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Vertical Dispersion in Oil Spill Fate and Transport Models

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ABSTRACT

The evolution of oil spilled in marine environments is affected by its spread, evaporation, emulsion, dissolution and dispersion in the water column. Although it has an environmental impact on marine ecosystems and affects determination of the spilled oil lifetime, vertical dispersion is of great importance; however, less attention has been paid to this complex phenomenon in comparison with other processes. This article is a critical review of the existing analytical relationships for oil dispersion calculation. The implementation of these formulae in numerical models is not straightforward. A comprehensive review of numerical oil dispersion models is presented with the advantages and disadvantages of each approach. In addition, experimental oil spill studies are reviewed and their obstacles are discussed. Analysis of experimental data cited in the literature has been carried out and variations in the oil concentration distribution in water bodies has been investigated. The current knowledge gaps and areas that require further investigation are identified and future research directions are proposed for in-depth assessment of vertical oil dispersion in the marine environment. Major areas of future study should focus on gradients of oil concentration by depth in the water column instead of overall penetrated oil mass in a water body. It is also suggested that advanced models use explicit physically-based formulations rather than empirical oil concentration relationships. It should be noted that selection of appropriate space and time intervals for sampling in experimental studies is required to form a proper understanding of the temporal and spatial oil concentration distribution in a water body.

1. Introduction

At the beginning of the 21st century, world oil production was about 11 million tons per day (NRC, 2003). About 30% of crude oil is extracted from the marine reservoirs and is transferred through waterways (Xie et al., 2007). During extraction and transport, a considerable amount (about 1.3 million tons per year) of oil is released accidentally and enters water bodies (NRC, 2003). Oil spills in water are disastrous and cause serious long-lasting damage, particularly to marine ecosystems. One liter of oil can pollute up to 10,000 liters of water (Amini, 2008). In recognition of this danger, attention has focused on the destructive effects of oil dispersion and scientific investigation in this field has been of great importance (Li, 2001; Liu and Writz, 2006; Ventikos et al., 2004).

The Persian Gulf is a high-risk marine environment. In recent years, two important oil spills have been reported in this area that have resulted in 1.45 million barrels of oil released along the coastline of Kuwait in 1991 and 0.6 million barrels spilled in Iranian coastal zones after an explosion in the Nowrouz oil fields in 1983 (ITOPF, 2001). In 2010, the largest accidental marine oil spill in the history of the petroleum industry occurred after an explosion on a US oil platform spilled 4.9 million barrels of oil into the Gulf of Mexico (Gong et al., 2014). These events demonstrate the vital need for thorough study of the processes associated with the evolution of a spill, especially its vertical dispersion.

Oil spreads in a thin layer after spilling on the water surface. Sea currents and winds are the main causes of lateral motion of this layer. An imbalance in the force between gravity, viscosity and surface tension and oil-water interfacial tension controls the direction of oil spreading. During the first period after the spill, which ranges from hours to days, the light components of the oil evaporate and the soluble parts dissolve in the water. The water emulsifies the oil and the heavier elements settle on the sea bed (Wrenn et al., 2010). Slower processes like photochemical oxidation and biological degradation become important after a longer time (a month to years) (Sharifi et al., 2011; Venosa et al., 2010). In some cases, oil can adhere to particles of sediment that sink, can interfere with the drifting of ice and spread under ice sheets and may contaminate harbor facilities and vessels (Fingas and Hollebone, 2003; Wang and Li, 2003; Yapa and Chowdhury, 1991). If oil penetrates the shorelines

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and estuaries, it will cause secondary damage to life in coastal regions (Tkalich, 2006). All of these oil spill processes are classified in Figure 1.

