

# RESEARCH ON UNBALANCED WEIGHING EXPERIMENT OF MULTI-POINT BRACED SWIVEL CABLE-STAYED BRIDGE

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## ABSTRACT

Rotating bridge structures encounter numerous challenges during the rotation process, and the pre-rotation weighing experiment is the key to addressing these difficulties. Therefore, in order to resolve the obstacles and provide reference for future bridge rotation construction in the context of dependent projects, this study focuses on a prestressed concrete cable-stayed bridge with twin towers and twin cable planes. It proposes a multi-point braced rotation weighing experiment, where both the arm-brace and the spherical hinge are subjected to simultaneous loading. Firstly, theoretical formulas for the weighing experiments under various conditions were derived. The field test results were then utilized to calculate the jacking force at the limit state during the jacking process. Subsequently, these values were substituted into the corresponding formulas to determine the relevant parameters of the weighing experiment. Finally, the counterweight was adjusted based on the weighing results to facilitate the structural rotation. Throughout the swiveling process, the angular velocity remained stable, resulting in the successful rotation of the structure. The successful implementation of a multi-point braced swivel weighing experiment, considering the joint force of the arm-brace and the spherical hinge, can serve as a valuable reference for the design and construction of similar bridges.

## KEYWORDS

Cable-stayed bridge, Swivel construction, Multi-point braced, Spherical hinge rotation method, Weighing experiment

## INTRODUCTION

Bridge construction in China is currently undergoing rapid development. In addition to spanning ravines, valleys, rivers, and seas, many new bridges must cross over busy transportation lines. Fortunately, the swivel construction method offers an effective solution, offering several advantages such as simplified construction procedures, accelerated construction speed, reduced material usage, and minimal disruption to existing infrastructure. These advantages yield significant economic and social benefits [1]~[4].

The swivel construction method can be classified into three categories based on the swivel direction: horizontal swivel, vertical swivel, and a combination of horizontal and vertical swivel methods [5]~[9]. The horizontal swivel method is widely used in road and railway engineering projects [9]. However, when the bridge constructed by the horizontal swivel method is faced with a swivel across existing lines, a specific obstacle in the process of swivelling, or a slight elevation difference between the bottom of the beam and the obstacles, the traditional single point braced swivel method no longer meets the complex construction conditions, which makes more and more horizontal swivel constructions constantly innovate. Based on this, this article proposes a multi-point braced swivel weighing experiment, which is based on the single-point braced swivel and involves the joint force of the arm-brace and the spherical hinge.

## BRIDGE OVERVIEW AND FINITE ELEMENT MODEL

The project-based bridge is on a north-south urban trunk road in Harbin, Heilongjiang Province. It features a twin-tower, double-cable prestressed concrete swivel cable-stayed bridge with a combined span length of (118 + 198 + 118) meters and a semi-floating structural support system. Tower nine rotated 79.31 degrees counter clockwise, while Tower ten rotated 96.12 degrees clockwise; the swivel weight of both towers is approximately 28,000 tonnes. Due to the bridge's location, the bridge spans 48 existing railways at an intersection angle of 80.4°. Furthermore, the main beams of Tower ten's side span must cross the railway catenary during the swivel process. The distance between the bottom of the beams and the railway catenary at its closest position is only 151 mm. In order to increase the distance between the main beams of Tower ten's side span and the railway catenary while maintaining the safety of the swivel process, the multi-point braced swivel method was used for Tower ten. In contrast, the traditional single-point braced swivel method was still used for Tower nine.

Through the finite element method to solve the problem, is the use of mathematical approximation method to simulate the actual physical system (geometry and load conditions). It approximates the real system of infinite unknowns with a finite number of unknowns using simple and interacting components (i.e. cells). Finite element analysis is inextricably linked to the solution of nonlinear issues. Based on actual construction stages and parameters, a static rod system model for the twin-tower, double-cable swivel cable-stayed bridge was developed using Midas Civil to provide theoretical data for the overall structure and precise substitute moments for simplifying the upper structure of the local model. Midas Civil, a general structural analysis and design system for bridges within the Midas suite of software components, incorporating current Chinese design standards, is frequently used by engineering firms for project design and academic structural calculations.

Midas Civil was used to constructing the Danyang Road overpass and the Lekai Street swivel cable-stayed bridge in Heze, China [10]. In his study of the mechanical behaviour of an inter-railway overpass in Zoucheng City subject to the coupled action of multiple elements, Guo [11] also used Midas Civil to create the static rod system model of the swivel cable-stayed bridge.

### 1. Nodes and units' creation

The nodes and units are created under the bridge's size and location. The overall model has 416 nodes and 393 units, with beam units for the main tower, main girder, and bearing platform; and truss units for the stay cable.

### 2. Material selection

According to the field experiment, material-related parameters refer to the corresponding material parameters in the Chinese specification database [12] and are given to the corresponding unit.

