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MOVEMENT AND EROSION OF ALBERTA BITUMEN ALONG THE BOTTTOM AS A FUNCTION OF TEMPERATURE, WATER VELOCITY AND SALINITY

BY

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Abstract

While many trajectory models exist to predict the movement of oil floating in or on water, few are designed to address heavy oil on the bottom of water bodies. In addition, remobilization (erosion) of the material into the water column is also difficult to predict. While properties such as adhesion, viscosity and density of oil may be readily measured, the critical shear stress (CSS) and the effect of (current) velocity, salinity, and temperature are virtually unknown for most heavy oils. The Coastal Response Research Center (CRRC) has a 4,000 L annular flume, with a water depth of 0.43 m. An inner rectangular flume (1.2 m length, 0.2m width, 0.9 m height), placed inside the annular flume, was preceded by two flow straighteners to reduced turbulence and produce a uniform, one dimensional flow field. The current is generated by an electric thrust motor and measured in 3D by a Nortek AS (Norway) Vectrino II Profiling Velocimeter. A 20g circle of Alberta bitumen (API ~ 10º) was placed on a laminated grid (1cm^2 square pattern) at the bottom of the straight flume. A total of 2.3m^3 of water was then gradually added to the flume. The electric motor was started and the profiler began collecting data. Two cameras, placed along the side and above the oil, collected video of the erosions and length/width changes of the oil. Conditions were held steady for one hour once the desired current velocity was achieved. Temperatures, current velocity (X, Y, Z), and digital videographic data were collected during each run. Erosions and percent lengthening of the oil was monitored as a function of water temperature, salinity and velocity. The turbulent kinetic energy (TKE) method was used to calculate the bed shear stress (BSS). In addition to the expected impact of higher temperature on the movement along the bed and erosion into the water column, the viscoelastic and shear-thinning properties of the bitumen played a role in its behavior (lowering

of viscosity at higher BSS slowing erosions and movement) and must be considered when predicting its behavior during a spill.

Introduction

There are only a limited number of oil recovery methods that are viable for non-floating oils. During non-floating oil spill response, tools such as modeling, tracking, and mapping are critical for predicting where the oil moves because of the impaired visibility. Challenges that arise when non-floating oil is spilled include: protecting cooling and drinking water intakes and sensitive environments, and forecasting the oil's fate and transport. The Office of Response and Restoration (ORR) of the National Oceanic and Atmospheric Administration (NOAA) currently uses mathematical model GNOME to predict the movement of spilled oil. The model is dependent upon the type of water body into which the spill occurs in (e.g. lake, river, ocean), the currents and tidal fluctuations, temperature, and the specific properties and rheological characteristics of the oil (such as shear rate dependent viscosity and density).

This paper focuses specifically on those non-floating oils that are located on the bottom (i.e., heavy crude oils), and how critical shear stress (CSS) affects the migration of the oil along the bottom of a water body or influences its resuspension into the water column. BSS is a stress which acts on the surface area of the oil mass; the oil mass sitting directly on the floor of the flume. The shear stress which causes erosions or migration to occur is known as the CSS; once the CSS is exceeded, the oil can migrate along the bottom or droplets of oil could break off from the mass and become suspended in the water column. Knowing the CSS of an oil is useful to responders as an indication of whether the sunken oil will become mobile and, in turn, pose a threat to human or environmental safety.

The research was conducted by the Coastal Response Research Center (CRRC) at the University of New Hampshire (UNH), using an annular flume equipped with an Acoustic Doppler Velocimeter (ADV) and high definition cameras. Alberta bitumen was used in these experiments; it is a heavy crude and considered a Group V oil due to the specific gravity being greater than 1.0. Group V oils have a tendency to sink when released into water. In some conditions, the oil may become neutrally buoyant or float, especially in water with high salinities. As defined by the United Nations Institute of Training and Research, classification of oils that have an American Petroleum Institute (API) gravity less than 20º and have very high viscosities, low volatility and lose very few constituents by evaporation (NRC, 1999) are considered heavy non-floating oils (Alberta bitumen ~ 10° API gravity). An API gravity of 10º is heavier than freshwater, alternatively, marine water has an API of 6.5º; which is heavier than that of Alberta bitumen.

