Concrete spherical joint contact stress distribution and overturning moment of swing bridge

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\textbf{A B S T R A C T}

The present study aims to address the instability mode of the concrete spherical joint in order to guarantee the safety of the rotating process of the swing bridge. A new critical overturning moment model is proposed to calculate the overturning moment of swing bridge based on the non-Hertz contact theory, and it is validated against the engineering application of the Nandu River Swing Bridge construction. The research indicates that the non-Hertz contact theory has superiority compared to the widely applied simplified formulation on the spherical joint surface stress calculation, by contrasting the results of the finite element model and the data collected during field monitoring. Furthermore, the resistance of the overturning coefficient is calculated, and the result turns out that the critical resistance of the overturning coefficient based on the non-Hertz contact theory is closer to the measured values compared to the simplified algorithm. The present research demonstrates the applicability of applying the new proposed formula to guarantee the safety of the rotating process during the swing bridge construction.

\section{1. Introduction}

Rotating method\cite{1-4} is an innovative bridge construction method that gains increasing popularity in recent years. The bridge that is under construction is separated into two rotating systems, which are built on each side of the surrounding terrain respectively and then rotated to the bridge axis to butt at the proper time (Fig. 1). The swing bridge construction method not only can enforce a strong spanning ability but also can make full use of the surrounding terrain to build the main structure, by which the construction of a large number of brackets in rivers and valleys can be avoided. So the rotating construction method is particularly applicable in mountainous areas, traffic inconvenience, construction site constraints, etc.\cite{5,6}. During the bridge rotating process (Fig. 2), the two bridge sections form an integral system with a spherical joint bearing the weight of the whole bridge (Fig. 3). Therefore, the swing process is the most critical stage in the entire bridge construction, and the rotating system may overturn when the system resistance of overturning ability is not sufficient\cite{7}.

During the design stage of the bridge, the resistance of the overturning moment must be calculated, in order to avoid the structural overturn and collapse in the rotating process\cite{8}. In addition, the slight tilt of the rotating system must be controlled\cite{9,10,11}. The contact stress distribution of the spherical joint is the key parameter to calculate the fractional moment of the spherical joint, and the resistance of the overturning moment is provided by the fractional moment. Thus, accurate prediction of contact stress and resistance of overturning moment are both critical issues in the rotating process concerning the construction safety of the swing bridge. Fuchs\cite{12} and Patsch et al.\cite{13} studied designing and constructing process of swing bridge, but the monitoring process was not addressed. Shi et al.\cite{14} carried out a case study about the overturning moment of the bridge under heavy vehicles, and they proposed that the second-order effects due to girder rotation should be considered when calculating the resistance of overturning moment. Mohsen\cite{15} investigated the overturning moment caused by tsunami loads, and a new design protocol was proposed to compute the maximum horizontal force, vertical force and overturning moment. Cai\cite{16} developed a two-dimensional (2D) fluid-structure interaction (FSI) model and validated it using experimental data and the significance of the negative overturning moment was revealed. These researches show the significance of the overturning moment of the bridge caused by

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limited to the case where the contact surfaces are very small. In the from Hertz spherical joint. Spherical joint surface contact problem was originated the spherical joint can accurately predict the frictional resistance of the accurate prediction of the contact stress distribution on the surface of is provided by the frictional resistance of the spherical joint. Therefore, which potentially may result in the collapse of the bridge during the rotating process .

During the rotating process, the overturning resistance of the bridge is provided by the frictional resistance of the spherical joint. Therefore, accurate prediction of the contact stress distribution on the surface of the spherical joint can accurately predict the frictional resistance of the spherical joint. Spherical joint surface contact problem was originated from Hertz’s research about contact with elastic solids . He found that the contact area of two in-conformal contact elastic surfaces was ellipted and named the elliptical major semi-axis ‘a’ as contact bandwidth, which was used to describe the magnitude of the contact area. Thus, the analytical solution of two in-conformal contact elastic surfaces under normal pressure is obtained, but the Hertz contact theory is limited to the case where the contact surfaces are very small. In the

external effect, but few studies concerned about the overturning moment in the rotating process of the swing bridge. Che [17] studied the overturning moment problem of swing bridge during the construction process, and a vertical compressive stress formula on the contact surface of spherical joints was deduced by using the boundary action concentration theory of half-space body, and then a formula of the critical overturning moment was derived. But the formula was based on an approximate calculating principle, which easily resulted in the overestimation of the critical overturning moment. Thus the calculated result of resistance of the overturning coefficient used to estimate the resistance of overturning ability would be higher than the actual value, which potentially may result in the collapse of the bridge during the rotating process [18].