### 3. Boundary setting

Because the rod system model is not required to provide seismic and other dynamic data for this paper, the "pile-soil" effect is not considered, and the bottom of the lower foundation slab is fully restrained by general support; the anchoring effect of the anchor on the stay cable and the bridge tower and main beam is simplified and replaced by a rigid connection. The tower beam before the swivel is temporarily consolidated by prestress, which is also replaced by a rigid connection. The tower beam and pier bearings are simulated by elastic supporting.

### 4. Construction stage

The construction phases of the model are divided into 47 stages, based on the engineering design documents and adjusted in real time according to the actual construction conditions on site.

The overall rod system model omits the detailed structures such as spherical hinges and arm-brace. The bridge layout is shown in Figure 1, and the Midas Civil model is shown in Figure 2.

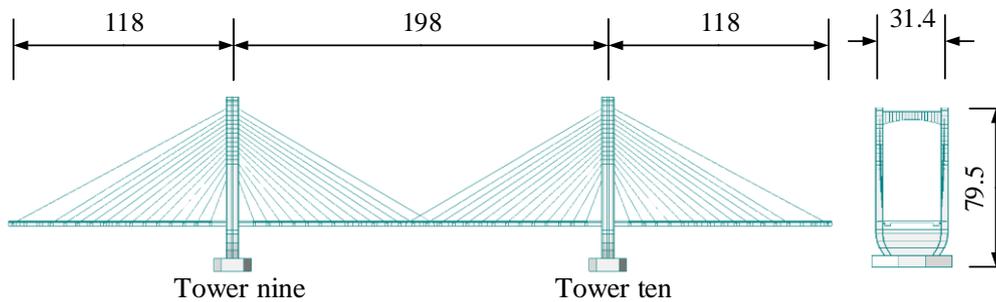


Fig.1 - Bridge layout diagram (unit: m)

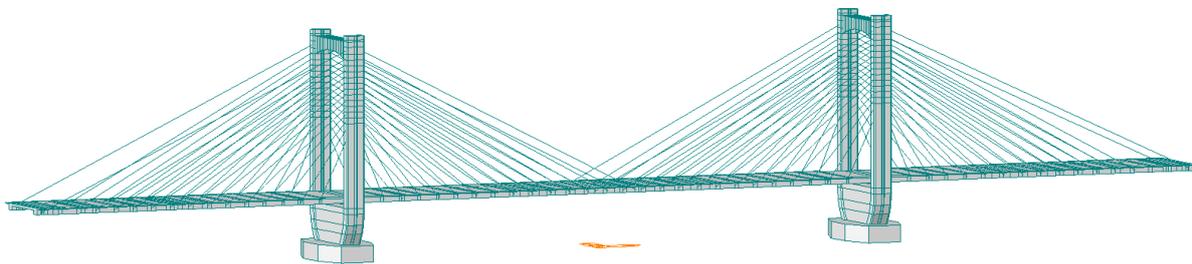


Fig.2 - Midas model diagram.

## THEORY RELATED TO MULTI-POINT BRACED SWIVEL WEIGHING EXPERIMENTS

### Test method of unbalanced moment of swivel

It is impossible to achieve complete symmetry on both sides of the swivel's spherical hinge during the construction process of a now-poured beam, so an unbalanced moment may occur, which is not conducive to the safe construction of a swivel. To ensure construction safety, it is essential to conduct an unbalanced moment test before swiveling, followed by a counterweight design based on the tested unbalance moment [13]. The test methods of unbalanced moment are as follows: (i) the method based on the stress difference at the root of the main beam; (ii) the method utilizing deflection estimation; and (iii) the spherical hinge rotation test method.

#### 1. The method based on the stress difference at the root of the main beam

The method based on the stress difference at the root of the main beam uses the principle that when pure bending occurs in the main beam, the bending normal stress varies linearly along the height of the beam. The unbalanced moment of the swivel structure is calculated using the stress difference at the root of the main beam.

#### 2. The method utilizing deflection estimation

The fundamental principle of deflection estimation is that after constructing a bridge using the horizontal swivel method, before and after the demolition of the brackets, the beam bodies on both cantilevers ends only produce elastic rotation around the spherical hinge and no other rotation parameters; thus, it is assumed that the difference in deflection between the two cantilever ends is due to the difference in the self-weight of the concrete.

#### 3. The spherical hinge rotation test method

Currently, the bridges constructed by the horizontal swivel method generally use the spherical hinge rotation test method to predict the unbalanced moment and the friction moment of the spherical hinge [14]~[16]. The fundamental principle is the theory of rigid body displacement mutation. This approach

solely considers the rigid body's displacement mutation, ignoring the effect of other factors, and has a high degree of precision, which satisfies the swivel's requirements.

Liu Jian [17] compared all three methods and concluded that the spherical hinge rotation test method is the most accurate. Combined with the construction situation, this project uses the spherical hinge rotation test method for weighing experiments.

