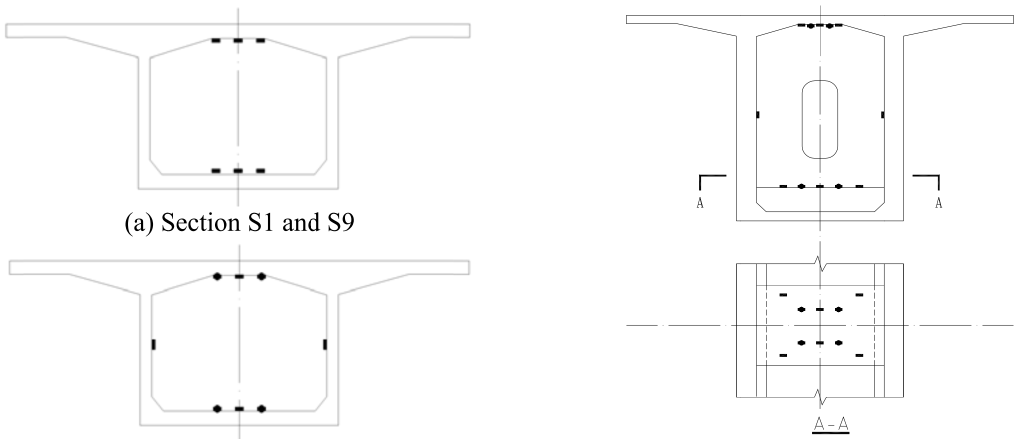
During the jacking construction, each interface to implement girder weighting, jacking and moving will show stress and displacement in the form of data display, and can be interchanged with a dynamic curve of pressure and displacement interface. Each monitor point such as single-cylinder pressure values can be called independently with human-computer interaction to adjust the hydraulic pressure for selected cylinder.



