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Novel Mathematical Model for Natural Dispersion of Oil Spill on Dyanmic Sea

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Abstract

Natural dispersion is an important weathering process that controls the transfer of oil from the sea surface into the water column. However, conventional dispersion models have limited capability to represent the combined effects of dynamic wave breaking, whitecap coverage, turbulence, oil properties, and droplet formation. The present study develops an energy-constrained natural-dispersion model in which whitecap coverage defines the dynamically active slick area and a wave-breaking energy-transfer efficiency determines the fraction of turbulent energy available for creation of new oil–water interfacial area. The proposed framework introduces whitecap coverage to represent the dynamically active fraction of the oil slick and an energy-transfer efficiency factor to account for the portion of wave-breaking energy available for droplet generation. The model also explicitly considers the interfacial energy required to create new oil–water surface area and couples turbulent energy dissipation with oil viscosity, interfacial tension, and droplet size. This provides a mechanistic relationship between sea-state forcing, wave breaking, useful dispersion energy, droplet generation, water-column entrainment, and subsequent resurfacing. The proposed approach provides an improved physical representation of natural oil dispersion under variable sea conditions and offers a basis for more realistic prediction of oil behavior during marine spill events.

1. Introduction

Natural dispersion is one of the major weathering processes governing the fate and transport of oil following a marine spill. Under turbulent sea conditions generated by wind-driven waves, a coherent oil slick can be disrupted by wave breaking and converted into oil droplets that are entrained into the underlying water column. This process, generally referred to as natural dispersion, transfers a fraction of the surface oil into the subsurface environment and consequently alters the subsequent transport, weathering, and persistence of the spilled oil. Natural dispersion can be broadly described through three interconnected stages: slick disruption and droplet generation, vertical transport of the generated droplets into the water column, and subsequent droplet resurfacing or retention within the water column (Sebastião and Soares, 1995; Sterling Jr. et al., 2004). The intensity of these processes depends on sea-state conditions, wave-breaking characteristics, and the physical properties of the spilled oil.

Propagating surface waves contain energy primarily in the form of potential energy associated with the vertical displacement of the water surface and kinetic energy associated with the motion of water particles. During wave propagation, part of this energy is dissipated through friction and, more importantly under energetic conditions, through wave breaking. Breaking waves redistribute this energy into several mechanisms, including turbulent stirring and mixing of the water, enhanced emulsification, heat generation, and acoustic energy. When a wave breaks in the presence of an oil slick, a portion of the wave energy is transferred to the water–oil system. If the available energy is sufficiently large, the continuous oil slick can be disrupted, generating a population of oil droplets that is subsequently entrained beneath the sea surface. These droplets are transported within the water column through advection and turbulent diffusion and may subsequently resurface depending on their size, density, and

the prevailing hydrodynamic conditions (Delvigne, 1985; Reed et al., 2009; Papadimitris, 2011; Xie et al., 2013). Thus, droplet generation and underwater transport are closely coupled processes that may occur simultaneously during natural dispersion.

The dispersed oil consists of droplets covering a wide range of size classes, with each class exhibiting different buoyancy and hydrodynamic behaviour. Droplet size and oil density strongly influence the resurfacing process. Relatively large droplets generally possess higher rising velocities and tend to return to the sea surface, whereas smaller droplets can remain suspended in the water column for longer periods. Very small droplets, particularly those below a critical or threshold size, have low rising velocities and may remain entrained within the water column. During this period, the increased oil–water interfacial area associated with dispersed droplets can enhance dissolution and biodegradation and may also influence sedimentation processes (Reed et al., 2009). Consequently, natural dispersion can both reduce the volume of oil remaining at the sea surface and redistribute the contaminant into the marine environment, making the prediction of oil recovery and response operations more challenging.

Several experimental and modelling studies have investigated the mechanisms governing oil-slick breakup, droplet generation, entrainment, and resurfacing. Raj and Griffith (1979) investigated slick breakup and dispersion under different sea-state conditions and examined the effects of wave breaking on droplet size and depth of entrainment. Their observations indicated that the maximum penetration depth of dispersed oil was reached after the passage of the breaking wave, suggesting that oil droplets are transported beneath the surface within the wake generated by the breaking wave. Delvigne and Sweeney (1988), based on laboratory-scale experiments, reported that the depth of droplet entrainment could be related to the height of the breaking wave, with an approximate relationship of 1.5 times the breaking-wave height. Li and Garrett (1998), however, suggested that this relationship may vary approximately between 1.2 and 1.6 depending on sea-state conditions. Their analysis also indicated that the turbulent energy dissipation rate within the entrainment region could remain relatively consistent with experimental observations.

