Diversion Oil Booms in Current

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Abstract: Diversion boom approaches are developed to contain oil spills close to shore when high-current velocities prevent normal booming operations. In the diversion boom configuration, one end is anchored outside the spill, while the other is secured to shore. The boom is angled to the current to deflect the oil towards a shore pickup point. Boom configuration (planform shape) must be designed for each site-specific current environment to prevent leakage under the boom. A mathematical model relating mooring points, boom parameters, and current is developed, calibrated, and validated. The model is applied, as a representative example, to the design of a boom configuration for the Northeast Petroleum terminal on the Piscataqua River, N.H. Current information is obtained, and trial configurations are evaluated employing the model and using a leakage criterion of 0.31 m/s (0.6 knots) for the maximum normal component of current. The recommended design is found to behave as predicted in a demonstration experiment (without oil). Thus, the model and design procedures are observed to be suitable for diversion configuration design in high-speed currents.

Introduction

Background

Current is often an important factor for oil spills occurring in near-shore areas. Estuaries, rivers, and ports are potential spill sites due to navigation problems and the large amount of transfer activity. Operations are also likely to be near environmentally sensitive areas. In shallow or constricted channels, current can attain high velocities and thereby hamper spill response using oil booms.

For example, the Piscataqua River, shown in Fig. 1, has a narrow channel subject to high-velocity tidal currents and has five petroleum product terminals along the New Hampshire side. Extreme main channel currents can reach five knots, which makes oil tanker/barge maneuvering difficult. Several serious accidents have taken place during the 1970s, and two small spills have occurred in 1990.

High-current speeds make it impractical to deploy a boom so that it is, at any point, perpendicular to the current. Structural loads are high; boom orientation can become unstable, and oil can leak past the boom. Leakage is the most limiting factor since it will occur at lower current speeds.

Leakage and other problems are minimized by deploying the boom in a diversion configuration. In the diversion boom configuration, the outer end of the boom is anchored in the channel, and the inner end is secured on shore as shown in Fig. 2. The boom is angled in order to divert the oil to a recovery point without actually trying to hold the oil against the current. The shore-based recovery point is usually within a slower current regime.

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Angling of the boom, as in Fig. 2, is effective in preventing leakage in fast current. Criterion for success involves keeping the normal, or perpendicular, component of current (U_n in Fig. 2) below a critical value for oil leakage under the boom. There is some uncertainty in how large this should be. Several operations manuals, such as Smith (1975), cite the range 0.31 to 0.46 m/s (0.6–0.9 knots). Carefully controlled experiments carried out at the Environmental Protection Agency's (EPA's) Oil and Hazardous Ma-

