International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:4, No:1, 2010

Research on Simulation Model of Collision Force between Floating Ice and Pier

Tianlai Yu, Zhengguo Yuan, Sidi Shan

***Abstract*—**Adopting the measured constitutive relationship of stress-strain of river ice, the finite element analysis model of percussive force of river ice and pier is established, by the explicit dynamical analysis software package LS-DYNA. Effects of element types, contact method and arithmetic of ice and pier, coupled modes between different elements, mesh density of pier, and ice sheet in contact area on the collision force are studied. Some of measures for the collision force analysis of river ice and pier are proposed as follows: bridge girder can adopt beam161 element with 3-node; pier below the line of 1.30m above ice surface and ice sheet use solid164 element with 8-node; in order to accomplish the connection of different elements, the rigid body with 0.01-0.05m thickness is defined between solid164 and beam161; the contact type of ice and pier adopts AUTOMATIC_SURFACE_TO_SURFACE, using symmetrical penalty function algorithms; meshing size of pier below the line of 1.30m above ice surface should not less than $0.25\times0.25\times0.5m^3$. The simulation results have the advantage of high precision by making a comparison between measured and computed data. The research results can be referred for collision force study between river ice and pier.

***Keywords*—**River ice, collision force, simulation analysis, ANSYS/LS-DYNA

I. Introduction

BRIDGE is one of the most important buildings of lifeline systems in human society. Floating ice sheet in spring is a great threat to the bridge in the extremely cold area of China, and ice damage usually occurring during the year with serious ice regime, as in [1]. Drift ice, as an occasional function, has serious influence on damage to bridge piers, stability of piers, and bridge vibration, imposing severe threat on safe operation of bridge structures. At present, there is less research on collision force between river ice and pier, for the interaction process between ice and structure is very complex. The present methods of ice loads calculation are dependent on empirical formula, as in [2]. LS-DYNA has more strongpoint of multi-kind element types, plentiful material model, and special contact ability, *et al*. It is extensive application in the field of contact and impact, explosion, perforation and penetration, stress wave propagation, metal working, as in [3]-[6]. It provides the possible to implement the simulation of collision force between river ice and pier.

The numerical simulations on collision force between ice sheer and bridge pier is applied with ANSYS/LS-DYNA in this paper, based on the collision force experiments of Jiamusi Songhua River highway Bridge, meanwhile, the key problems and the main factors affecting accuracy in model simulation are discussed.

Tianlai Yu, PhD, Professor, Northeast Forestry University, Harbin, 150040, P. R. China; Beijing Jiaotong University, Beijing 100044, P. R. China (86-451-82191672; TianlaiYu@126.com).
Zhengguo Yuan, PhD Candidate, Lecturer, Northeast Forestry University, Harbin, 150040, P. R. China (86-451-82191771; yzg0308@126.com).
Sidi Shan, Researcher, Northeast Forestry University, Harbin, 150040, P. R. China (Shansidi@163.com).
Supported by Scientific Research Fund of Heilongjiang Provincial Education Department (No. 11544012) and Technical Project of West Transport Construction of the Ministry of Communications (200731800035).

II. Establishment of Simulation Model

A. Introduction of Jiamusi Songhua River Highway Bridge

The Jiamusi Songhua River Bridge main span structure is prestressed concrete T-frames and the side span is prefabricated prestressed concrete beams, as shown on Fig. 1. The span arrangement is 8×30+55+100+5×120+100+55+ 8×30(m). The bridge width is 16 meters.

The pier concrete strength is C25, and the main beam concrete strength is C40. The 30m hung-beam is used in the midspan of 100m span or 120m span T-frames. The bridge substructure consists of gravity piers supported on well foundations in main span and piles in side span or abutment.

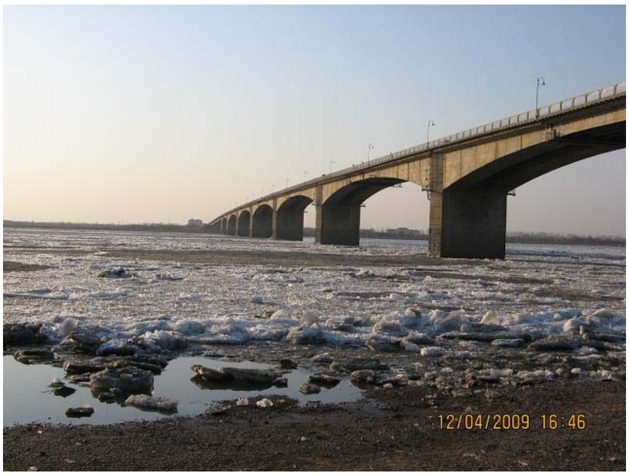

Fig. 1 Jiamusi Songhua River Highway Bridge

Based on investigation of Songhua River's floating ice condition in previous years in Jiamusi Reach, Pier 10 in main channel is selected for the instrumentation. The test was