### Derivation of weighing experiment formula based on spherical hinge rotation method

The spherical hinge rotation method is widely used as a test method for weighing experiments. The specific derivation process of its equation is as follows:

After demolishing the temporary consolidation of the upper swivel structure, which was generated by the boost counterforce seat, the following circumstances will be faced:

#### 1. Calculation of the moment when the spherical hinge frictional moment $M_z >$ the rotational unbalance moment $M_g$ :

As shown in Figure 3, an example of a single point braced swivel weighing.

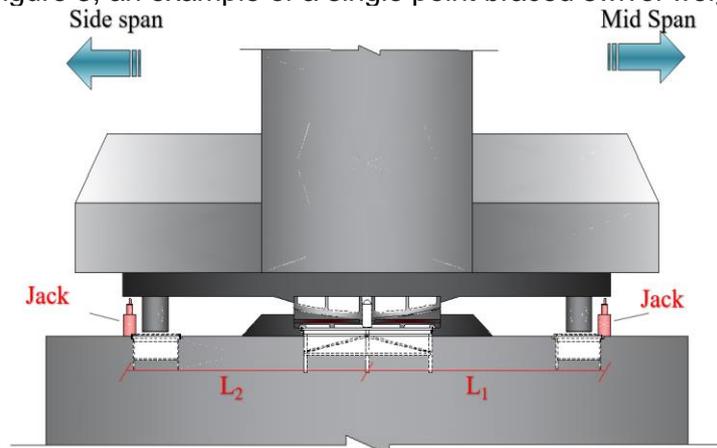


Fig.3 - Schematic diagram of single point braced swivel weighing

In Figure 3  $L_1$  is the distance from the jack to the spherical hinge centre in mid-span;  $L_2$  is the distance from the jack to the spherical hinge centre in the side-span; Jack is used to apply jacking force; The jack's loading point is situated in the upper foundation slab part on the outside of the arm-brace.

It is assumed that the centre of rotation is biased towards the mid-span direction, and the jacking force  $P_1$  is applied to the foundation slab in the mid-span direction. When the jacking force  $P_1$  is progressively increased to the moment when the spherical hinge experiences a slight rotation, that is,  $M_z$  and  $M_g$  in different direction, it will be obtained according to the principle of moment balance that:

$$P_1 L_1 + M_g = M_z \quad (1)$$

It is assumed that the centre of rotation is biased towards the side-span direction, and the jacking force  $P_2$  is applied to the foundation slab in the side-span direction. When the jacking force  $P_2$  is progressively increased to the moment when the spherical hinge experiences a slight rotation, that is,  $M_z$  and  $M_g$  in the same direction, it will be obtained according to the principle of moment balance:

$$P_2 L_2 = M_g + M_z \quad (2)$$

Combining the (1) and (2) equations, we can obtain:

$$M_g = \frac{P_2 L_2 - P_1 L_1}{2} \quad (3)$$

$$M_z = \frac{P_2 L_2 + P_1 L_1}{2} \quad (4)$$

## 2. Calculation of the moment when the spherical hinge frictional moment $M_z <$ the rotational unbalance moment $M_g$ :

The counterweights of the single-point and multi-point braced swivel are not the same. Before the weighing experiment, the multi-point braced swivel needs a larger counterweight to raise one end of the main beam.

Because of the giant counterweight of the multi-point braced swivel, only one instance exists, the spherical hinge frictional moment  $M_z <$  the rotational unbalance moment  $M_g$ . As a result, it is challenging to balance the structure with the spherical hinge frictional moment  $M_z$  alone. However, the structure will be re-balanced when the two arm-braces on the mid-span counterweight side contact with the lower foundation slab's slideway to provide the support moment for the structure. Therefore, the arrangement of the jacks is different from the single point braced swivel, which only needs to be arranged on one side, as shown in Figure 4.

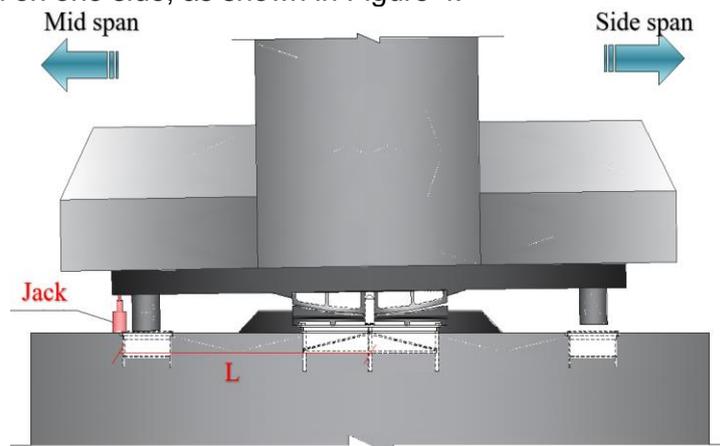


Fig.4 - Schematic diagram of multi-point braced swivel weighing

In Figure 4  $L$  is the distance from the jack to the spherical hinge centre in mid-span.