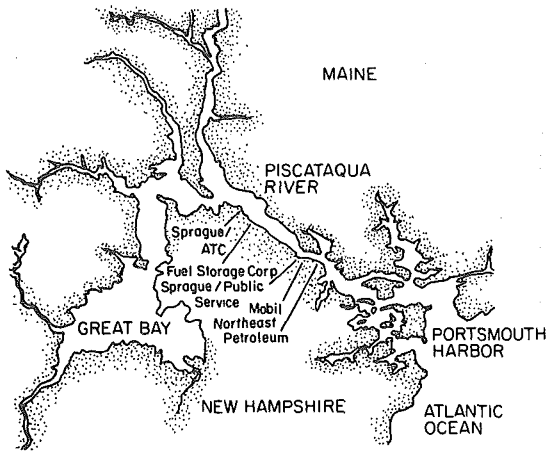

FIG. 1. Piscataqua River Petroleum Terminal Facilities

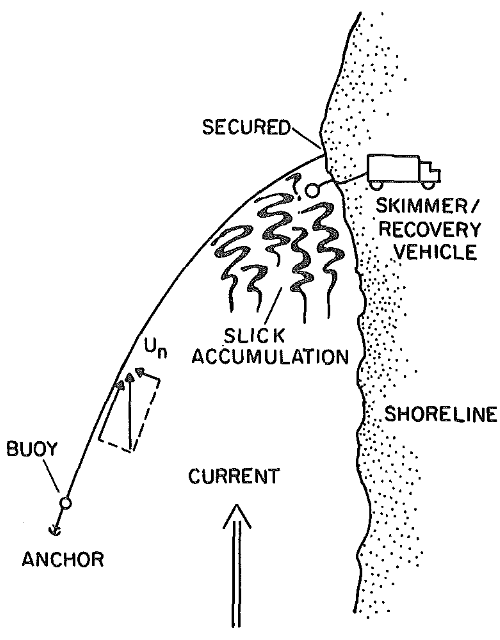

FIG. 2. Diversion Configuration for Oil-Boom Deployment

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terials Simulated Environmental Test Tank (OHMSETT) facility and reported by Breslin (1978) put the limit on U_n at 0.51 m/s (1.0 knot). In the work presented here, a conservative value of 0.31 m/s (U_n = 0.6 knots) was used as the leakage criterion.

If a spill occurs during transfer at a terminal, diversion booms can potentially be used to contain and recover a spill at the site. For high-speed–current environments, however, planning is essential. Currents, anchor-point locations, boom length, and tension are all critical factors and should be determined before an emergency. To understand how these variables are related, a reliable model for boom planform shape, or configuration, is necessary. Previous work has been based on the catenary model approach described by Cross and Hoult (1970) and Milgram (1971). The catenary model, however, assumes that fluid drag is perpendicular to the boom and that the current is uniform along the boom. In many diversion boom applications, these restrictions are not satisfied. A large portion of the boom may be nearly parallel to the current, so there is a significant tangential component of drag as well as the perpendicular component. The boom often encounters diminished current as the shore is approached, so spatial variation in current is of concern.

Approach

In the study described here, a mathematical model is developed for long booms used to divert oil. The model includes tangential fluid drag and accounts for spatially varying current. Theory is first derived, and then the model is calibrated and validated using data from a boom-shape experiment.

Next, the model is applied to the specific problem of responding to a flood-tide spill at the Northeast Petroleum Terminal on the Piscataqua River (see Fig. 1). This example is intended to show the procedures necessary to design a boom configuration that will deflect oil to a designated shore-recovery point. The leakage criterion, involving the normal component of current, will be a critical consideration. The first task of acquiring a surface current data set in a field program is described. Then the boom-configuration design and analysis step, using current data as input to the model, are detailed. Lastly, the results of implementing the recommended design in a boom demonstration experiment (without oil) are presented.

Mathematical Model

Theory

In order to determine boom planform shape and, therefore, the maximum magnitude of the current velocity normal to the boom, a general mathematical/computer modeling approach was developed. Input is the proposed boom design, including anchor point positioning, the boom length and skirt depth, and the spatially variable current field acting on the boom. The model relates these design parameters to mooring loads, boom tensions, and shape as well as maximum current perpendicular to the boom.

The force balance on a differential element of the boom is shown in Fig. 3. In the tangential direction (along the boom segment) equilibrium requires that

$$\sum F_t = \frac{1}{2}\rho C_t h U_t^2 \Delta s - T\cos\left(\frac{\Delta\theta}{2}\right) + (T + \Delta T)\cos\left(\frac{\Delta\theta}{2}\right) = 0 \quad \ldots. (1)$$

