Study on dangerous collision area of ships out of control in Sutong Bridge area

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Abstract: Motion state of ship out of control in bridge area was analyzed. Motion procedure after losing control was divided into two steps. One is drift step within stopping period. The other is drift step without inertia, which is induced by wind and current. Mathematical model for motion of ship out of control, considering wind - induced drift, current - induced drift, stopping ability, etc., was established. Dangerous collision areas for main pier and auxiliary piers were analyzed according to different calculation conditions.

Key words: Sutong Bridge; ship out of control; dangerous collision area; drift induced by wind; drift induced by current; stopping ability

1 Introduction

The navigation environment in bridge area is horribly complicated. There are many factors, such as wind, current, vessel traffic flow, fairway condition, bridge construction, etc., should be taken into consideration to analysis navigation environment in bridge area. In order to keep not only ships' safety, but also bridge's safety, objective and subjective strategies should be systematically analyzed.

There are many ways, including theoretical modeling[1], full - scale experiment and simulation[2], to analysis navigation environment to ensure navigation safety in bridge area. Xu Yanmin, et al, put forward the theory of critical uncontrollable hydrodynamic interaction and analyzed the initiative collision avoidance system[3,4]. However, most of current researches focus on ships under control.

Sutong Bridge, connecting south and north part of Jiangsu Province, is significant to regional economy development. However, the pier will seriously influence on navigational environment in bridge area. Above mentioned methods are suitable for ships under control. If ship is out of control, however, how to analysis ship's motion in Sutong Bridge area? And in which area the collision between ship out of control and Sutong Bridge will be unavoidable? In this article, motion model of ship out of control was established to analysis ship motion states in bridge area, and to plot the area, named dangerous collision area, in which collision between ship and bridge is unavoidable.

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2 Coordinate system

Between north and south main piers, the fairway in Sutong Bridge area were divided into five parts, upward and downward fairways for big and small ships, as well as traffic separation zone located in the middle of space between two piers. Motion of ships out of control can be divided into two steps. First step, ship lost control on point *A*. Then the ship approached to point *B* with inertia. It is consumed that propeller and rudder are out of order. Second step, ship drifted to point *C* influenced by wind, current and other factors. Coordinate system and motion steps of ship out of control were plotted in Fig. 1 and Fig. 2 separately. Fig. 1 shows that if drift width is bigger than valid navigation zone, collision between ship and pier might occur. Therefore, if point *A* were adjusted to not only fore and aft, but also port and starboard, by competing total drift width and valid navigation zone, a region, named as dangerous collision area, in which collision between

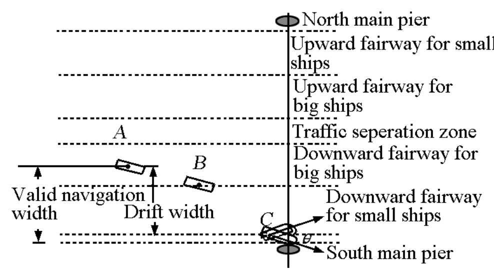


Fig. 1 Coordinate system

ship out of control and pier will occur.

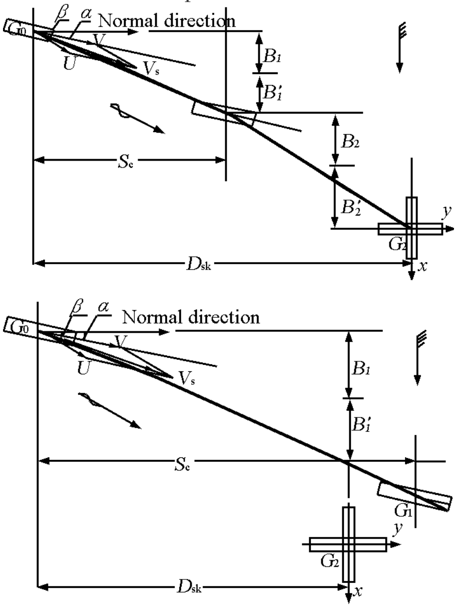


Fig. 2 Motion steps of ship out of control

3 Theoretical modeling

Total drift of ship out of control induced by inertia, wind and current is an important parameter to evaluate whether the ship will collide with the bridge or not. In order to describe ship motion precisely, two conditions should be analyzed separately. First condition, after ship lost control, the inertia is not big enough to help ship pass the bridge transect. Ship will drift through the bridge transect with the influence of wind and current.

