Pergamon

Spill Science & Technology Bulletin, Vol. 7, Nos. 5–6, pp. 223–228, 2002
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Printed in Great Britain
1353-2561/02 $ - see front matter

PII: S1353-2561(02)00038-5

RESEARCH

Field Experiments at the Ohmsett Facility for a Newly Designed Boom System

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In this paper, the full-scale test performance of an innovative boom system is analyzed. The boom system consisted of a ramp boom, which is inclined 15° with respect to the water surface, followed by three conventional booms with different draft lengths. According to the test results, the boom system is observed to have a better collection efficiency than simple conventional booms. The efficiency of simple booms is known to be very low at oil–water relative velocities greater than 1 knot. A high of 86.5% collection efficiency was achieved by the new boom system at a tow speed of 1.5 knots. The new boom system was found to have a critical tow speed of 1.89 knots, beyond which the collection efficiency decreases rapidly. This tow speed of 1.89 knots corresponds to a critical Froude number of 0.36.

Keywords: **Boom, oil spill, test facility, collection efficiency**

Introduction

Large quantities of oil are produced, distributed and consumed throughout the world. Petroleum-based oil is used as a major power source to fuel the factories, various modes of transportation, and in many everyday products. For USA only, on average over 250 billion gallons of crude oil and other petroleum products are being used (Doerffer, 1992). At every point in the oil production, distribution, and consumption process, oil is invariably stored in storage tanks. With billions of gallons of oil being stored throughout the world, the potential for an oil spill is significant, and effects of spilled oil can pose serious threats to the environment.

The most common equipment used for controlling oil spill is the oil boom. Booms are used to contain the oil and keep it from spreading. Specially designed, fire resistant containment booms can be used to contain burning oil, if *in situ* burning is approved. Following containment, three distinct approaches can be taken to physically remove the oil from the water. These are the use of mechanical skimmers, the use of sorbent material, and manual removal by the cleanup work force. Dispersants are also sometimes used.

Conventional oil booms essentially consist of flotation, skirt and ballast. For this type of oil-water-boom system, various hydrodynamic instabilities (Delvigne, 1989) contribute to a fairly low practical limit on the oil–water relative velocity, of the order of 1 knots. The prototype of a newly designed boom system that has a collection efficiency better than that

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of simple conventional booms has been tested at Ohmsett.

The New Boom System

The new boom system is an innovative boom arrangement, consisting of a ramp boom and three other conventional booms of different drafts, forming three oil collection zones (see Fig. 1). As a first step in the design procedure, the designed boom configuration was tested with the aid of a hydrogen bubble flow visualization equipment (Wong & Wolek, 1996). This experiment showed that the designed boom configuration was very promising. Based on scale model tests that were carried out in the open channel apparatus (Wong & Guerrero, 1995) and computer simulation experiments, a prototype ramp boom model has been designed. The concept of using an inclined ramp-type boom in relatively fast currents (i.e. up to three knots) has been proven in scale model tests to be effective in the collection/containment of the surface oil from oil spills. As the full-scale ramp boom system is intended to be much greater in length than the prototype, certain features have been incorporated into the prototype design that should enhance the eventual deployment of the full-scale system at sea. These features include (see Fig. 2):

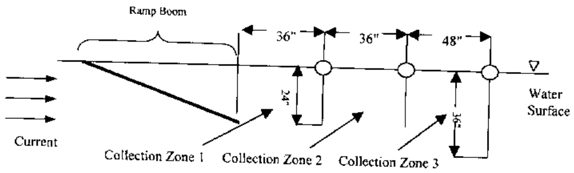

Fig. 1 Ramp boom system schematic.

- Air inflatable cylindrical pontoons to serve as oil booms, provide lateral stiffness and to provide reserve buoyancy for the ramp boom system.
- An array of aluminum angle stiffeners with integrally cast lead ballast weights positioned and bolted onto the top of the ramp boom surface to provide stiffness to the ramp boom.
- Fixed syntactic foam flotation blocks located in the leading edge of the ramp boom to provide the desired positioning of the ramp's leading edge surface with respect to the water surface and also to provide some degree of desirable heave stiffness to the system.
- Adjustable nylon webbing straps to attach and restrain both of the inflatable pontoons.
- Use of 36 oz/yd^2, fabric reinforced polyurethane sheet for the ramp boom surface to enhance the durability and flexibility of the system.

