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Study on the optimization of boom performance and oil interception strategy in the emergency response to oil spill in rapids-type rivers

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Abstract

This paper investigates the performance optimisation and oil interception strategies of booms in emergency response to oil spills in rapids-type rivers. The limitations and failure mechanisms of traditional booms under torrent conditions are analysed, including oil film submergence and structural failure. The structural optimisation direction of the new type of boom is proposed to improve the anti-slumping and interception efficiency by adding gradient counterweights and integrating anti-splash components. Combined with the example of Lancang River, a scientific and reasonable selection of oil spill interception points, boom deployment angles and methods, and multi-stage deployment strategies are proposed. The research results are of practical significance in guiding the selection, deployment and optimisation of oil containment booms in the emergency response to oil spills in rapids-type rivers.

Keywords

Rapids-type river; Oil spill emergency response; Boom performance optimisation; Structural optimisation; Oil interception strategy

1. Introduction

With the growth of global energy demand and frequent oil transport and storage activities, the risk of oil spills has increased. In rapids-type rivers, oil spills spread rapidly, threatening the aquatic ecology and the safety of coastal residents, and even triggering international disputes. As a key emergency response equipment, the performance optimisation and oil stopping strategy of oil booms are of paramount importance. Although the traditional booms are technically mature, they often face the problems of oil film submergence, structural failure, unstable anchorage, etc., and the oil interception efficiency is low under the surge conditions. The purpose of this paper is to analyse the failure mechanism of traditional booms in rapids, explore the direction of new structure optimization, and put forward effective oil stopping strategies in combination with cases, so as to provide scientific basis and practical guidance for the emergency response to oil spill in rapids-type rivers, and enhance the efficiency of oil spill emergency response and environmental protection level in China.

2. Analysis of boom performance under surge conditions

2.1.Overview of conventional booms

2.1.1 The basic construction and working principle of traditional booms

Conventional booms consist of three parts: a float, a skit and a counterweight. The floating body provides buoyancy, the skirt forms an underwater barrier and the counterweight ensures a vertical condition, Its working principle is based on oil-water density difference and physical barrier, which can reach 80% efficiency at flow velocity <0.5m/s [1].

2.1.2 Main types of conventional booms and their characteristics

Solid float type booms use fixed floats to provide buoyancy, with a flexible skirt suspended below the float. Its greatest advantage is its simple and reliable structure and relatively easy maintenance. However, the limitations of this design are also very obvious. Due to the fixed float spacing, the overall flexibility is poor, it is easy to be damaged due to uneven force under large wave conditions, and it requires a larger space for storage [2].

Inflatable booms use an inflatable tubular structure in place of fixed floats. providing the required buoyancy by adjusting the internal air pressure. Compared with the solid float type, the inflatable boom shows obvious advantages: it can be compactly rolled up when not inflated, which greatly reduces the storage and transport space; the length can be flexibly adjusted according to the needs when in use; more importantly, the continuous air chamber structure gives the product better wave-following performance, and it can adapt to the wave movement more effectively.

Curtain booms are constructed with a continuous curtamn fabric structure that evenly distributes buoyant material throughout the boom. This design eliminates the connection weaknesses of traditional segmented structures and demonstrates superior containment continuity in calm water environments such as harbours and inland rivers. However, the overall flexible structure also brings the disadvantage of weak resistance to currents, and the effectiveness of oil containment is significantly reduced in waters where the flow velocity exceeds 0.5 metres per second. Therefore, this type of boom is mainly deployed in protected waters or used as a secondary barrier.

Fire Resistant Oil Boom [3] High temperature resistant materials and cooling system are added on the basis of ordinary oil booms, which can withstand the high temperature of oil fire while intercepting the oil spillage, and these products play a key role in the handling of oil spillage accidents where combustion is likely to occur. Adsorption booms, with oil-absorbing materials integrated into the boom structure, can intercept and absorb oil at the same time, especially suitable for the treatment of light oil products.

It is worth noting that even today, when new types of booms are emerging, many of the core concepts of the traditional design are still retained and optimised, which fully proves the rationality of their basic design ideas. In practical application, choosing the appropriate type of boom according to the specific environmental conditions is still one of the key factors to ensure the success of oil spill emergency response.

