Vessel Traffic Control Strategy under Complex Weather Conditions for Three Gorges Reservoir

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Abstract: To ease ship traffic overstock and accidents caused by complex weather in Three Gorges reservoir, the paper took ship traffic organization as the research object. Combined with the features of inland navigation, the paper built up both the safety distance model and safe model for Three Gorges reservoir under complicated weather conditions, which would provide references for safety distance and safety speed control. On the above basis, the paper put forward the specific vessel traffic control strategy including ship speed limit, dynamic ship monitoring, etc., to ensure ship navigation safety and improve management skills under complex weather conditions in Three Gorges reservoir.

Introduction

In recent years, with the development of western economy and Yangtze River Golden Waterway in China, vessel traffic flow is increasing massively in the Three Gorges Reservoir channel. Ship backlog results from the Three Gorge shiplock’s “out of service” due to complex weather conditions including fog, strong wind, etc. What is more, complex weather conditions often cause maritime accidents and (or) dangerous situations, which can be seen by analysing vessel traffic accident statistics.

In view of bad influence on navigation efficiency and safety caused by complex weather, numerous scholars have studied the ship navigation security technologies for Three Gorges Reservoir and reached some achievements. However, the present studies focus on: (1) analysing characteristics of the complex weather [1-3], (2) risk analysis and assessment of navigation environment [4-7], (3) early warning mechanism for complex weather [8, 9], and maritime emergency management [11, 12], there is little studies taking vessel traffic control technology as the theme of research. In this paper, vessel traffic control strategy in Three Gorges Reservoir will be treated as the subject, ship safety speed limit, safety distance limit, etc. will be discussed and recommended, combined with the constraint conditions for ship safety under abnormal weather and microscopic traffic flow theories. The research aims to provide theoretical and technical support for developing vessel traffic management measures for Three Gorges Reservoir under abnormal weather conditions.

Ship safety distance control

Under certain traffic environment, a ship is required to keep certain speed and a safe distance h with rear ship for safety navigation. The goal of safe distance h and safe time t is in order to ensure that the
ship had enough time to take proper and effective action to avoid collision and stopped the ship in the safe distance.

Due to the Three Gorges Reservoir routing system has been implemented and the middle and lower of Yangtze River have implemented traffic separation rules, so we can use ship follow state to derive safety distance.

To ensure the safety of navigation, the driver always make the worst prepare about the in front of ship, that is the in front of the ship will suddenly slow down or malfunctioning. We assumed two ships before and after traveling speed is equal, the safety distance should be the minimum distance that can ensure when the before ship have emergency braking or failure, but the after boat have not the collision danger. Fig. 1 shows the braking process of the later ship for safety.

![Diagram](image)

| Later Ship | Front Ship |
|------------|------------|
| ![Diagram](image) | ![Diagram](image) |

(a) The position of the two ships when the front ship begins to slow down

(b) Locations of ships after their maneuvering

Fig. 1. The braking process of the later ship for safety

The expression of safe distance can be obtained from Fig. 1:

$$H = l + S_s + S_0 - S_1$$

In formula (1): $h$ stands for safe distance (m); $l$ represents standardized captain (m), the values depend on the tonnage of the ship. $S_s$ is safe stopping distance, which shall not be less than 80m according to the provisions of the Yangtze River Maritime Bureau; $S_0$ is the glide distance of the later ship when the front ship has been found (m); $S_0 = vt$; $S_2$ is the later ship's reversing stroke; $S_1$ is the front ship's reversing stroke; $v$ is ships traveling speed; $t$ is Driver's reaction time when the visibility suddenly reduced. It is hard to the driver to adapt to this change, so under the most unfavorable conditions we take $t$ as 2min.

Conclusion can be drawn from expressions (1) that safe distance have a closed relationship with the sailing speed, reaction time, braking time between two ships and other factors. Consider the more rational conditions, we set the same two ships braking performance, which means $S_1 = S_2$.

And the safety distance relationship becomes:

$$H = L + S_s + vt$$

Vessel traffic control method under complicated weather conditions

Complex weather means what have bad impacts on the traffic safety. According to the different weather, it can be divided into two categories, one is the weather only affects effective visibility $S_D$, such as fog, rain, snow early and so on; The second category refers to the impact of the ship maneuverability limitations caused by water conditions, mainly include strong wind weather.