The prototype ramp boom has been designed to automatically maintain a 15° angle of attack with respect to the water surface without the need for external mechanical support. The ramp boom directs the oil and gives it a vertical momentum. If the angle of the ramp boom is kept at an angle which is larger than 15°, the oil would have enough vertical momentum to counteract its own buoyancy force and overshoot the line of conventional booms (Wong & Kusijanovic, 1998). Lead ballast weights have been strategically positioned on the ramp boom top surface to counteract the calculated lift forces on the ramp boom undersurface caused by a maximum design current of 3 knots, the fixed syntactic foam ballast, and the aft inflatable pontoon. At currents less than 3 knots, this angle will be somewhat greater than 15°, but should not exceed

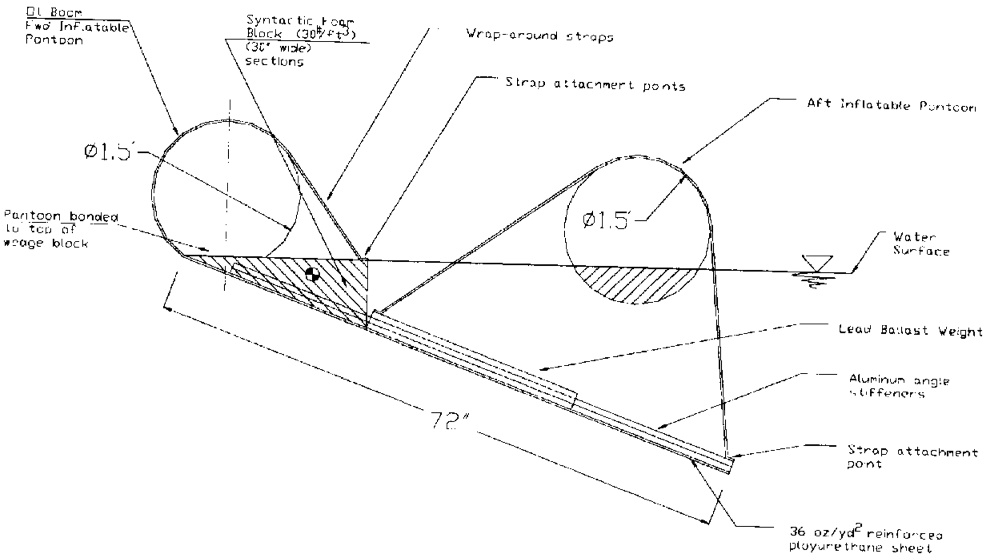

Fig. 2 Ramp boom system components.

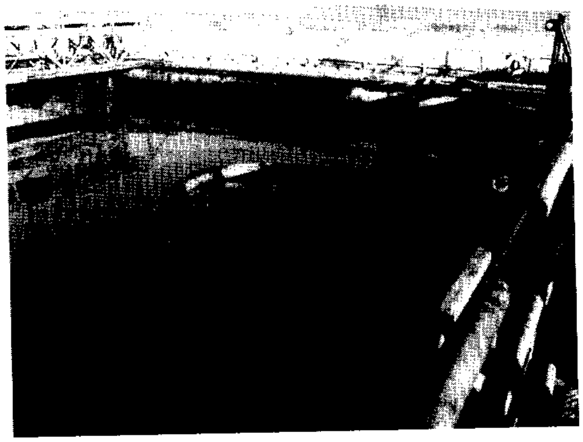

Fig. 3 Ramp boom system arrangement.

16.5° (corresponding to the static equilibrium position of the ramp boom), which was within the design constraints of the intended ramp boom design.

To contain the oil diverted by the ramp boom a series of conventional oil booms were used. The system was formed as a U-shaped wrap-around arrangement (see Fig. 3).