2.1.3 Limitations of traditional booms

At higher flow velocities(>l m/ s),conventional booms are prone to the phenomenon of "oil film submergence". This is due to the hydrodynamic effect of the oil layer being "sucked" underwater as a result of the pressure difference generated by the high-speed water flow under the boom.Research shows that when the flow velocity reaches 1.5 m/s, the interception efficiency of traditional booms may drop to less than 50%. Secondly, the structural stability of traditional booms is insufficient under severe sea conditions. Large wave impacts may lead to breakage of the boom or failure of the connectors, especially in the case of long-term deployment, where material fatigue is a more prominent problem.

Despite its limitations, traditional booms have made an indelible contribution to the history of marine and riverine environmental protection. From the perspective of technological development, traditional booms have laid the foundation for modern oil containment technology. The design concept of many new booms. The large amount of experience accumulated in the use of traditional booms also provides an important reference for the development of relevant standards and specifications.

2.2.Failure modes of conventional booms under rip current conditions

In the practice of river oil spill emergency response, the performance failure of traditional booms in torrent environment [4] problem has been troubling engineers and technicians. When the flow velocity exceeds 1 m/s, these oil containment devices originally designed for use in calm waters tend to show various forms of failure, which seriously affects the oil spill control effect.

2.2.1 Failure Mechanism of Oil Film Submergence

When the flow rate exceeds a critical value, the booms experience oil film dive. It was found that this phenomenon stems from two key factors:

Firstly, the flow of water through the boom creates a significant pressure difference. At a flow rate of 1.2 metres per second, the pressure difference between the onshore and backshore sides can be as much as 200-300 Pascals, and this pressure gradient pushes the oil layer downwards.

Secondly,the vortex formed by the current has a strong swirling effect. High-speed photography shows that the vortex can carry oil droplets underwater, resulting in a dive depth of more than 40 per cent of the design depth. It is worth noting that the use of a corrugated skirt design increases the critical flow velocity from 0.8 to 1.l metres per second.

2.2.2 Structural failure analysis

In a rip curent environment, boom structures face multiple challenges: the joints are subjected to a tensile force of 300-400 Newtons per metre at a flow velocity of 2 metres per second, which, together with the superimposed effect of waves, makes them highly susceptible to fatigue fracture. Material analyses show that the seawater environment accelerates stress corrosion, causing surface micro-defects to expand into macro-cracks.

2.2.3 Mechanical mechanisms of anchorage system failure

Field measurements show that 1.5 ms flow velocity can result in anchor displacement of 5-10 metres. More seriously, the instantaneous shock loads on the mooring system can be 4-6 times the average value, which poses a severe test for conventional anchoring design.

3. Optimised direction of the new boom structure

According to the failure mode, the oil spill control effect is improved by optimising the boom structure. The structural design of the boom can be optimized from two dimensions: floating body and skirt. The floating body, as the core buoyancy unit, not only needs to guarantee the overall floating performance, but also undertakes the function of oil spill prevention and control. By innovating the floating body configuration design, the longitudinal size and cross-section shape of the boom can be optimised, combined with the centre of gravity distribution adjustment technology, to significantly enhance its anti-slippage performance and splash suppression capability in the surge environment, which is more suitable for oil spill containment and control operations in turbulent waters. The skirt design focuses on the optimisation of hydrodynamics, which reduces the impact load of the water flow by changing the shape and effective water contact area, and ensures the overall stability of the system while maintaining the effectiveness of the oil film interception above.

3.1 Float structure optimisation

The optimisation strategy of the float structure can be based on the principle of stability mechanics: based on the mechanical criterion of "downward shift of the centre of mass to enhance stability", the centre of mass of the system can be offset to the connecting end of the skirt through the addition of a gradient counterweight module inside the traditional float, so as to effectively avoid the risk of capsizing due to the impact of the rapids. Aiming at the characteristics of the elastic float which is prone to secondary splashing when impacted by oil spill, a composite splash-proof component can be integrated on the top of the foat, which adopts a lightweight energy-absorbing frame filled with multi-layer oil-absorbent cotton material, which can not only absorb kinetic energy in the moment of impact, but also adsorb the splashing oil droplets, forming a dual protection mechanism of "interception adsorption". The counterweight design of the floating body makes the floating body present a low mass distribution in front and high mass distribution at the back, together with the hydrodynamic shape of the top anti-splash module, which significantly improves the effectiveness of oil interception while guaranteeing the stability of the system.Further optimisation needs to consider the coupling relationship between material specific strength and shape resistance, and analyse the effects of different material combinations, geometrical configurations and filling schemes on the position of the centre of gravity through parametric modelling.