The dynamics of droplet resurfacing are also strongly influenced by the frequency and intensity of wave breaking. Raj and Griffith (1979) reported that the resurfacing velocity of dispersed oil droplets decreases with increasing wave-breaking frequency because droplets can be repeatedly transported beneath the surface by successive breaking waves. Aravamudan et al. (1982) further demonstrated that oil droplets initially generated during slick breakup may undergo secondary breakup within the water column under turbulent inertial forces associated primarily with pressure fluctuations. The droplet size decreases until the disruptive inertial forces become balanced by the stabilizing effect of oil–water interfacial tension (Dunnewind et al., 2003; Vankova, 2007). This balance can be characterized using the Weber number, which provides a measure of the relative importance of inertial forces and interfacial tension in controlling droplet deformation and breakup.

Several empirical formulations have subsequently been developed to quantify natural dispersion. Audunson (1979) proposed a simplified relationship for estimating oil mass loss due to dispersion as a

function of wind speed, threshold wind speed, and exposure time. In this formulation, wind speed was considered the primary controlling parameter, with a relatively high threshold wind speed of 8.0 m/s, compared with the lower wind speeds of approximately 5–6 m/s associated with the onset of significant wave breaking reported in other studies. Mackay et al. (1980) developed an empirical dispersion model based on a constant dispersion rate, expressed through the fraction of surface oil dispersed and the corresponding volume of oil transferred into the water column. The dispersed fraction was related to wind speed, while the volume of oil lost from the surface was associated with slick thickness, wind speed, oil–water interfacial properties, and oil viscosity.

Experimental investigations by Delvigne (1985) demonstrated that dispersed oil concentration is related to the rate of dispersion and that increasing wind speed enhances the vertical mixing of oil droplets within the water column. Delvigne and Sweeney (1988) subsequently developed an empirical relationship for the rate of oil entrainment based on wave-dissipation energy per unit surface area, droplet-size distribution, and a proportionality parameter related to oil viscosity. Their work established the importance of wave energy dissipation in controlling natural dispersion and indicated that dispersed droplets undergo underwater advection and diffusion. They also observed that the maximum droplet diameter depends on the duration of turbulence and decreases with increasing time following the passage of a breaking wave. Within the investigated slick-thickness range of 0.2–1.2 mm, droplet-size distribution and oil entrainment were reported to be relatively independent of slick thickness. The authors further suggested that oil–water interfacial tension and oil viscosity could be important parameters controlling droplet-size distribution. Sebastião and Soares (1995) similarly identified surface tension as an important parameter affecting droplet formation and coalescence and suggested that increasing oil viscosity reduces the ability of an oil slick to undergo natural dispersion.

Despite its widespread application, the Delvigne–Sweeney model has limitations in representing the complex physical mechanisms involved in natural dispersion. In particular, the formulation does not explicitly incorporate surface rheological properties such as oil–water interfacial tension, which can influence droplet formation and breakup (Dunnewind and Koops, 2003). Furthermore, the model assumes relatively homogeneous and stationary turbulent conditions, whereas wave breaking and turbulent energy dissipation in real marine environments are spatially heterogeneous and intermittent (Reed et al., 2009). The influence of oil properties is also represented primarily through viscosity, although density, interfacial tension, and other properties can affect droplet formation, entrainment, and resurfacing. Reed et al. (2009) reported that droplet-size distributions exhibit a log-normal behaviour, in contrast to the linear relationship considered in earlier formulations. They also found that the influence of viscosity on droplet size was relatively small over the range of approximately 1000–3000 cP but became more pronounced at higher viscosities.

Alternative approaches have attempted to incorporate additional oil and mixing characteristics into natural-dispersion models. Tkalich and Chan (2002) introduced a mixing factor to estimate the rate of oil entrainment into the water column and the subsequent resurfacing rate. Tkalich (2006) further related the mixing factor to oil density, viscosity, and interfacial tension. Their results indicated that increased

mixing intensity promotes enhanced shearing of droplets from the oil-slick surface. The entrainment rate was found to vary with oil properties, with oil viscosity exhibiting an inverse relationship with the amount of oil retained within the mixing layer. Interfacial tension was also identified as an important parameter influencing droplet formation. In addition, increasing turbulence intensity was associated with a reduction in droplet size. FrechMcCay (2004) reported that significant wave breaking begins at wind speeds of approximately 6 m/s and increases with increasing wind speed, further demonstrating the importance of accurately representing the relationship between atmospheric forcing, wave breaking, and oil dispersion.