Safe distance control

Under the first kind of weather conditions, it will cause the driver effective sight distance $S_D$ shortened. In order to keep traffic safety, we need to increase the perception reaction time $t$ and adjust the pitch and speed of ships. In this case of traffic safety control, the constraints are classified as:
When a valid ship safety distance SD is far more than the horizon h, the driver necessary perception reaction time t need to fixed, and adjust the speed V to make ship distance H satisfy:

\[ H \geq h \quad (3) \]

Where \( h = L + S_s + vt_1 \), \( t_1 \) is reduced visibility due to weather shortens.

When the effective horizon SD spacing is less than the safety distance of the ships h, In order to ensure the safety of traffic condition like this: Boats driver need to master the dynamic of the front ship to ensure that boat driver have enough time and safe distance to take corresponding measures ,when unexpected situation occurs. Thus in this case, it is need to adjust the speed v to satisfy traffic safety control model of variable constraint.

\[ D_S \geq H \geq h - L_S \quad (4) \]

Where \( L_S \) is reduced visibility result in the driver effectively SD horizon shortened, and the amendments to ship safe distance is \( h, h = L + S_s + vt_1 \).

**Safe speed control**

Considering the safe speed is the ship appropriate speed at that moment, it is too fast, or too slow is not the safe speed. That means in the same waters, a ship speed may be a safe speed while another ship is at the same speed or low-speed may be unsafe speed. Therefore, the selection of safe speed ship should be determined by the ship’s own situation and the navigable environment.

**Safe speed under the first kind of weather conditions**

In case of weather conditions, when the effective horizon SD less than the safety distance h, we see the effective horizon SD as safe distance, and draw the appropriate speed of the ship as a safe speed limit. Which is

\[ S_D = h = L + kS_s + vt_1 \quad (5) \]

Where, \( v \) is the vessel’s speed(kn);t is the driver’s reaction time. In case of poor visibility, the corrected time is \( t_1 \), and the driver’s reaction time after the correction value of 2min;L is the total length of the ship, unit m; \( S_s \) is safe stopping distance, unit m;k is the correction coefficient under poor visibility conditions for safe distance, which ranges from 1 to 8, we generally take 4 as in the inland situation.

The safe limit speed of the ship can be calculated

\[ v = (S_D - L - kS_s) / t_1 \quad (6) \]

Ship speed limit values under different visibility conditions can be calculated by formula (6), as shown in Table 3.
Table 1. Ship speed limit values under different visibility conditions

| Visibility | The maximum safe speed | Visibility |
|------------|------------------------|------------|
| Ship types | Tonnage | Length | 1000m | 500m | 200m |
| Bulk cargo | 5000 Ton | 110 m | 9.5kn | 1.2 kn | Prohibit sailing |
| | 3000 Ton | 95 m | 9.7 kn | 1.4 kn | Prohibit sailing |
| Liquid cargo | 3500 Ton | 100 m | 9.6 kn | 1.3 kn | Prohibit sailing |
| | 1000 Ton | 75 m | 10 kn | 1.8 kn | Prohibit sailing |
| Ro-Ro | roll-on/roll-off (70-110 seats) | 110 m | 9.5 kn | 1.2 kn | Prohibit sailing |
| Ro-Ro | (300-800 seats) | | | | |
| Container | 350TEU | 110 m | 9.5 kn | 1.2 kn | Prohibit sailing |
| | 200TEU | 90 m | 9.8 kn | 1.5 kn | Prohibit sailing |

Safe speed under the second kind of weather conditions

Ship speed limit aims to avoid serious sway, water on deck and the ship slap phenomenon in big storm. Refers to speed calculate method that allowed in the large sea waves, we propose speed design formulas under river big storm as follows:

$$V_a = V_0 \left[1 - \left(\frac{m}{L + N}\right)\right]$$  \(7\)

In the formulas (7): \(V_a\) is the allowed speed in the large waves, \(V_0\) is ship design speed, \(L\) is the length of the ship, \(m, N\) are the parameters whose value can be taken in Table 4.