International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:4, No:1, 2010

implemented on April 12, 2009. Pier 10 and its upper structure are selected as analysis model for ice collision with pier, according to bridge structure, mechanism characteristics, and collision force experimental conditions. The suspension beams of both sides are placed at the hanging beam support which is at the end of the main beam cantilever, while the bridge deck pavement is placed on the main beam.

B. Element Types and Algorithm Selection

Based on the structure characteristic and calculation speed savings, solid164 element with 8-node is adopted in ice sheet and the pier below the line of 1.30m above ice surface, and beam161 element with 3-node is adopted in the rest of pier and main beam. It is very difficult to get best results, only by co-node method to couple solid164 with beam161 with different degree of freedoms (DOF). It is always error termination or abnormal result during the simulation process, by adopting constraint function method, rigid area method, and pseudo-beam method. Therefore, in order to implement the transition between two kinds of elements, a rigid body with suitable thickness is used between solid164 and beam161. The DOFs of all nodes are coupled in the mass center of rigid body, thus it only has six physical degrees of freedom, no matter how many nodes defined. Rigid body and beam161 element share the node, the degree of freedom coupling of physical element and beam element can be well achieved.

Solid164 element adopts center point Gauss integration rule, Lagrangian algorithm, and hourglass control, which can save time and enhance reliability for large deformation conditions. Beam161 has two basic algorithms: Hughes-Liu and Belytschko-Schwer. By pilot calculating, Belytschko-Schwer Beam, 2×2 gauss integral and Lagrangian algorithm are adopted.

C. Material Constitutive Relation

(1) Concrete constitutive relation

The pier's mechanism behavior can be regarded as elastic stage, as the collision force between floating ice and pier is not big, and the pier is not damaged. Reference [7] shows that the material parameters of C25 or C40 concrete are as follows: the elastic module is 28.0GPa or 32.5GPa, the density is 2500kg/m^3, and the Poisson's ratio is 0.2.

(2) River Ice Constitutive Relation

River ice's constitutive relation model is an abstracted model based on the mechanical behavior test of river ice. Ductile-brittle transition is an important property of river ice. In low strain rate, the river ice break as ductile failure. In high strain rate, the river ice break as brittle failure. The observed stress-strain relationship is shown in Fig.2. Known from the mechanical behavior test of river ice, the strain rate of the point which divides ductile failure and brittle failure is between 0.0476×10^{-3} *ε/s* and 0.952×10^{-3} *ε/s*. The stress-strain relationship is linear elastic in the high strain rate, as in [8]-[9]. Because the ice raft's velocity of flow is high, the ice raft is adopted linear elastic material model and added failure criteria of the maximum tension stress. According to the mathematical model of the ice temperature-strength relationship, elasticity modulus-ice temperature relationship and the strain rate of the ice, as in [10]-[11], figure out the ice's modulus of bending elasticity is 0.8GPa and the flexural strength is 1.26MPa. Because the strength of river ice fluctuate in large range when river is thawing, the standard value of river ice strength is usually adopted 1/3~1/2 of the experimental value. Therefore, the flexural strength value of river ice is between 0.240MPa and 0.695MPa and the failure stress of ice sheet is adopted 0.63MPa at ice-floating temperature. Reference [12] shows that the density of the river ice is 916.8kg/m^3 and the Poisson's ratio is 0.33.

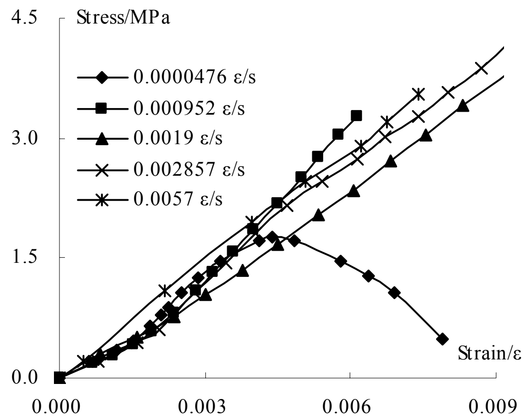

Fig. 2 Stress-strain curve under pressure

D. Model Boundary Conditions, Contact Types and Algorithms of Ice and Pier

Because the pier adopted well foundation in fact, the consolidation constraint was applied in bottom node of the pier in simulation model.

