CHAPTER 105

OIL BOOMS IN TIDAL CURRENTS

by

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INTRODUCTION

The classic, and most effective way to prevent the spread of oil spilled in harbors is by surrounding the spill with a floating barrier, or boom In calm water, with no currents, early devices made from telephone poles and canvas were more or less effective In the presence of currents, however, and particularly with larger spills, the problem rapidly becomes more complex, and the rational design of oil booms requires an understanding of the behavior of the oil and the boom in the current

This paper presents the results of an investigation into the oil holding capacity of a boom in a steady current, and the forces and moments acting on such a boom

I OIL CAPACITY

A floating oil boom anchored at each end in a current to form a U-shaped pocket, with the opening in the U facing upstream, can gather and hold significant volumes of oil under proper conditions There are two main features which determine whether such a boom will hold oil, and how much oil can be held The first is the existance of a critical Froude number, above which the boom holds no oil, and the second is the shape and behavior of the pool of oil held by the barrier

A Critical Froude Number

A quick estimate of whether or not a boom will hold oil at all can be made by comparing the forces acting to draw a small column of oil under the barrier with the buoyancy of such a column of oil, for a section of barrier perpendicular to the current For a column of oil of depth equal to the barrier depth, d, and unit cross-sectional area (in the horizontal plane), the force driving the oil downward is the difference between the stagnation pressure where the free surface of the water intersects the boom and the free-stream pressure near the bottom of the boom Neglecting hydrostatic pressures (included in the buoyancy term), this difference is $U^2/2g$, where U is the current velocity and g is the acceleration due to gravity The resulting downward force is, thus $1/2\rho_w U^2$ The net buoyancy is given by ρ_w g Δ d, where ρ_w is the mass density of the water and Δ is the fractional density difference between the oil and the water, conveniently given by Δ = (1-specifc gravity of oil) At incipient failure of the boom to hold any oil, these two expressions can be equated, yielding a densimetric Froude number

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$$F' = \frac{U}{\sqrt{g\Delta d}} = 2^{1/2} \qquad (1)$$

At Froude numbers above $\sqrt{2}$, the barrier will hold no oil, while below this figure, some quantity of oil will be held

Since the stagnation pressure depends on the component of the velocity normal to the barrier, this analysis also shows that failure will occur most readily in the apex of the boom (bottom of the U)

B Capacity of the Boom

Given conditions, then, under which a barrier will hold oil, the remaining question concerns the amount of oil held This question can be approached by considering a two-dimensional pool of oil held up against a barrier by a current (Fig 1) If the oil is significantly more viscous than the water, motions in the oil itself are small, and the configuration of the pool, h(x) vs x (see Fig 1), is determined by a balance between the shear stresses on the underside of the oil, τ, and the horizontal hydrostatic pressure gradient corresponding to an increase in thickness of the pool of oil

$$\rho_w g \Delta h \frac{dh}{dx} = \tau = \frac{1}{2} \rho_w C_f U^2, \qquad (2)$$

where C_f is the friction coefficient Rearranging and integrating,

$$h^2 = \frac{U^2}{g\Delta} \int_0^x C_f dx \qquad (3)$$

which shows that the shape of the pool depends on the distribution of the shear stress coefficient along the underside of the slick

Near the leading edge of the pool (x = 0), the above analysis does not always apply For velocities above 0 75 to 1 0 ft/sec, a "head wave" forms, as described in Wick (1969) While the details of this phenomena are not well understood, it has been noted that leakage of the barrier can occur by entrainment of oil droplets from the head wave into the floor, and, moreover, it is believed that the head wave does not scale according to the densimetric Froude number

Near the barrier, the slick can become slightly thinner, due to stagnation pressures against the barrier This, however, does not materially affect the volume of oil held

C Experimental Results

A series of experiments were performed in the glass-walled sedimentation flume in the Ralph M Parsons Laboratory for Water Resources and Hydrodynamics of the Department of Civil Engineering at M I T This flume is

2 5 ft wide, 1 0 ft deep, and 40 ft long, and is equipped with a self-contained recirculating flow system capable of discharges up to 1 75 ft^3/sec

The barrier used consisted of a masonite panel extending across the channel, and mounted from above so that its depth of immersion, or draft, d, could be adjusted For given flow conditions, oil was added upstream, and allowed to collect against the barrier until leakage was imminent Slight leakage at either end of the barrier, where it met the glass tank walls, was ignored Measurements were then taken of the pool thickness, h, at various distances from the barrier, using a scale on the glass tank walls Two types of oil were used in these experiments soybean oil and No 2 fuel oil, with the following properties