The theoretical derivation is as follows:

(1) When the jack is loaded on the mid-span side to cause the mid-span side to rise to a slight rotation, that is,  $M_z$  and  $M_g$  in the same direction, according to the principle of moment balance, it will be obtained:

$$PL = M_g + M_z \quad (5)$$

In the formula:  $P$  is the critical force when the jack is loaded to the point of slight rotation, kN.

(2) When the jack is unloaded on the mid-span side to cause the mid-span side to drop down to a slight rotation, that is,  $M_z$  and  $M_g$  in the different directions, according to the principle of moment balance, it will be obtained:

$$P_3 L = M_g - M_z \quad (6)$$

In the formula:  $P_3$  is the critical force when the jack is unloaded to the point of slight rotation, kN. Combining the (5) and (6) equations, we can obtain:

$$M_g = \frac{(P + P_3)L}{2} \quad (7)$$

$$M_z = \frac{(P - P_3)L}{2} \quad (8)$$

There were partial minor vertical rotations because the Tower ten of the bridge needed counterweights before the weighing experiment. The model of spherical hinge frictional moment [18] is shown in Figure 5.

As shown on the right-hand side of Figure 5., the spherical surface of the spherical hinge is differentiated into tiny circles, and the moments of several circles to the centre O of the upper spherical hinge are summed, yielding the moment equation:

$$dM_z = R \cos \theta dF \quad (9)$$

Integrating Formula (9), we can obtain:

$$M_z = \int_0^\alpha \frac{2\mu_0 GR}{\sin^2 \alpha} \sin \theta \cos^2 \theta d\theta = \frac{2(1 - \cos^3 \alpha)}{3 \sin^2 \alpha} \mu_0 GR \quad (10)$$

In the formula:  $\mu_0$  is the maximum static friction coefficient of the spherical hinge;  $\alpha$  is half of the central angle of the spherical hinge, °;  $R$  is the radius of the spherical hinge, m.

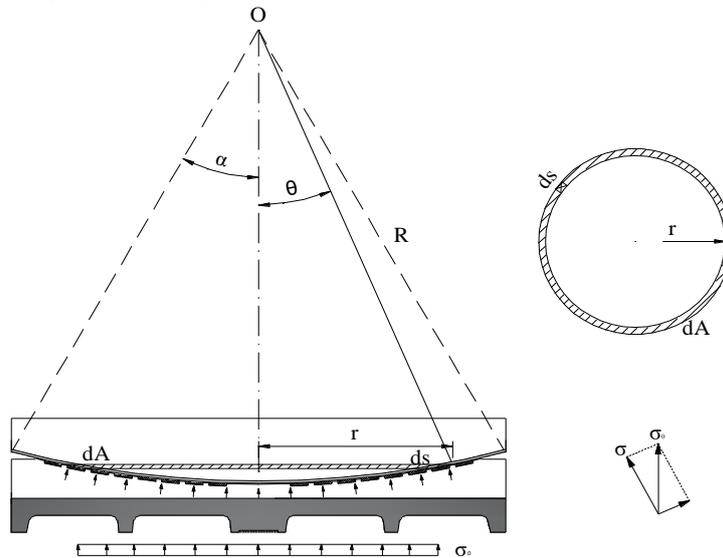


Fig.5 - Model for the frictional moment of a spherical hinge

The eccentricity of the rotating system is calculated as follows:

$$e = \frac{M_g}{G} \quad (11)$$

In the formula:  $e$  is the eccentricity of the rotating system, m;  $G$  is the weight of the swivel, kN. After counterweighting, the moment provided by the counterweight is added to the unbalanced moment, and the eccentricity of the rotating system is calculated as follows:

$$e' = \frac{G_1 l + M_g}{G + G_1} \quad (12)$$

In the formula:  $e'$  is the eccentricity of the rotating system after the weighing experiment, m;  $G_1$  is the weight of the counterweight of the weighing experiment, kN.

## MULTI-POINT BRACED SWIVEL UNBALANCED WEIGHING EXPERIMENT

### Preparation before weighing experiment

Based on the actual conditions of this bridge, the distance between the main beams of Tower ten's side span and the metal catenaries of the high-speed rail below it at their closest point is only 151 mm, posing a collision risk during rotation; thus, the distance between the main beams and the metal catenaries must be increased. As a result, it is calculated that 1,603 tons of concrete heavy blocks must be placed on the main beam of Tower ten's midspan side before the weighing experiment. Because spherical hinges and arm-braces were not simulated in Midas Civil, a comparison of the values in the overall rod system model before and after balancing the counterweights, taking only the rigidity of the main beams into account, revealed that the height of the main beams of the side span of Tower ten and the metal catenaries of high speed rail at their closest point increased by 57mm. Assuming that the integral rigidity is infinite, according to the similar triangle principle, when the arm-braces dropped 20mm to contact the slideway, the closest point of the metal catenaries of the high speed rail and the main beams of Tower ten would rise  $20/6500 \times 90630 \approx 279\text{mm}$  (by measuring, the distance from the nearest point of the metal catenaries and the main beams to the centre line of Tower ten of the bridge is 90.63m, the radius of the slideway centre is 6.5m). In conclusion, the closest point of the metal catenaries of the high-speed rail and the main beams of the side-span was lifted by a total of 336 mm by placing 1,603 tons of concrete heavy blocks on the main beams of the mid-span side of Tower ten before the weighing experiment and considering the factors of the contact between the drop of the arm-braces and the slideway and the stiffness of the main beam. The photographs of the counterweight on site in Tower ten are shown in Figure 6.



