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Structural analysis of oil-spill containment booms in coastal and estuary waters

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ABSTRACT

In this paper, the oil-boom concept is studied using a numerical model based on a non-linear membrane finite-element method. Several parameters are identified as having significant influence on the boom section geometry, on its mechanical stress and on its efficiency. The principal parameter acting on the boom efficiency is the normal sea current velocity. The main observed variable for the boom efficiency is the vertical angle of its skirt. A proposed numerical method is applied to the computation of a boom contingency plan. It is tested in the real environmental conditions of an estuary and a full tide cycle. The Elorn River Contingency Plan in France's Brittany Region was carried out to study oil containment efficiency. It is analysed during tide periods of a reference day. The role of the anchorage system on dead-masses and buoyancy coffers is emphasized. The tensions on the dead-masses, the mooring lines and the buoyancy coffers are considered in the computation. The result of the analysis in the boom stress limit suggests safety coefficients should be included in a boom contingency plan.
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1. Introduction

Oil spill is a tragic anthropic pollution occurring in coastal and estuary waters. A main technological response used during oil-spill crisis is floating barriers called booms. They confine or deviate the floating oil pollution. They are positioned on the surface of the sea in estuaries, rias and coastal waters. Depending on the sea current, oil booms can confine oil at low current velocity. It can also deviate oil at high current velocity. It is important to emphasize that booms can only contain, concentrate, or deviate pollutants. The recovery of pollution is accomplished by using a pump or a skimmer. A boom can also be used at high sea. It can be tugged by an oil recovery vessel and used as a kind of sweeping arm on the surface of the sea.

Booms are made of a floating tube, an immersed skirt, a longitudinal leach and a longitudinal chain. The chain contributes both weight and tension. The leach is generally located on the skirt top. The chain is located on the skirt bottom. Booms are moored on the seabed near the shore, a port or an oil terminal.

The intrinsic limitation of the boom efficiency is the presence of sea current. The boom efficiency is limited by the normal component of the current velocity with respect to a boom's direction. Our case study analysis of boom inefficiency is shown in Fig. 1. It shows an environmental condition where a strong current is present. We observe that the boom skirt becomes quasi horizontal. This skirt angle can result in the leakage of some floating oil pollution. The empirical value of 0.35 m/s is commonly admitted for the maximal current velocity. When the current velocity is under this limit the boom can be placed normally in the current. If the boom has a quasi-vertical skirt then it can confine the oil. When the current exceeds this limit, to reduce the hydrodynamic pressure, the boom is placed in such a way that its normal direction is at an angle with the current direction. Empiric rules exist to define this angle and in that case, the boom skirt must remain in a quasi-vertical position to guarantee oil deviation. In order of importance, two other physical effects have less influence on the boom efficiency: (1) the waves force and (2) the wind pressure.

Choices made about efficient boom devices and their installation plan are the main critical issues when organizing counter-pollution actions. Due to the complexity of the coastal environment to be protected, many kinds of booms and many different boom applications are available. An overview of the existing boom equipment indicates the existence of more than a thousand boom references and a hundred manufacturers [1]. In a given pollution crisis, the crisis team has to make a choice about the best kind of boom and the best installation plan. Note that a boom moored on shore has intrinsic limitation. It is also important to note the natural coastal sea conditions vary in space and time. Consequently, a boom installation problem is complex to formulate and to solve. Most of the tools available for decision-making are empirical. Therefore limits of booms suggest the use of mechanical modelling.

The aim of this paper is to propose a numerical modelling for the structural analysis of oil booms. For that purpose we will do two complementary studies. The first study concerns the modelling of a boom section and the second study concerns the modelling of a complete boom plan.

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Fig. 1. Boom behaviour under a strong current.

Published scientific research about booms focuses mainly on the hydrodynamic aspect [2–4]. The oil boom structural behaviour is less studied. The first structural analysis on booms was published in 1993 by a USA team. They used a finite-element method based on a beam element [5]. A one dimensional simplified method exists where a Catenary Curve is proposed for the boom geometry on the surface of the sea [6], and a first-order differential equation is proposed for the boom tension vector [7]. Here, we propose to use a three dimensional model based on a non-linear membrane finite-element. In addition, we notice a similar approach for the modelling of fishing nets when using a non-linear cable finite-element [8]. When it comes to technological innovations of booms very little research has been published: studies focus on hydrodynamic of booms having multiple skirts [9] and mechanical behaviour of booms adapted to rivers [10].