Oil	Δ	μ/μ_{water}
No 2 fuel	077	30
Soybean	138	2

The profiles so obtained are shown dimensionlessly as $g \Delta h/U^2$ vs $g \Delta x/U^2$ in Fig 2, taken from work done by Robbins (1970) The scatter can be attributed to several sources

1 As the water flow velocity was not constant across the tank, the position of the leading edge varied, the point chosen was an "eyeball average" of its position across the tank

2 The presence of interfacial waves on the oil-water interface made an accurate measurement of thickness difficult At higher flow rates, these waves were 1/8" - 1/4" high and an inch or two in length Near the boom, especially, reflections from the boom acted to make the waves higher Superposed on the interfacial waves were longer surface waves of similar height generated by the turbulence at the upstream end of the tank

The data of Fig 2 gives $h \propto x^{1/2}$, implying that C_f is independent of x, Eq 3 then becomes

$$h^2 = \frac{U^2}{g\Delta} C_f x$$

or

$$\frac{g\Delta}{U^2} h = C_f^{1/2} \left(\frac{g\Delta}{U^2} x \right)^{1/2} \qquad (4)$$

For the fuel oil, $C_f = 005$, while for the soybean oil, $C_f = 008$ for $g \Delta x/U^2 > 120$ (The deviation for low $g \Delta x/U^2$ for soybean oil is believed due to low Reynolds' numbers)

The difference between the values of C_f observed is probably due in part to the scatter in the data, however, weak viscosity or surface tension effects cannot be ruled out

The arguement for a constant C_f at sufficiently high Reynolds' number (based on x, the distance from the leading edge), has been made by Robbins and Hoult by analogy with a sand roughened flat plate For low Reynolds numbers, the plate looks smooth, and C_f decreases with increasing x For high Reynolds numbers, with the sand grain size, k_s, increasing with increasing x such that the ratio k_s/x is constant, C_f is constant (Schlichting 1960) In the oil slick, the sand roughness corresponds to the growing interfacial waves

Using a value of 008 for C_f Eq 4 can be written

$$\frac{g\Delta}{U^2} h = 0\ 09 \left(\frac{g\Delta}{U^2} x\right)^{1/2}$$

or

$$h = 0\ 09 \left(\frac{U^2}{g\Delta}\right)^{1/2} x^{1/2} \qquad (5)$$

By inserting the effective boom draft, d, for h, and the slick length, ℓ, for x in Eq 5, a relation between slick length and boom draft is obtained

$$\ell = \frac{d^2}{(0\ 09)^2\ (U^2/g\Delta)} \qquad (6)$$

To obtain the volume stored per foot width, h can be integrated against x to give

$$V = \int_0^{\ell} h(x)\ dx = \frac{2}{3} \left[\frac{U^2}{g\Delta} C_f\right]^{1/2} \ell^{3/2}$$

or, in dimensionless form,

$$\frac{V}{d^2} = 82/F^{1/2} \qquad (7)$$

The profile data was integrated numerically to find the volume stored, the results are shown in Fig 3 (Included in Fig 3 are data from preliminary runs using other oils The scatter in this data is generally worse) It can be seen from Fig 3 that Eq 7 gives good engineering prediction of oil retention capacity, and that the critical Froude number is approximately 1 3

II FORCES ON BARRIERS

This section treats the forces on a vertical flat plate oriented normal to the current, a geometry typical of most barriers Two cases will be considered the barrier alone, without oil, and the barrier full of oil to its depth, d

A Two-Dimensional Forces

In the absence of oil, the barrier is simply a vertical flat plate, at high enough Reynolds numbers, the drag coefficient, C_D ($D = 1/2\rho_w U^2 C_D dL$, where D is the drag force and L is the barrier length) is independent of Reynolds number With a free surface present, however, one should anticipate a dependence on the Froude number, $F = U/\sqrt{gd}$, and a similar dependence for the location of the resultant force