The studies demonstrate that natural dispersion is governed by the interaction of wave-breaking energy, turbulent dissipation, oil viscosity, density, interfacial tension, droplet size, and sea-state conditions. However, existing formulations generally represent only a subset of these interacting mechanisms. In particular, the connection between the dynamically active portion of an oil slick, wave-breaking conditions, available turbulent energy, and the interfacial energy required for droplet generation remains insufficiently represented in conventional empirical formulations. Whitecap coverage provides a potential means of representing the fraction of the sea surface directly affected by active wave breaking, while an energy-transfer formulation can account for the fact that only a fraction of the available wave-breaking energy contributes to the generation of new oil–water interfacial area.

Therefore, the present study develops a modified mathematical framework for natural oil dispersion under dynamic sea conditions. The proposed approach extends the conventional Delvigne–Sweeney framework by incorporating whitecap coverage and an energy-transfer efficiency concept to establish a mechanistic relationship between wave-breaking conditions and droplet generation. The formulation further considers the interfacial energy required to generate new oil–water surface area and couples turbulent energy dissipation with oil viscosity, interfacial tension, and droplet size. The resulting framework provides a continuous physical pathway from sea-state forcing and wave breaking to useful dispersion energy, oil-droplet generation, water-column entrainment, and subsequent resurfacing. The proposed model is intended to provide a more physically representative description of natural dispersion under variable and dynamic marine conditions and to provide a basis for improved prediction of oil behaviour during marine spill events.

2. Model development

The natural dispersion of surface oil is primarily governed by wave breaking, which disrupts the coherent oil slick and transfers a fraction of the wave energy to the oil–water interface. The resulting oil droplets are entrained into the upper water column, where their subsequent transport and resurfacing are controlled by droplet size, oil properties, turbulence, and the prevailing hydrodynamic conditions.

3.1 Baseline formation

The present model is developed by extending the simplified formulation proposed by Aravamudan et al. (1981) for estimating the rate of oil entrainment into the water column.In the formulation of Aravamudan et al. (1981), the volumetric rate of oil entrainment is related to the portion of the oil slick affected by wave-breaking events and the local slick thickness. The rate of oil transfer from the surface slick to the water column may be expressed as

$$\frac{dV}{dt} = \dot{V}(t) = NA(t)\,h(t)$$
$$\left(\frac{m^3}{s}\right) = \left(\frac{1}{s}\right).\left(m^2\right)(m)$$

1

$$N = \Pr\frac{\bar{\omega}}{8\pi}\ (1/s)$$

2

Where, V is the volume of oil entrained into the water column, A is the affected slick area (m^2), h is the mean slick thickness (m), N represents the frequency or fractional occurrence of wave-breaking events acting on the slick and Pr probability of wave breaking.

The original formulation assumes that a breaking event affects the slick over its width and approximately normal to the direction of wave propagation. The frequency of wave breaking is subsequently related to the prevailing sea-state conditions through the probability of wave breaking, Pr, and the associated wave parameters. Although this formulation provides a useful representation of the geometrical contribution of wave breaking to oil entrainment, it does not explicitly account for the energy available for droplet generation or the fraction of wave-breaking energy that is effectively transferred to the oil slick. In particular, the occurrence of a breaking event does not necessarily imply that the entire affected slick volume is converted into dispersed droplets. A physically based dispersion formulation must therefore distinguish between the area subjected to active wave breaking and the energy actually available for oil-slick disruption and droplet formation.

