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Study on failure mode of oil interception fence in turbulent river

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Abstract

To reduce environmental pollution caused by oil spills in turbulent river conditions, the key to researching oil spill recovery technology for turbulent rivers is to identify the critical factors leading to the failure of oil booms. This paper establishes a two-dimensional three-phase flow model based on FLUENT technology to simulate the transient changes and distribution patterns of oil and water under the influence of oil booms; it uses ANSYS to build a mechanical model of the oil boom, calculating the deformation degree and oil interception efficiency under turbulent conditions, and investigates areas with higher probabilities of structural failure. Additionally, based on similarity principles, a laboratory small-scale oil spill tank experiment is established to provide a basis for optimizing new oil boom structures and deployment methods.

Keywords

Turbulent river; Oil spill accident; Oil boom

1. Introduction

In the context of oil and its applications, oil spill incidents occur frequently worldwide, causing significant environmental and economic losses. According to statistics from the International Maritime Organization (IMO), at least 3.2 million tons of oil are discharged into the marine environment annually from various pollution sources. Oil spills not only pollute water bodies but also severely impact fisheries and water safety. Oil booms are powerful tools in oil spill emergency response, excelling in containing the spread of oil pollution, guiding its safe transfer, and effectively preventing potential leakage risks. However, in practical deployment and operation, the effectiveness of oil booms often faces challenges from natural conditions such as waves and currents, as well as limitations in their design, leading to less than satisfactory oil containment results. Therefore, in-depth exploration of the dynamic behavior of oil booms in complex wave and current environments and their oil containment efficiency not only injects new vitality into relevant theoretical research but also provides valuable reference for engineering practice. This is particularly important and urgent given the severe situation where oil spills can severely pollute sensitive water bodies like rivers once they occur.

2. Spill accidents at home and abroad

An oil spill incident refers to the leakage from ships, oil storage facilities, and other sources, causing petroleum and its products to enter oceans, lakes, or other water bodies, leading to significant impacts on the ecological environment and human society. According to statistics, there have been 13 major spill incidents both domestically and internationally since 2000. Each oil spill not only results in substantial economic losses but also causes severe damage to the local ecosystem. In June 2011, the Penglai 19-3 oilfield, jointly developed by CNOOC and U.S.-based ConocoPhillips, experienced a blowout and leak. The incident led to the release of approximately 700 barrels of crude oil and 2,500 barrels of mineral-based mud, polluting about 5,500 square kilometers of sea. On March 10,2025, the oil tanker "Stena Immaculate" collided with a cargo ship "Solong" flying the Portuguese flag in the North Sea, causing an explosion and fire. The accident resulted in the leakage of about 800 tons of aviation fuel, posing a serious threat to marine ecosystems. Fortunately, all 37 crew members were rescued. In summary, oil spill incidents have had significant impacts on the ecological environment and human society, necessitating effective measures for prevention and response.

3. Study on failure mode of oil booms

3.1 Research status of oil booms at home and abroad

In China, it was founded in 1995[1] The finite element analysis of the oil boom structure was carried out for the first time, which laid a foundation for the optimization direction of the oil boom. Wei Fang[2]The shape and Angle of the skirt were optimized to improve the failure rate and cumulative failure time of oil barriers. Hou Shuping[3]The failure of the oil boom under different parameters was simulated and analyzed by FLUENT software. In foreign countries, Kim[4]For the first time, Hou et al. used laboratory scale models and two-dimensional numerical models to study the optimization direction of oil booms[5]A multiphase flow analysis model was established to simulate the oil level around the oil boom. Numerical methods were used to analyze the impact of various operating conditions on the oil absorption efficiency of the boom, providing a reference for its design. These studies have yielded rich results in designing oil booms, enhancing structural stability, improving usage efficiency, and ensuring effective oil absorption.

3.2 Characteristics of oil spill barriers in oil spill accidents

As the industrial sector rapidly expands, the sharp increase in oil demand has directly led to frequent surface oil spills. To address this severe challenge, researchers worldwide have delved deeply into oil boom technology. Today, the rapid advancement of computer technology has opened new avenues for developing oil booms. With advanced numerical simulation techniques, researchers can now accurately evaluate the oil containment performance of various deployment methods with unprecedented convenience and speed. In terms of application, innovations in oil boom technology are equally significant. The new generation of oil booms is designed to be more efficient, capable of responding quickly, and engaging in operations promptly. Their structural design and forms are also more diverse, encompassing multiple components such as floats, clusters, tension bands, weights, and joints, leading to various types including fence-like, external tension, solid float, and inflatable designs. For different characteristics of oil spills, researchers have meticulously developed targeted and adaptable deployment strategies, such as induction methods, staggered arrangement, and towing techniques, aiming to achieve more precise and efficient response and handling of oil spills. Ordinary oil booms should have specific oil containment capabilities, including good wave-riding ability, wind resistance, wave resistance, and water flow resistance. Additionally, they should be easy to use, durable, easy to maintain, and marine-friendlyProperties such as difficulty in attaching to organisms[7]. With the rapid development of industry, oil booms have made certain progress in application, with more diverse structures and forms. The structure is divided into: floating bodies, groups, tension belts, weights, and joints; in terms of form, there are fence-type oil booms, external tension-type oil booms, solid float-type oil booms, and inflatable oil booms[8]. For different oil spill accidents, appropriate deployment methods have been developed, including induction method, alternating arrangement method, and dragging method[9]. The oil boom will fail in different modes under the influence of wind, waves, and flow, such as entrainment failure, oil layer flow chamber failure, splash failure, and overpass failure.