With the barrier full of oil, the densimetric Froude number must be less than 1 3 For a typical value of Δ of 0 10, the regular Froude number is thus less than 0 4 Since the Froude number squared represents the ratio of dynamic ($1/2\ \rho U^2$) to hydrostatic (ρgd) forces, and since this number is small, a balance of hydrostatic forces from the water on one side and the oil on the other can be made, recognizing that the free surface of the oil lies $d\Delta$ above the water surface

$$D/L = \rho_o g \left(\frac{\rho_w}{\rho_o}\frac{d}{2}\right)^2 - \rho_w g \frac{d^2}{2} = g\ \rho_w\ \Delta \frac{d^2}{2} \qquad (8)$$

Note that D is independent of the velocity, U The location of the resultant force can be shown by a similar calculation to be approximately 2/3 d above the bottom of the barrier For convenience, the force expressed by Eq 8 can be converted to a drag coefficient, as

$$\frac{1}{2}\rho\ U^2\ d\ L\ C_D = \frac{1}{2} L\ \rho\ g\ \Delta\ d^2$$

Thus,

$$C_D = 1/F'^2 \qquad (9)$$

A series of experiments was performed in the tank described above, but with a barrier hung vertically from long wires, and constrained horizontally only by three LVDT-type force transducers, connected to an operational manifold and a digital voltmeter, arranged and adjusted to give direct readout of force and moment data Dead-weight calibrations were used throughout

Figs 4 and 5, from Robbins' paper, show values of C_D and the height, z, of the resultant force, both as functions of the Froude number Without oil, the drag coefficient varies from about 1 6 at low Froude numbers to 1 2 at higher Froude numbers With oil, the behavior predicted by Eq 9 appears, verifying the hydrostatic assumptions

The moment data, shown as z/d, the relative height of the resultant force, also support the assumptions, particularly for lower Froude numbers With oil, z/d is approximately 0 55 to 0 65, and without oil, 0 45 to 0 55 It is important to note that a variation of approximately 0 2d will be encountered in the depth of the resultant force, so any barrier design has to have adequate roll stability to resist this varying moment

III THE DEPLOYED BOOM

To find the total oil held by a boom anchored by its ends in a current (Fig 6), the shape taken must be found Since the momentum of the flow against the barrier depends on the velocity component normal to the barrier, as $\rho U^2 \cos^2\theta$, one can assume for simplicity that the drag coefficient for a section of boom at an angle θ is

$$C_D(\theta) = C_D(\theta = 0) \cos^2 \theta \tag{10}$$

Assuming that tangential forces on the boom are negligible, and that the boom has zero bending stiffness, an analysis of a differential section of the boom shows that the tension is constant throughout, and that the normal force on the boom is balanced by the tension divided by the local radius of curvature of the boom This can be expressed as

$$L \frac{d^2x}{dy^2} = \frac{1}{\lambda} \left[1 + \left(\frac{dx}{dy}\right)^2 \right]^{1/2} \tag{11}$$

where L is the total length of the boom λ is a tension factor which relates the tension in the boom, T, to the normal force on a "stretched-out" boom,

$$\lambda = \frac{T}{\frac{1}{2} \rho U^2 d L C_D(\theta = 0)} \tag{12}$$

Assuming d and C_D ($\theta = 0$) to be constant, equation 11 can be integrated, using the boundary conditions

$$x(0) = x'(0) = 0$$

$$\frac{L}{2} = \int_0^{y_{max}} \frac{dy}{\cos\theta}$$

The first boundary condition states that the slope of the barrier (dx/dy) is zero at the apex of the boom, and the second, that the boom has length L

The solution to Eq 11 gives the boom shape,

$$\frac{x}{L} = \lambda\left(\cosh \frac{y}{L\lambda} - 1\right) \tag{13}$$

where λ is obtained as a function of y_{max}/L (see Fig 6) from

$$\frac{1}{2} = \lambda \sinh \frac{y_{max}}{L\lambda} \tag{14}$$

The table below gives values of λ for different values of y_{max}/L

y_{max}/L	λ	y_{max}/L	λ
10	028	30	163
15	050	35	231
20	078	40	336
25	115	45	560

Note that the ratio of opening width to boom length is 2 y_{max}/L

The approximate spread of the mooring lines can be computed from the barrier angle at $y = y_{max}$, from

$$\frac{dx}{dy} = \sin \frac{y_{max}}{\lambda L} \tag{15}$$

For $y_{max}/\lambda L < 1$, Eq 13 can be approximated by

$$\frac{x}{L} = \frac{1}{2\lambda}\left(\frac{y}{L}\right)^2 \tag{16}$$

In fact, $y_{max}/\lambda L$ is less than 1 only for $y_{max}/L > 0\ 42$, however, this parabolic approximation is useful over a much wider range of values