Optimization of the Ramp Boom

The preliminary design of the ramp boom called for the use of 66-in. long aluminum stiffeners with 130.6 lb/ft of lead ballast cast on top of these stiffeners (see Fig. 2). The geometric positioning of the ramp boom components were done according to the force analysis of the ramp boom subjected to a water current of 3 knots. Figure 2 illustrates the equilibrium position of the ramp boom when it is subjected to a 3-knots current. It was desired that the forward pontoon to be totally above the water surface whereas the aft-pontoon to be submerged in the water at this equilibrium position. This arrangement ensured that there was enough reserve buoyancy to keep the system afloat at current velocities less than 3 knots. Owing to the very large lift force associated with 3 knots of current, there was a need of large ballast weight (130.6 lb/ft) to keep the ramp boom stable. This ballast weight corresponds to more than 90% of the overall weight of the ramp boom system and it was a major concern as far as the flexibility of the system is concerned.

For this reason, an optimization study was performed to minimize this ballast weight. In this study, the preliminary design materials, dimensions and positions of the system components other than the lead ballast were taken as pre-assigned parameters since they did not contribute too much to the overall weight of the system. A total of seven design variables, namely, the tensile forces induced in the straps at both sides of the aft pontoon, the angles formed by these straps with respect to the water surface, the inclination angle of the ramp boom, the depth of submersion of the aft pontoon, and the position of the lead ballast weight were used in defining the optimization problem. The force equilibrium equations on both the ramp boom surface and the aft pontoon as well as the equations that stem from the geometry of the system were used to relate the design variables. As a result, the force applied by the lead ballast weight was expressed in terms of those seven design variables together with the associated equality constraints to complete the problem definition. In addition, some inequality constraints were introduced in order to meet some design needs. For that purpose, an upper bound of 9 in. was introduced on the depth of submersion of the aft pontoon to preserve the necessary amount of reserve buoyancy. The angle of inclination of the ramp boom in static (zero current velocity) condition was given a maximum permissible value of 25°. Additionally for stability purposes, the ballast weight was required to be positioned between the forward tip of the ramp boom and the vertical line passing through the center of the aft pontoon.

Generalized reduced gradient method was used in order to solve this nonlinear optimization problem. The method used an initial trial vector of design variables to minimize the ballast weight while the optimum solution satisfied all constraints. The minimum weight was found to be 113.15 lb/ft with a ramp boom inclination angle of 15°. A sensitivity analysis was also performed to check the system stability against manufacturing defects. This was performed such that the component dimensions and other parameters that are set as pre-assigned parameters were perturbed by 5% of their original values and the optimum solution was determined in each case. As a result, it was shown that the optimum solution was insensitive to those perturbations, proving the system to be stable against manufacturing faults.

Testing at Ohmsett

The tests were carried out between December 6 and 7 of the year 2000. Tests were performed as explained in the users guide to the Ohmsett Test Facility (Mullin & Lane, 2000).

Two test oils, Calsol 8240 and Hydrocal 300, were used (see Table 1). Nine test runs were made in all, the first being without oil (see Table 2). The purpose of the first test was to observe how the boom arrangement floated and moved in the water. It was verified that the boom system floated and moved well.

Test 2 was carried out at 1 knot tow-speed, and 67 gal of Calsol was used. Most of the oil collected in front of the ramp boom. There was not enough speed

Table 1 Test oil data

Test oil	Specific gravity	Interfacial tension (dynes/cm^2)	Surface tension (dynes/cm^2)	Water temperature (°C)	Viscosity at 1.44 °C (N s/m^2)	Oil relative viscosity at 1.44 °C
Calsol 8240	0.93	32.50	36.50	1.44	18.92	11064.3
Hydrocal 300	0.88	26–28	29–32	1.44	0.88	514.6

Table 2 Test results

Test number	Oil type	Tow speed (knots)	Volume distributed (gal)	Volume recovered (gal)	Throughput efficiency (%)
1	None	1.0			
2	Calsol 8240	1.0	67.00	≈67	≈100
3	None	1.5			
4	Calsol 8240	2.0	49.70	7–10	14–20
5	Calsol 8240	1.5	49.30	28–35	55–71
6	Hydrocal 300	2.0	44.50	≈16	36
7	Hydrocal 300	1.5	55.90	48.34	86.47
8	Hydrocal 300	1.5	68.80	35.82	52.06
9	Hydrocal 300	1.5	72.00	19.47	27.04

(energy) to move oil past the ramp boom. In other words, the boom was effective in keeping the oil out.