That is $D_{sk} > S_c$, the total drift is

$$B = B_1 + B_2 + B_1' + B_2' \tag{1}$$

Where, D_{sk} is distance between point ship losing control and bridge transect; S_c is projection on axis y of stopping distance induced by stopping ability and current.

Drift period is

$$T_z = T + t_p \tag{2}$$

Where, T is stopping time, calculated by integral t; t_p is drift time, s.

Second condition, after the ship lost control, the inertia can help ship pass the bridge transect.

If $D_{sk} > S_c$, the total drift is

$$B = B_1 + B_1' \tag{3}$$

Where, B_1 is drift on axis x induced by current within stopping period;

$$B_1 = v_0 \cdot T_{st}(1 - e^{-T/T_{st}})\sin\alpha + U \cdot T \cdot \sin\beta \tag{4}$$

Where, v_0 is ship speed of losing control; T_{st} is time constant of ship slowdown, and $T_{st} = c/\ln 2$, the constant c can be indexed from the Table 1 by ship displacement.

Table 1 Time constant for different displacement (disp.)

Disp. /t	c /min	Disp. /t	c /min	Disp. /t	c /min
1 000	1	~36 000	8	~120 000	15
~3 000	3	~45 000	9	~136 000	16
~6 000	3	~55 000	10	~152 000	17
~10 000	4	~66 000	11	~171 000	18
~15 000	5	~78 000	12	~190 000	19
~21 000	6	~91 000	13	~210 000	20
~28 000	7	~105 000	14		

$$v = v_0 \cdot e^{-t/T_{st}} \tag{5}$$

Where, v is ship instantaneous speed, m/s; α is leeway; β is drift angle induced by current; and B_1' is drift on axis x induced by wind within stopping period;

$$B_1' = K \cdot K' \cdot \sqrt{B_a/B_w} \cdot e^{-0.14 v_{a1}} \cdot V_{a1} \cdot T \tag{6}$$

Where, $K \in (0.038, 0.041)$; K' is correction modulus for shallow water, which is indexed in Table 2. Where, H is water depth and d is draft.

Table 2 Correction modulus for shallow water K'

Ship type	H/d		
	1.1	1.5	2.0
Common ship	0.6	0.7	0.8
Huge ship (C_b >0.8)	0.5	0.6	0.7

B_a is hull area above waterline, m^2; B_w is hull area below waterline, m^2; v_{a1} is average ship velocity within stopping period, m/s; V_{a1} is relative wind velocity within stopping period, m/s; B_2 is drift on axis x induced by current without inertia.

$$B_2 = U \cdot t_p \cdot \sin\beta = S_p \cdot \tan\beta \tag{7}$$

Where, U is current speed, m/s.

$$t_p = S_p/U \cdot \cos\beta = (D_{sk} - S_c)/U \cdot \cos\beta \tag{8}$$

Where, S_p is drift distance on axis y induced by current without inertia.

$$S_p = U \cdot t_p \cdot \cos\beta = (D_{sk} - S_c) \tag{9}$$

$$S_c = v_0 \cdot T_{st}(1 - e^{-T/T_{st}})\cos\alpha + U \cdot T \cdot \cos\beta \tag{10}$$

Where, B_2' is drift on axis x induced by wind without inertia;

$$B_2' = K \cdot K' \cdot \sqrt{B_a/B_w} \cdot V_{a2} \cdot t_p \tag{11}$$

Where, V_{a2} is relative wind velocity, m/s.

4 Calculation conditions

Take 52300DWT bulk cargo as typical vessel.