A final calculation of the total amount of oil held can now be made, using Eqs 5 and 16

$$\text{Volume} = 1\ 9 \times 10^3\ L\ d^2 \left(\frac{\lambda d}{L}\right)^{1/2} \left(\frac{g\Delta h_o}{U^2}\right)^3 \tag{17}$$

Here h_o is the depth of the oil in the apex of the boom, this must be less than the draft, d. Moreover, $F = U/\sqrt{g\Delta h} < 1.2$, and $\ell < x_{max}$

CONCLUSION

Using the above information on oil holding capacity, barrier shape, and forces on barriers, it is possible to design and operate floating barriers to capture oil spills in rivers and tidal currents, at least at modest velocities. At higher velocities, but sub-critical Froude numbers, some leakage from head wave entrainment can be expected. The concentration of oil in such a pool will greatly simplify the collection and removal of oil from the water surface.

REFERENCES

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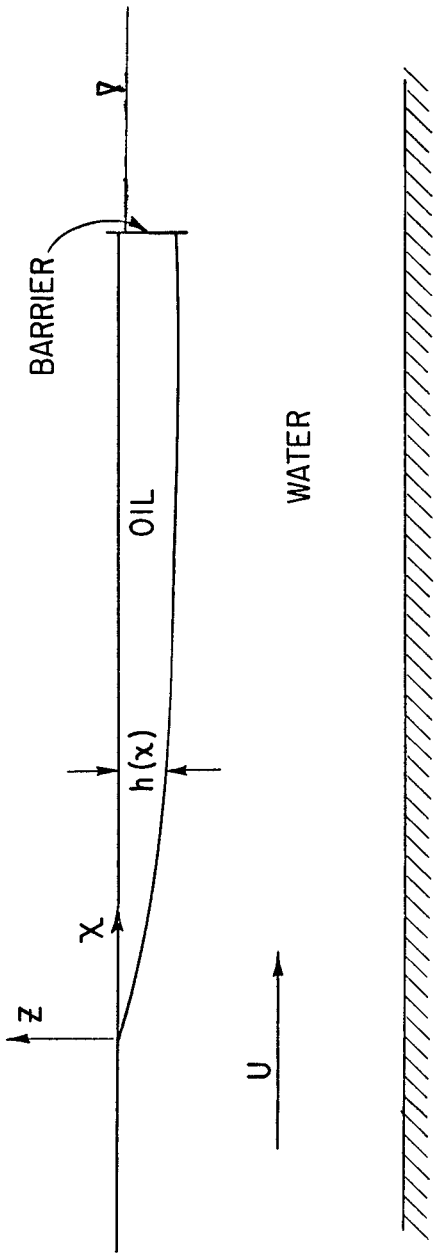