The present study aims to provide a more accurate approach for the calculation of contact stresses and enhance the safety of the rotating process during the swing bridge construction. To characterize the distribution of spherical joints precisely, the Non-Hertz contact theory is firstly used to calculate the spherical conformal contact stress on the surface of spherical joints. The results of contact stress distribution are compared with the simplified algorithm and the finite element model results, which turn out that the Non-Hertz contact theory is more accurate than the simplified algorithm. Then a new critical overturning moment formula of bridge based on Non-Hertz contact theory is proposed, and results show that the critical resistance of overturning coefficient of bridge calculated from the new formula is closer to the on-site measurement that contributes to improved safety in terms of the overturning moment, preventing overestimation of overturning resistance ability. In the Supplementary material, the stress distributions and proposed formula for overturning moment calculation are also verified by literature case study [29].
2. Spherical joint instability and overturning resistance system

2.1. Spherical joint instability

The problem of spherical joint instability was investigated in many fields [30]. There are two types of instability in the course of bridge rotation [31] (Fig. 4).

(1) Spherical joint instability: Before the supporting foot has landed, the entire bridge body will rotate around the spherical joint.

(2) Supporting foot fulcrum instability: Supporting foot lands on the slideway, the entire bridge overturns around the foot fulcrum.

The rotating process should ensure that the supporting foot does not fall onto the slideway, because the friction between the supporting foot and slideway is too large, and is not conducive to the smooth rotation of the bridge [32]. Moreover, the calculation of the supporting foot fulcrum instability is relatively simple. Therefore, the spherical joint instability condition is only considered in this study.

![Fig. 4. Types of instability.](image)

![Fig. 5. Overturning moment of rotating system (without spherical joint). The dotted line represents the original position, and the solid line represents the current state.](image)

![Fig. 6. Resistance system of the overturning moment (R – Radius of the spherical joint, R’ – Plane radius of the spherical joint, α – Angle of the outer edge of the spherical joint, θ – Angle of the spherical joint).](image)
2.2. Resistance system of overturning moment

When the center of gravity of the rotating system is not at the center of the spherical-joint grinding center, the eccentric distance of the rotating system causes the overturning moment of the whole rotating system. Since the rotating process is the most critical and dangerous construction stage in the construction of the rotating bridge, the inclination of the whole rotating system should be monitored in real time during the rotating process. The change of elevation angle can be used to indicate the change of the overturning moment of the rotating system. The relationship between the overturning moment and the inclination of the back wall is shown in Fig. 5.

The calculation formula of the overturning moment and back wall inclination angle is:

\[ M_1 = Ge \]  \hspace{1cm} (1)

\[ e = \sin \delta \]  \hspace{1cm} (2)

In which: \( M_1 \) is overturning moment. \( M_2 \) is the resistance of overturning moment, namely, friction moment of spherical joint. \( e \) is the eccentric distance. \( F_2 \) is the Supporting force. \( G \) is the mass of back wall. \( l \) is the gravity center height of rotating system. \( \delta \) is the inclination of the back wall.

The overturning resistance system of the swinging bridge is composed of an annular slideway, several supporting feet, and a locating pin, as shown in Fig. 6. When the supporting foot of the rotating bridge does not touch the ground, the overturning resistance moment is provided by the friction moment of the spherical joint; when the supporting foot touches the ground, the overturning resistance ability of the rotating system reaches the maximum, and the supporting foot is the last barrier of the overturning resistance system.

3. Algorithms for the calculation of contact stress

3.1. Simplified algorithm of spherical-joint stress

In the Chinese bridge monitoring standard [20], the contact surface of the spherical joint is simplified as a plane contact calculation model, and the stress of spherical joint is simplified as a plane uniformly distributed force, which is used to calculate the contact stress of two elastic infinite half-space bodies when they contact each other on two surfaces.