The Shields Principle relates the critical force (i.e., shear stress), required to dislodge a grain from the bed of a stream with uniform grain size, as a function of the velocity and viscosity of the water (i.e., the Reynolds Number) (Shields, 1936). We applied the essence of Shields' research (i.e., "how great is the resistance of the grain to movement?") to submerged oil residing on the bottom (bed) of a water body.

Describing sediment transport in rivers (which is an analogy to the movement of heavy oil on the bed of aquatic systems), Garcia (2000) noted that small changes in BSS could result in large changes in sediment transport rate. Applying this concept to sunken oil, small increases in BSS could cause migration or erosions of the oil mass. A permanent deformation includes: oil migration (i.e., elongation or spreading that increases the original size of the oil blob on a grid sheet) and erosions (i.e., droplets that erode from the oil mass and become resuspended in the water column).

The molecular make-up of oil impacts its fate and transport (e.g., Alberta bitumen is a viscoelastic material) because the oil exhibits viscoelastic (both viscous and elastic) characteristics (Roberson & Crowe, 1997). Typically, hydrocarbons transition from viscous (fluid behavior that undergoes non-recoverable deformation) behavior at high temperatures to elastic (solid behavior with tendency to recover its original shape and dimension) at low temperatures. Between these extremes, mechanical behavior of material is viscoelastic that exhibits both viscous and elastic tendencies. Viscoelastic effects are significant for all petroleum products consisting of high molecular weight compounds, asphaltenes, and large amounts of paraffin wax (Abivin et al., 2012; Wardhaugh & Boger, 1991).

When the overlying water is in motion, it applies a force to the sunken oil blob; this force per unit area is the shear stress (i.e., *shearing* or *frictional stress*), and is a function of the water's velocity, depth of flow, specific weight, energy gradient, and bed roughness. Dynamic Viscosity, μ, $(Pa * s)$ will have an effect on the fluid movement under the applied shear stress. It plays a major role in determining the critical shear stress (CSS) (i.e., the point at which permanent deformation occurs); the higher the viscosity of an oil, the higher the cohesion between layers within it, requiring a larger force to move it. The shear stress (τ) is a direct function of the rate of strain ($\frac{du}{dy}$). Therefore, larger velocities result in higher rates of strain and increase the overall shear stress that result in oil blob deformations. The rate of strain (the velocity gradient) is driven by the change in velocity divided by the change in height in the boundary layer directly above the oil blob.

$$\tau = \mu \frac{du}{dy}$$

Equation 1 provides a symbolic version of this phenomena (Newton's law of viscosity), but is limited to non-turbulent fluid motion. The concepts from this equation were used to further analyze results.

$$\tau = \mu \frac{du}{dy} \qquad \text{Equation 1}$$

Where: τ is the shear stress (Pa), μ is the sunken oil's (dynamic) viscosity (Pa*s), and $\frac{du}{dy}$ is the rate of shear strain (m/s/m) as a function of boundary layer height and water velocity.

The research reported in this paper includes 21 saltwater annular flume test runs conducted at different temperatures (15.7-28 ° C) and current velocities (0.17-1.2 knots, or 8.5 to 60 cm/s). The tests were each 60 minutes long and observations of permanent deformations were recorded. The BSS and CSS were calculated using the Turbulent Kinetic Energy (TKE) Method (Soulsby, 1983; Stapleton & Huntley, 1995). This method was selected because it uses three-dimensional velocity fluctuations (Stapleton & Huntley, 1995), which were measured by the ADV.