PILE-UP OF A SLICK AGAINST A BARRIER

FIGURE I

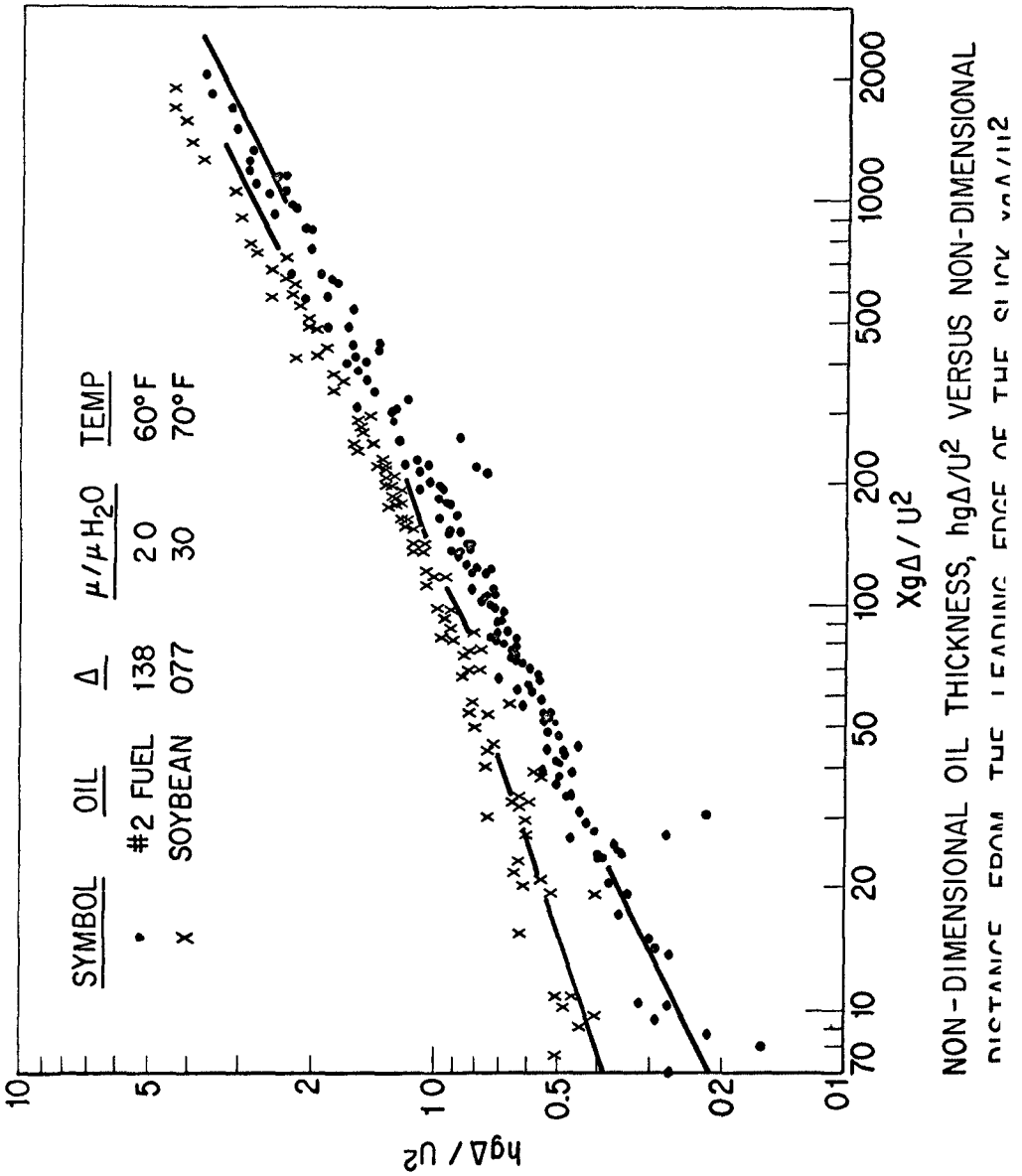
SYMBOL OIL Δ μ/μH2O TEMP
• #2 FUEL 138 20 60°F
x SOYBEAN 077 30 70°F
hgΔ / U2
XgΔ / U2
NON-DIMENSIONAL OIL THICKNESS, hgΔ/U2 VERSUS NON-DIMENSIONAL

