THE STABILITY OF POLLUTING OIL SLICK ON THE WATER SURFACE

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The oil boom

Oil booms have been used over a long time to confine oil pollution (e.g. in oil harbours). Unfortunately the pollution does not affect the waters in the quiet, windshielded area of the harbours' basin alone but it gets more and more frequently to the drift of the streams. To combat pollution the most important task is to stop and to remove the material floating on the water surface thus preventing further reaches, river banks and other downstream water-based interests (e.g. intake works) from being damaged.

The use of traditional oil boom structures in open watercourses seemed at first to give satisfactory protection against the spread of the drifting materials. It became, however, soon manifest that these were often inefficient in retarding the oil slicks on flowing water. The probability of failure was seen to be proportional to the flow velocity at the place to be protected. Nevertheless, the systematic research work on the hydraulic problems of the oil booms has started only recently.

From the aspect of fluid mechanics, the stability of the oil slicks can be described as a phenomenon of density currents. The latter was known and its theory usually applied in connection with cooling ponds and with water intake works. This result, however, could not be directly related to the behaviour of the oil pollution for the water layers of different temperature — hence density — are intermingled in the turbulent zone of the flow due to turbulent diffusion, with no sharp interface, even without any motion at present.

Only few studies have been published on the analytic examination of the hydraulics of floating oil pollution stopped by a submerging oil boom, where the theoretical considerations have been supported by laboratory tests [1, 2]. The conclusions made therein have been supported also by our test results, but the authors referred to failed to give the full physical explanation of the stability's deterioration on the oil-water interface.

The basic principle of the oil booms is that by blocking the layer near the water surface (or by surrounding it in still water) the floating materials may be prevented from proceeding. In the actual case, this floating material is some petroleum product of relatively low specific weight kept on the water surface by static buoyancy. Under normal circumstances — moderate turbulence, room temperature, etc. — these materials do not mix with water, but under different conditions they disintegrate into tiny drops forming an aqueous quasi-emulsion, breaking in lasting rest alone. Of course, oil booms shall only be adopted for removing coherent oil pollution floating on the surface.

Model tests on the stability of oil slicks

Experience shows an interaction to develop at the interface of stopped surface-oil and the underlying water flow. This has been investigated in the form of two-dimensional flow in the glass flume of the Laboratory having a useful length of 8.85 m, a width of 0.50 m and a wall height of 0.575 m over the bottom. Tests were made with horizontal flume bottom, while the oil boom's section was located upstream the lower control sluice of the flume at a distance of 6.25 m from the latter.

Hydraulic similitude was aimed at by the identity of two dimensional magnitudes, the Froude and the Reynolds numbers. Perfect satisfaction of this condition is known to be equivalent to simulate reality, hence to apply a scale of 1 : 1, much restricting the generalization of test results.

During the tests no particular difficulties were encountered when adjusting the required Froude number but this restricted much the range of possible scales as well as that of the scale factors. In this case the Reynolds number was disregarded.

The Reynolds number characterizes the viscous forces in the flow and is known to indicate the presence of interface only in the laminar domain. A main characteristic of the turbulent flow is that very small resistance variations — of the viscous wall friction type — belong to even very high Reynolds number variations, simplifying the requirement of similitude to provide for a sufficiently high Reynolds number together with preserving the invariance of the Froude number, equivalent to performing the tests in turbulent flow. Thus, laboratory equipment and commercial oil suited for the experiments.

During the work, scale factors of the various characteristics were not previously fixed but the two dimensionless magnitudes were derived separately in each case, for the sake of generalization. Later, this procedure helped to recognize the physical interpretation of the phenomenon, at the same time it was a good basis of comparison with the — unfortunately scarce — published data.

The dimensionless magnitudes, a kind of state characteristics of the main flow features, were interpreted in examining stratified flow as follows:

In the Froude number, inertia and gravity forces determining the flow due to the partially submerging oil boom and to the thin surface oil layer are considered as principal forces, and the flow condition in open channels is described in the general form:

$$Fr = \frac{v}{c} \tag{1}$$

where v is mean velocity of the examined section, and c its characteristic wave propagation celerity, usually expressed by the Lagrangian form of wave celerity:

$$c = \sqrt{g \cdot h} \tag{2}$$

h being the water depth at rest in the section.