where C_t = drag coefficient in the tangential direction; ρ = density; h =

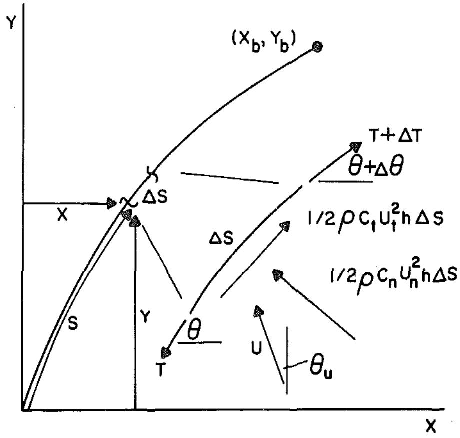

FIG. 3. Model Nomenclature and Boom Element Free-Body Diagram

skirt depth; s = distance coordinate along the boom; T = boom tension; θ = boom angle with respect to x-axis; U_t = component of current in the tangential direction = $U \sin(\theta - \theta_u)$; U = current magnitude (speed); and θ_u = current angle counterclockwise from y-axis. Dividing through by Δs, taking the limit as Δs, $\Delta\theta$, $\Delta T \rightarrow 0$, and rearranging yields

$$\frac{dT}{ds} = -\frac{1}{2}\rho C_t h U^2 \sin^2(\theta - \theta_u) \quad (2)$$

In the normal direction (perpendicular to boom), equilibrium will be satisfied when

$$\sum F_n = \frac{1}{2}\rho C_n h U_n^2 \Delta s - T \sin\left(\frac{-\Delta\theta}{2}\right) - (T + \Delta T)\sin\left(\frac{-\Delta\theta}{2}\right) = 0 \quad (3)$$

where C_n = drag coefficient in the normal direction; and U_n = component of current in the normal direction = $U \cos(\theta - \theta_u)$. Dividing through by Δs; taking the limit as Δs, $\Delta\theta$, $\Delta T \rightarrow 0$; and rearranging provides

$$\frac{d\theta}{ds} = \frac{-1}{2T}\rho C_n h U^2 \cos^2(\theta - \theta_u) \quad (4)$$

Eqs. (2) and (4) represent two equations with independent variable s and two independent variables T and θ. To obtain boom shape, $x(s)$ and $y(s)$ for the boom must also be known. Equations governing these relationships are found from the segment geometry and are, respectively

$$\frac{dx}{ds} = \cos(\theta) \quad (5)$$

and

$$\frac{dy}{ds} = \sin(\theta) \quad (6)$$

Thus, (2), (4)–(6) form a system of four first-order differential equations

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with s as the independent variable and θ, T, x, and y as dependent variables. Since the current field is to be specified, current speed, U and angle, θ_u, are regarded as known functions of x. Using the coordinate system shown in Fig. 3, the boom starts at the origin that is placed at the outer anchoring point. With this system, $x(s = 0) = 0$ and $y(s = 0) = 0$. At the other end, s equals the specified boom length l_b, and the shore tie-off point should be at the specified coordinate position $x(s = l_b) = x_b$ and $y(s = l_b) = y_b$.

The set of equations is highly nonlinear, and unlike most structural equilibrium problems, the position (or even approximate position) between the end points is not known a priori. This makes the usual boundary value problem approaches difficult to apply. In view of these problems, the equations were integrated numerically from the origin (the outer end) along the boom to the shore end. This solution approach is often used for solving mooring cable-shape problems as discussed, for example, by Berteaux (1976).

The governing equations all have the form

$$\frac{dV}{ds} = f(V, s) \quad \text{(7)}$$

in which V = the dependent variable; and f = the right-hand-side expression. To integrate numerically using the Euler method, the length is divided into a large number of short segments. Then V_{i+1} at the $i + 1$ point is found from V_i, the value at the previous point, according to

$$V_{i+1} = V_i + \left(\frac{dV}{ds}\right)_i \Delta s \quad \text{(8)}$$

In (8), $(dV/ds)_i$ is evaluated from (7) applied at the previous point i. Thus, the solution proceeds segment by segment from the origin to the opposite end.

Specifically, the integration begins with $x = 0$, $y = 0$ and estimates for $\theta(s = 0)$ and $T(s = 0)$. A solution for these values is found using the aforementioned approach from $s = 0$ at the origin to $s = l_b$ at the shore end. Values calculated for x_b, y_b are then compared with the desired end-point coordinates and the initial estimates for θ and T adjusted accordingly. The process is repeated until the boom ends at the desired point within a specified tolerance (small compared to the overall boom-shape dimensions).

