Critical Shear Stresses of Sunken Oils

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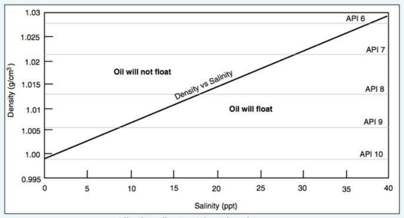
ABSTRACT: As observed in several recent cases (e.g., DBL-152, Enbridge-Kalamazoo), under certain circumstances, spilled oil can sink to the bottom of a water body. Once on the bottom, the oil can move or even remobilize into the water column. The critical shear stress (CSS) is used to accurately predict the movement of sunken oil along and off the bottom. Unfortunately, shear stress has only been measured for one sunken oil (Hibernian Crude API = 34). The Coastal Response Research Center (CRRC) at the University of New Hampshire (UNH) has an annular flume equipped with high-definition cameras and an acoustic velocimeter that can be used to estimate CSS by measuring the instantaneous, three-dimensional water current velocities at which sunken oils move and erode as visible oil droplets. The results reported are for an Alberta bitumen, tested at temperatures between 5° and 28°C in freshwater.

Background

Nonfloating Oil: Oil spilled into water can float, be neutrally buoyant, or sink depending on: the density of the water and the specific properties of the oil as well as interactions with suspended material (e.g., sediments, marine snow).



Spills of Nonfloating Oils: Risk and Response

Response Challenge: Oil that sinks to the bottom (sunken oil) poses response challenges floating oil does not. While the U.S Coast Guard R&D Center has had recent success with new detection methods for sunken oil, many issues of predicting its behavior and transport remain unresolved. Recovery of sunken oil and protection of natural resources is dependent on understanding and predicting its *in situ* transport.

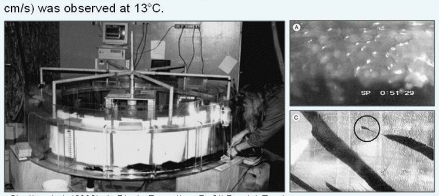
Locating Oil: V-SORS (EPA)

Case Studies: Remobilization of sunken oil has been observed at several spills under various wave and bottom current conditions (e.g., DBL-152, Enbridge-Kalamazoo).

DBL-152 off Texas (NOAA)

Kalamazoo River, Michigan (U.S. EPA)

Previous Work: Data on the velocity and shear stress needed to mobilize and erode sunken oil from a bed is lacking. Cloutier et al. (2002) have provided the only published data. Their laboratory experiments, using an annular flume (Ames et al; 1992), determined the CSS necessary to re-suspend an Hibernian crude. At 4°C, no erosion was observed up to 8 Pa (~75 cm/s) and a CSS of 5 Pa (~55 cm/s) was observed at 13°C.



Cloutier et al. (2002) A. Ripple Formation B. Oil Droplet Erosion

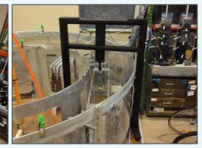
Data Gap: Currently, a spill modeler's only option to predict the remobilization of sunken oil is to use the CSS of the Hibernian crude (API 34). Group V oils with low API gravities (<15) will likely have greater density and viscosity than the Hibernian (Garbini, 1999) and hence, will likely have a greater threshold for mobilization or erosion. Therefore, experiments are needed to estimate the CSS for a range of oils, particularly those with low API gravities that may readily sink. This is especially true with the increase in shipping of heavier crudes.

Sunken Oil: DBL-152 (NOAA)

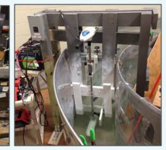
Methodology

Facility: The CRRC's annular flume has a 4000-L capacity with a 9-m track length and a 0.8-meter channel width. A 110-lb electric thrust motor is used to generate current of ≤1 m/s. The test area consists of a 1.2-m long straight flume section (0.2-m wide, 0.9-m tall) with inlet and outlet structures and two flow straighteners to reduce turbulence.

Flume



Test section



Motor

Experimental Design: Laboratory experiments were conducted using the CRRC flume to determine velocities and CSS for oil spreading and erosion of an Alberta bitumen. Duplicate runs were made in freshwater at temperatures between 5° and 28°C. The test oil was introduced in 5g and 20g aliquots into the flume and stranded on a Lexan plate on the bottom of the inner flume. High-definition video cameras monitored oil behavior above and adjacent to the stranded oil. Times recorded by the video were correlated with velocity data collected by a velocimeter.

Top Camera

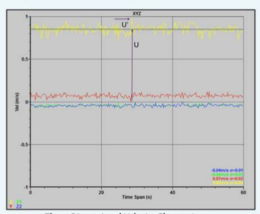
Side Camera

Oil Re-suspension: Sunken oil erodes into the water column from the bottom when the magnitude of the total bed shear stress exceeds the CSS, overcoming the forces holding the oil to the bed. The CSS was determined by progressively increasing current velocities until deformation, movement and erosion of the stranded oil was observed visually. The bed shear stress was determined from:

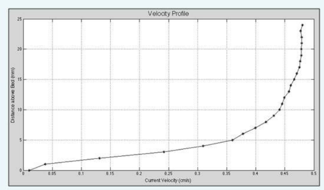
$T_o = \rho_w u_*^2$ (eq. 1)

Current Velocity Profile Method: The von Karman-Prandtl law of vertical velocity distribution equation can be written as:

$U_z = (u_*/k)\ln(z/z_0)$ (eq. 2)



Three-Dimensional Velocity Fluctuations

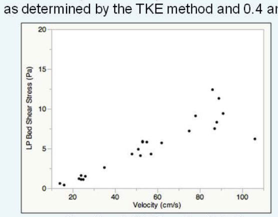


Logarithmic Vertical Velocity Profile

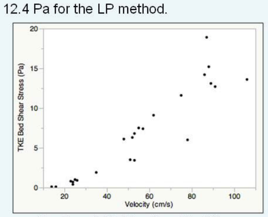
Turbulent Kinetic Energy Method: Turbulent fluctuations can estimate bed shear stress:

$T_o = C(1/2)\rho_w[u'^2 + v'^2 + w'^2]$ (eq. 3)

Bed Shear Stress: Flume experiments were conducted in current velocities ranging from 14 to 106 cm/s (0.3 – 2.1 kn). Minimum and maximum bed shear stresses were 0.1 and 18.9 Pa as determined by the TKE method and 0.4 and 12.4 Pa for the LP method.



Flume Generated Bed Shear Stress Using LP

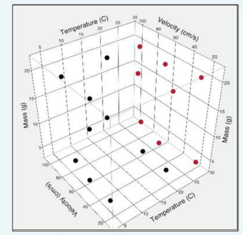


Flume Generated Bed Shear Stress Using TKE

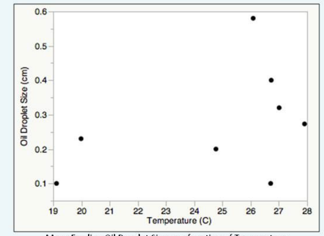
Adhesion Test: The adhesion number of the bitumen was measured using ASTM D 5. It was 3150 and 376 g/m^2 at 5 and 27°C, respectively. Adhesion was 531 g/m^2 at 20°C.

Findings

Temperature Effect on Erosion of Bitumen: CSS of bitumen was a function of temperature. No erosion was observed < 17°C or below in current velocities up to 106 cm/s and under bed stress conditions of 18.9 Pa. At 20°C, mass erosion of visible oil droplets was observed in current velocities greater than 23 cm/s, corresponding to a CSS of 0.8 Pa. At 27°C, the CSS was 0.1 Pa. in a 16 cm/s current.

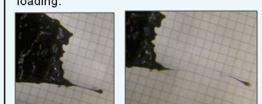


3D Erosion Scatterplot (Red = Observed Erosion)

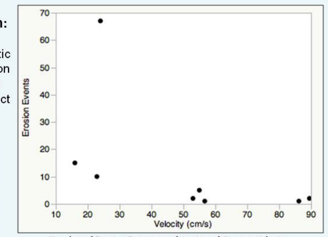


Mean Eroding Oil Droplet Size as a function of Temperature

Velocity Effect on Erosion of Bitumen: Erosion was less frequent with increasing velocity. Bituminous materials are viscoelastic – meaning their behavior depends not only on magnitude of loading, but also on the rate at which the load is applied. The bitumen will act stiffer (deform less) under faster rates of loading.

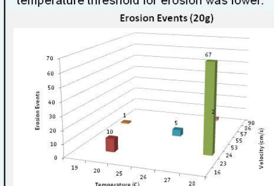


Ripple Migration and Erosion

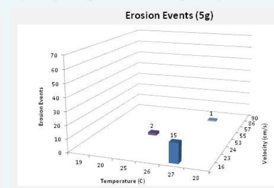


Number of Erosion Events as a function of Current Velocity

Mass Effect on Erosion of Bitumen: Erosion frequency was greater in the larger aliquot and its temperature threshold for erosion was lower.



Erosion Events in 20g Aliquot Runs

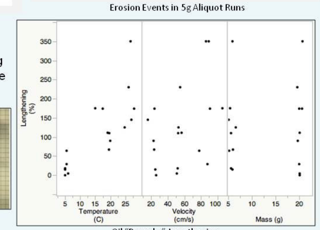


Erosion Events in 5g Aliquot Runs

Lengthening of Bitumen: Temperature greatly influenced the rate of lengthening along bottom as viscosity decreased and temperature increased.

5°C , 23 cm/s

26°C , 55 cm/s



Oil "Pancake" Lengthening

Implications: Bitumen is often diluted prior to transport and while dilbit (API 18-21) is lighter, its heavier components can sink significantly changing spill response and impacts (Enbridge-Kalamazoo River Spill). Erosion of Alberta bitumen (API 8.5) was not observed in freshwater temperatures less than 17°C (62°C) up to 106 cm/s (2 kn) under bed shear stress of 19 Pa (which erodes gravel with 4-cm diameter). At 20 and 27°C, the CSS was 0.8 and 0.1 Pa, respectively. Spill modelers can use this data to help predict the fate and transport of sunken oil. Sunken bitumen spills occurring in frigid or temperate climates and at depth offshore would likely remain stranded on bottom. Potential for erosion of bitumen exists in tropical or sub-tropical climates where water temperatures can reach 20°C (68°F) or higher (i.e., T/B Morris J. Berman Spill in San Juan, Puerto Rico). Further research is needed to determine CSS of more oils with varying API gravities stranded on different bottom types (i.e., sand, mud, etc.) in both freshwater and seawater.

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