After the simultaneous consideration of Eqs (1) and (2), the value of the Froude number allows to draw the following conclusions:

Until the flow velocity v is less than the computed wave celerity c, the Froude number given by Eq. (1) shall be less than 1.0. This is physically understood as the surface disturbance incited on the surface and propagating in a wave form according to the laws of gravity field is able to proceed also against the flow. The inverse is true for Froude numbers above 1.0, namely then the flow velocity being the greater one, the flow entrains the surface wave, and the disturbances are only felt downstreams. The two different flow conditions are usually distinguished as subcritical and supercritical flow, respectively.

For stratified flow the so-called densimetric Froude number characterizing the flow can also be produced in its usual form:

$$Fr' = \frac{v}{v'} \tag{3}$$

where v is the mean velocity of relative displacement of adjacent fluids along the interface in the examined section, and v' is the so-called densimetric wave celerity, having a formula rather similar to Eq. (2) for the wave celerity:

$$v' = \sqrt{\Delta \cdot g \cdot h_w} \tag{4}$$

where $\Delta = \frac{\varrho_w - \varrho_0}{\varrho_w}$ is the specific difference between densities of water and oil, and h_w is water depth in the examined section. Substitution transforms Eq. (3) into:

$$Fr' = \frac{v}{\sqrt{\Delta \cdot g \cdot h_w}}. \tag{5}$$

Subsequently, the densimetric Froude number in Eq. (5) will be demonstrated to be the principal factor describing the state of stability of the interface.

The Reynolds number describes the degree of turbulence:

$$Re = \frac{v \cdot h_w}{\nu} \tag{6}$$

where, in addition to the former notations, ν is the kinematic viscosity of the water. Usually $Re = 1000$ is taken as critical value between laminar flow and turbulent flow in open channels. During the tests, the Reynolds numbers for the flow were kept well within the turbulent range, thus permitting the generalization of observations made on the scale model.

Behaviour of the oil-water interface

By proper adjustments in the flume (as changes in water discharge and depth, oil boom's submergence, etc.) any phase of stability could be produced, from resting interface to interface instability. Characteristic phases were described by the hydrodynamical stability of the flow and by the intensity of the viscous and turbulent effects developing on the interface.

On the surface of motionless or slowly flowing water the oil — with a specific density lower than water's — forms a sharp and nearly smooth interface. On still water, in the case of a constant volume of oil, this interface will be horizontal, while at low flow velocities the tangential stresses in the viscous boundary layer along the interface produce a mild slope downstream, maintaining relative smoothness there. The slow current will thus drive the oil towards the downstream oil boom, where it becomes retained. In this state, only slight tangential stresses are transmitted upon the oil layer leaning to the boom, thus the thickness of the oil layer upstream the boom decreases but slowly.

The edge of the surface oil in this phase is seen from the flow direction to be about pushed ahead on the free water surface. In the glass flume this front here was clearly visible. It was characterized by an abrupt increase of the oil layer thickness attributed to the dynamic effects of the flow. Under this condition this dynamic force is a multiple of the viscous forces, it amounts to about ten times the former at a distance of about 20 oil layer thicknesses from the front of oil slick [2]. Downstream the front, with the dynamic forces decreasing abruptly, viscous forces become predominant at a distance of about 200 layer thicknesses, responsible for the subsequent increase of the layer thickness.

As it follows from the nature of dynamic effects, the oil-water interface in the relatively short frontal zone performs a slight undulatory motion even in case of slow current, but thereafter the interface remains smooth up to a densimetric Froude number of about 0.15 (Fig. 1a).

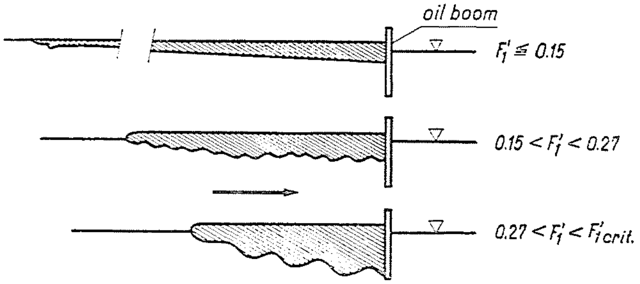

Fig. 1. Typical oil-water interfaces in different states of flow

Increasing the densimetric Froude number (either by increasing the mean velocity or by reducing the specific density difference between water and oil, or by a combination of both), a regular wave pattern arises in the interface in the range of densimetric Froude numbers from 0.15 to 0.27, covering the full, and up to then smooth interface (Fig. 1b).