The stress distribution on the contact surface can be described as a simplified algorithm for spherical joint stress \( p \):

\[ p = \frac{F}{\pi R^2} \]  \hspace{1cm} (3)

In which: \( p \) is the maximum average contact stress. \( F \) is the total load. \( R \) is the horizontal radius of the spherical joint.

In the American standard [21], the stress distribution \( p \) of the spherical joint on the contact surface is described as:

\[ p = \frac{F}{\Phi \pi a^2} \]  \hspace{1cm} (4)

In which: \( \Phi \) is the resistance factor, there is very little experimental evidence to precisely define \( \Phi \) for each limit state. \( \Phi \) is often taken to be equal to 1.0 in many situations.

Thus, Eq. (3) is equal to Eq. (4), in other words, the stress of the spherical joint is simplified as a plane to conveniently calculate the contact stress in the actual construction process. The stress \( p \) is the maximum average contact stress, so the calculation result is conservative, therefore it may lead to the computation deviation of the fraction moment.

3.2. Non-Hertz contact theory

Non-Hertz contact theory is named relative to Hertz theory. It deals with the contact stress problem depending on the load contact area. The Non-Hertz contact theory calculation model is suitable for conformal contact, which means the curvature center of two contact bodies is on the same side of the contact surface, and its curvature radius is closed.

The conforming surface contact shape cannot be expressed completely by quadratic polynomial [19], but by the following formula, the initial clearance of the axisymmetric structure is \( S = A_1 x^2 + A_2 x^4 + \ldots + A_n x^{2n} + \ldots \).

The calculation can be carried out by only taking the first 2 items and ignoring the other items, without affecting the precision of the results [28].

\[ S = A_1 x^2 + A_2 x^4 \]  \hspace{1cm} (5)

In Eq. (5), \( A_1 \) and \( A_2 \) are quadratic parabolic coefficients. For two-dimensional axisymmetric shapes in the form of \( A_n x^{2n} \) the total load function and its pressure distribution curve are obtained [22]:

\[ F_n = \frac{4nE_A A_{2n+1}}{2n+1} \frac{2\cdot4\cdot\ldots\cdot2n}{1\cdot3\cdot\ldots\cdot(2n-1)} \]  \hspace{1cm} (6)

\[ p_2(x) = \frac{nE_A A_{2n-2}}{\pi} \left[ \frac{2\cdot4\cdot\ldots\cdot2n}{1\cdot3\cdot\ldots\cdot(2n-1)} \right]^2 \left( \frac{4}{3} x^{2n-2} + \frac{3}{2} x^{2n-4} + \ldots + \frac{1\cdot3\cdot\ldots\cdot(2n-3)}{2\cdot4\cdot\ldots\cdot(2n-2)} x^{2n-4} \right) \]  \hspace{1cm} (7)

In which: \( F_n \) is the total load. \( \alpha \) is the contact bandwidth. \( E \) is the equivalent modulus of elasticity. \( A_n \) is the coefficient of \( x^{2n} \).

\[ \frac{1}{E} = \frac{1}{E_1} + \frac{1}{E_2} \]  \hspace{1cm} (8)

\[ A_2 = \frac{R_2^2 - R_1^2}{8R_1^2 R_2^2} \]  \hspace{1cm} (9)

In which: \( E_1 \) & \( E_2 \) are the elastic modulus of two elastic bodies, respectively. \( \mu_1 \& \mu_2 \) are the poisson’s ratio of two elastic bodies, respectively. \( R_1 \& R_2 \) are the radius of the contact surface, respectively.