3.2 Optimisation of the skirt structure

Skirt optimisation requires a balance between interception efficiency and structural safety: although theoretically an increase in skirt height can improve anti-escape performance, the skirt height is positively correlated with the force area in the fully submerged state, and a structure that is too high is prone to material tearing due to the increase in hydrodynamic pressure in the rapids. Therefore, it is difficult to adjust the skirt size to meet the stability and interception requirements at the same time, and a composite optimisation strategy is needed. It is suggested to set up a regular arrangement of circular overflow holes in the skirt, on the one hand, the porous structure maintains the effective interception area and significantly reduces the flow load; on the other hand, the oil spill layer presents a thin curtain under the high-speed flow condition, and the contact time between the oil film and the boom is very short, so the design of the overflow holes will not cause the oil leakage.

4. Study on oil spill interception strategy of Lancang River

For the Lancang River crude oil across the pipeline, there is a greater risk of environmental pollution in the event of oil spillage, and if it flows outside the country, it may even cause more serious international disputes. In order to make the leaked oil into the water body can be quickly and effectively intercepted and recovered. to avoid the spread of oil leakage to the maximum extent and to reduce the impact of the consequences ofthe incident,combined with the geographic location and geomorphological conditions of the waters of the Lancang River, to determine the oil spill interception point, to formulate the emergency response preparations, to speed up the reaction speed after the occurrence of the oil spill accident, and to improve the efficiency of emergency response.

4.1 Selection of Oil Spill Interception Points

The scientific setting of oil spill interception points and the precise deployment of booms are the key links to effectively control the spread of oil spill pollution in rivers and enhance the efficiency ofemergency response.

The selection of the interception point should follow the principles of "focusing on prevention", "rapid disposal" and "adapting to local conditions". Understanding the horizontal mixing behaviour of the oil spill, combined with the long-distance longitudinal oil spill transport law and terrain conditions, can further determine the oil spill interception point, for the deployment of the location of the oil fence (specific interception point), deployment methods and length (width of the interception) to provide guidance. In order to arrive at a better oil spill interception effect, the following principles should be considered for the interception point [5] :

(1)Timeliness, oil spill accidents have the characteristics of suddenness and rapid proliferation, the timeliness of emergency response directly affects the effect of pollution control. Selection of site needs to ensure that the oil spill disposal material storage and advance construction of infrastructure coordination is convenient, so that the emergency response forces can arrive at the incident waters within the shortest response time, and quickly carry out siege control operations to minimise the oil spill pollution of sensitive waters.

(2)Economy:Under the premise of guaranteeing timeliness, it is necessary to comprehensively consider the whole life-cycle costs of emergency rescue points including construction costs, operation and maintenance costs and material reserve costs. By optimising the site layout and reducing redundant equipment points, the cost of emergency rescue can be minimised.

(3)Interception points should be selected in relatively low-flow reaches with gentle currents, looking for relatively still-water areas of the river, generally on the inside of bends in the river, where the riverbanks protrude, where vegetation grows, or where there are rocky outcrops.

(4)Considering comprehensively on the water system basin, rationally set up single-acting interception points, multi-acting interception points and key-acting interception points, and systematically plan the setting up of interception points according to the disposal effect and the limit risk that can be borne, and clarify the function and role of each interception point.

4.2 Boom deployment angle

When using various booms, it is necessary to ensure that the vertical relative velocity between the boom and the water flow is less than 0.38 m/s. When the vertical relative velocity is greater than 0.38 m/s, the oil spill starts to escape from the bottom of the boom. Therefore, when deploying the oil containment boom, the oil containment boom and the water flow should form a certain angle, in order to reduce the flow velocity perpendicular to the oil containment boom. At the same time, the oil spill can also be directed to the water with lower flow velocity for recovery [6] .The formula for calculating the angle between the boom and the water flow is as follows:

$$\sin\alpha = \frac{V_{\lim}}{V_{Water}} . \tag{1}$$

a——the angle between the boom and the water flow;

$V_{\lim}$ ——the limiting flow velocity perpendicular to the boom;

V_{Water} ——the actual water flow velocity.