Table 2. Allowed parameter under high waves

| Beaufort wind scale | Top Lang | Slant wave | Transverse wave | Shun oblique wave |
|---------------------|----------|------------|-----------------|-------------------|
| m                   | N        | m          | N               | m                 |
| 5                   | 9        | 0.02       | 7               | 0.02              |
| 6                   | 13       | 0.06       | 10              | 0.05              |
| 7                   | 21       | 0.11       | 14              | 0.08              |
| 8                   | 36       | 0.18       | 23              | 0.12              |

The ship allowed speed under different winds can be derived from formula (4). And the allowed safety speed value the least favorable condition that ship takes top wave sailing.

Specific limit values shown in Table 5.

Table 3. Allowed speed under different winds

| Beaufort wind scale | The maximum safe speed | Beaufort wind scale |
|---------------------|------------------------|---------------------|
| Ship types | Tonnage | Length | Designed speed | 5 | 6 | 7 | 8 |
| Bulk cargo | 5000 Ton | 110 m | 9.7 kn | 8.7 kn | 8.0 kn | 6.8 kn | 4.8 kn |
| | 3000 Ton | 95 m | | 8.6 kn | 7.8 kn | 6.5 kn | 4.3 kn |
| Liquid cargo | 3500 Ton | 100 m | 9.7 kn | 8.6 kn | 7.9 kn | 6.6 kn | 4.5 kn |
| | 1000 Ton | 75 m | | 8.3 kn | 7.4 kn | 5.9 kn | 3.3 kn |
| Ro-Ro | roll-on/roll-off | 110 m | 11.3 kn | 10.1 kn | 9.3 kn | 7.9 kn | 5.6 kn |

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### Vessel traffic flow control under complex weather conditions

We use the ship safety distance $H$, safety sailing time $T$ and speed $V$ to describe waterway traffic flow. There is a relationship between traffic flow variables $H = VT$. In this equation, any two can be used as an argument, the other one as the dependent variable. The ship safe time can be calculated based on the safe speed, resulting in the water traffic flow.

$$T = \frac{H}{V} \quad (8)$$

$$Q = \frac{3600}{T} \quad (9)$$

In formula (9), $T$ is the safe speed between the two ships; $H$ is the safe distance, $V$ corresponds to the maximum safe speed in the visible conditions; $Q$ is the flow of ships under the current weather conditions.

Ship traffic limit under different visibility is shown in Table 6.

**Table 4. Ship traffic limit under different visibility**

| Ship types    | Tonnage | Visibility (m) | Themaximum safe speed (kn) | Ship traffic flow (ships/h) |
|---------------|---------|----------------|---------------------------|-----------------------------|
| Bulk cargo    | 5000 Ton| 1000           | 9.5                       | 17                          |
|               |         | 500            | 1.2                       | 4                           |
|               | 3000 Ton| 1000           | 9.7                       | 17                          |
|               |         | 500            | 1.4                       | 5                           |
| Liquid cargo  | 3500 Ton| 1000           | 9.6                       | 17                          |
|               |         | 500            | 1.3                       | 4                           |
|               | 1000 Ton| 1000           | 10                        | 18                          |
|               |         | 500            | 1.8                       | 6                           |
| Ro-Ro         | roll-on/roll-off (70-110 seats) | 1000 | 9.5 | 17 |
|               | Ro-Ro (300-800 seats) | 500 | 1.2 | 4 |
| Container     | 350TEU  | 1000           | 9.5                       | 17                          |
|               |         | 500            | 1.2                       | 4                           |
|               | 200TEU  | 1000           | 9.8                       | 18                          |
|               |         | 500            | 1.5                       | 5                           |
Vessel traffic control strategy under complex weather conditions

Limiting speed
Depending on the security models, we calculate the speed limit values about dry bulk carriers, tankers, ro-ro, container ships and cruise ships sail under different wind and visibility conditions, listed in Table 7.