(a) Bridge longitudinal profile

(b) Plan layout of bridge

Fig. 5 Monitoring point's location



(a) Section S1 and S9

(b) Section S2,S4, S5, S6 and S8

(c) Section S3 and S7

Fig. 6 The monitoring points distribution of stress

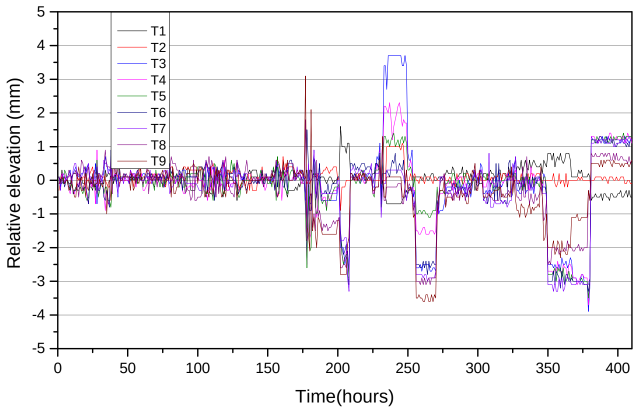


Fig. 7 Relative elevation of deck change with time

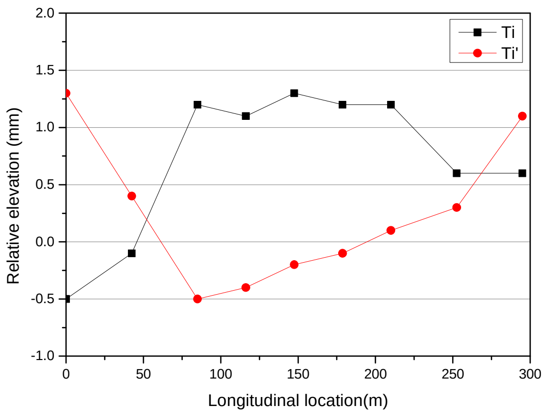


Fig. 8 The final relative elevation of deck

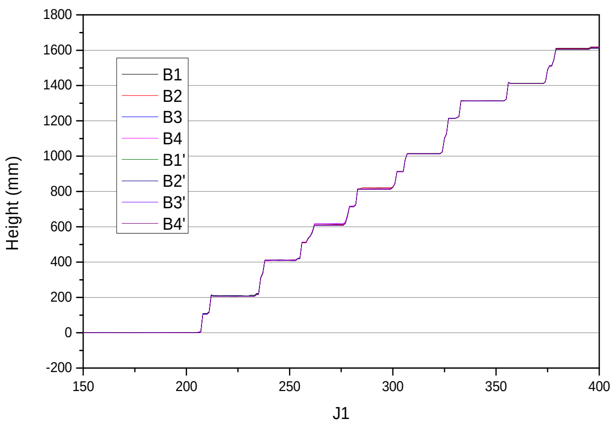
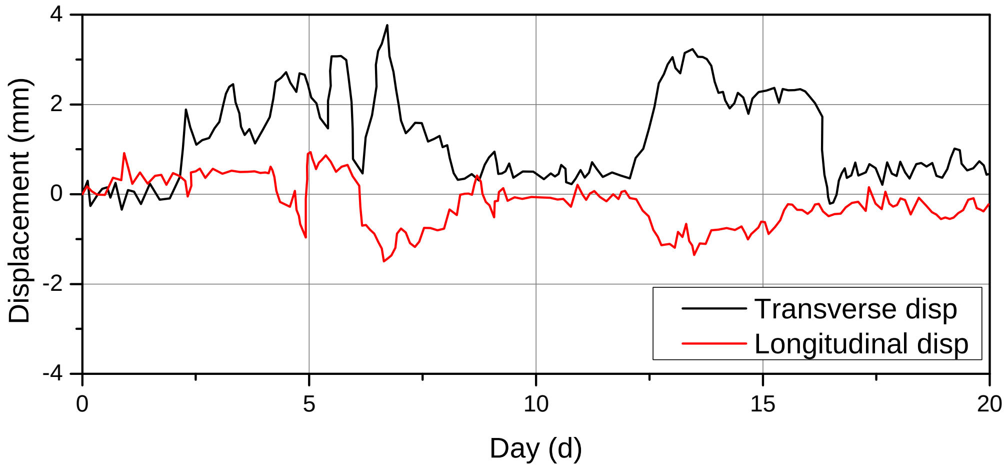
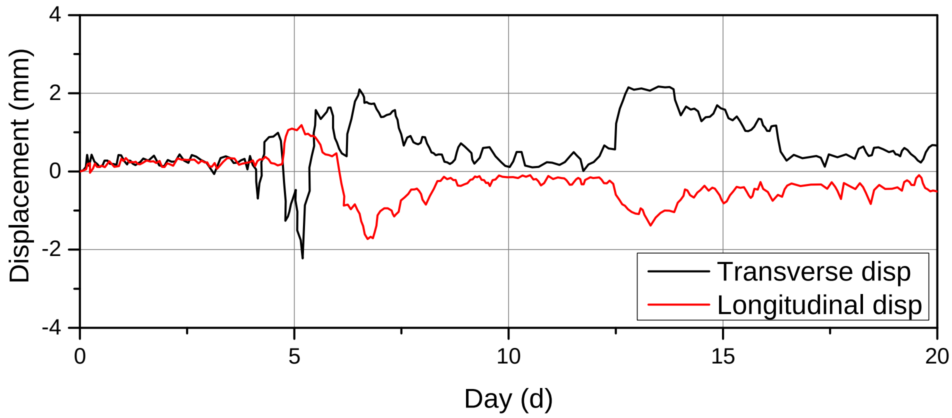


Fig. 9 Lifting height of the second stage changing with time



(a) Displacement of point D1



(b) Displacement of point D2

Fig. 10 Displacement of girder changing with time

5.2 Synchronized jacking structural monitoring contents and plan

Structural monitoring content includes the structure of the translation, rotation, skew, and structural stress. In addition to hydraulic system and structural monitoring, the security monitoring includes jacking equipment failures, safety of protective support systems, weather conditions and navigation safety of ships.

Relative to the structural monitoring, the monitoring of hydraulic and weather and navigation have no difference with routine monitoring. This article only reported the bridge structural monitoring, including:

- Deck relative elevation changes;
- Height monitoring of box girder;
- Longitudinal and transverse displacement monitoring;
- Section stress and supporting system state.