*Fig. 6 - Photographs of the counterweight on site in Tower ten*

After Tower ten's counterweight was completed, the temporary loads were taken from the beam body, the steel tube brackets were removed, and the closure facilities were installed. Following the principle of symmetry, the temporary consolidation of the spherical hinge was eliminated, including the brackets of the spherical hinge, the brackets of the arm-braces, the sand bucket, etc., to ensure the free fall of the swivel structure in the vertical direction and avoid the artificial eccentricity and the beam body in the inclined state. During the process of removing the temporary consolidation, the status of the swivel structure was determined by monitoring the displacement of the beam end and the change in the space between arm-braces in real-time. After the removal was complete, monitoring data were used to assess whether the beam body was in equilibrium; the weighing experiment could be performed only when it was in equilibrium [19].

### Test loading and measuring point arrangement

Considering a series of factors such as site conditions, before the weighing experiments, eight sets of 5000 kN jacks were symmetrically placed on both sides of the swivel of Tower nine, with the centerline of the bridge as the axis of symmetry. Four sets of 5000 kN jacks were symmetrically placed on the mid-span side of the swivel of Tower ten, with the centerline of the

bridge as the axis of symmetry, which were used to jack up the swivel and to test the values of the reaction force of the temporary fulcrum during the weighing experiments. The layout of the weighing experiment test devices for Tower nine and Tower ten are shown in Figure 7 and Figure 8 respectively.

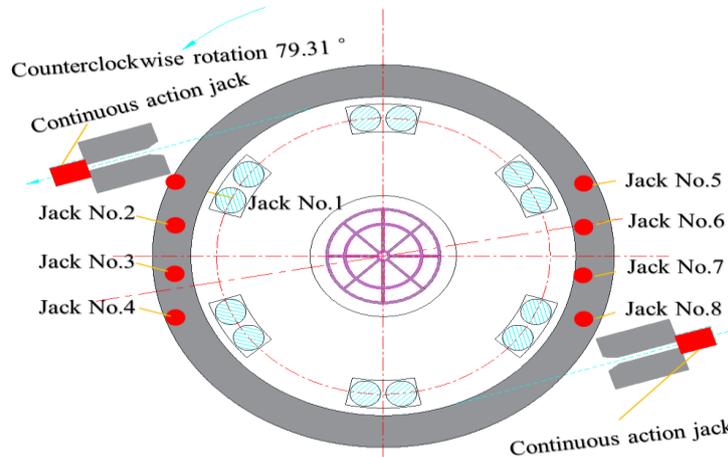


Fig.7 - The layout of the weighing experiment test instruments for Tower nine

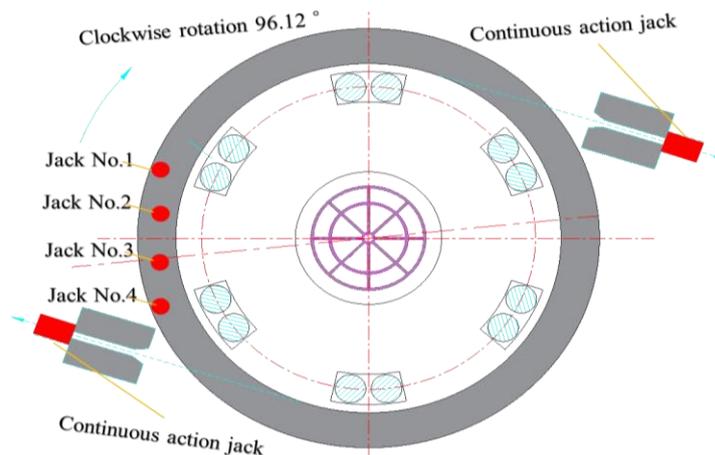


Fig.8 - The layout of the weighing experiment test instruments for Tower ten

Four displacement sensors were placed on both sides of the arm-braces to measure the vertical displacement at each loading stage to ensure the accuracy of the experiment results. Four horizontal displacement sensors were placed on adjacent positions to record the corresponding horizontal displacement at each loading stage, which was used to comprehensively judge the critical state of spherical hinge rotation and reasonably determine the value of critical force. The displacement sensors adopted wireless displacement sensors (range: 0-50 mm, resolution: 0.01/0.005, measuring force: < 2.2 N). The layout of displacement sensors is shown in Figure 9 and Figure 10.

