Applied Ocean Research 31 (2009) 186–196

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Behavior of rigid and flexible oil barriers in the presence of waves

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ARTICLE INFO

Article history:
Received 22 December 2008
Received in revised form
6 July 2009
Accepted 19 August 2009
Available online 17 September 2009

Keywords:
Oil spill containment barrier
Flexible barrier
Interfacial instability
Kelvin–Helmholtz instability
Wave height
Wave period
Wave steepness
Surging drainage
Towing velocity

ABSTRACT

Although oil barriers have been used for many years to contain slicked oil in open seas, the effect of waves on them has been rarely considered. In the present study, we investigated the response of rigid and flexible oil containment barriers in the presence of currents with and without waves. Two-dimensional experiments with both rigid and flexible oil containment barriers were carried out in a laboratory flume equipped with a pneumatic wave generator. The initiation of containment failure for various conditions were analyzed and compared.

In the course of this study, the effect of wave characteristics on containment failure was discussed and some empirical equations were proposed to predict the initiation of failure in different conditions. Once the failure started, the effect of wave steepness on the loss rate was investigated. Finally a failure mode occurring due to the waves' effect, called surging drainage failure, was studied.

1. Introduction

Oil spills are of major environmental concern in coastal regions as they can pollute the coastal environment and damage marine life. Most oil spills occur during operational discharges of ships in the vicinity of marine oil platforms as well as from accidental tanker collisions and groundings.

The need to confine spilled oil to a small area as quickly as possible, in relatively thick layers, is a practical necessity, since experience shows that even the best efforts cannot prevent the occasional occurrence of major accidents at sea. Practically, many competitive methods are available, but they are mainly accompanied by adverse side effects. Containment and physical removal are recognized to be the most desirable methods of oil spill cleanup. Mechanical oil barriers, or ''booms'', used to contain or divert oil spills are key tools in oil spill response. Booms are widely used to collect and contain oil on the sea surface, or to protect specific areas against slick spreading.

Several mechanisms can cause the oil booms to fail. There are three main failure mechanisms namely entrainment, drainage, and critical accumulation failures. Entrainment failure occurs when interfacial waves are caused by a high relative oil–water velocity and oil droplets detach from the oil–water interface and pass under the barrier [1–5]. The second failure mechanism is called drainage failure and happens when the barrier's draft is not deep enough to prevent the slick from plunging under the barrier [6–9]. For oils with higher viscosity, or in the case of water–oil emulsions, a third failure mechanism, called critical accumulation failure, may occur, in which the whole oil volume accumulates behind the barrier and passes under the barrier suddenly [4,10].

In the present study, we investigated the containment process of low-viscosity oils, for which the containment failure mode is mostly entrainment failure.

Oil spill removal and control in open seas can be seldom conducted under calm conditions, so the effects of waves on the performance of oil spill equipment must be dealt with. However, only few researchers studied the wave effect on containment efficiency. [11,12] presented the equations of motion for thin oil layers due to gravity, inertia, surface tension, and stresses imparted by wind and water waves. Kordyban [13–15] also made a major attempt for taking effects of waves and wind into account and found that instability in the presence of waves occurs much earlier than without waves.

All the previous studies have been conducted with a fixed boom, while, in practice, the barrier is subjected to various motions in the presence of waves and wind, and follows the wave crest and

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0141-1187/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apor.2009.08.005

trough. Performing experiments with a rigid fixed barrier, Kordyban [15] reported that the oil layer is thicker at the crest, and as the interface moves down, the thickness decreases significantly. It is minimum at the trough, but increases rather suddenly thereafter and reaches the bottom of boom. As the upward travel continues, the oil still escapes until the interface, eventually, returns to its normal shape. [14] also examined the effect of the wind on the distribution of an oil layer on wavy water, since the waves exist usually in windy weather. It was found that the wind tends to decrease the difference between the oil layer thickness at the wave crest and the wave trough.

A comprehensive investigation of oil spill containment barriers under various current, wave, and wind conditions was provided by [16] and [17–19]. They developed a local two-phase nonlinear hydrodynamic numerical model to simulate oil containment by a rigid fixed boom under open sea conditions. The results were compared with those obtained from experiments with different oils. The study approved that the failure mode is independent of wave characteristics and is only influenced by the oil viscosity. However, the initiation of failure can be considerably influenced as the wave height or wave frequency increases.

On the other hand, although flexible barriers have become increasingly common as a cleanup facility, there is still a lack of knowledge about their behavior. According to an extensive literature review [20], most of existing research, either physical or numerical, have been done for rigid barriers. Accordingly, the main concentration in the present study is devoted to the response of a flexible barrier in the presence of currents and sea waves.