A computer program was written to implement the solution procedure. The program also contains a component to allow current information to be input at the discrete values of x for which data is available. Lagrangian interpolation is used to calculate a continuous $U(x)$ and $\theta_u(x)$ needed in the solution algorithm. Program output includes boom tension and angle, coordinate position, and normal component of current as a function of distance along the boom.

Model Comparison with Experiment

A boom-shape/tension experiment was carried out at Fuel Storage Corp., shown on Fig. 1, for the purpose of calibrating drag coefficients and evaluating boom mathematical models. Surface current was measured using current meters just upcurrent of the boom. Boom shape was determined by placing markers on the boom and sighting these using on-shore transits. The boom was moored at intermediate points dividing the boom into sections. Two sections of the boom provided data sufficiently accurate for comparison with this model. Boom tension was measured at one end of each section to be used.

Two independent data sets were, therefore, available for comparison. One data set was used to determine the optimum values of C_n and C_t. The second data set was then employed to test the calibrated model.

Drag coefficient values were calibrated using a 152-m (500-ft) section of boom in 0.90 m/s (1.75 knots) of current. The model was run while systematically varying C_n and C_t. Tension at the model origin (outer anchor point) was matched with the measured tension of 1,837 N (413 lb). The best fit with the shape data, shown in Fig. 4, occurred when $C_n = 1.8$ and $C_t = 0.029$. The normal component drag coefficient, $C_n = 1.8$, agrees with that found by LeCompagnon (1984) and is slightly higher than the value of 1.5 recommended by Larrabee and Brown (1974) and Thaller (1983). The tangential drag coefficient, $C_t = 0.029$, is consistent with values found from tension measurements made when the boom was deployed from the stern of a boat.

The model, using the aforementioned coefficients, was next applied to the second set of data. In this case, boom length was 122 m (400 ft) and current speed was 0.30 m/s (0.59 knots). The shape comparison, shown in Fig. 5, is good. Tension at the boom end away from the origin was calculated

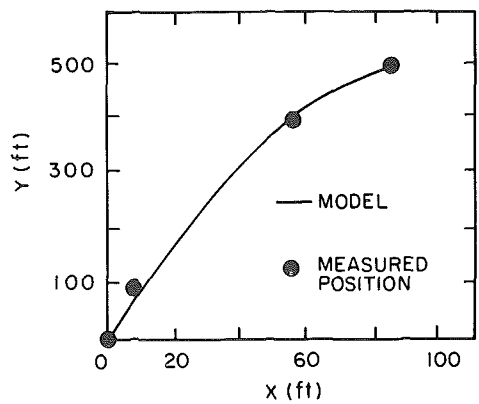

FIG. 4. Predicted and Measured Boom Shape Used for Calibration

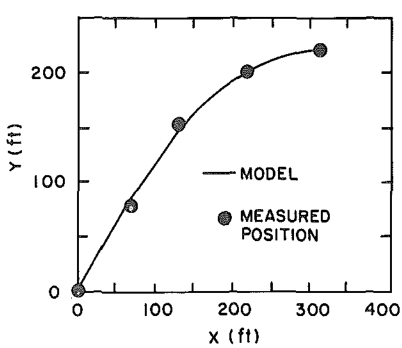

FIG. 5. Predicted and Measured Boom Shape Used for Verification

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by the model to be 1,922 N (432 lb), while the measured tension was 1,877 N (422 lb). The difference of less than 3% also supports the model. On the basis of the comparisons, the boom model was judged to be sufficiently reliable to be used for boom-configuration design.

Diversion Configuration Design

Representative Application

The boom-configuration model was used to aid in designing boom configurations for each of the five petroleum-product terminals on the Piscataqua. The designs address the problem of spills originating at a terminal during transfer operations. Each terminal is a site-specific problem, and different designs are necessary depending on whether the tidal flow is ebb or flood and where the spill occurs at the berthed vessel. In each configuration design, anchor location, shore attachment point, boom dimensions, and shape, as well as normal component of current, are identified.