Research Objectives

The objectives of this research were to: (1) estimate the CSS of Alberta bitumen by calculating BSS under a variety of conditions, (2) analyze the bitumen's erosions and migration in saltwater, and (3) determine if the Shields' Principle (Shields, 1936) maybe applied, if an oil's viscosity and the water temperature are known. Such a relationship could be used to aid responders to predict how far and in what direction an oil mass residing on the bottom could move during an emergency response.

Methods and Materials

Logistics of Experimentation

The sunken oil experiments were conducted in the CRRC's annular flume, which has a capacity of 4,000 L, the working water volume is 2,500 L with a water depth of 0.43 m. An inner rectangular flume (1.2 m length, 0.2m width, 0.9 m height), placed inside the annular flume, was preceded by two flow straighteners to reduced turbulence and produce a uniform, one dimensional flow field. Two GoPro Hero 3 cameras (San Mateo, CA) were placed along the side and above the inner flume in order to capture dimensional data of each test run in form of videos. The camera placed above the tank (i.e., plan view) recorded high definition video in the X and Y directions; while the video along the side (i.e., longitudinal section) captured erosions of oil during the course of the run in the X and Z directions.

An oil sample, 20 ± 0.2 g, was placed on the bed of the inner flume and then water was circulated in the flume using a 36-V (Motor Guide; Tulsa OK, Model #9CX53KQAX) trolling motor. Each run lasted 60 minutes at a constant motor speed, thus creating a constant velocity.

Temperature, distance of the probe above the flume floor, and water velocity (X, Y and Z directions) were measured using the Vectrino Profiler II (Nortek, Vangkroken, Norway). Factory calibration was done to the Vectrino II Profiler, but no additional calibration was required due to the geometry of the ADV sensor head. Various other checks were performed (e.g., sensor, bottom and tilt checks) to ensure measurements were accurate.

Sampling Controls and Variables

There were 21 saltwater runs; the salinity was maintained within a range of 30,000 mg/L to 35,000 mg/L (Cargill, Hi-Grade, granulated salt). This range is representative of oceanic concentrations and a refractometer (model: RHS-10ATC) was used to ensure an adequate quantity of salt was added to water filling the flume. Vectrino profiler was used to monitor the water temperature during a run to ensure it was stable.

Oil blobs, 20 ± 0.2 g, were added to sheets of laminated paper prior to filling the tank; the oil mass was verified using an Ohaus AdventurerPro balance (Parsippany, NJ). Throughout the experiment, a no-slip condition was assumed (i.e., the boundary layer water velocity, at the flume bottom, was considered zero), as it was in other experiments involving bitumen (Abivin et al., 2012). The flume was filled slowly so that the bitumen was not prematurely eroded or moved.

A run time of 60 minutes was established by previous studies conducted by Watkins (2015) which showed that the rate of elongation/spreading reduced greatly after one hours' run time.

Dynamic Viscosity

The viscosity of the Alberta bitumen was analyzed at the UNH Materials Laboratory (Durham, New Hampshire), using a TA Instruments (New Castle, DE) HR-1 Discovery Hybrid Rheometer. Viscosity measurements were conducted using a 25 mm diameter oscillating parallel plate geometry with 1 mm gap setting. Measurements were conducted in a temperature sweep mode with tests at multiple strain rates.

Calculating Shear Stress

BSS, a master variable that prompts permanent oil deformations (e.g., oil erosions and elongation), is a function of water velocity, depth of flow, energy gradient, bed roughness and water density. The shear stress acting upon the oil is the ratio of the tangential force to the surface area at a point on the surface (Elger et al., 2013). If the BSS acting upon the oil is great enough, it causes the oil to migrate or droplets of oil to erode from the mass and become suspended in the water column. When permanent deformations occur, BSS has reached its maximum threshold or CSS. BSS was calculated using the Turbulent Kinetic Energy (TKE) method [