3.3 Research content

First, based on the current research status both domestically and internationally, summarize the materials and structural parameters of commonly used oil booms to determine the parameter range: using FLUENT software, establish a transient oil barrier model to investigate the distribution patterns of oil and water under conventional oil booms, and develop a time-varying oil spill distribution model. Then simulate the mechanical behavior of conventional oil booms, analyzing the stress conditions of oil booms under turbulent flow impact and oil spills. Using ANSYS software, create numerical simulations of mechanical behavior, employing structural analysis methods to study the mechanical behavior of oil booms under high flow velocity impacts. Combine mathematical models to analyze the relationship between deformation levels of conventional oil booms and factors such as water flow velocity, boom length, material, and structural dimensions. Next, according to the principle of similarity, establish a small-scale oil spill tank, and through oil barrier interception experiments at high flow velocities, observe parameter changes and their effects on the mechanical properties and interception efficiency of oil booms by altering predicted parameters and deployment angles, verifying structural deformation and failure modes. Finally, analyze the limitations of conventional oil booms in intercepting oil spills in turbulent rivers, propose optimization ideas and principles for oil booms under existing technical conditions; based on the impact of key parameters, suggest optimizations for the structure and deployment methods of oil booms for intercepting crude oil pipeline leaksSuggestions.

3.4 Analysis of research results

Simulation results show that as the flow velocity increases, the angle at which the oil boom is set up relative to the riverbank should gradually decrease. However, when the angle decreases to a certain extent, the length of the oil boom will significantly increase, and the impact force from the flowing water will also grow accordingly. Therefore, the relationship between flow velocity and setup angle needs to be reasonably designed based on the width of the river channel. When the flow velocities are 1m/s, 2m/s, 2.5m/s and 3m/s, the twisting angle of the oil boom increases with the rise in flow velocity, making it more prone to failure at higher flow rates. Additionally, there is a point on the oil boom where deformation is most severe; its displacement is not constant but proportional to the flow velocity. Thus, when the flow velocity reaches a certain level, the oil boom has a risk of breaking. Through numerical simulations of the oil interception process under different flow velocities, we found that at lower flow velocities (approximately 1m/s), the oil boom still has some interception effect, with leakage being the primary mode of failure. Therefore, by appropriately increasing the number or size of oil booms when the flow velocity is low, the likelihood of interception failure can be effectively reduced. When the flow velocity exceeds 1.5m/s, the interception efficiency of the oil boom begins to decline significantly, with splash-out becoming the main mode of failure. And when the flow velocity continues to increase to 2m/s, the oil boom almost completely failsThe interception effect is lost, and the main failure mode is still splash failure. Therefore, the oil containment effect can be improved by improving the skirt design of the oil boom.

4. Oil spill water pool test verification

The experimental oil boom differs objectively from the actual river conditions in terms of size and flow model. Therefore, based on the existing laboratory conditions, using the principle of similarity in flow models, a laboratory similar model design is carried out to ensure the effectiveness and authenticity of the experiment, reducing the design cost of the oil boom. This experiment selects a hydrodynamic test tank with dimensions of 20m in length, 2m in width, and 1.2m in depth. Additional instruments such as force gauges and anemometers can be added to complete small-scale experiments on the oil boom, measuring the tension on the booms cables and observing failure. The oil boom is deployed at a 60° angle, capturing parameters including deformation of the oil boom and oil interception ratio. According to the scale reduction plan, the state at a flow velocity of 0.61m/s is simulated, adding oil material that acts as spilled oil. By pushing the speed plate, a flow velocity of 0.61m/s is simulated, observing that about 0.3 seconds after the spilled oil contacts the oil boom, a small portion of the oil overflows from the top of the boom, causing splashing failure. At the same time, the boom undergoes flipping deformation but experiences another splash failure over time. Finally, almost all the spilled oil overflows from the top of the boom, leading to complete failure of the oil boom, which is almost identical to the simulation process.

5. Summary

According to the research, we found that the failure of oil booms is mainly due to several aspects. First, when the rivers impact force is strong, the oil boom deforms, leading to structural failure. Second, the lack of dampers in groups of oil booms can cause them to tip over easily, resulting in splash failure and entanglement failure. Methods for optimizing oil booms can be approached from multiple angles. Here are some specific optimization strategies: Improving skirt design: By increasing the thickness of the skirt, using more robust materials, or adopting special structural designs, we can enhance the skirts resistance to deformation, reducing deformation and failure caused by water flow impacts. Optimizing the shape of the skirt to better adapt to different water flow environments at various speeds, thereby improving oil interception effectiveness. For example, using streamlined design to reduce water resistance. Optimizing the connection between floats and skirts, adopting more reasonable connection structures, such as using high-strength bolts, welding, or special connectors, to improve fatigue resistance at connection points. Alternatively, selecting materials with high strength, corrosion resistance, and wear resistance for making oil booms, such as high-strength steel or titanium alloys, to enhance the overall strength and durability of the oil boom. Adjusting the placement angle between the oil boom and the riverbank based on water flow velocity and river width to reduce water impact forces and improve the stability of the oil boom.In cases of high flow velocity or wide river channels, the effectiveness of oil interception can be enhanced by increasing the number or length of oil booms. Additionally, multi-segment oil booms can be combined to form longer barriers. In situations with extremely high flow velocities, a multi-level deployment strategy can be adopted, setting up multiple layers of oil booms at different positions to intercept oil layer by layer, thereby improving overall oil interception efficiency.

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