4.1 Ship parameters are shown as follows

LOA: 182 m;

Wide of the ship: 32.26 m;

Full load displacement: 62 078 t;

Ballast displacement: 25 342 t;

Ship speed: 11 kn;

Depth: 17.2 m;

Full load draught: 12.2 m;

Ballast draught: 5.34 m.

4.2 Calculation conditions

1) Loading condition: full load and ballast.

2) Ship speed, considering influence of current, when losing control

$$V = [(v_0 \cos\alpha + U\cos\beta)^2 + (v_0 \sin\alpha + U\sin\beta)^2]^{1/2} \qquad (12)$$

According to different calculation conditions, current speeds were evaluated as 3.5 m/s, 2.5 m/s and 1 m/s correspondingly.

3) Point of ship out of control

1, 2, 3.5 km upward from bridge transect;

1, 2, 3, 5, 7 km downward from bridge transect.

4) Speed of tidal stream: 3.5, 2.5, 1 m/s; current direction: flood tide 272°, ebb tide 106°.

5) Wind force: beaufort wind scale 7; wind direction: N.

5 Dangerous collision area

Fig. 1 shows that collision between ship and pier lies on the relationship of valid fairway width and total drift.

$$\Delta B = B_V + B_H - (B + B_S + 0.5\mathrm{LOA} \cdot \sin\theta) \qquad (13)$$

Where, B_V is valid fairway width; B_H is adjustment quantity of ship position to ensure passing bridge safely; B_S is ship width; θ is angle between heading and normal direction of bridge.

If $\Delta B > 0$, ship can pass bridge transect safely, otherwise, ship will collide with pier or ship passes through auxiliary bridge hole.

According to the result of ΔB, dangerous collision area can be plotted.

6 Calculation results

Calculation results were plotted as below.

From Fig. 3 to Fig. 4, we can find that, ship losing control does not mean that the ship will collide with bridge. Collision or not lies on many factors, such as fairway condition, current, wind, piers position, etc. Dangerous collision areas stand for the area in which ship loses control could result in collision with bridge.

In Fig. 3, ships out of control in region A will collide with south main pier. If ship loses control at the port edge of region B, the ship will pass south edge of north main pier. And, if ship loses control at the starboard edge of region B, the ship will pass north edge of

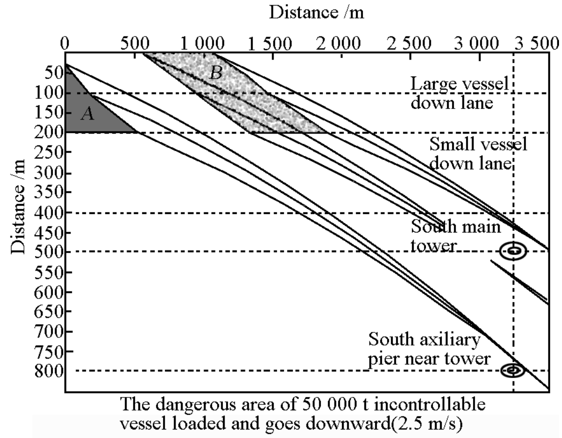
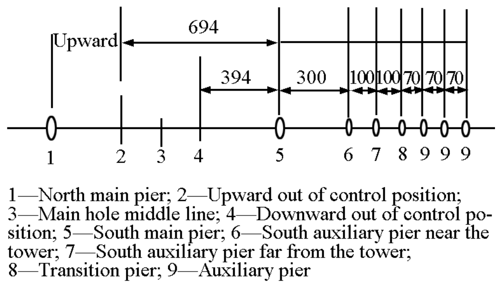


Fig. 3 Dangerous collision area of 50 000 t bulk carrier out of control (downward)

north main pier. That is, if ship loses control in region B, collision with bridge will be unavoidable. Region B is named as one of dangerous collision area.

Considering sketch of piers of Sutong Bridge (Fig. 4), upward ships could collide with not only south main pier, but also auxiliary piers.