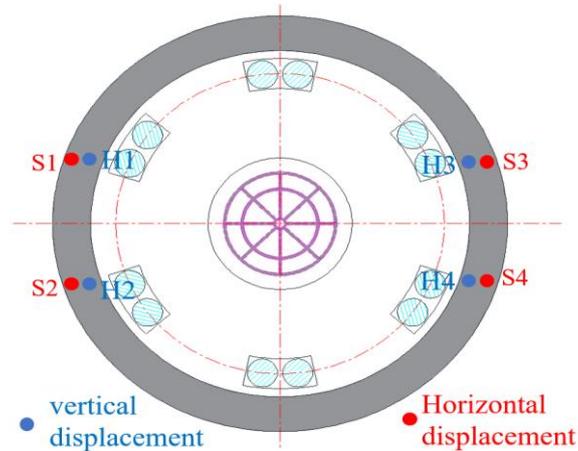


Fig.9 - The layout of displacement sensor

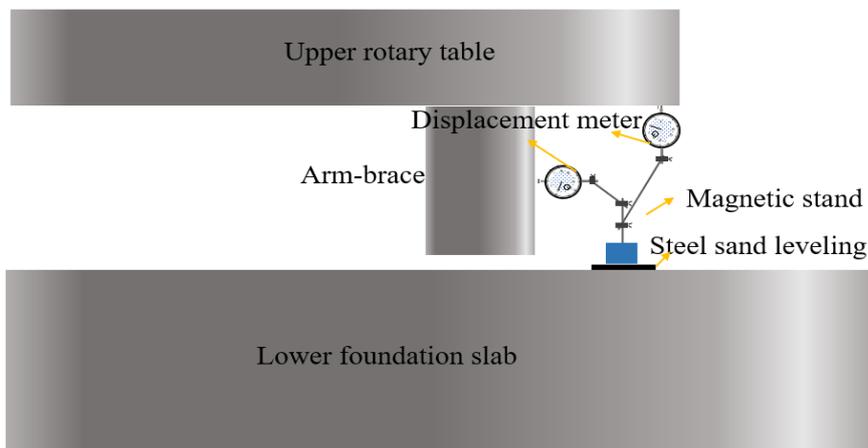


Fig.10 - Side view of displacement sensor arrangement

## Experimental procedure

All displacement sensors were reset to zero after the device was set up. After the initial readings were taken, the jacking equipment was synchronously jacked up and held load when loaded to 100 kN. At that point, the values of the horizontal and vertical displacement sensors were read, and the corresponding jacking forces were recorded simultaneously. Following the preceding method, the displacement and load values were read every 100 kN until there was a sudden change in the vertical and horizontal displacement sensor readings. At that point, the critical load (the value of  $P1$ ) and displacement were recorded, followed by continued loading and counting at 100 kN per level and unloading after three-level loading. If the swivel was to be carried out in the conventional way, the remaining four jacking equipment would need to be positioned in jacking positions 5 to 8, loaded and counted according to the preceding method, and the critical force (the value of  $P2$ ) and displacement would be recorded. The multi-point swivel, on the other hand, needed only that the jack be placed in positions 1 to 4, and the critical force (the values of  $P$  and  $P3$ ) could be determined by loading and unloading the jack. The jack positions are shown in Figure 7 and Figure 8 The flow chart of the weighing experiment is shown in Figure 11.

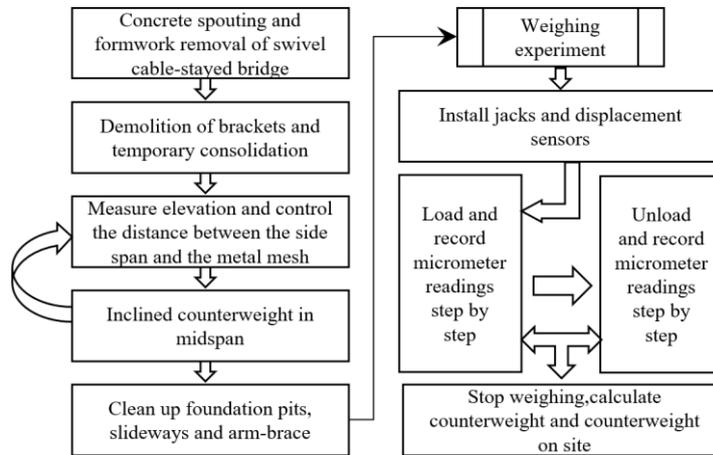


Fig.11 - Flow chart of weighing experiment

## RESULTS ANALYSIS

Weighing experiment data are analyzed to determine the rotational unbalance moment  $Mg$ , the spherical hinge frictional moment  $Mz$ , and the friction coefficient of the spherical hinges  $u$ .

### Experimentation results

The jacking force at the limit state is determined using the weighing experiment's jacking force-vertical displacement curve. When performing a comprehensive evaluation, it is necessary to use the jacking force-horizontal displacement curve and the jacking force-vertical displacement curve to minimize errors in determining the jacking force when the experimental data is more complicated. Occasionally, during the weighing experiments, it is necessary to combine the disturbance of the beam body and the stability of the sustained load of the jacks [19].