$BSS\ = \tau_0 = C\ \cdot E$ Equation 2 and 3], as defined by Stapleton & Huntley (1995).

$$BSS\ = \tau_0 = C\ \cdot E \qquad \text{Equation 2}$$

Where: (Soulsby, 1983) and (Stapleton & Huntley, 1995) defined *C* as a proportionality constant, typically 0.19, and was also used in this analysis. *E* (Pa) is stress due to kinetic energy calculated as a function of the fluctuations in the X, Y, and Z water current velocities measured by the Vectrino:

$$E = \left[\frac{1}{2}\right]\rho_w(u'^2 + v'^2 + w'^2) \qquad \text{Equation 3}$$

Where: ρ_w is the density of salt water (kg/m^3) and *u'*, *v'*, and *w'* (m/s) are the velocity fluctuations in the X, Y, and Z directions, respectively. It is important to note that the Vectrino Profiler has a Z-velocity measurement associated with both the X and Y prongs, yielding two Z-velocity measurements that should be identical. The Z-velocity associated with the X prong was used in this analysis, since the two Z-velocities were similar.

For calculations, the density of saltwater was assumed to be 1026 kg/m^3 (API = 6.4^o). This density was used since the effects of temperature-related density changes within the water body was assumed to have negligible effects on BSS calculations.

Results and Discussion

The temperature ranged from 15.5ºC to 30ºC, the salinity varied 30,000± 2,000 mg/L (30 ± 2 ppt), and the water velocity remained within the bounds of 0.17 knots and 1.2 knots (8.5 to 60 cm/s).

Bitumen Viscosity The viscosity here is expressed as complex viscosity due to oscillatory nature of the test procedure. This allowed researchers to determine the extent of fluid like viscous and solid like elastic behavior. For the test temperatures used in this study the material behaved predominantly in viscous manner.

$$Complex\ Viscosity, \eta^{*} = 1 * 10^{8}(T)^{-4.172}$$

Equation 4 for the complex viscosity (η*) of the Alberta bitumen was derived from the rheological results (Figure 1), where T is the temperature (˚C). The viscosity here is expressed as complex viscosity due to oscillatory nature of the test procedure. This allowed researchers to determine the extent of fluid like viscous and solid like elastic behavior. For the test temperatures used in this study the material behaved predominantly in viscous manner.

$$Complex\ Viscosity, \eta^{*} = 1 * 10^{8}(T)^{-4.172} \quad \text{Equation 4}$$