2. Experimental set-up and conditions

Experiments were conducted in a 12 cm wide, 6.5 m long and 1.2 m deep laboratory flume, with both rigid and flexible barriers under alternative flow conditions, and in the absence and presence of waves. A pneumatic wave generator was utilized to generate monochromatic unidirectional waves. Waves were generated by periodic air pressure applied uniformly over the water surface and their crests were always perpendicular to the channel side walls. The periodicity was produced by a metallic arm connected from one side to a rotating disk and from the other side to a wind piston. The generated wave had the same frequency as the motor axes rotation. The arm length could be changed by sliding its end over the rail fixed on the disk, applying changes on the generated wave height.

Fabricating a flexible barrier that can deform under flow conditions, and at the same time, is tight enough so that oil can be contained behind it without leakage from the sides, was the key challenge. This has been achieved using a slitted side skirt on the boom where it faces the lateral wall of the flume (Fig. 1) [21]. For experiments in the presence of waves, it was important that the barrier follows the surface movements and stays floating over the water surface. To achieve floating conditions, the barrier was connected to a cubic floating element at the top (Fig. 1f), which allows the displacement of the barrier due to waves. The floating barrier was connected to the side walls by a rope at each side.

Rapeseed oil was chosen for experimental study. It has a viscosity of 88.8 *cSt* (mm^2/s) and a density of 0.91 gr/cm^3 at room temperature (15 to 20 °C). The interfacial tension of rapeseed oil and water is 30 mN/m. As it was discussed, for such an oil the dominant failure mode was entrainment failure.

A first series of oil experiments were carried out in the presence of currents in the laboratory flume, with no waves. The response of flexible and rigid barriers were examined for different experimental conditions. The second series of oil experiments were undertaken in the presence of both currents and waves in the laboratory flume with focus on the effect of wave characteristics on containment procedure. The experimental conditions for experiment with and without waves are shown in Tables 1 and 2 respectively.

Table 1
Experimental conditions for oil tests with rigid and flexible barriers without waves, velocity range: 10 to 35 cm/s.

Group	Test number	Oil volume [m^3/m]	Barrier draft [cm]	Ballast weight [kg/m]
Rigid barrier	OR1	0.01	10	–
	OR2	0.01	20	–
	OR3	0.02	10	–
	OR4	0.02	20	–
	OR5	0.015	15	–
Flexible barrier	OF1	0.01	10	0.6
	OF2	0.01	10	1.5
	OF3	0.01	20	0.6
	OF4	0.01	20	1.5
	OF5	0.02	10	0.6
	OF6	0.02	10	1.5
	OF7	0.02	20	0.6
	OF8	0.02	20	1.5
	OF9	0.015	15	1.05

Table 2
Experimental conditions for oil tests with rigid and flexible barriers with waves, flow (towing) velocity range: 10 to 35 cm/s.

Group	Test series	Oil volume [m^3/m]	Barrier draft [cm]	Ballast weight [kg/m]
Rigid barrier	SR1	0.02	10	–
	SR2	0.02	20	–
Flexible barrier	SF1	0.02	10	0.6
	SF2	0.02	10	1.5
	SF3	0.02	20	0.6
	SF4	0.02	20	1.5
	SF5	0.03	10	0.6
	SF6	0.03	20	0.6

The experimental procedure is described below:

1. With the flow set at 10 cm/s, oil was poured below the water surface to prevent droplet formation and penetration into the flowing water.
2. The water flow was slowly increased (2 cm/s till 24 cm/s and 1 cm/s after it).
3. Steps 2 was repeated until oil droplets were observed to escape under the skirt and failure happened.

In the presence of waves, the same above mentioned steps were followed. In the beginning, after pouring the oil over water surface, the desired wave was generated.

2.1. Downscaling of containment failure

It is generally accepted that there are different scaling rules which have to be considered for different oil containment failure modes [4]. According to comprising experiments of [22] on scaling oil droplet formation, geometric downscaling used for small-scale laboratory experiments is unnecessary when modeling the generation of droplets from interfacial instabilities.

The formation of droplets is caused by unstable increasing waves on the interface due to Kelvin–Helmholtz instability ([1]). Kelvin–Helmholtz instability can occur when velocity shear is present within a continuous fluid or, when there is sufficient velocity difference across the interface between two fluids. These interfacial waves and instabilities are influenced only by three oil parameters: density difference between oil and water, $\Delta\rho$, viscosity, ν, and interfacial tension, σ_{ow}. As such, using a real oil permits doing full scale experiments to model droplet entrainment failure.