This study focuses on the analysis of the multi-point braced swivel weighing experiment based on the traditional single-point braced swivel weighing experiment.

#### 1. Results of the weighing experiment at Tower nine

The weighing results of Tower nine under a single-point braced swivel were documented based on the on-site weighing situation. According to the records, the mutation value  $P_2$  during the jacking-up process in the mid-span side of Tower nine is 4200 kN, and the mutation value  $P_1$  during the jacking-up process in the side-span side of Tower nine is 1700 kN.

Tower nine used the single-point braced swivel weighing method, and the relevant parameters of the weighing experiment are shown in Table 1.

Tab. 1 - Parameters for weighing experiment on Tower nine

Parameters		Units	Remarks
$L_2$	8.00	m	Distance from jack to spherical hinge center in side - span
$L_1$	8.00	m	Distance from jack to spherical hinge center in mid - span
$P_2$	4200	kN	Critical force when the jack is loaded to the point of slight rotation in side-span
$P_1$	1700	kN	Critical force when the jack is loaded to the point of slight rotation in mid-span
$G$	280000	kN	Total weight of the swivel
$R$	9	m	Spherical radius of the spherical hinge

Parameters		Units	Remarks
$\alpha$	13.59	°	Half of the central angle of the spherical hinge

By substituting the values from Table 1. into equations (3), (4), (10) and (11).

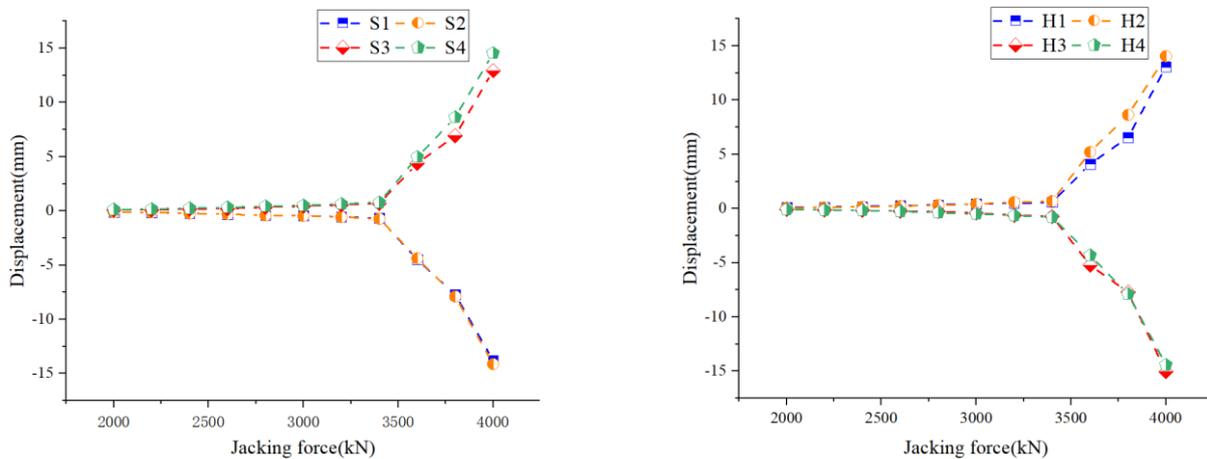
The results of the weighing experiment calculations are collated in Table 2.

Tab. 2 - Data analysis from weighing results of Tower nine

Parameters		Units	Remarks
$Mg$	10000.0	kN·m	
$Mz$	23600.0	kN·m	
$e$	0.036	m	Bias towards the mid-span side
$u$	0.0095		

## 2. Results of the weighing experiment at Tower ten

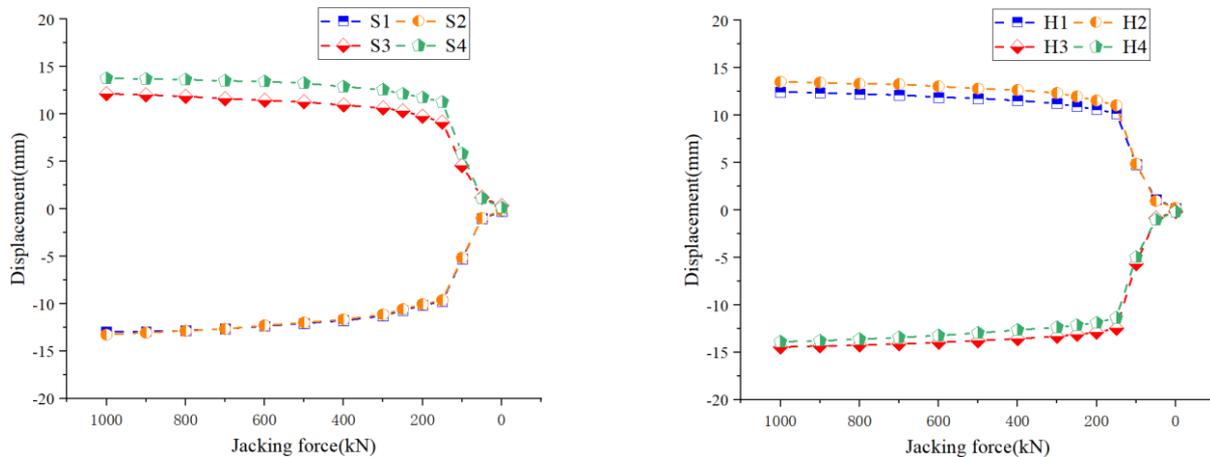
Unlike the traditional single-point braced swivel weighing experiment, the multi-point braced swivel weighing experiment only required jacks to be placed on one side for loading and unloading. The weighing results of Tower ten under a multi-point braced swivel were documented based on the on-site weighing situation. During the loading procedure, the jacking force and the values of displacement meters S and H on both sides were recorded in real-time. Four displacement meters, two by two on each side, are accordingly divided into four groups, numbered loading groups 1 to 4, and their jacking force and displacement changes are plotted as shown in Figure 12 and Figure 13.