2.2 Dynamically active slick area

Wave breaking is spatially and temporally intermittent, and natural dispersion consequently occurs over only a fraction of the sea surface at any given time. Whitecap coverage (WCC) provides an observable representation of the fraction of the sea surface associated with active wave breaking. Previous investigations have demonstrated the relationship between whitecap coverage, wind forcing and wave-breaking activity (Callaghan et al., 2008; Johansen et al., 2015). On this basis, the present model represents the dynamically active fraction of the oil slick using WCC. The wave-breaking term in Eq. (1) is therefore reformulated in terms of the whitecap coverage.*N* in Eq. (1) could be replaced by percentage whitecap coverage in Eq. (2);

$$F_{wc} = \frac{WCC\ (\%)}{T_{avg}}\ (1/s)$$

3

$$\frac{dV}{dt} = F_{wc} A\,(t)\, h\,(t)$$

4

This modification provides a direct representation of the spatially active portion of the slick rather than assuming that the entire slick is exposed uniformly to wave-breaking forcing. However, WCC alone describes the occurrence and spatial extent of wave-breaking activity and does not quantify the mechanical energy available for droplet formation. The conversion of a coherent oil layer into dispersed droplets requires deformation of the slick and the creation of new oil–water interfacial area. Consequently, an additional energetic constraint is required.

2.3 Energy limitation for droplet generation

The formation of oil droplets during natural dispersion involves an increase in oil–water interfacial area. The associated work is governed by the oil–water interfacial tension. The minimum energy required to generate a new interfacial area can be expressed as

$$E_i = A_{o/w}\sigma_{o/w}$$

5

Where, $E_i$is the interfacial energy required for droplet formation, σ is the oil–water interfacial tension (N/m), and $A_{o/w}$ is the newly generated oil–water interfacial area (m^2).

For a spherical oil droplet of diameter d, the droplet volume and surface area are given by

$$V_d = \frac{\pi d^3}{\sigma}$$

6

$$A_d = \frac{\pi d^2}{\sigma}$$

7

Therefore, the surface-area-to-volume ratio is

$$\frac{A_d}{V_d} = \left(\frac{6}{d}\right)$$

8

Thus, the generation of smaller droplets requires a substantially larger interfacial area per unit volume of oil. The interfacial tension therefore provides an important physical constraint on the fragmentation of the oil slick.

2.4 Energy-transfer efficiency

The energy supplied by breaking waves is not entirely converted into oil-droplet formation. A portion of the available energy is dissipated through turbulent mixing of the surrounding water, deformation of the oil slick, viscous effects and other hydrodynamic processes. Consequently, only a fraction of the total wave-breaking energy is available for the generation of new oil–water interface. To account for this effect, an energy-transfer efficiency factor, η_E, is introduced:

$$E_{useful} = \eta_E \cdot \varepsilon$$

9

Where,E_{useful} is the effective energy available for droplet formation, $\varepsilon$is the turbulent energy supplied by wave breaking, and η_E is the energy-transfer efficiency, with $0 \leq \eta_E \leq 1.0$.

The limiting condition $\eta_E = 1$ corresponds to the idealized case in which all available turbulent energy contributes to droplet formation, whereas values of $\eta_E < 1$ represent energy losses associated with the surrounding hydrodynamic processes. The introduction of $\eta_E$provides an energetic interpretation of the dispersion process and is conceptually analogous to the mixing factor used in previous oil-dispersion formulations (Tkalich and Chan, 2002). However, in the present formulation, the parameter is specifically introduced to quantify the fraction of wave-breaking energy available for the generation of new oil–water interfacial area. Therefore, the interfacial energy required to create the new oil–water interface during dispersion is calculated from Eq. (8)

$$E_i = \frac{6\sigma V_{disp}}{d}$$

10

2.5 Total dispersed oil volume

Considering the spherical nature of the oil droplets generated by natural dispersion the total volume of oil dispersed can be calculated from Eq. (11) as a function available turbulence energy and oil droplet size.

$$V_{disp} = \frac{\eta_E \cdot \varepsilon d}{6\sigma}$$

11

Where, $\eta_E$is the fraction of energy available for dispersion (%),$\varepsilon$is the turbulent energy, σ is the oil–water interfacial tension (N/m) and dis spherical oil droplet of diameter(m).