LS-DYNA has three contact types. They are single surface type, node to surface type, surface to surface type, as in [3] and [13]. And there are several collections in each type. The surface to surface type is used when one object's surface penetrates another object's surface. And because of the complication of the ice sheet and pier collision topic, it is hard to make certain the orient of the contact. Therefore the article adopt the Automatic Surface To Surface type (ASTS), and the static friction coefficient, the dynamic friction coefficient, scale factor for sliding interface penalties are all 0.1, as in [4].

LS-DYNA mainly has three different algorithms to process Contact-Collision Interface, which is kinematic constraint method, symmetrical penalty function method and distributed parameter method, as in [3] and [13]. The first is merely used in solid even interface; the third is merely used in sliding interface; the second is a new and generally used algorithm. It is good at processing node and has high calculation accuracy. This article adopted symmetrical penalty function method to finish the simulation analysis of the ice raft and pier's collision force. Penalty function method checks whether each slave node penetrates the main surface in each step. If not, they do nothing. But if penetrate, an interface contact force is added between this node and the penetrated surface. It is in direct proportion to penetrative depth and master surface stiffness, and it is called penalty function value. Its physical significance is that added a vertical spring between the node and the surface to restrict the penetration between the slave node and the penetrated surface. Symmetrical penalty function method also process each slave node adopted the same algorithm. This algorithm has the symmetry, which is more exact in momentum conservation and not easy to give rise to sandglass.

E. Meshing

The pier and main beam are simulated using physical modeling function according to the design drawing of the Jiamusi Songhua River Highway Bridge. According to the observational data on the testing site, the ice sheet is rectangular shape and its size is approximate $60\times80\times0.45m^3$ with a velocity of 1.42m/s.

Mesh density has a great influence on the astringency of the calculative result, especial the Mesh density of the contact area. If the Mesh density is too low, it's hard to satisfy the calculation accuracy, while if too high, it is possible to lead to stress concentration in local area of the model, and it is hard to astringe the result eventually. So it is important to choose a suitable Mesh density which is cannot be too high or too low. The whole model is shown as Fig. 3, and part of the ice sheet model is shown as Fig. 4.

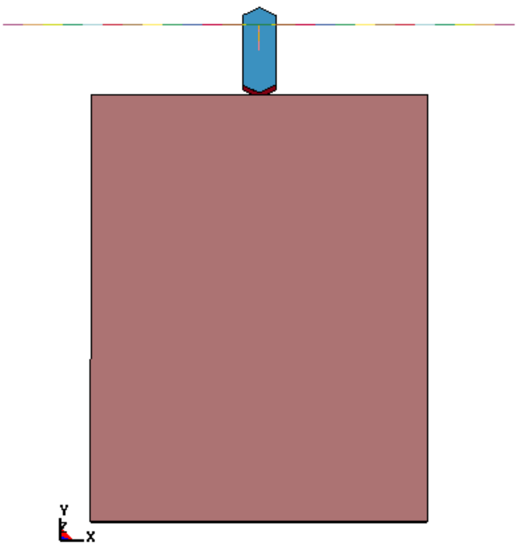

Fig. 3 Entire model of ice and bridge

III. Accuracy Analysis of Main Factors Affecting the Computational Model

According to the model analyzed above, each main factor affecting the calculation accuracy of impact force between ice and bridge pier is respectively discussed by changing the main factors affecting the accuracy of calculation model with the same parameters.

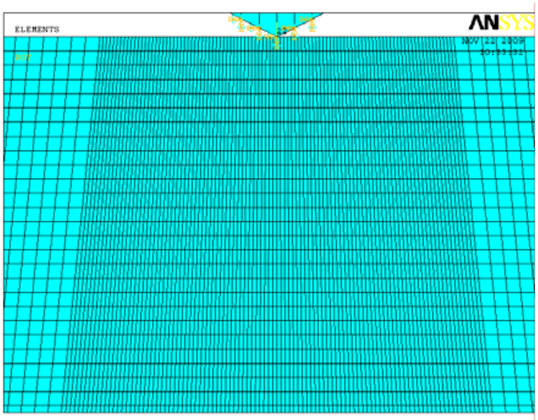

Fig. 4 Ice sheet meshing

A. Influence of Transition Zone Dealing Mode Connecting Different Units on Calculation Accuracy

When other conditions remain unchanged, only changing the height of transition zone including 3 kinds of situations: 0.01m, 0.05m, 0.10m, the results were shown in Table I and the simulation curve of ice sheet impact force in second case was shown in Fig. 7.