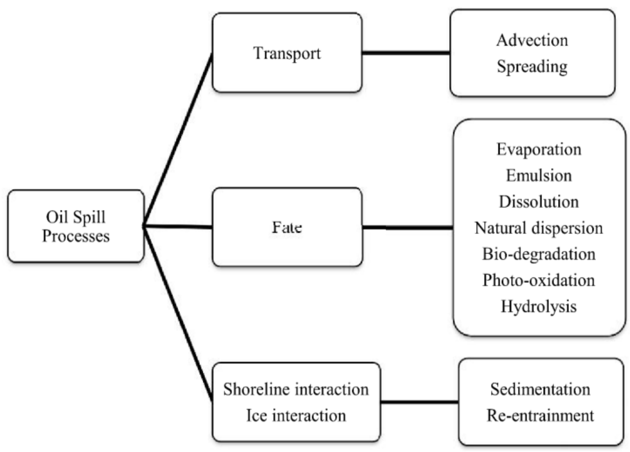

Figure 1. Diagram of classified physical, chemical and biological oil spill processes.

Waves can naturally disperse spilled oil in a water column. Some contamination removal methods can eliminate surface oil by dispersing it from the sea surface and transferring it to the water column (Page et al., 2000). Vertically-dispersed oil calculation is thus a vital process to estimating the lifetime of the spilled oil on the sea surface. How long the oil will remain on the sea surface is fundamental to assessing oil spill incidents, planning contingency operations, evaluating alternative oil spill response strategies, determining the probable impact on coastlines and in estimating the potential effects on marine organisms in the path of the slick. Nevertheless, little attention has been paid in the technical literature to this component of the fate of oil spills.

Although many oil transport and fate studies are available, they do not cover all aspects of this phenomena in a unified approach. The current article is the first to review and categorize a wide range of oil transport and fate studies using empirical relationships to calculate dispersion, dispersion relationships for use in numerical models and oil dispersion data from laboratory experiments. These are surveyed comprehensively and the difficulties, deficiencies and shortcoming of each approach are reviewed and discussed. Future challenges in the study of vertical dispersion of oil spills are identified and discussed. The results can be applied as guidance to avoid decentralized oil spill studies.

2. Methods

Natural dispersion of oil spilled into the ocean is key to determining the expected lifetime of the oil slick under different environmental conditions. This process is discussed in-depth below.

2.1. Oil natural dispersion in water column

Natural dispersion is the mixing of oil droplets with water and their transfer to a water column. Some authors do not consider oil dispersion as a fate process because the properties of the droplets do not differ from those of the spilled oil. Nevertheless, oil droplets dispersed in a water column are more exposed to fate processes and their chemical combination will change over time. The dispersion rate depends on sea conditions and oil characteristics. Dispersion usually increases dissolution and bio-degradation and decreases evaporation. The sequence for natural dispersion of oil comprises three stages: surface oil fragmentation and entrainment (droplet formation), conversion of smaller droplets into sub-surface oil droplets due to turbulent mixing and resurfacing of larger droplets and the transfer and dispersion of oil droplets in the water column with ambient currents and turbulence. Re-entrainment to the surface sometimes occurs, which is considered a fourth stage.

The oil droplets dispersed in water are exposed to turbulent currents which play an important role in their evolution. Smaller, denser droplets are distributed downwards in the water column and remain there for a long time, while larger and lighter droplets resurface again due to their buoyancy. Primary penetration of oil droplets into a water column is carried out by strong large eddies, whereas strong small eddies generate sufficient shear velocity and break the oil into smaller droplets. It can be assumed that oil droplets disperse in water when the turbulent force in vertical direction is greater than the buoyancy of the droplets (ASCE, 1996).

Independently of the source of the oil spill (sea bed or surface), the currents always cause natural dispersion of the oil spills along the water column and formation of small oil droplets. Physical dispersion of spilled oil, the scattering and drowning of the surface oil slick and its splitting into smaller droplets depends on the turbulent flow structure (Delvigne and Sweeney, 1988; Li *et al.*, 2008; Page *et al.*, 2000). At the surface, the waves contribute to diffusion of the oil slick and their spread in turbulent currents through shear velocity. On the bed, the bottom boundary layer (when present) is the main cause of turbulence.

3. Results

The existing analytical relationships for oil dispersion calculation and numerical models are presented with the pros and cons of each approach and experimental studies and their problems are reviewed below.