2.6 Charteristics droplet size limits

Natural dispersion produces droplets over a range of sizes rather than a single characteristic diameter. The total dispersed volume should therefore be obtained by accounting for the contribution of individual droplet-size classes. The maximum and minimum oil droplet size is calculated using Eq. (29)-Eq. (30)- Delvigne and Sweeney Model

$$d_{mean} = \frac{1818\nu_{oil}^{0.34}}{\sqrt{\varepsilon}} = \frac{1818}{\sqrt{\varepsilon}} \cdot \left(\frac{\mu_{oil}}{\rho_{oil}}\right)^{0.34}$$

12

$$d_{\max} = d_{mean}$$

13

$$d_{\min} = 10\% \cdot d_{mean}$$

14

The corresponding dispersion rate can be expressed in terms of the volume of oil dispersed per unit volume of water per unit time:

$$V_{Total} = \int_{d_{\min}}^{d_{\max}} V\Delta d = \frac{\eta_E \cdot \varepsilon}{\sigma} \int_{d_{\min}}^{d_{\max}} \left(\frac{d}{6}\right)\Delta d \,(15) V_{Total} = \frac{n_E \varepsilon}{6\sigma}\left(\frac{d^2}{2}\right)_{d_{\min}}^{d_{\max}} = \frac{n_E \varepsilon}{6\sigma} \cdot \frac{\left(d_{\max}^2 - d_{\min}^2\right)}{2}$$

(16)

Where, V is volume of oil dispersed per unit volume of water per unit time (m^3 of oil /m^3 of water/sec), sigma is the oil water interfacial tension.

Breaking waves generate droplets and inject them into the water column.Oil droplet generated simply by forcing the oil into the water column. Thus, the processes causing the droplets to break no longer exist. In that case total number of oil droplets will remain equal to number of oil droplets produced in the process of slick breaking and entrainment stage. The droplet size, resurfacing velocity and frequency of breaking then determined the volume oil permanently entrained. The smallest of these droplets will be forced to maximum depth. The largest droplet will exist in the near surface layers. As the larger oil droplets are much bigger in size the buoyancy or the up-thrust force and water resistance or drag forces will be much higher. This will results in the larger droplets to resurfacing faster than the smaller one. Moreover it will also results in their entrainment depth to minimum. The total volume of oil resurface can therefore be obtained using Eq. (12). The volume of crude oil resurfacing can be estimated from Eq. (12).

$$V_{resurf} = \sum_k n_k V_k = \sum_k \left(\frac{4\pi}{3}\right) n_i R_i^3 = \sum_k \frac{n_i d_i^3}{6}$$

12

The resulting formulation establishes a sequential physical relationship between atmospheric forcing, sea-state development, wave breaking, active slick area, turbulent energy, oil-droplet generation and subsequent resurfacing. The principal modification introduced in the present study is therefore the coupling of the dynamically active slick area with an energy-based representation of droplet generation. Whitecap coverage is used to represent the spatial occurrence of active wave breaking, while the energy-transfer efficiency accounts for the fact that only a fraction of the available turbulent energy contributes to the formation of new oil–water interfacial area. The formulation further incorporates oil viscosity, interfacial tension and droplet size to establish a physically interpretable relationship between sea-state forcing and natural oil dispersion.

This framework provides a basis for representing natural dispersion under temporally varying sea conditions while retaining the fundamental physical mechanisms of wave-induced slick breakup, droplet formation, water-column entrainment and subsequent resurfacing.

3. Conclusion

A novel mathematical framework was developed for predicting the natural dispersion of oil spills under dynamic sea conditions. The proposed model extends the conventional dispersion approach by incorporating whitecap coverage to represent the dynamically active portion of the oil slick and an energy-transfer efficiency factor to account for the fraction of wave-breaking energy effectively utilized for droplet generation. The formulation establishes a physical relationship between wave-breaking activity, turbulent energy, interfacial tension, oil properties, and droplet size.The model also provides a framework for estimating oil entrainment into the water column and subsequent resurfacing based on droplet characteristics. By considering the energy required to generate new oil–water interfacial area, the proposed approach provides a physically interpretable representation of the droplet-generation mechanism. This framework can be further extended to incorporate realistic droplet-size distributions and time-varying wind and wave conditions.

The present study focuses on the development of the mathematical formulation and provides a foundation for further computational investigation of natural oil dispersion. The developed framework has the potential to improve the representation of natural dispersion in marine oil-spill fate and transport models.

Statement and declaration

Declarations

Competing Interests

The authors declare that they have no financial or non-financial competing interests that are directly or indirectly related to the work submitted for publication.

Author Contribution

Aditya Kumar Mishra: Conceptualization, mathematical model development, methodology, literature review, formulation of equations, analysis, and manuscript preparation. Suresh Kumar G.: Supervision, research guidance, critical review of the mathematical formulation, and revision of the manuscript. Both authors contributed to the development of the work, reviewed the manuscript, and approved the final version for submission.

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