2. Mechanical modelling

The French Administration of Ecology and Sustainable Development funded the national research project, SIMBAR, about "Oil Spill Boom and Contingency Plan Modelling". It was launched in March 2004 under the label of the research and innovative technologies network, RITMER, on accidental maritime pollutions. The main objective of SIMBAR was the knowledge improvement of oil booms under operational constraints. To this end, the project provides a modelling of booms by coupling a hydrodynamic study with structural analysis [11]. This paper focuses solely on the structural analysis of booms. The computations were done by using a non-linear membrane finite-element method because the boom device and the boom plan mechanical models needed to be well defined.

2.1. Boom device section

According to the large transversal displacement of a boom, the structural computations are based on a non-linear membrane finite-element. The geometry of each element is a quadrilateral bi-linear surface [12]. The finite-element mesh uses a boom section composed of four different parts. The boom section mesh is shown in Fig. 2. The description of these four parts follows:

(1) The cross-section of the float is decomposed into an even number of elements to maintain a symmetrical motion. The first possibilities for the float cross-section decomposition are four, six, eight or ten equal parts. The sixth and tenth part decompositions are incompatible with both vertical and horizontal internal membrane partitions of the float (double chamber float). Thus the total number n of finite-elements must be reduced hence the computational time is limited. Considering that the computational time is proportional with n^3, we chose to decompose the cross-section of the float into four equal parts. The decomposition with eight parts has been eliminated because it exceeded a moderate computational time. If the float is a circular tube it means the finite-element mesh of its cross-section is a square. Note that the float extremities are closed like a toothpaste tube bottom (Fig. 1). It is important to note the float mesh must also be compatible with supplementary vertical closings. The study of these supplementary vertical closings is not presented here.

(2) The skirt cross-section is decomposed with a minimum number of elements. A two element decomposition was chosen so that a three node parabolic interpolation can give the skirt vertical curvature.

(3) The finite-elements of the chain are attached to the skirt bottom elements. The chain elements at the boom section extremities have a reduced width. These two width reductions favour the chain elements rotation around their axis.

(4) The finite-elements of the leach join the skirt top elements with the float bottom elements. The material thickness of the leach is a multiple of the fabric thickness of the skirt.

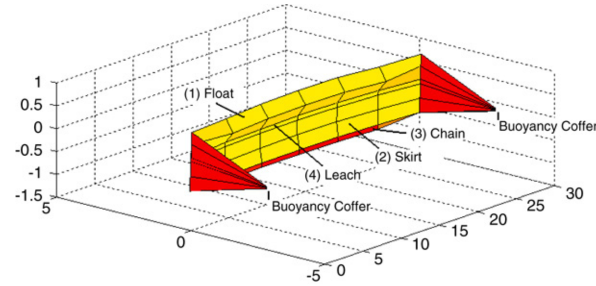

Fig. 2. Mesh of a boom section with its triangular fixations.

The main dimensions of the boom taken as a reference are: 50 cm for the float diameter, 75 cm for the skirt height, including 10 cm height for the chain and 10 cm height for the leach (Fig. 2). In this figure, the two triangular parts placed perpendicularly at the boom section extremities are the stabilizing devices of the boom section on two buoyancy coffers. These coffers are not represented in Fig. 2. From each coffer starts a mooring line attached to a dead-mass on the seabed of coastal or estuary water. A mooring line is composed of lengthened membrane finite-elements. The horizontal projection length of a mooring line is equal to the depth of the sea multiplied by three. The current direction is assumed to be normal for the boom section in the analysis carried out (Section 3.1).

2.2. Elorn boom plan

The Elorn River Estuary is located east of the French city, Brest. The Elorn River Boom Contingency Plan is shown in Fig. 3. In Fig. 3 the west direction is on the left. The letters A to G indicate the locations of the boom section extremities. The Elorn Boom Plan is rectilinear. It is composed of six boom sections. The boom sections are each 171.2 m long. The total boom plan length exceeds 1 km. The $2m^3$ buoyancy coffers are placed at several locations from points B to F. The boom is attached to a rigid coastal structure at points A and G on the shore. The buoyancy coffers are moored on dead-masses weighing 6 T. At point E, the coastal water depth reaches 12 m at high tide.

As a consequence of the current inversion due to the tide effect, two stabilizing devices and mooring systems (buoyancy coffers, mooring lines, and dead-masses) exist upstream and downstream. The boom plan mesh is shown in Fig. 4. Doubling the stability permits reducing boom displacement amplitude when the tide reverses.

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