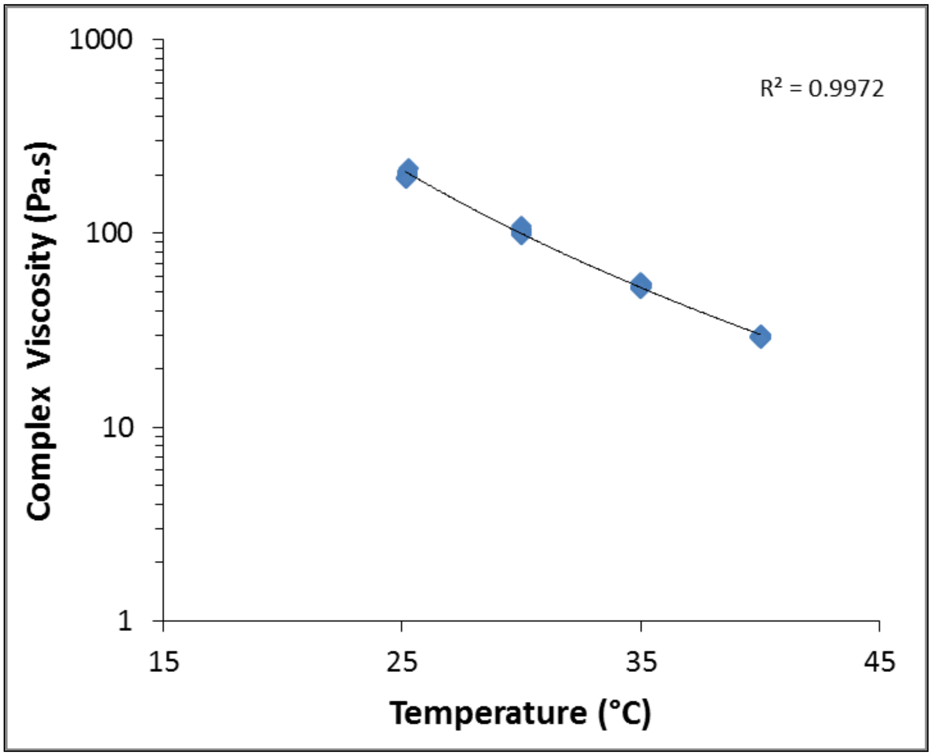

Figure 1: Viscosity Analysis with respect to Temperature

Bitumen Temperature – Viscosity Relationship

As the temperature of a liquid increases, its viscosity decreases (Elger et al., 2013). It is expected that during trials with higher water temperature, the Alberta bitumen would increase in temperature and its viscosity would decrease, resulting in greater permanent deformations.

When calculating BSS using the TKE method, velocity fluctuation is the master variable that influences CSS threshold (i.e., the point at which permanent deformations occur). Generally, for Newtonian fluids (e.g., light oils), as CSS increases, the rate of erosions or extent of elongation is expected to rise. Oils with an API gravity of less than 22.3˚(e.g., heavy oil) (Rønningsen, 2012) such as Alberta bitumen (10˚API, contains paraffin waxes and asphaltenes with complex molecules with high carbon to hydrogen ratios) (Souraki et al., 2012), may have viscoelastic tendencies (Rønningsen, 2012) that will inhibit erosions or migrations at high water velocities.

The shear rate is calculated using the viscosity of oil and the shear stress imposed upon the oil mass due to water's motion (Equation 1). If the oil's viscosity is assumed to be constant (within a temperature range), the graph of a shear rate vs. shear stress exhibits a linear trend (i.e., a Newtonian fluid). For the Alberta bitumen, the percent lengthening (analogous to shear stress) increased rapidly until it reached a threshold. This corroborated the findings of Abivin et al., (2015), that Alberta bitumen, a non-Newtonian fluid, exhibits shear-thinning behavior. The Alberta bitumen behaves as a shear-thinning fluid (at higher temperatures); although shear stresses increase on the oil mass, the viscosity cannot withstand these forces and the oils' resistance to flow decreases.

There are no known studies that have analyzed the viscosity of Alberta bitumen across a temperature spectrum. The Alberta bitumen data followed the trend of an Athabasca bitumen (Souraki et al., 2012) quite closely.

Bitumen Erosions

The number of erosions ranged from none to five (Figure 2); 29% of the trials had no erosions and with a maximum of five occurring at 33.0˚C and 1.1 knots and 25.0˚C and 0.72 knots. Overall, there was no correlation between the water velocity/temperature and erosions.