Test 3 was carried out at 1.5 knots tow speed, the oil was present in the first collection zone. It was observed that all of the oil remained in the first collection zone.

Test 4 was carried out at 2 knots tow speed, with 49.7 gal of Calsol used. At this speed, the oil had enough energy to go under the ramp boom and most of the oil escaped. A rough estimate of the amount of oil collected by the booms ranged from a low of 7 gal to a high of 10 gal. This would correspond to collection efficiencies of 14–20%.

Test 5 was carried out at 1.5 knots tow speed and 49.3 gal of Calsol 8240 was spilled. Calsol was too viscous to be pumped into the measuring tanks. The estimate of oil collected ranged from a low of 28 gal to a high of 35 gal. The corresponding collection efficiencies were 55–71%.

Test 6 was carried out at 2.0 knots tow speed and about 44.5 gal of Hydrocal 300 was spilled. About 16 gal of the oil was collected, giving 36% collection efficiency.

Test 7 was carried out at 1.5 knots tow speed and 55.9 gal of Hydrocal 300 was spilled. The collection efficiency was evaluated as 86.5%.

Test 8 was carried out at 1.5 knots tow speed and 68.8 gal of Hydrocal 300 was spilled. The collection efficiency was evaluated as 52%. In this case, some of the oil flowed to the sides of the boom arrangement system, as a result of use of large amount of oil.

Test 9 was carried out at 1.5 knots tow speed with about 6-in. waves created in the test tank. 72 gal of Hydrocal 300 was spilled. The collection efficiency was evaluated as 27%. As it was in test 8, use of large amount of oil increased the end effects, which, in turn, contributed negatively to the collection efficiency. It was observed that the ramp boom system had very good wave-following characteristics.

Analysis

The Froude number, Fr_d, is defined as $Fr_d = (U_0/\sqrt{gd}) = 0.409U_0$, where $g = 9.81$ m/s^2 (gravitational acceleration), $d = 24$ in. $= 0.61$ m (draft of the conventional boom), $U_0 =$ tow speed. At tow speed of 1.5 knots: $Fr_d = 0.316$. At tow speed of 2 knots: $Fr_d = 0.421$.

The parameters needed to characterize the prototype have been obtained. The paper "Instability study of the oil slicks contained by a boom system" (Fang & Wong, 2000) is referenced for determination of the corresponding model parameters. In that study, automotive oil was used as the test oil. The properties of the automotive oil were: $\rho_{\text{oil}} = 870$ kg/m^3, $\mu_{\text{oil}} = 9.5 \times 10^{-2}$ N s/m^2, $s_\mu = 79$.

The Froude number, with $d = 4.5$ cm draft for the model boom is $Fr_{\text{m}} = 1.49U_0$. Hence the model current speeds corresponding to 1.5 and 2 knots prototype tow speeds are 0.212 and 0.283 m/s, respectively.

The prototype test data and the model test data are plotted in Fig. 4. Figure 4 has been adapted from a figure in "Optimization of an Oil Boom Arrangement" (Fang & Wong, 2001). The figure is a plot of the coefficient of collected oil vs. the current velocity, and the corresponding Froude number. The computational model simulated the boom arrangement system that was tested at Ohmsett. In Fig. 4, the coefficient of collected oil is the collection efficiency for the system.

According to the test results, where both Hydrocal 300 and Calsol were used as test oils, the collection efficiency of the boom system was almost 100% at a