In designing all of the configurations, site maps and maps of surface current under maximum flow conditions are required. This information is used as the basis for a trial configuration that is then evaluated using the boom mathematical model. The major criterion is that there be no leakage; thus U_n must be less than 0.31 m/s (0.6 knots) as discussed previously. Trial configurations are evaluated iteratively until the leakage criterion is satisfied with minimum boom length and mooring loads.

The process is described in this paper for the Northeast Petroleum Terminal on the Piscataqua shown in Fig. 1. The specific situation considered is a spill on the outside of a berthed tanker during flood tide. The steps necessary in generating the design are developed in detail, and the results of a field-demonstration experiment are described. This problem is a representative application of diversion boom contingency planning for other ports with similar high-current environments as well as other Piscataqua River terminals. Boom configurations for other Piscataqua sites have been summarized by Goodwin (1991).

Current Data

A map of surface current vectors in the vicinity of the deployed boom is necessary for configuration design. Current information is specifically required in the boom-configuration mathematical model. Thus, a field program was initiated for obtaining surface current due to the tides. Because tidal currents are repeatable, the currents used for design are the same as those at future times corresponding to a similar stage in the tidal cycle. Wind-driven currents are generally less important in this application since the tides are strong and the river terminals are relatively sheltered.

General aspects of the tidal currents in the Piscataqua River have been the subject of a number of previous University of New Hampshire (UNH) studies. Current data obtained in a cooperative field program involving UNH and National Ocean Survey (NOS), and summarized by Swenson et al. (1977), indicate that currents are due principally to the tides. Typical main-channel measurements have normally ranged from 0.5 to 2.6 m/s (1 to 5 knots). Current variability within this range is due to several important factors. The variation in current amplitude along the channel has been considered by Swift and Brown (1983), who have shown that currents are greatly affected by changes in cross-section area, while current variation over the spring/neap cycle is approximately 20%. Data reported by Swenson et al. (1977) and results of a dye study conducted by Schmidt (1980) indicate that maximum flow tends to be confined to a narrow central core; thus, there is considerable cross-channel variation. In fact, the near-shore area is often characterized by greatly reduced currents and/or countercurrents as discussed by Savage et al. (1982) and Swift et al. (1990).

Our general approach was to measure surface currents using two current meters, each of which was deployed from the side of a research vessel. An array of stations were marked by buoys and used as measurement sites. These were located in the area of possible oil-boom deployment (that is, at and down-current of the terminal-docking area). A vessel would stop at a station, make a 3-min measurement, then proceed to the next station in its assigned sequence. Normally, all stations could be sampled well within an hour. In addition, surface-current trajectories were determined using drogues released and tracked by a third vessel. Release points included those at potential oil-spill sources and points in the vicinity of complex current areas (near objects and in countercurrent regimes).

Our original goal was to schedule all current measurement experiments for times when a tanker or barge was in place. We found that this was not possible, however, due to unpredictable last-minute changes in tanker arrival and departure times. Our strategy for dealing with this problem was based on the idea that only some of our measurements were directly influenced by the presence of a ship. Thus, measurements away from the tanker pier were scheduled regardless of whether or not a tanker was present. When a tanker was actually unloading, measurements were made alongside and in the current shadow.