According to the construction process, from the cutting of the pier to jacking completion stage, all above factors will be real-time monitored in 24 hours each day.

(1) Relative elevation of the deck

The elevation of different observation points on the deck can calculate the relative deviation, which can help to control the jacking speed and the pose of the bridge effectively. Deck elevation monitoring mainly uses the static water level gauge which can achieve real-time monitoring 24 hours a day, maximum precision for 0.01mm. The observation points (Ti and Ti' point) were located as shown in Figs. 5(a) and 5(b). Point Ti and Ti' respectively located at upstream and downstream of the bridge along the longitudinal direction.

The entire testing process of the monitor system and data processing are automatic by the monitoring software. The monitoring point selection and instruments installation:

- Install 18 static-water-lever gauges on the deck, which geoids are adjustable.
- The static-water-level gauges are screwed on the bracket; all can be adjusted to the same height.
- The gauges are connected with connecting pipes and injected the solution into them, and then drain the bubble from the solution.
- Observe the liquid height and adjust the liquid height of all gauges to the same level.
- Debug the monitor lever with bubbles on the bench.
- Considering the same construction influence, install one water level gauge as described above and communicates with baseline monitoring as the datum point of the entire static level monitoring system.
- After the installation is complete, check all equipments and connections, such as whether the instruments are fixed securely, whether the connected pipes are leakage, whether the data cables are normal.
- Install shields for each monitor as needed after everything is fine.
- Pre-test after the installation is complete.

(2) Monitoring of the girder bottom elevation

Monitoring the bottom elevation of the girder is to get the lifting height relative to the pier. The instrument is pull-string displacement sensor and aided with an electronic total station to track and measure the precise lifting height for jacking construction reference. The results can be supplements and reviews for the above relative elevation of the deck.

In order to get more accurate lifting height, close to each bearing location of the main bridge, there is a pull-string displacement sensor. For a single girder bridge, total eight sensors were installed at upstream and downstream, as Bi and Bi' points, which are shown in Fig. 5.

(3) Longitudinal and transverse displacement monitoring

Longitudinal and transverse displacements of the bridge are monitored by full automatic tracking total station and determined by the method of multiple differential technique and polar monitoring to address automatic observation of three dimensional coordinates of a point. It can automatically monitor multiple connecting objectives continuously or timed including identification, track, angular, ranging, as well as the three dimensional coordinate measurement. This high automation system, particularly in dynamic displacement and deformation monitoring showed great superiority to review and calibrate the deck elevation and bottom elevation.

Each pier has one monitoring points (See points Di in Fig. 5) for the full automatic tracking total station which installed about 50m away from the bridge.

(4) Section stress and supporting system state

Table 3 Targeted value for monitoring and controlling

	Early-warning value	Warning value
Deck elevation deviation value	2.5	5
Displacement along longitudinal direction	7.5	15
Displacement along transverse direction	5	10
Lifting height deviation of jacking point	10	5
Section tensile stress of girder	0.5	1
Section compressive stress of girder	1	2

The section stresses and the support system are monitored with stress sensors for real-time monitoring. The section stress can master the state of the bridge in real time in the process of jacking when the support has a non-uniform force, then to help controlling the lifting posture.

Through monitoring of the support system, can master the force and deformation of supporting system in time, take measures to control the deformation of the supporting system, ensure that the construction conduct in a safe and controlled environment. The vibrating wire strain gauges will measure them and be aided with deformation detection for their working state.

The stress monitor points are selected according to the structural characteristic of a continuous box girder bridge. There are nine sections selected including the middle span's section, quarter span's section of the main span, and the sections above the piers are selected (See Fig. 5). At the section S1 and section S3, several strain rosettes are added on the girder internal webs.

The monitoring points of the sections locate at the same place except the web points changed with the height of the section. The locations of each monitoring point of stresses of the section are shown in Figs. 6(a)-6(c). There are three type class sections: sections (S1 and S9) above the side piers (Fig. 6(a)), sections (S2, S4, S5, S6 and S8) of the middle span (Fig. 6(b)), sections S3 and S7 above the middle piers (Fig. 6(c)). The strain rosettes for the shear located on the webs of the section which are close to the piers.