Since it is known that when the water velocity exceeds 0.38m/s, the boom will fail, according to the vector relationship between the boom and the angle of water flow, see Table 1, we can calculate the relationship between the deployment angle of the boom and the water velocity, such as Table -3.2l shown. In the actual deployment process the angle between boom and water flow should not exceed ±10 of the theoretical yalue.

Table 1. Relationship between boom deployment angle and water velocitye

serial number	water velocity $/m \cdot s^{-1}$	Boom Clip Angle $/^{\circ}$
1	0.51	48
2	0.7	29
3	1.02	22
4	1.27	17
5	1.53	15

4.3 Boom deployment method

Commonly used in the project boom deployment methods are: "a word" "zigzag","herringbone" and "U-shaped "etc.

Generally, the flow velocity is highest in the centre of the river and lower near the river bank, When the river channel is straight at the selected interception point, the oil spill should be directed to the area of lower river flow velocity as far as possible and then recovered, so a zigzag or herringbone shape can be used to deploy oil booms. If there is no natural oil spill recovery point, an oil catchment pit can be dug on the river bank to direct the oil spill to that area for recovery, Standard closed herringbone boom deployment uses one anchor point located in the middle of the water column, two sets of booms attached to the anchor point in the middle, and boom tails attached to the anchor points on each bank, Generally the booms do not need to be secured by additional anchors and the length of the boom determines the angle between the boom and the current, this method is most effective where there

are pre-built anchor posts [7,8].
In some special geographical areas such as prominent bank walls and concave areas the water tends to flow gently, and at river bends, near the inside of the bend there is generally a calm zone where the flow velocity is zero. According to the specific movement characteristics of the river, the oil spill will be diverted to the river bank in the form of water flow and then recovered [6].
When there is an important area to be protected downstream of the interception point, the oil spill area is large, and the water current is slower, a U-shaped deployment can be used.The U-shaped deployment has the characteristics of high efficiency and flexibility, but it requires a high degree of co-ordination and co-operation between the vessels in the deployment process. On a wide river or coast, use two vessels to tow oil booms to form the sides of a -shape to enclose a large oil slick, and then move the oil slick downstream to an area with slower currents and use skimmers to recover it.

4.4 Multi-level deployment strategy

In the actual oil spill interception operation in the rapids river, the breakage accident through the pipeline is relatively rare, so the oil spill is mostly in the form of small holes or localised. Due to the large width of the river, it is usually difficult to form a continuous oil spill cover for such spills, and the oil spill drift path is often characterised by meandering valley channels. In the bends of the river, affected by the topography of the shoreline, the oil spill is prone to fracture and fragmentation phenomenon, forming discontinuous oil film distribution.
For such oil spill scenarios, a multi-stage boom deployment strategy can be used to construct an oil containment area, which effectively improves the recovery efficiency and enhances the stability of the system. The technical principle is as follows: deploy the main boom on the side where the oil spill is widely distributed, and set up a flow-guiding device on the side where the oil spill is small. Through the guiding effect of the guide rail, the scattered oil spill will be centrally directed to the main interception area to form a continuous oil layer for recovery. Multi-stage deployment is conducive to reducing the direct contact area between the boom and the water flow, reducing the impact of the water flow and improving the overall stability of the system.

5. Reach a verdict

Through the systematic research on the performance optimisation and oil stopping strategy of booms in the emergency response to oil spill in rapids type rivers, this paper proposes the structural optimisation direction of the new type of booms for the failure mechanism of traditional booms under rapids, such as the addition of gradient counterweight module, the integration of composite splash-proof components and the optimisation of skirt design, etc., which can effectively improve the anti-slippage performance, splash inhibition capability and interception efficiency of the booms. At the same time, combined with the actual case of Lancang River, this paper puts forward the scientific and reasonable principles of oil spill interception point selection, boom deployment angle and method, and multilevel deployment strategy, which can significantly improve the efficiency and effect of emergency response, and is of great significance to reduce environmental pollution.

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