3.1. Analytical-empirical relationships for dispersion calculation

Many studies have been carried to model oil spills and their components, beginning with Haung (1983), Zhao *et al.* (1987) and Spaulding (1988, 1995) (Kolahdoozan and Nagheeby, 2007). Yapa and Shen (1994) focused on river oil spill modeling. Cekirge *et al.* (1995) introduced the techniques, abilities and characteristics of an ideal oil spill model. A relatively comprehensive review by ASCE (1996) discussed dispersion and fate processes, numerical modeling and compared different models in a few oil spill cases. Reed *et al.* (1999) focused on results of oil spill modeling during the 1990s.

Hinze (1955) and Friedlander (1957) were among the first researchers to study the relationship between dispersion and turbulent energy. They found that oil viscosity and oil-water interfacial tension are the most important parameters in this process. Laboratory studies by Forester (1971) attributed dispersion to the turbulent energy domain. A great number of oil spill models calculate dispersion by simple relationships based on experimental measurements. For instance, Blaikley (1977) suggested that the dispersion rate depends mainly on oil type, hydrodynamic condition and time. He stated that the dispersion rate may produce losses in the surface slick of crude oil from 20% per day in a low sea state (<1 m significant wave height) to 50% per day in a high sea state (>6 m significant wave height).

Audunson (1979) and Johansen (1982) related the second and first power of wind speed to the scales of wave break energy and dispersion rate, respectively. Mackey *et al.* (1980) and Mackey and Zagorski (1982) introduced an empirical relationship in which the oil slick is divided into thin and thick layers (Mackey *et al.*, 1980). They calculated the dispersion rate as a product of sea surface area (exposed to dispersion) and amount of oil droplets having a size small enough to be dispersed in a water column. They presented their relationship as a function of oil viscosity, thickness of the oil slick, tension between oil and water and the second power of wind speed. Based on this method, the thin layers with low viscosity and surface tension are more exposed to dispersion than the thick layers with high viscosity and surface tension. It should be noted that turbulent energy is not considered explicitly in their proposed equation, but its effect is present indirectly through wind speed. The relationship is presented in mathematical form as:

$$dm_d/dt = 0.11 m_{oil}\,(1+W)^2/(1+50h\sigma\sqrt{\mu}) \quad (1)$$

Where m_d is the oil dispersed in the water column (kg), t is the time (h), m_{oil} is the oil mass on the water surface (kg), W is the wind speed (m/s), μ is the oil dynamic viscosity (cP), h is the oil layer thickness (cm) and σ is the interfacial tension of the oil and water (dyne/cm). Regardless of oil transport from the thick to the thin part of the slick, this formulation slightly underestimates the dispersion value (ASCE, 1996; Lehr *et al.*, 1984; Mackey *et al.*, 1980).

Based on Mackey's theory, Reed *et al.* (1989) presented a method for estimating the oil entrainment rate in a water column. They calculated the oil dispersed in a water column (D) by multiplying the fraction of oil slick entering the water column in one hour (D_a) by the fraction which does not resurface (D_b) as:

$$D = D_a D_b \quad (2)$$

$$D_a = 0.11(1+W)^2 \quad (3)$$

$$D_b = 1 + 50\,\mu^{0.5} h\sigma \quad (4)$$

Where W is the wind speed (m/s), μ is the oil dynamic viscosity (cP), h is the oil layer thickness (cm) and σ is the interfacial tension of the oil and water (dyne/cm).

Delvigne and Sweeney (1988), Delvigne (1994, 1991) and Delvigne and Hulsen (1994) conducted laboratory research to determine the oil dispersion rate, dispersed oil size distribution and penetration depth of the oil in the water column. They recognized dissipation of turbulent energy due to wave breakage as the most important parameter in oil dispersion. They presented a relationship for the dispersion rate for different ranges of droplet size as a function of energy dissipation due to wave breakage and oil type.