(a) horizontal displacement

(b) vertical displacement

Fig. 12 - Jacking force-displacement diagram for the mid-span side of Tower ten after jacks loading



(a) horizontal displacement

(b) vertical displacement

Fig.13 - Jacking force-displacement diagram for the mid-span side of Tower ten after jacks unloading

From the above loading displacement diagrams, it can be seen that the mutation value  $P$  in the process of the jacking-up in the mid-span side of tower ten is 3400 kN, and the mutation value  $P_3$  in the process of the jacking-up in the side-span side of tower ten is 150 kN.

Tower ten used the multi-point point braced swivel weighing method, and the relevant parameters of the weighing experiment are shown in Table 3.

Tab. 3 - Parameters for weighing experiment on Tower ten

Parameters		Units	Remarks
$L$	8.00	m	Distance from jack to spherical hinge center
$P$	3400	kN	Critical force when the jack is loaded to the point of slight rotation
$P_3$	150	kN	Critical force when the jack is unloaded to the point of slight rotation
$G$	280000	kN	Total weight of the swivel
$R$	9	m	Spherical radius of the spherical hinge
$\alpha$	13.59	°	Half of the central angle of the spherical hinge

By substituting the values from Table 3 into equations (7), (8), (10) and (11).

The results of the weighing experiment calculations are collated in Table 4.

Tab. 4 - Data analysis from weighing results of Tower ten

Parameters		Units	Remarks
$Mg$	14200.0	kN·m	
$Mz$	13000.0	kN·m	
$e$	0.051	m	Bias towards the mid-span side
$u$	0.0052		

### Setting of the eccentricity of the center of gravity and adjustment of the counterweight

According to the results of the unbalanced weighing and the actual situation on site, Tower nine adopted a balanced counterweight scheme for the beam, with the eccentric distance generally controlled at 0~5 cm, the calculated eccentric distance based on the findings of the weighing

experiment is approximately 0.036 m (bias towards the mid-span side), which satisfies code requirements [20]. Hence no counterweight is carried out.

The beam of Tower ten adopted a longitudinal tilt counterweight arrangement, with eccentric distances generally controlled at 5~15 cm. It is calculated that the bridge is counterweighted by 20 tons at 80 m from the centreline of the bridge at mid-span. After counterweighting, the system can be recalculated using Equation (12) to produce a new eccentricity of approximately 0.108 m (bias towards the mid-span side), which satisfies code requirements [20].

## CONCLUSION

A twin-tower and double-cable prestressed concrete swivel cable-stayed bridge with a span combination of (118 + 198 + 118)m was used for the project. A combination of single-point braced, and multi-point braced swivelling weighing experiments was used to determine the spherical hinge frictional moment  $M_z$ , the rotational unbalance moment  $M_g$ , the eccentricity of the rotating system  $e$ , and the maximum static friction coefficient of the spherical hinge  $u$ , and the structural counterweight was adjusted based on the experiment results. Finally, Tower nine successfully rotated counterclockwise  $79.31^\circ$ , with a rotational angular velocity ranging from 0.015 rad/min to 0.023 rad/min. Tower ten successfully rotated clockwise  $96.12^\circ$ , with a rotational angular velocity ranging from 0.015 rad/min to 0.024 rad/min. Both towers demonstrated stable rotational angular velocities throughout the swiveling process, guaranteeing the successful completion of the structural swivel and uninterrupted operation of the existing line. Therefore, the multi-point braced swivel weighing experiment, involving the combined forces of the arm-braces and spherical hinges, can be effectively applied in scenarios where a horizontally swiveled bridge encounters rotation across existing lines, specific obstacles, or slight elevation differences between the bottom of the beam and the obstacles. Accordingly, this method also provides an important reference value for the construction of similar bridges in the future.

## ACKNOWLEDGMENTS

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