Flow with a still higher densimetric Froude number gradually disrupted the regular wave sequence and produced still greater, irregular waves along the interface. Then the oil still resisted the increased entraining forces, but stability reserves tended toward exhaustion. With further increase of flow the oil front was crammed nearer to the boom increasing thus the layer's thickness there and at the same time further narrowing the passage by constricting the water depth. For a densimetric Froude number of about 0.50 — referred to the initial water depth — the intense undulation near the boom terminated at any case the stability of the oil layer and it could be conveyed to the downstream side of the oil boom. While in any of the previously mentioned three phases oil trapping by sinking the lower edge of the boom was sufficiently successfull, in this critical state no increase of the submergence over one third of the total depth could restore the equilibrium for the interface.

The critical state of the oil-water interface

For the sake of complete understanding, let us consider now the value obtained for the densimetric Froude number by applying it for the characteristics prevailing at the place of failure (i. e. where the boom is located)

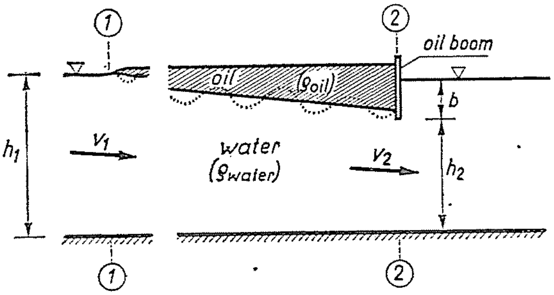

Fig. 2. Interpretation of the densimetric Froude number

rather than for the initial, hence fictitious flume section. With the symbols in Fig. 2 the densimetric Froude number in Section 1 will be:

$$F_1' = \frac{v_1}{\sqrt{\Delta \cdot g \cdot h_1}}$$

whereas in Section 2:

$$F_2' = \frac{v_2}{\sqrt{\Delta \cdot g \cdot h_2}}$$

and

$$b = \frac{h_1}{3} \quad h_1 \cong h_2 + b \quad m = \frac{b}{h_1} = \frac{1}{3}\,.$$

On the basis of continuity:

$$h_1 \cdot v_1 = h_2 \cdot v_2 \quad \text{and} \quad h_2 = h_1 - \frac{h_1}{3} = \frac{2}{3}\, h_1\,.$$

After substituting and rearranging:

$$v_2 = 1.5 \cdot v_1.$$

After the above substitution the densimetric Froude number at Section 2 (i. e. that of the partial closure) will be:

$$Fr_2' = \frac{1{,}5 \cdot v_1}{\sqrt{\Delta \cdot g \cdot \dfrac{2}{3} \cdot h_1}} = 1{,}873 \cdot Fr_1'. \tag{7}$$

By referring to earlier statements on the meaning of the Froude number, the evaluation of the test results has shown the — from the aspect of oil layer stability — critical state of flow to be where the densimetric Froude number related to the narrowest section is unity. In this interpretation, at this critical densimetric Froude number the flow velocity through this section reduced in size by the submerging oil boom equals the densimetric wave celerity of Eq. (4) corresponding, as stated, to the interface wave propagation celerity. Thus, according to the densimetric Froude number referred to the constricted section, the critical state of flow for the oil-water interface stability is obtained at:

$$Fr'_{\mathrm{crit}} = 1.0 \ . \tag{8}$$

The condition of stability as described above is in good agreement with the test results, including those found in the quoted publications. In the possession of this knowledge, a design aid has been elaborated for the practical use of oil booms and/or for deciding over their feasibility [3].

Laboratory tests included also further aspects of oil booms (shape, location, dynamic pressures, etc.) beyond the scope of this paper. The research work has been done at the Department of Hydraulic Engineering, Institute of Water Management and Hydraulic Engineering, Technical University, Budapest, upon commission by the National Water Authority (Water Quality Inspectorate) in 1976. The author was given valuable assistance by the specialists of the NWA and by his colleagues engaged in laboratory measurements.

Summary

Two-dimensional scale model tests have been made on the applicability of oil booms. A novel interpretation of the densimetric Froude number helps to demonstrate that for unity and higher values of the densimetric Froude number referred to the contracted boom cross section, the wave sequence generated along the oil-water interface will necessarily be dragged to the downstream side of the partial closure. In this state, the oil layer being relatively thin, the entire cross section of the two-layer liquid will participate in the flow.

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