The monitoring points of the support system are selected according to the form of the bridge structure and the cutting construction of the piers, selected at all four sides of the pier along the centerlines and close to the cutting line. At the same time, one point locates in each protective frame centerline in transverse direction. There are total 32 points, six points for each side pier and 16 points for each main pier.

5.3 Monitoring control indices

To ensure the construction safety and the lifting precision to meet the design requirements, the definite accuracy for lifting monitoring should be specific according to the different indicators for monitoring. There are two grade warning values: early warning and alarm value. Where early-warning value is one-half of the specification of the design documents on controlling precision for the main bridge jacking, the alarm value is just the controlling precision. The monitoring indicators are listed in Table 3.

5.4 Monitoring results

The schedule of jacking construction progress as following:

From 5th September 2011 to 13th September 2011, completed the cutting and reinforced of pier with corresponding monitoring of this first stage.

From 14th September 2011, the second stage began to test jacking, and then completed the whole jacking construction on 24th September 2011.

The whole progression lasted 410 hours for the bridge. Because the first-stage results were stable and the second stage is the key stages, in this paper only the results of the second stage were introduced.

(1) Relative elevation monitoring of the girder deck

Fig. 7 shows the monitoring result of relative elevation of the deck of Ti points from the beginning of pier cutting to the end of jacking construction.

The results indicate that although the relation elevations of the deck in some construction periods are exceptional but still smaller than 5.0 mm safe warning value. The maximum difference value is 3.9 mm at T9. Most values are located between -1.0 mm and 1.0 mm. At the end of construction, the value range is from -0.5 mm to 1. 5 mm. The main reason for some large value in some period is the difference shifting length of the jacks; the unsynchronized jacking reactions are varied for different support on side piers and middle piers. However, with the construction progress, these differences will be adjusted for the force redistribution and jack's reaction revision.

At the end of jacking construction, at 17:00 24th September 2011, the final relative elevations are shown in Fig. 8. It indicated that the deck twisted and cocked in cross section. The side of Ti points rises higher than the Ti' points.

(2) Height monitoring of girder bottom

The lifting heights of the girder bottom at each jacking step of the second stage are shown in Fig. 9.

The monitoring results prove that along the longitudinal direction, all the main sections were raised as the same time almost with the same speed. Only when the jacking construction was stopped to exchange the jacks, there was small difference at each section. It can be drawn that in all the steps, the jacking heights at each support were kept a better synchronization.

(3) Displacement of the girder along longitudinal and transverse direction

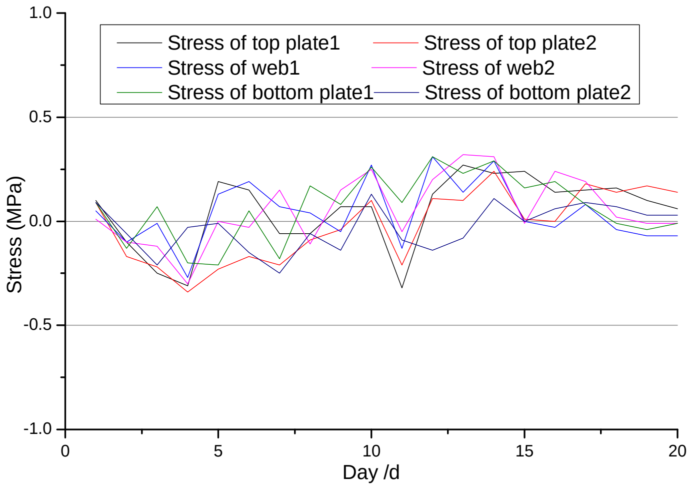
The displacements along longitudinal and transverse direction at each support point are monitored. Fig. 10 shows the data of D1 and D2 points at one side pier and one middle pier.

All the displacements of two piers show that the displacements along longitudinal direction are smaller than transverse direction. The transverse displacements of the side pier are about two times that of the middle pier, especially at the beginning stage. The reason is the smaller support reaction increase the difficulty to the jacks at the same section to adjust their reactions. However, after the medium term, the displacements will be similar in two directions.