The resultant force \( F \) and stress distribution \( p(x) \) can be solved by using \( n = 2 \) into Eqs. (6) and (7).

\[ F = \frac{64}{15} E A_2 \alpha^2 \]  \hspace{1cm} (10)
Structures 28 (2020) 1187–1195

E∗A2 \frac{128}{9\pi} \left( \frac{a^2}{x^2} + 1 \right) \left( a^2 - x^2 \right)^{\frac{1}{2}} \tag{11} 

Eq. (6) can be rewritten, yielding the contact bandwidth \( a \):

\[
a = \sqrt{\frac{15F}{64E^*A_2}} \tag{12}
\]

3.3. Finite element model

The 3D model of the concrete spherical joint is established by using the ABAQUS finite element model, which is an important method to calculate the contact force [33–35]. The length unit of the model is mm, the corresponding unit of force is N, and the unit of stress is MPa. As shown in Figs. 7 and 8, the upper spherical joint is a concave sphere with a missing surface corresponding to the lower spherical joint. The lower spherical joint, the upper spherical joint, and the locating pin are assembled. The model has 10,000 C3D8I entity units in total.

The total load applied to the model is 59600 KN, and the radius of the upper spherical joint is 1300 mm, thus uniformly distributed stress on the top surface of the upper spherical joint is 11.23 N/mm². In order to make the convergence of the simulating model, 10KN force is applied on the surface of the upper spherical joint, eliminating the calculation errors by the initial clearance between the upper and lower spherical joints [33].

The internal contact is modeled as a deformable/deformable contact [36], assuming that both spherical joints (C45 cement) have equal elastic properties, with a Young modulus of \( 3.35 \times 10^{10} \) Pa and a Poisson ratio of 0.2. Concerning boundary conditions (BC), the displacement and rotation constraints are applied at the bottom surface of the lower spherical joint boundary. During the load application process, no damage will happen on the BC.

4. Comparative analysis of contact stress

4.1. Engineering background

The construction of the Nandu River Swing Bridge (190-meter main span) in Hubei province, China is studied in this research. The stress of the spherical joint of the swing bridge is calculated by the simplified algorithm, Non-Hertz contact theory, and finite element simulation model, respectively.

The size of the spherical joint part (unit: mm) is shown in Fig. 9.

![Fig. 9. Upper (left) and lower (right) spherical joint.](image)

![Fig. 10. R2 calculation sketch map.](image)
During the construction of the concrete spherical joint, the upper spherical joint, and the lower spherical joint grind each other continuously until the height difference \( d = 8 \text{ mm} \) at the edge, as shown in Fig. 10.

Therefore:

\[
R_1 - \sqrt{R_1^2 - R_2^2} - R_2 - \sqrt{R_2^2 - R_2'^2} \tag{13}
\]

In which, \( d = 8 \). The parameters of the rotation system are listed in Table 1.

4.2. Results analysis

When calculating the stress distribution of the spherical joint with Eq. (10), it is necessary to convert the load into the radial load of the spherical joint in a two-dimensional direction because it is a two-dimensional stress distribution formula, the two-dimensional \( F_{R'} \) of the axisymmetric load is calculated, as shown in Fig. 11:

The gravity of the rotating system is 5960000 N, therefore:

\[
59600000 = \int_0^{2\pi} F_{R'} \, d\theta
\]

\( 2F_{R'} \) (the total load of the diameter direction) is brought into the Eq. (11), and the contact bandwidth is \( a = 1373.58 \text{ mm} \), however the Horizontal radius is 1300 mm, so \( a = 1300 \text{ mm} \).

The 3D model of the concrete spherical joint is established by using the ABAQUS finite element model. Before rotation, the spherical joint is static. If the center of gravity of the swing bridge is on the axis of the center of the spherical joint, the total weight of the rotating body is applied to the contact stress of the spherical joint, as shown in Fig. 12.

Vibrating wire stress sensors (downward lower spherical joint, red fork for the sensor) are installed in the concrete spherical joint of the Nandu River Swing Bridge to measure the contact stress of the spherical joint. The sensor arrangement is shown in Fig. 13.

In order to analyze the stress distribution at different distances from the spherical joint center, the results of all the algorithms and the measured data are statistically analyzed in Fig. 14.

The results of the contact stress on the surface of the spherical joint are shown in Table 2 (from sensors 1 to 5). The deviation in the table refers to the deviation with the observed data.