FIGURE 2

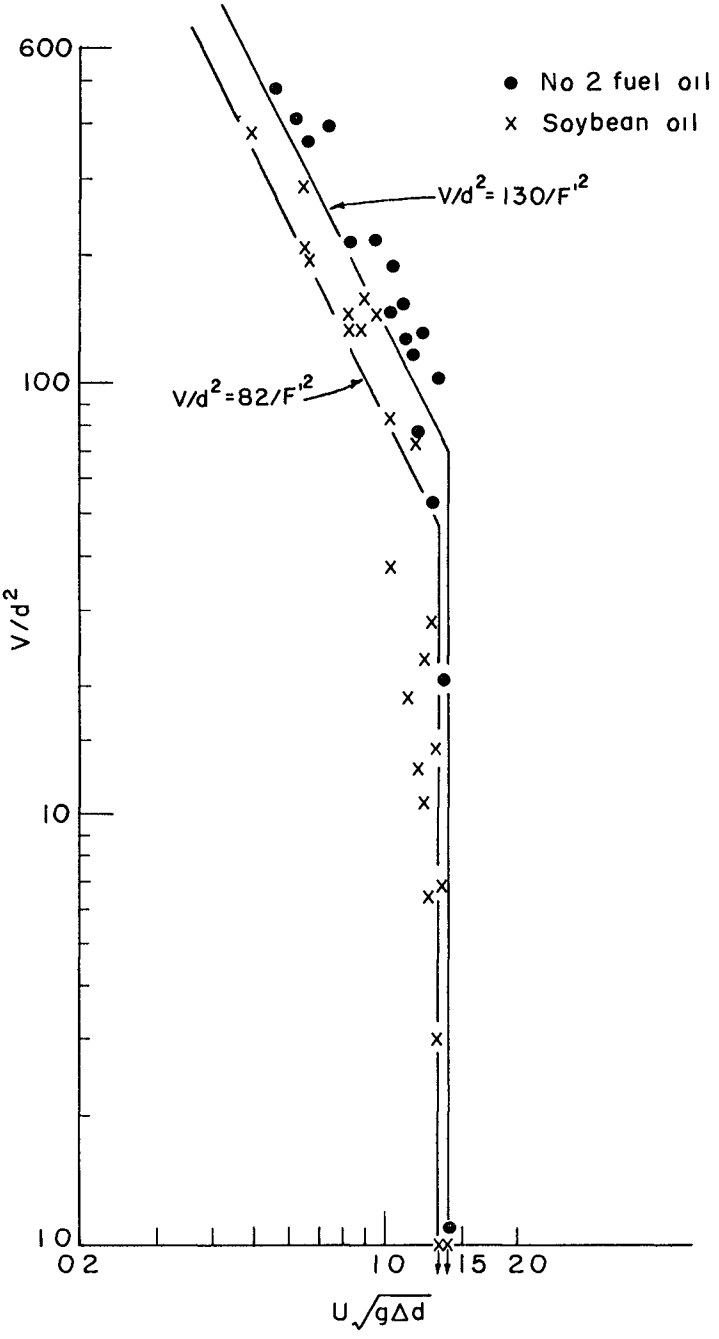

FIGURE 3 Non dimensional oil volume held, V/d^2, versus densimetric Froude number, $U\sqrt{g\Delta d}$

