Ship Impact Force Analysis and Design Project Selection of Pinghai Bridge

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Abstract. Based on summing up the domestic and foreign ship impact force calculation formula, the finite element method was used to establish the Pinghai Bridge analysis model. The pier ship impact force as a reference came from relevant design data, and the finite element calculation and analysis on ship impact were carried out. For there is auxiliary pier and not, the internal forces of main pier, cap bottom of main pier and a single pile under the combinations of ship impact force along and across the bridge direction of Pinghai Bridge were respectively calculated and reinforcement designed. The results show that the section of main pier can meet the force requirements only by the structural reinforcement; under the ship impact loads, saving the auxiliary pier has little effect on the results of section reinforcement of the main tower and the main pier. These conclusions have reference values to some extent for the design plan selection under the action of ship impact force.

1. Introduction
With the rapid development of road and rail transport networks in recent years, a large number of bridges across the busy waterway were constructed. With the gradual increase in the number of ships, the ship hit event with a bridge in the domestic often occurred. On May 23, 2012, when the "Pearl 7" was towed by a tugboat to downtown Guo Gongshan pier, the ship was accidentally hit by Wenzhou Bridge. At 4:20 on May 12, 2013, a grazing seagoing was impacted with some pier of Nanjing Yangtze River Bridge and lost its power, and finally sank after floated 3.5 km downstream. The research on the bridge by the ship's general strike action focuses on the anti-impact of main piers in large-span bridges the ship impact probability and impact force, etc (YU Xing-quan, 2006; CHEN Gang, 2010) With the improvement of the design requirements for impact avoidance, ship impact force analysis and design comparison is very important.

With the development of the ship bridge impact theory and the corresponding experimental research, scholars put forward many different ship impact force simplified calculating formulas. There were mainly Woisin formula, Pedersen formula (Pedersen P T, 1993), AASHTO Standard Formula, Eurocodes formula (A.C.W.M.Vrouwenvelder, 1998) abroad.

For example, the impact load in public road system and pontoon bridge in the provisions of the Norwegian Public Roads Authority (Bo Geng, 2007) was as follows:

\[ F = 3.5(DWT)^{1/3} \]  \hspace{1cm} (1)

The impact force of the bridge and ferry in the public road system of Nordic Public Roads Administration (WANG Jun-jie, 2006) was as follows:

\[ F = 0.5(DWT)^{1/2} \]  \hspace{1cm} (2)
The specific formulas are given in "General Code for Design on railway bridges and Culverts" (TB10002.1-2005) and "General Code for Design of Highway Bridges and Culverts" (JTGD60-2004) (WANG Jun-jie, 2009). According to the characteristics of the Three Gorges reservoir area, the impact force calculation of the ship was divided into impact force calculations of ship on the pier, bridge superstructure and the barge impact force on bridge substructure in "Guide Specification for Vessel Collision Design of River-Crossing Bridges in Three Gorges Reservoir of ChongQing City" (DBJ/T50-106-2010). In the mentioned formula in the Guide, the ship sailing speed, impact angle, piers shapes, the impact site and other factors were considered.

The positive impact force between ships and piers can be calculated by the following formula:

\[ F = \alpha \eta \xi (DWT)^{\beta} \cdot V \]  

Where \( k = m, 1, g \), respectively, represent coefficients of the maximum ship impact force, the local average ship impact force and the overall average ship impact force.

Each formula comes mainly from three ways, namely energy theory, experiment research and numerical calculations, and the effect on the impact force were mainly considered from the impact tonnage and impact velocity. The finite element method is used to analyze the ship impact force of Pinghai Bridge and compare the design plan in this paper.

2. Finite element model of the ship impact of Pinghai Bridge

The main bridge of Pinghai Bridge has a length of 604m and the span is a combination of 152 + 300 + 152m. The twin towers and single cable plane are used. It is a pre-stressed concrete cable-stayed bridge with a consolidation of pier, tower and girder. Auxiliary piers were set at 99.5m from the centerline of the main tower at the side span. Ship impact force analysis was carried out on the structures with and without auxiliary piers (YU Jun-jie, 2010).

| Piers        | Recent security standards | Long-term security standards | Anti-impact measures       | Anti-impact force (MN) |
|--------------|---------------------------|-----------------------------|----------------------------|------------------------|
| Main pier    | 2000                      | 21.8                        | 5000                       | 28                     | Boxed cofferdam of caps | 21.2 |
| Auxiliary pier| 1000                      | 7.4                         | 3000                       | 13                     | Independent anti-impact | 6.5  |
| Transition pier | 1000                      | 5.25                        | 3000                       | 8                      | Independent anti-impact | 4    |

Note: The above is the transverse anti-impact force of piers, the anti-impact force values along the bridge is 50% of that.

ISATM software was adopted to build the model based on space grillage –truss theory. Model of single pier pile was built according to actual location. A single pile was simulated with the mode of “single cantilever column + capital spring”. The finite element model of full-bridge structure with and without auxiliary pier is shown in Figure 1, respectively. According to relevant research reports, the ship impact force of Pinghai bridge piers are shown in Table 1.
3. Ship impact force analysis of original design structure (with auxiliary pier model)

The internal force state needed to be considered when the ship involved in impact action during the analysis. When the bridge was finished, the bottom moment of the main pier was 79365kN.m (the side of main span subjected to tension), and the shear force of the pier was 653kN (point to side span); ten years later, due to shrinkage and creep secondary internal forces, the bottom moment of the main pier was 94877 kN.m (the edge span side subjected to tension), and the shear force of the pier was 4855kN (point to main span).