The overall structure of the near-shore surface current regime at maximum flood tide is shown in Figs. 6–8. Figs. 6 and 7 plot the trajectories of drogues, which were released and tracked during flood tide. Fig. 8 presents surface current velocity vectors obtained from the current meter measurements. The conditions illustrated are average over the spring-neap cycle. The currents are seen to be over 1.5 m/s (3 knots) near the main channel with the flow following the shoreline. There is significant reduction in current

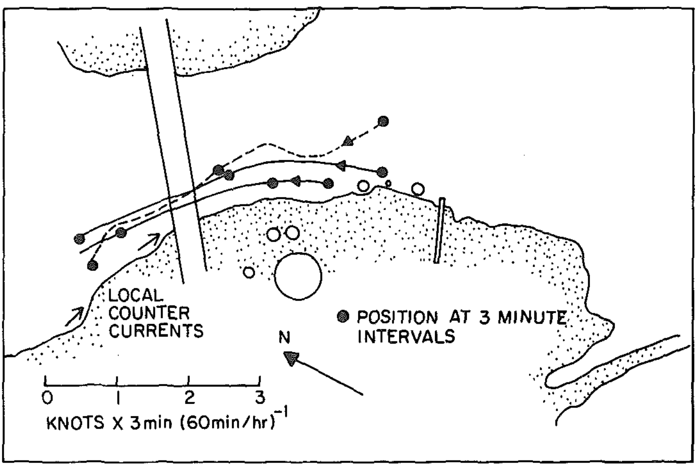

FIG. 6. Drogue Trajectories at Northeast Petroleum during Flood Tide

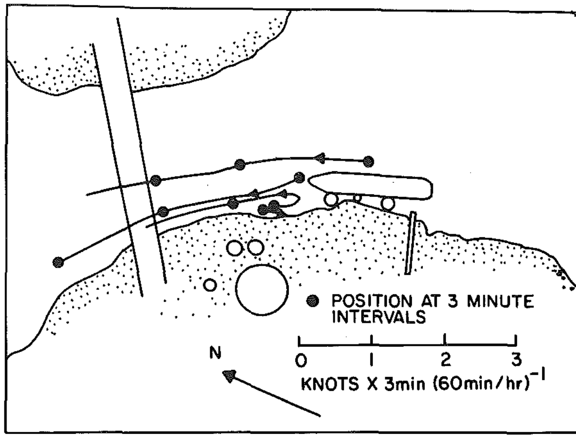

FIG. 7. Drogue Trajectories at Northeast Petroleum during Flood Tide

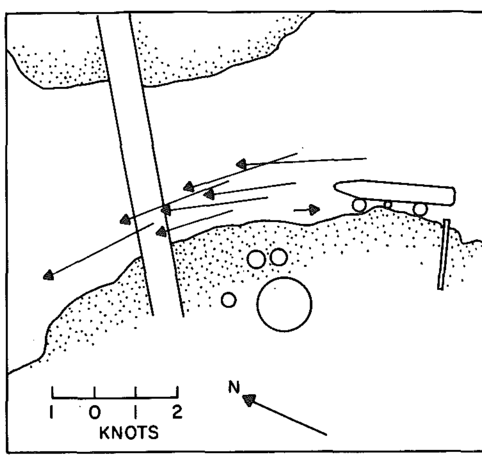

FIG. 8. Current Vectors at Northeast Petroleum during Flood Tide

speed as the shore is approached. In addition, small countercurrents appear down-current of obstructions and in coves.

Design and Analysis

The physical conditions at the site determine the general form of the boom configuration. For a spill on the channel side of the tanker, the boom must be anchored just outside the vessel. In view of the strong currents (over 1.5 m/s (3 knots)) at Northeast Petroleum outside the vessel, the boom must initially be nearly parallel to the flow necessitating a long boom. The boom can then gradually be brought towards the shore until the area of diminished current is reached. At this point, the boom can be turned more directly towards the shore and secured.