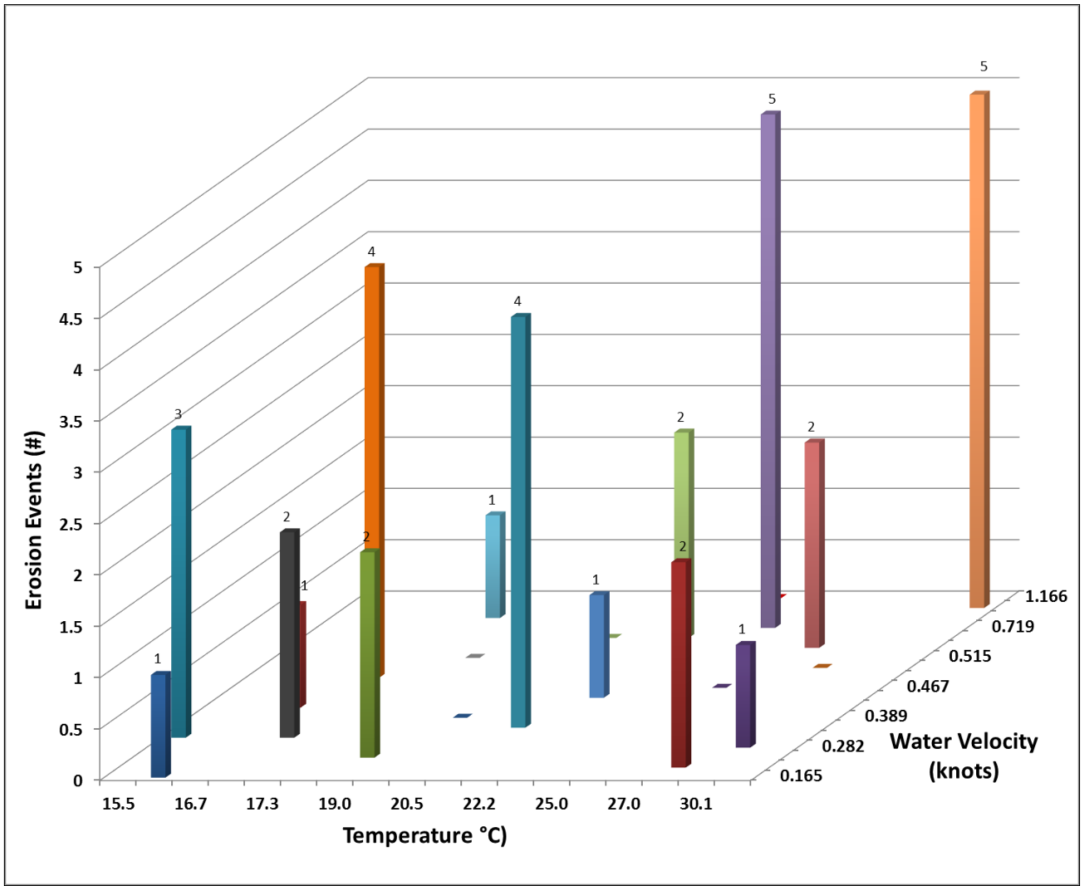

Figure 2: Results of Temperature/Velocity vs. Erosion Events

Bitumen Lengthening

While bitumen migration was observed in the X- and Y-directions, only lengthening, (X-direction) was reported here because it was far greater than spreading (Y-direction)

Temperature appeared to be the driving factor in lengthening of the oil mass (X-direction) in the direction of the water flow (

Figure 3). The higher temperatures (~30℃), experienced increased lengthening, especially when compared to the coldest temperatures (~15℃), at their respective velocities.

This trend was expected because the viscosity is highly dependent upon temperature; at higher temperatures, the bitumen is less viscous and exhibits greater lengthening.