The following findings can be drawn from Fig. 14 and Table 2:

1. Overall deviation analysis: The deviations of various algorithms relative to the actual stress magnitude are in general more than 12%.
2. Respective deviation analysis: The deviation of the simplified algorithm is 17.7% except the No. 4 measurement sensor, and the deviation of other sensors is more than 40%. Especially the No. 3 measurement sensor is up to 212.8%. That is to say, the deviation of the simplified algorithm is too high for stress calculation and the stress prediction is too conservative.
3. The deviation of the FEM simulation calculation is above 20% except for the No. 3 and 4 measurement sensors, and the deviation of other sensors is more than 40%.
4. The deviation of the Non-Hertz contact theory calculation method is 152.6% at the center of spherical, and the deviation of stress prediction in another position is less than 22.3%.

Although the physical boundary analysis of the Non-Hertz contact theory is not very close to the FEM and actual situation, the results turn out that it has a smaller deviation than the simplified algorithm in the physical boundary.

From the above comparisons, the deviation of the Non-Hertz contact theory calculation results is less than that of the simplified algorithm,

### Table 1: Parameters of the rotation system.

| Upper spherical joint curvature (mm) | Lower spherical joint curvature (mm) | Horizontal radius (mm) | Locating pin diameter (mm) | Modulus of elasticity (MPa) | Rotating system gravity (KN) | Poisson’s Ratio |
|--------------------------------------|---------------------------------------|------------------------|---------------------------|-----------------------------|------------------------------|----------------|
| 8500                                 | 7878.07                               | 1300                   | 100                       | 33,500                      | 59,600                       | 0.2            |

Fig. 11. Load calculation sketch.

Fig. 12. Spherical joint contact stress cloud picture.

Fig. 13. Sensor arrangement, red labels are sensor number (mm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
about 20%, which is more conducive to grasp the distribution of contact stress on the spherical joint surface.

5. Overturning moment during rotating construction

5.1. Resistance of overturning moment formula deduction

5.1.1. Formula deduction based on the Non-Hertz contact theory

The geometry of the spherical joint is shown in Fig. 15.

On the micro-plane A, the micro frictional resistance \( f_1 \) can be calculated by:

\[
 df_1 = \mu \sigma ds
\]

In which \( ds = R^2 \sin \theta d\theta dy \), \( \mu \) is friction coefficient, therefore:

\[
 df_1 = \mu \sigma R^2 \sin \theta d\theta dy
\]

The resistance of overturning moment \( M_2 \) is

\[
 dM_2 = L df_1 = L \mu \sigma R^2 \sin \theta d\theta dy
\]

In which \( L \) is overturning arm, for every micro-plane \( L = \sqrt{\left(R \cos \theta\right)^2 + \left(R \sin \theta \sin \gamma\right)^2} \), and Eq. (11) is

\[
 \sigma = \frac{128E}{9\pi} \frac{A_a \alpha^2}{A} \left(\frac{x^2 + y^2}{a^2} + 1\right) \left(a^2 - x^2 - y^2\right)
\]

In which \( x^2 + y^2 = r^2 = (R \sin \theta)^2 \)

Therefore

\[
 \sigma = \frac{128E}{9\pi} \frac{A_a \alpha^2}{A} \left(\frac{R \sin \theta}{a}\right)^2 + 1 \left(a^2 - (R \sin \theta)^2\right)
\]

The whole bridge resistance of overturning moment is

\[
 \sigma = \frac{128E}{9\pi} \frac{A_a \alpha^2}{A} \left(\frac{R \sin \theta}{a}\right)^2 + 1 \left(a^2 - (R \sin \theta)^2\right)
\]
5.1.2. Formula deduction based on the simplified algorithm

If using the simplified algorithm, the stress is $\sigma = \frac{F}{\pi R^2}$, therefore

$$M_2 = \mu \int_0^{\beta} \int_0^{\alpha} \frac{128E^2 A \sigma^2}{9\pi} \left( \frac{\text{sin}^2 \theta}{a^2} + 1 \right) \pi \cdot (a^2 - (R\text{sin}\theta)^2)^{\frac{3}{2}} \pi \cdot \sqrt{(R\cos\theta)^2 + (R\text{sin}\theta)^2 \text{sin}^2 \theta} d\gamma$$