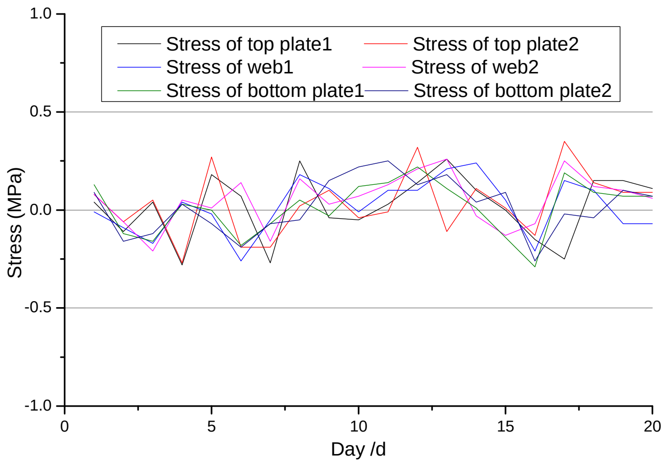
(4) Stress of the girder and deformation of the protective support frame

When the jacks have difference shifting length, the stress redistribution of the girder will show at each section. It is very clear that during the jacking stage, the stresses of each section are fluctuant with jack's pressure pressurizing, releasing and maintaining. The stresses of Section S2 and Section S5 are plotted in Fig. 11. During whole jacking stage, the maximum compressive stress and tensile stresses are smaller than 0.4 MPa, less than 1.0 MPa limited tensile stress and 2.0 MPa compressive stress.

Similar to the difference of relative elevation, at the beginning stage, the stress varied evidently than the end stage because the jack's supports adjusted promptly. However, the maximum stress emerged within the last half stage which matched the displacement rules along longitudinal and transverse directions.



(a) Stress of section S2



(b) Stress of section S5

Fig. 11 Middle section stresses changing with time

Because the displacement of the girder in longitudinal and transverse directions is smaller than expectation value, there are no support reactions between the protective support frame and the girder. So this paper does not report the monitoring stress of the support frames.

5.5 Monitoring results summary

During the whole synchronous jacking progress, all technical parameters did not exceed the limited.

In the first stage for pier cutting construction, because the weight is still on the old piers even the piers have been cut, the girder almost has no movement to change the elevation and the displacement. The small fluctuation of the stress in piers and girder for the cutting construction and jacking installation are smaller than the limited warning stress. After cutting and installation, all the technical parameter resume to the stable state, these proved that the jacks can keep their oil pressure stably.

During the main jacking stage, the acceptable elevation change indicated that the difference of the jacks shifting is small and the hydraulic system is adaptable, which can ensure the jacks to control their attitude immediately according to the state of the girder. Even in some part time, the relative elevations are some large range change but are still acceptable, not exceeded the limited warning value. The displacement of the girder along longitudinal and transverse directions indicated that the error accumulation of jacking shifting was unavoidable. The displacement amount along transverse direction at the side pier is larger than the middle pier, which still can be adjusted through the jacks to change their attitudes. These can resume the displacement in some degree, but the remains are still allowable.

6. Conclusions

The maximum compressive and tensile stresses have a linear relationship with the unsynchronized difference; the maximum compressive stress exists at the hemline of mid-span section of the side-span and the maximum tensile stress occurs at the apical margin of the end beam section.

The asynchrony of the jacking positions at the end beam in the transverse direction has the control function for a control value of 3.33 mm. There is small influence on the critical value in the cases of other jacking positions' asynchrony. The asynchrony in the transverse direction between the jacking positions on the main pier has smaller influence in the value of 34.09 mm, while the asynchrony in the axial direction has the smallest influence in the value of 72.01 mm.

The monitoring results proved that for the difference reaction at differing piers in different stages are acceptable, and the elevation change indicated that the difference of the jacks shifting is in control and the hydraulic system is adaptable.

Corresponding to the mechanical analysis, especially for the difference of jack's shifting effect, during the whole synchronous jacking progress, all technical parameters matched up to the design requirement. The Hengliaojing Bridge was opened again on 30th December 2011 after all the modification construction. During the past 1.5 years service, continuous inspection proved that the construction was success and confirmed that the construction effect achieved the desired.

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