The main pier and girder forms a continuous rigid frame system, showing a longitudinal framing effect. The space model was loaded by the ship impact force along the bridge. The calculation and analysis showed that in the ship impact force of 10900kN along the bridge, 75% was born by the pier foundation subjected to impact, and the other 25% was transmitted to the other main pier through the main beam. The bending moment and shear force diagram was shown in Figure 2 respectively when the main pier suffered from longitudinal ship impact forces.

![Figure 2](image)

(a) bending moment diagram of the main pier (the force comes from the main span side)  
(b) shear force diagram of the main pier (the force comes from the main span side)  
(c) bending moment diagram of the main pier (the force comes from the edge span side)  
(d) shear force diagram of the main pier (the force comes from the edge span side)

Figure 2 the internal force diagram of the main pier under the ship impact force along the bridge

The most unfavorable moment of the body of main pier under the ship impact forces taken place at the end of the decade after the bridge was finished and during this time the impact force of ships came from the edge of the main span. The maximum bending moment of the pier body and the corresponding axial force and shear force are shown in table 2. The most unfavorable moment of the foundation bottom of main pier under the ship impact forces taken place at the end of the decade after the bridge was finished and during this time the impact force of ships came from the edge of the side span. The maximum shear force of the caps and the corresponding axial force and bending moment are shown in table 3.

| model                                    | ship impact force combination | \( M_{\text{max}} \) (kN.m) | \( N_{\text{cor}} \) (kN) | \( Q_{\text{cor}} \) (kN) | remark                                |
|------------------------------------------|-------------------------------|-----------------------------|---------------------------|---------------------------|---------------------------------------|
| the model with auxiliary pier along the bridge |                               | 415042                      | 271294                    | 12057                     | the participating ship impact force after a decade comes from the main span side |
| across the bridge                        |                               | 139837                      | 266046                    | 1566                      | the ship impact force is 21800kN      |

Table 2 Internal force of main pier body under various combinations
According to the internal forces of caps bottom, the most unfavorable internal forces of the pile calculated with m method are shown in Table 4.

### Table 4 internal force of a single pile and reinforcement calculation

| model                  | ship impact force of the main pier | internal force of the section | calculated reinforcement area (cm²) | calculated reinforcement ratio | remark |
|------------------------|-----------------------------------|-------------------------------|------------------------------------|------------------------------|-------|
|                        |                                   | axial force N[kN] | bending moment M[kN.m] |                               |       |
| the model with auxiliary pier |                                   | -9796              | 19329                               | 380                           | 0.62% A |
|                        | along the bridge                  | -332705            | 19329                               |                               | B     |
|                        | across the bridge                 | -7951              | 23200                               | 546                           | 0.89% A |
|                        |                                   | -34741             | 23200                               |                               | B     |
| the model without auxiliary pier |                                   | -9661              | 19697                               | 399                           | 0.65% A |
|                        | along the bridge                  | -32853             | 19697                               |                               | B     |
|                        | across the bridge                 | -7417              | 23857                               | 591                           | 0.96% A |
|                        |                                   | -35103             | 23857                               |                               | B     |

Note: A is the minimum axial force and B is the maximum axial force.
4. Ship impact force analysis of saving auxiliary pier structure (without auxiliary pier model)

4.1. the ship impact force of main piers along the bridge

For the saving auxiliary pier structure, when the bridge was finished, the bottom moment of the main pier was 70509kN.m (the side of main span subjected to tension) and the shear force of the pier was 1630kN (point to side span); ten years later, due to shrinkage and creep secondary internal forces, the bottom moment of the main pier was 106072kN.m (the edge span side subjected to tension) and the shear force of the pier was 3017kN (point to main span).

The main pier and girder forms a continuous rigid frame system, showing a longitudinal framing effect. The analysis showed that in the ship impact force of 10900kN along the bridge, 77% was born by the pier foundation subjected to impact, and the other 23% was transmitted to the other main pier through the main beam. The bending moment and shear force diagram was shown in Figure 3 respectively when the main pier suffered from longitudinal ship impact forces.

4.2. transverse ship impact force of the main pier

Since the transverse stiffness of main pier foundation is greater than that of the superstructure, when the transverse ship impact force of 21800kN acted on the main pier, 96% was transferred to the foundation of the main pier. The bending moment and shear force diagram of the main pier when it is acted by transverse ship impact force are shown in Figure 4, respectively.

5. Conclusions

The following basic conclusions can be obtained from the study:

1. Based on the ship impact force analysis and calculations of the structures with and without the auxiliary pier, under the ship impact forces along and cross the bridge, the requirement of cross-section of main pier body can be met according to construction reinforcement.

2. The reinforcement of main pier pile was controlled by the condition of transverse ship impact force. When there were auxiliary piers, the reinforcement ratio of the main pier piles was 0.89%; when auxiliary piers were saved, the reinforcement ratio needed to be increased to 0.96%.

3. Under the ship impact force, it had a little effect on section reinforcement of the main tower and the main pier for saving auxiliary pier.
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