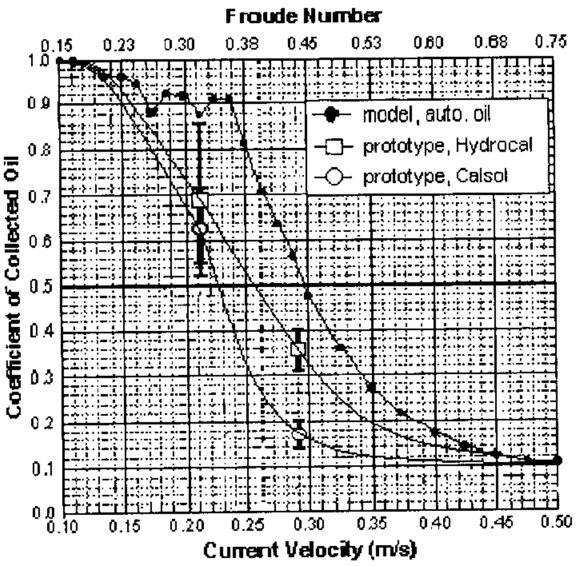

Fig. 4 Coefficient of collected oil vs. current velocity.

tow speed of 1 knot. Obviously the collection efficiency was 100% when the tow speed was zero. Therefore the logical deduction was that the collection efficiency of the oil boom system was 100% for tow speeds between 0 and 1 knot. For the two different test oils (Calsol and Hydrocal 300), there was an observed range of collection efficiencies corresponding to 1.5 and 2 knots of tow speeds. Two available test points for Hydrocal 300 are plotted on the graph. The first point (see Fig. 4) is the arithmetic mean of collection efficiencies that are observed in tests 7 and 8 (tow speed 1.5 knots). The second point corresponds to the mean of observed range of collection efficiency at test 6 (tow speed 2 knots). The error bars are also included in order to indicate the interval of uncertainties. The two available test points for Calsol 8240 are plotted in a similar way (see Fig. 4), together with the error bars associated with the observed ranges of collection efficiencies.

Discussions and Conclusion

The following observations can be made from Fig. 4:

1. The optimum tow speed is 0.212 m/s for the model, which corresponds to 1.5 knots for the prototype.
2. The critical tow speed is 0.24 m/s for the model (at tow speeds higher than this value, the collection efficiency decreases rapidly), which corresponds to 1.89 knots for the prototype.
3. The general behavior is correct since the curves obtained both for model and prototype have similar characteristics.

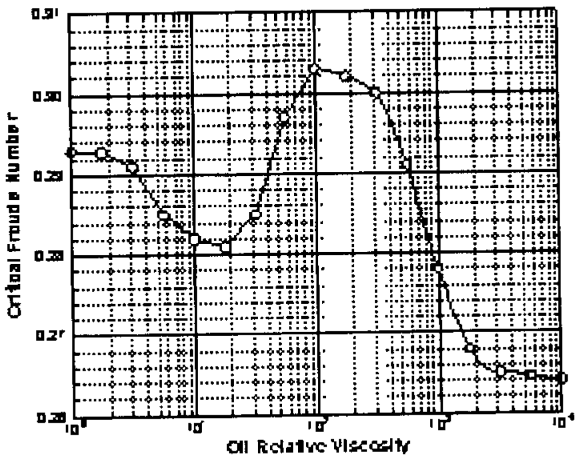

Fig. 5 Oil relative viscosity vs. the critical Froude number.

4. There seems to be a critical Froude number beyond which the collection efficiency drops significantly. This was very evident during the prototype testing at Ohmsett in December 2000. The change in collection efficiency was so drastic that it appeared that an optimum velocity existed for the boom system. In effect, it was changed from almost 100% collection efficiency at one knot to very low collection efficiency at 2 knots. This was not so much a "surprise" as there is a critical Froude number that lies between 1.5 and 2 knots.

The critical Froude numbers of the model and the prototype appear to be different. The reason can be obtained from Fig. 5. The oil relative viscosity for the model test was 79, which corresponds to a higher critical Froude number than both Hydrocal 300 (s_μ = 514.6) and Calsol (s_μ = 11,064.3). The more viscous oils that were used to test the prototype caused the critical Froude numbers to be lowered. For this reason, the critical Froude number of the more viscous oil Calsol 8240 appears to be less than that of Hydrocal 300 (see Fig. 4); both of them were more viscous than the motor oil used in the computational model that produced Fig. 4. So with the computed curve, shifted to the left because of the smaller Froude number for Calsol 8240 and Hydrocal 300, the experimental curves for the Calsol and the Hydrocal could be obtained.

Acknowledgement—This work was funded in part by the Minerals Management Services.

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