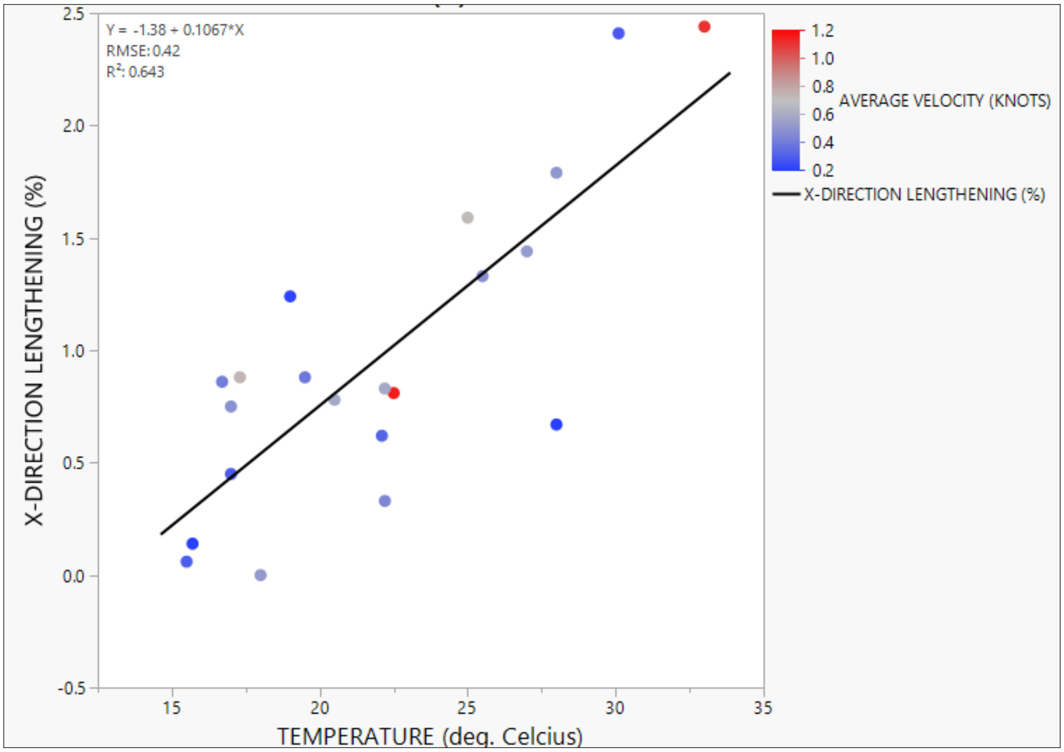

Figure 3: Velocity vs. X-Direction Oil Lengthening, showing temperatures effect on oil elongation

Estimating Migration of Sunken Bitumen

The Shields Principle uses dimensionless parameters to estimate transport of sediment materials along the bed of a moving waterbody (e.g., river) through the characterization of incipient motion (Garcia, 2000). The dimensionless parameters create dynamic similarity and could be applied to spill response models to predict transport of sunken oil along the bed. Using the data from the trials, we generated a stress-strain graph, analogous to the Shields Principle, where the X-axis is a dimensionless value characterizing physical and chemical properties of the oil and water, and the Y-axis is the Percent Lengthening in the direction of water flow (current) (Figure 4). The dimensionless parameter, known as the Dimensionless Globule Migration (DGM) Parameter, was calculated using the viscosity of the oil (Pa*s), at the temperature on the bottom of the flume, the initial spilled oil length in the direction of the current (m), the density of the water at the bottom (kg/m^3), and the current velocity (m/s) along the bottom (X-direction).

$$\mu^* = \frac{\eta^*}{\rho_{H2O}} \quad \text{Equation 5}$$

$$DGM = \frac{\bar{U}_{current} * L_{oil}}{\mu^*} \quad \text{Equation 6}$$

Where: η^*(m^2/s) is the complex viscosity of the oil adjusted by the in-situ properties of the water (at the location of the oil), $\bar{U}_{current}$ is the mean water velocity (m/s), and L_{oil} (m) is the initial oil mass length, in the direction of flow. The DGM is in essence a Reynold’s number, and as such is comparing the magnitudes of fluid momentum to oil resistance to movement.

During a sunken Alberta bitumen spill, the responder could calculate μ* ($\mu^* = \frac{\eta^*}{\rho_{H2O}}$ Equation 5) using the in-situ water temperature, at the location of the spilled oil, and the temperature-adjusted viscosity of the bitumen (e.g., see The viscosity here is expressed as complex viscosity due to oscillatory nature of the test procedure. This allowed researchers to determine the extent of fluid like viscous and solid like elastic behavior. For the test temperatures used in this study the material behaved predominantly in viscous manner.

$Complex\ Viscosity, \eta^* = 1 * 10^8 (T)^{-4.172}$ Equation 4 above).