From the general form, the specific design was developed using the boom mathematical model. Current information was input, and several trial ver-

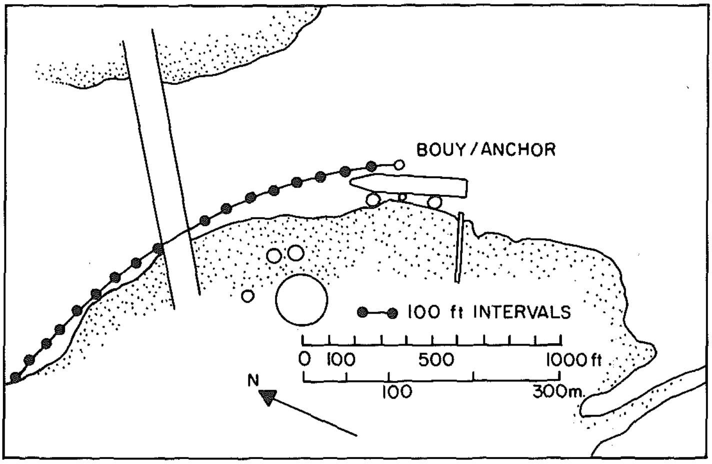

FIG. 9. Boom-Configuration Design for Northeast Petroleum during Flood Tide

sions of the general form were analyzed. Each trial varied as to mooring point locations, length, and tension. Though the outer anchor point could be adjusted slightly, most changes involved length, tension, and where the boom was secured to shore. The best combination is that shown in Fig. 9. The maximum normal component of current is 0.31 m/s (0.60 knots), which just satisfies the leakage criterion. The boom is 518 m (1,700 ft) long, and it is necessary for the boom to closely parallel the shore for most of its length. The area between the boom and shore is narrow, but there is still sufficient clearance for passage of oil. The bank is very steep here so that the shoreline does not move much horizontally with changing tidal elevation. There is access to the shore-attachment point for boom-handling crews and to make use of skimmers. The maximum boom tension is 14.5 kN (3,270 lbs) at the outer anchor point, and this must be sustained by the mooring.

Field Experiment

The Northeast Petroleum configuration was deployed by the New Hampshire Water Supply and Pollution Control Commission (WSPCC) in a demonstration experiment. No oil was used. The deployed boom was observed to be stable and to have the designed shape. Normal current to the recommended design was within the leakage-criterion limitation.

Experiments had also been made using a reduced boom length and bringing the boom to shore sooner. The shortened boom, however, encountered larger currents perpendicular to the boom as described by the WSPCC (*Portsmouth Harbor* 1983). Since these normal currents exceeded 0.3 m/s (0.6 knots) the longer boom recommended in this study is necessary.

Summary and Conclusions

The boom-configuration mathematical model was found to agree well with experimental data using the drag coefficient values determined from calibration. This boom model is especially suitable for the diversion boom problem since it takes into account current spatial variability and tangential as well as normal drag forces. Using the model, trial boom configurations

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can be evaluated for shape, tension, and maximum normal component of current.

The model was used in a representative diversion boom design application at Northeast Petroleum on the Piscataqua River. Necessary steps were shown to include obtaining current data, developing possible boom shapes, and analyzing these trial designs using the model. In the Northeast Petroleum application, the principal design criterion—to limit the maximum normal component of current to no more than 0.3 m/s (0.6 knots)—was satisfied. This is known from previous work to prevent leakage so that the oil will be successfully diverted to a shore pickup point. The recommended design was found to behave as predicted in a demonstration experiment. Thus, the model and design procedures are suitable for diversion configuration designs in high-speed currents.

Further work includes improving the methods and logistic support for deploying the boom quickly during an emergency. Use of permanent moorings and waterfront boom storage are presently under consideration. A mobile boom-storage and deployment barge is also under study. The training of personnel is an additional component in a practical contingency plan, and this is being addressed as well.

Acknowledgments

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C_n = drag coefficient in normal direction;
C_t = drag coefficient in tangential direction;
h = skirt depth;
l_b = boom length;
s = distance coordinate along boom;
T = boom tension;
U = current magnitude (speed)
U_n = component of current in normal direction;
U_t = component of current in tangential direction;
x = coordinate perpendicular to shore;
x_b = x-coordinate at shore end of boom;
y = coordinate parallel to shore;
y_b = y-coordinate at shore end of boom;
θ = boom angle with x-axis;
θ_u = current angle with y-axis; and
ρ = density.

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