Unit: m

Fig. 4 Relationship of piers and fairway

Dangerous collision area of upward ships, region C and region D, were plotted in Fig. 5. Table 3 shows the calculation data.

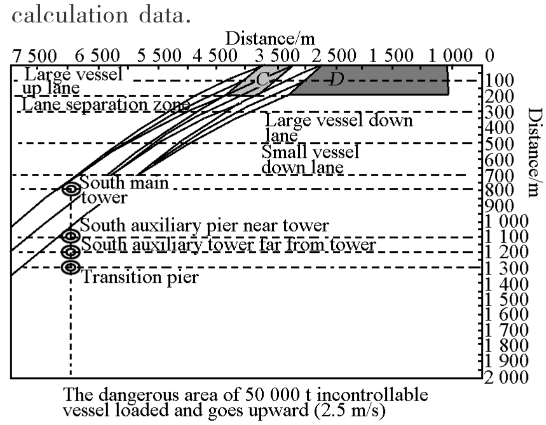


Fig. 5 Dangerous collision area of 50 000 t bulk carrier out of control (upward)

Table 3 Results of dangerous collision area

Upward	Drift/m			615.3	748.4	925.3	1 364	2 294
	Current velocity 1.0 m/s	Full load	Distance/m	4 020	4 515	5 100	6 410	7 000
			Velocity/($m \cdot s^{-1}$)	1.49	1.28	1.14	1.04	1.03
			Time/s	1 450	1 810	2 300	3 530	4 080
		Ballast	Distance/m	2 365	2 605	2 880	3 480	4 610
			Velocity/($m \cdot s^{-1}$)	1.64	1.45	1.29	1.13	1.07
			Time/s	820	980	1 180	1 690	2 370
	Flow velocity 2.5 m/s	Full load	Distance/m	4 490	5 300	6 320	7 000	7 000
			Velocity//($m \cdot s^{-1}$)	3.02	2.84	2.69	2.63	2.63
			Time/s	1 150	1 430	1 810	2 030	2 030
		Ballast	Distance/m	3 013	3 490	4 090	5 500	7 000
			Velocity/($m \cdot s^{-1}$)	2.96	2.81	2.70	2.58	2.55
			Time/s	790	960	1 180	1 720	2 280
Downward	Drift/m			315.3	448	625.3	1 164	2 094
	Flow velocity 1.0 m/s	Full load	Distance/m	2 517	3 000			
			Velocity/($m \cdot s^{-1}$)	2.65	2.20			
			Time/s	660	870			
		Ballast	Distance/m	1 620	2 005	2 380	3 000	3 000
			Velocity/($m \cdot s^{-1}$)	2.59	2.03	1.63	1.24	1.24
			Time/s	440	610	820	1 280	1 280
	Flow velocity 2.5 m/s	Full load	Distance/m	2 500	3 000			
			Velocity/($m \cdot s^{-1}$)	3.83	3.57			
			Time/s	550	690			
		Ballast	Distance/m	1 780	2 370	3 000		
			Velocity/($m \cdot s^{-1}$)	3.64	3.25	2.96		
			Time/s	410	580	790		

7 Conclusions

1) Dangerous collision areas exist subjectively. a. Upward ship: under full load condition, critical edge of dangerous collision area for main pier is 4 ~ 5.5 km to the bridge transect. Drift period is 20 min (flow velocity: 2.5 m/s). Under ballast condition, critical edge of dangerous collision area is 2 ~ 3.5 km to the bridge transect. Drift period is 13 min (flow velocity: 2.5 m/s). b. Downward ship: for main pier, critical edge of dangerous collision area is 2.5 km to the bridge transect. Drift period is 13 min (flow velocity: 2.5 m/s). For auxiliary piers, probability of collision with bridge is small.

2) Different ships has different dimension of dangerous collision area.

3) For one ship, different load condition has different dimension of dangerous collision area.

4) In order to pass bridge safely, ship position should be adjusted properly in advance. Too big or too small hanging up will both result in collision with bridge.

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