Table 5. Ships limit speed in different weather conditions

| Weather Speed Limit | I class weather conditions | II class weather conditions |
|---------------------|---------------------------|-----------------------------|
|                     | Poor visibility (m)       | Big waves weather           |
|                     | >1500 | 1000 | 500 | <200 | Fresh breeze | Strong breeze | Moderate gale | Fresh gale |
| Bulk cargo          | Any   | 9.5 kn | 1.2 kn | Prohibit | 8.2 kn | 7.3 kn | 5.6 kn | 2.8 kn |
| Liquid cargo        | Any   | 9.6 kn | Prohibit | navigation | 8 kn | 6.9 kn | 5.1 kn | 1.9 kn |
| Ro-Ro               | Any   | 9.5 kn | 1.1 kn | Prohibit | 10.1 kn | 9.3 kn | 7.9 kn | 5.6 kn |
| Container           | Any   | 9.5 kn | 1.2 kn | Prohibit | 9.3 kn | 8.3 kn | 6.6 kn | 3.7 kn |
| Passenger           | Any   | 9.8 kn | Prohibit | navigation | 10.5 kn | 8.8 kn | 5.7 kn | 0.3 kn |

Based on the above analysis, traffic management strategies can be developed under complicated weather conditions:

(1) In the case of poor visibility, when the visibility is less than 1500m, taking ship speed restrictions, prohibiting visibility tankers and cruise ships sail below 500m. When the visibility is less than 200m, prohibiting all vessels navigable.

(2) When in windy weather conditions as the wind above 5 degree, speed restrictions measure should be taken. Taking into account the large wind relative area of container ships and ro-ros and the influence of navigation and cargo security by wind is obvious, so when the wind reached more than degree, we prohibit container vessels and ro-ro ships sailing. In order to protect the ship navigation safety, we should ban all ships sailing when wind above 8 degree.

Monitoring
Because of the uncertainty of the weather, it is difficult for driver to adjust the safety sailing speed and distance timely. It is easily to have an accident without taking effective action. Depending on the impact that weather conditions have, we can take reasonable traffic control strategy, level management and a special one-way segments, also can enhance on-site supervision, so as to mitigate the effects of weather. Traffic management strategies in complex weather conditions shown in Table 8.
| Visibility (m) | Traffic Flow | Regulatory Policy | Traffic control | Preventive measures |
|---------------|--------------|-------------------|-----------------|--------------------|
| >1000         | Normal       | Warning deceleration, Reminded to keep a proper look Speed limit, To draw attention to traffic safety Speed limit, warned ahead Lag | 19 ships/h | Timely weather warning information release, Step up patrols |
| 500~1000      | Normal       | Speed limit, Posted fog warning, Pay attention to the safety of navigation Speed limit, Posted fog warning, Keep the ship pitch Speed limit, Posted fog warning, Assist ship diversion | 17 ships/h | Strengthening site supervision, Cooperative Vessel Traffic Organization |
| 200~500       | Normal       | Speed limit, Posted fog warning, Control of Ship Traffic Speed limit, Posted fog warning, Assist ship diversion Posted fog warning, Anchoring and berthing arrangements for vessels | 7 ships/h | Coast Guard boats deployed on-site duty, Ships moored tie matte organization |
| <200          | Normal       | Speed limit, Posted fog warning and suspended info, Vessel Traffic Organization, Vessel Traffic ban Traffic control, Post closure navigation information. | Blockage | Firefighting, maritime travel on high alert, ready to go to implement emergency. |
| >1000         | Normal       | Post navigational notices, Inform Accidents properties, Deceleration Inform Accidents properties, Tips shunt Speed limit, Post navigational notices, Temporary traffic control | 19 ships/h | Fire, Marine accordance with their respective responsibilities deal with the accident scene, and directing passing ships navigation |
| <1000         | Normal       | Speed limit, Inform Accidents properties, Tips shunt Speed limit, Inform Accidents properties, Control of Ship Traffic Traffic control, Tips to choose the right anchor waters | 17 ships/h | Fire, Marine deal with the accident scene according to their respective responsibilities, maintain navigation safety, emergency preparedness |
Conclusions

In view of the complex weather’s influences on water transportation in Three Gorges Reservoir, ship safety speed limit, safety distance limit, etc. were discussed and recommended in this paper, combined with the constraint conditions for ship safety under abnormal weather and microscopic traffic flow theories. Further, vessel traffic control strategy under complex weather conditions in Three Gorges Reservoir were propose. The research can provide theoretical and technical support for developing vessel traffic management measures for Three Gorges Reservoir under abnormal weather conditions.

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