(19)

5.2. Inclination analysis of back wall

The inclination tracking system is arranged on the spot for the rotating system of Nandu River Swing Bridge to track the change of the inclination angle of the back wall in the rotating process and to judge the change of the overturning moment of the rotating system in real time. When the inclination angle of the rotating system is too large, the inclination angle of the rotating system can be corrected in real time to ensure the safety, stability, and smoothness of the rotating system. The parameters of the rotating system are shown in Table 3.

| Parameter | Friction coefficient $\mu$ | Gravity Height | Gravitation of rotating system |
|-----------|---------------------------|----------------|-------------------------------|
| Value     | 0.1                       | 17.802 m       | 59600 KN                      |

Spherical joint $R = 8500$ mm, contact bandwidth $a = 1300$ mm, the upper and lower limit of $\theta$ is $\alpha = \text{Arcsin}(50/8500)$, $\beta = \text{Arcsin}(1300/8500)$. Substituting all parameters in Eq. (17) and using Mathematica software yields the resistance of overturning moment $M_{\text{non-Hertz}} = 4499.79$ KN-m. Substituting all parameters in Eq. (18) yields the resistance of overturning moment $M_{\text{simplified}} = 6327.84$ KN-m.

The inclination angle of the back wall is measured, and the overturning moment of the back wall in the direction of X (along the bridge) and Y (across the bridge) can be calculated by Eqs. (1) and (2). The results are shown in Fig. 16:

From Fig. 16, at the 480 min. of rotating process, the maximum inclination angle appeared. Eqs. (1) and (2) are used to calculate the maximum overturning moment yielding the maximum value of 2094.38 KN-m, which is smaller than the resistance of the overturning moment. Therefore, the rotating system remains safe during the entire rotating process. The spherical joint resistance of overturning coefficient $K$ is:

$$K = \frac{\text{Critical overturning moment}}{\text{Actual maximum overturning moment}}$$

(21)

Therefore

$$K_{\text{non-Hertz}} = \frac{4499.79}{2094.38} = 2.15$$

$$K_{\text{simplified}} = \frac{6327.84}{2094.38} = 3.02$$

From the calculation results of the resistance of the overturning coefficient based on the simplified algorithm, it can be seen that the resistance of overturning coefficient had been overestimated by the simplified algorithm. Therefore, the critical overturning moment obtained by the Non-Hertz calculation theory is more conducive to grasp the actual resistance of the overturning ability of the rotating system and is conducive to the safety of rotating monitoring of swing bridge.

6. Conclusions

In this study, the spherical joint instability issue during the construction of the swing bridge is addressed. A new formula is proposed based on the Non-Hertz theory to calculate the contact stress of the spherical joint. The comparative analysis shows its superiority compared to the currently applied simplified algorithm and finite element method. Based on the accurate prediction of contact stress, a new formula to describe the resistance of the overturning moment is proposed. The results show that the resistance of the overturning moment based on the new formula is reliable in predicting the critical overturning moment, which guarantees the safety of the rotating process. The following conclusions can be obtained from the acquired results and supplementary case study:
When the spherical joint of the rotating bridge is in a static state, the stress calculation of the spherical joint based on the newly proposed method is closer to the actual situation than the simplified algorithm, and the deviation is reduced by 20%. Moreover, the contact stress of Non-Hertz contact theory is generally lower than the results calculated by simplified algorithm against other engineering cases (see case study in Supplementary materials). The new calculation method reflects the stress distribution of the spherical joint more precisely.

The new critical resistance of overturning moment calculation formula yields smaller values than that of the simplified algorithm, and the calculating accuracy of critical overturning moment formula is improved, which decreases the resistance of overturning moment by 40.5%. Moreover, the new overturning moment calculation is lower than the that of the simplified algorithm at 37.70% (see case study in Supplementary materials). The new formula to calculate the critical resistance of the overturning moment is more applicable to the actual rotating process.

Based on the new resistance of the overturning moment algorithm, the resistance of the overturning coefficient can estimate the overturning resistance of the rotating process accurately up to 40.5%, which guarantees the safety of bridge construction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/jistruc.2020.09.053.

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