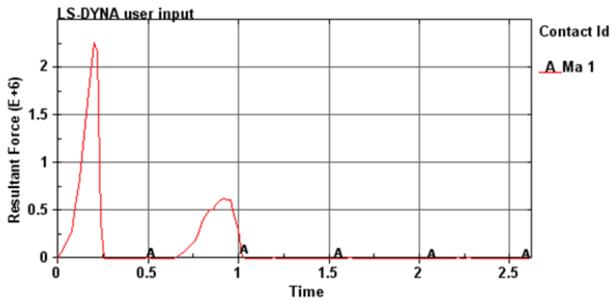

Fig. 7 Simulation curve of ice sheet impact force

Table I showed that the height of the transition zone has certain influence on force results. The impact force tends to reduce as the height of the transition zone increases. When the height of the transition zone is 0.01m or 0.05m, the results is more close to test value. Therefore the height of the transition zone can be 0.01m   0.05m in model.

B. Influence of Main Beam Mesh Density on Calculation Accuracy

When the other conditions remain unchanged and the height of transition zone is 0.05m, only changing the length of the main beam with the value of 0.2m, 0.4m, 0.8m respectively, the number of the main beam element is 448, 224, 112 correspondingly. The three kinds of main beam mesh density results are shown in Table II.

Table II showed that the length of the main beam element has little influence on the force result. Therefore, the affect of it may be omitted in simulation analysis.

C. Influence of Solid Element Mesh Density of Pier below the Line of 1.30m above Ice Surface

When the other conditions remain unchanged, the height of the transition zone is 0.05m, and the main beam's element length is 0.8m, only the mesh density of pier below the line of 1.30m above ice surface is changed. In the case of element size using $0.5\times0.5\times1.0m^3$, $0.3\times0.3\times0.8\ m^3$ and $0.25\times0.25\times0.5m^3$ respectively, the results are shown in Table III.

Table III shows that the mesh density of the pier below the line of 1.30m above ice surface has a great influence on force result, but the mesh density is irrelevant to the calculation accuracy. Generally speaking, when the size of the pier below the line of 1.30m above ice surface is less than $0.25\times0.25\times0.5m^3$, the force result has a high precision; when the size of the pier's solid element is less than $0.5\times0.5\times1m^3$, the result also has an appropriate accuracy and can improve the computing speed at the same time.

D. Influence of Contact Method between Ice and Pier on Calculation Accuracy

When the other conditions remained unchanged, only changing the contact types, ASTS and ESTS contact type are respectively applied and the symmetric penalty function method is used in Contact algorithm. The result is showed in the Table IV.

Table IV shows that contact types has a great influence on force result and ESTS contact type is not suitable to ice sheet's impact simulation. On the other hand, ASTS contact type is more suitable and has a high precision.

E. Influence of Ice Sheet Mesh Density on Calculation Accuracy

In the base of the model discussed above, for the reason of studying the mesh density's influence on result in the contact area of ice sheet, the mesh density in the contact area of the ice sheet is changed. The results showed that the mesh density in the contact area of ice sheet has a great influence on force result. It will have high calculation accuracy if adopted an element size as follows: 0.15m in through-thickness direction, 0.10m in width and 0.4m in length. And compared to test value, the relative error is less than 6.8%.

TABLE I
CALCULATION RESULTS OF CHANGING THE TRANSITION ZONE OF PIER RIGID CONNECTION

Item	Test Value /kN	Height of transition zone					
		0.01m		0.05m		0.10m	
		calculated value /kN	error	calculated value /kN	error	calculated value /kN	error
Force	2432.82	2550.93	4.9%	2266.9	-6.8%	1852.38	-23.9%

TABLE II
CALCULATION RESULTS OF CHANGING THE MAIN BEAM MESH DENSITY

Item	Test Value /kN	Length of the main beam element					
		0.8m		0.4m		0.2m	
		calculated value /kN	error	calculated value /kN	error	calculated value /kN	error
Force	2432.82	2266.9	-6.8%	2380.09	-2.2%	2265.12	-6.9%

TABLE III
CALCULATION RESULTS OF CHANGING THE PIER MESH DENSITY

Item	Test Value /kN	Solid element size of pier					
		$0.5\times0.5\times1.0m^3$		$0.3\times0.3\times0.8\ m^3$		$0.25\times0.25\times0.5\ m^3$	
		calculated value /kN	error	calculated value /kN	error	calculated value /kN	error
Force	2432.82	2266.9	-6.8%	1326.28	-45.5%	2416.98	-0.7%

TABLE IV
CALCULATION RESULTS OF CHANGING CONTACT TYPE

Item	Test Value /kN	Contact type			
		ASTS		ESTS	
		calculated value /kN	error	calculated value /kN	error
Force	2432.82	2266.9	-6.8%	4083.10	67.8%

IV. CONCLUSIONS

After the research of computer simulation model of floating ice collision with pier, some important conclusions are obtained.