Then, the DGM Parameter ($DGM = \frac{\bar{U}_{current} * L_{oil}}{\mu^*}$ Equation 6) would be calculated using the in-situ average current velocity and the estimated <u>initial</u> length of the oil mass in the direction of the current. Finally, Figure 4 would be used to predict the percent lengthening of the oil mass that would occur in the direction of the current.

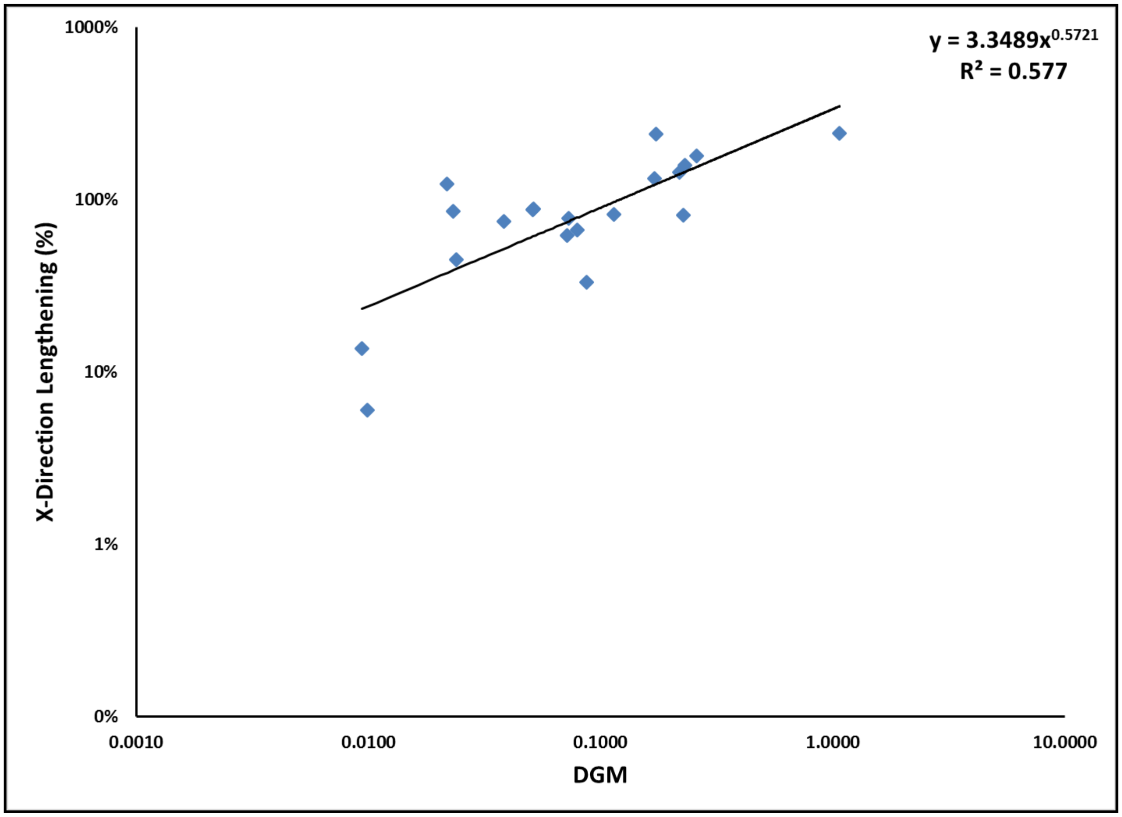

Figure 4: Analysis of Oil Lengthening, utilizing a dimensionless parameter for in-field predictions

As the DGM Parameter increases (e.g., with warmer temperatures, higher current velocity or a larger bitumen mass), the migration of the bitumen is expected to increase.

Future work is needed to validate this approach using field data from bitumen spills, in addition, experiments should be done on other transported shear-thinning oils and applied to varying types of bathymetry.

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