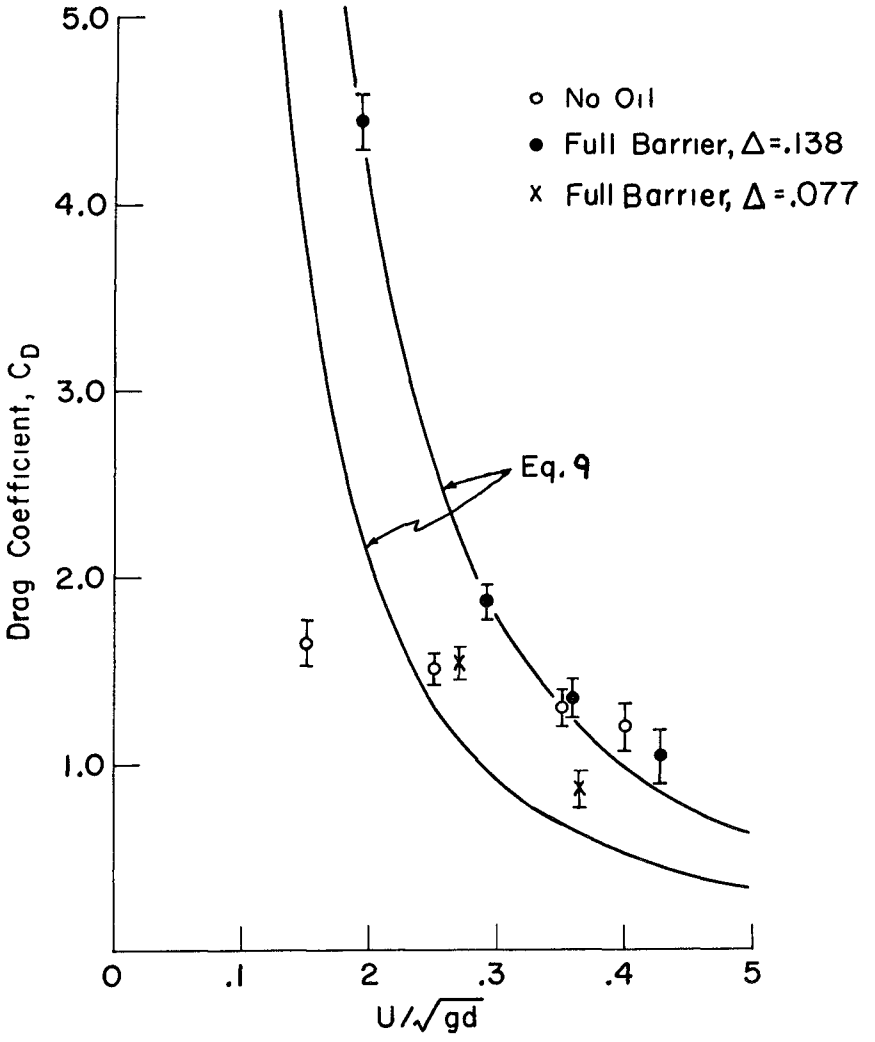

FIGURE 4 Drag coefficient, C_D, versus $U/\sqrt{gd}$

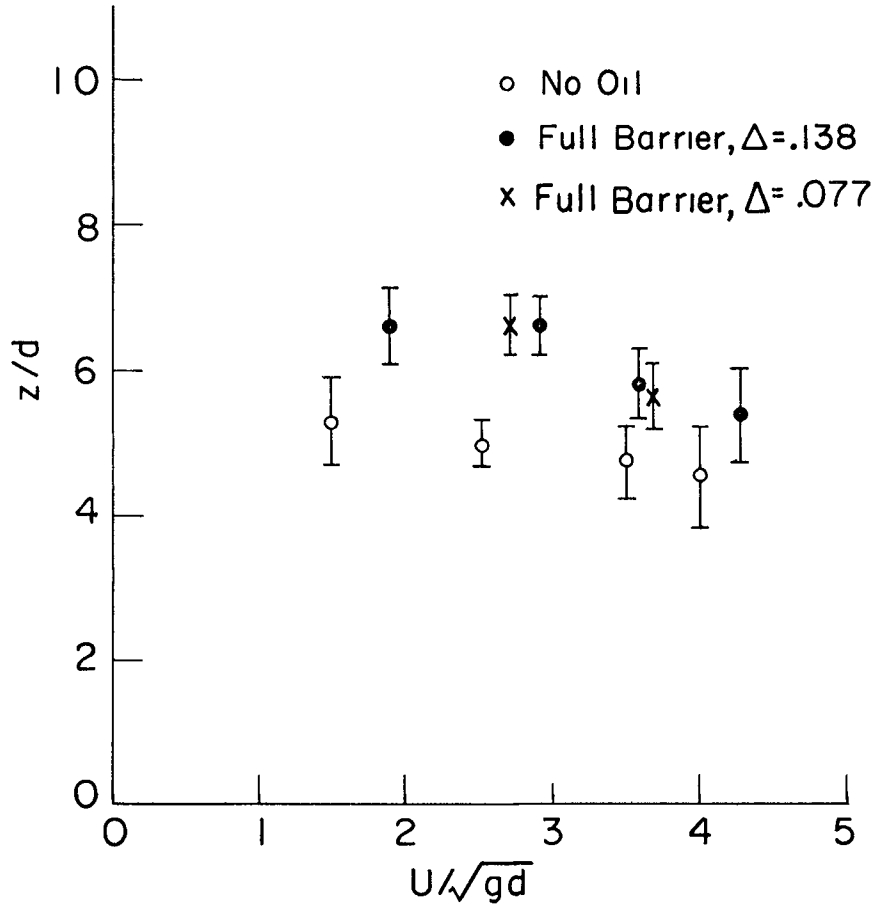

FIGURE 5 Location of drag force from lower edge of boom, z/d, versus $U/\sqrt{gd}$

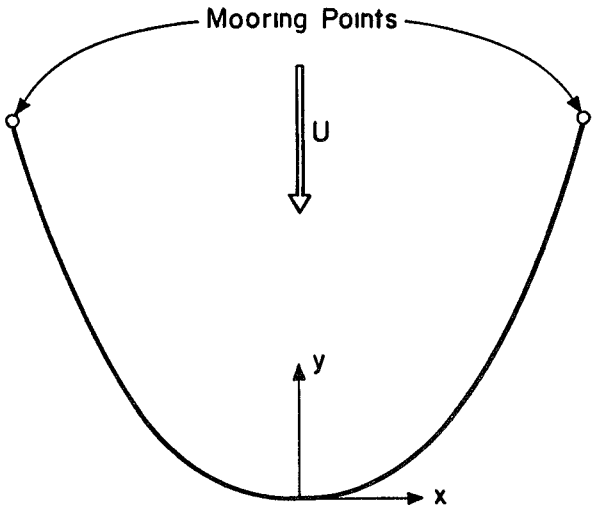

Figure 6 Sketch of planform of a boom in a current showing coordinates