(1) In order to improve the compute efficiency, the methods that main beam adopts beam161 element with 3-node, pier below the line of 1.30m above ice surface and ice sheet adopts solid164 element with 8-node are feasible.

(2) The rigid body with a certain thickness is defined between the solid164 element and beam161 element, and the rigid body is co-node with beam161 element. This method can accomplish the connection of the two different elements, and the rigid body can define 0.01-0.05m.

(3) The mesh density of pier below the line of 1.30m above ice surface has more influence on the result of collision force between floating ice and pier. When the pier mesh size adopts $0.25\times0.25\times0.5m^3$, the simulation results of collision force have a very high precision.

(4) River ice adopts linear elastic material model with failure criteria of the maximum tension stress during the simulation analysis.

(5) The automatic-surface-to-surface method and symmetrical penalty function algorithms are used in ice sheet and pier, which is available for analysis on collision force between floating ice and pier.

REFERENCES

[1] Gao Pei and Jin Guohou, "Investigation and analysis of river ice disaster in cold regions of North China," *Journal of China Institute of Water*, vol. 1, no. 2, pp.159-164, June. 2003.

[2] Lu Qinnian, Duan Zhongdong and Ou Jinping, "Calculational method of river ice loads on piers( ): the formula for ice pressure," *Journal of Natural Disaster*, vol. 11, no. 4, pp.112-118, Nov. 2002.

[3] John O. Hallquist, *LS-DYNA Theoretical Manual: Nonlinear Dynamic Analysis of Structures*, Livermore Software Technology Corporation: Livermore, CA, 1999.

[4] Wu Wenhua, Yu Baijie and Xu Ning, "Numerical simulation of dynamic ice action on conical structure," *Journal of Engineering Mechanics*, vol. 25, no. 11, pp.192-196, Nov. 2008.

[5] Karma Yonten, Majid T. Manzari and Azim Eskandarian, "An Evaluation of Constitutive Models of Concrete in LS-DYNA Finite Element Code," in *the 15th ASCE Engineering Mechanics Conference*, Columbia University, New York, NY, June 2-5, 2002.

[6] Liu Jiancheng, Gu Yongning and Hu Zhingqiang, "Response and damage of bridge pier during ship-bridge collision," *Journal of Highway*, no. 10, pp.33-41, Oct. 2002.

[7] *Code for design of concrete structures*, National standards of People Republic of China GB50010-2002.

[8] Wang Jinfeng, Yu Tianlai and Huang Meilan, "Experimental research on uniaxial and unconfined compressive strength of river ice," *Journal of Low Temperature Architecture Technology*, no.1 pp.11-13, 2007.

[9] Yu Tianlai, Wang Jinfeng and Du Feng, "Experimental research on ice disaster in Huma River," *Journal of Natural Disaster*, vol. 16, no. 4, pp.43-48, Aug. 2007.

[10] Yu Tianlai, Yuan Zhengguo, Huang Meilan, "Experiment Research on Mechanical Behavior of River Ice," in *Proceedings of the 19th International Symposium on Ice*, Vancouver, British Columbia, Canada, July 6 to 11, 2008, Vol. 1 and 2, pp.519-530.

[11] Tianlai Yu, Junqing Lei, Chengyu Li, Haibo Yu and Sidi Shan. "Mechanics of Ice Failure and Ice-Structure Interaction during Ice Collision with Bridge Piers." in *Proceedings of the 14th Conference on Cold Regions Engineering*, Duluth, Minnesota, August 31 - September 2, 2009, pp.609-617.

[12] Su Shengkui, Song Wenyou and Liu Yun, "Ice action on hydraulic structure," *Journal of Haihe Water Resources*, no.3, pp. 42-48, 1992.

[13] John O. Hallquist, *LS-DYNA Keyword User Manual: Nonlinear Dynamic Analysis of Structures*, Livermore Software Technology Corporation: Livermore, CA, 1999.