The coefficient of this relationship is nearly constant for oil having a viscosity lower than 100 cSt; however, increasing the viscosity will decrease this coefficient substantially. It is recommended to integrate the relationship from the smallest to largest oil droplet size such that the penetrating oil mass becomes equal to the concentration of surface oil. Because the components of this method can be easily determined, it is widely used in research and commercial models. This relation can be simply followed as:

$$Q(d) = K_{en} D_{ba}^{0.57} S_{cov} F_{cw} d^{0.7} \Delta d \quad (5)$$

Where d is the diameter of the oil droplets (m), Q(d) is the penetration rate into the water column of oil droplets with diameters of [d-Δd; d+Δd] (kg/m^{2}s), K_{en} is the experimental constant function of the oil type and erosion condition, D_{ba} is the energy dissipation at wave break (J/m^2), S_{cov} is the fraction of surface covered by oil and F_{cw} is the part of surface hit by waves in the time unit. The parameters of F_{cw} and D_{ba} can be calculated in the following experimental relations as:

$$D_{ba} = 0.0034\,\rho_w\,g\,H_{rms}^2 \quad (6)$$

$$F_{cw} = 0.032\,(U_{wind} - U_i)/T_w \quad (7)$$

where ρ_w is the water density (kg/m^3), g is the gravity acceleration (m/s^2), U_{wind} is the wind speed (m^2/s), T_w is the period of breaking waves (s), H_{rms} the root mean square of wave height (m) and U_i is the minimum wind velocity for the wave break (m/s) (usually about 5 m/s). The total dispersion rate for a group of particles of different diameter can be obtained through integration of the range of particle sizes as:

$$S_{vd} = \int_{d_{min}}^{d_{max}} Q(D)\Delta d \quad (8)$$

The limits of the above integration can be obtained as (Chao *et al.*, 2003):

$$d_{min} = 0.12\sigma^{3/5}\omega^{2/5}/g^{4/5}\rho_w^{3/5} \quad (9)$$

$$d_{max} = \sqrt{12\sigma/g(\rho_w - \rho_o)} \quad (10)$$

Where w is the wave frequency, σ is the interfacial tension of oil and water and ρ is the oil density.

Almost all analytical-experimental studies have focused on the role of wave breakage as the scattering factor of surface oil slicks. Delvigne (1993) studied different sources of dispersion, including overtopping, hydraulic jump in rivers, rapid flow around an obstacle and shipping through an oil slick and similarly identified the rate of energy dissipation as the main parameter of dispersion.

One of the first successful steps in 3D simulation of oil dispersion was performed by Elliott (1986), who used the random-walk technique. This particle-based method, together with the experimental formula of Delvigne and Sweeney (1988), is a suitable base for the group of models later developed by Al-Rabeh *et al.* (1989), Reed *at al.* (1994) and Elliott (2004).

A key point in vertical mixing is the formation, movement and distribution of oil droplets (Chen *et al.*, 2009). Raj (1997) and Li and Garrett (1998) used different assumptions to study the forces producing oil droplet breakage. Aravamudan *et al.* (1981) and Bouwmeester (1986) presented theoretical equations for dispersed droplet size. Large and small scale tests showed that the size distribution of the droplets dispersed by wave break is between 1 and 1000 μm. Lunel (1993) measuring the dispersed droplet size distribution in the sea. He assumed that droplets with a threshold of 70 to 150 μm in size are distributed in the water column; however, considering a specific size as the threshold diameter cannot explain the physical situation of the phenomenon (ASCE, 1996; Reed *et al.*, 1999). Lunel (1993) conducted laboratory and field measurements to show that droplet size distribution does not depend on oil type and flow dynamics. In reality, the dispersion rate and largest oil droplets depend on these parameters.

Wind shear force displaces the slick upper layer, which is exposed to the atmosphere, whereas the lower layers are left behind and form a tail for the slick. This process produces an oil flow with thick to thin sections, which increases dispersion. Although the thin part forms a small fraction of the whole slick, it represents the major contribution to overall dispersion. This has been observed in particle-based models such as Johansen (1987), Elliott (1991) and Reed *et al.* (1994). It has been shown that the entrainment rate of oil into a water column has an inverse relationship with oil kinematic viscosity; however, this trend reverses at lower viscosities (Tkalich and Chen, 2002). Delvigne and Hulsen (1994) showed that increasing the viscosity to about 500 cSt considerably increased the formation of oil droplets due to dispersion.

Breaking waves develop a mixing layer in the upper part of the water column. In this layer, the oil concentration is much larger than in the lower layers. The oil concentration distribution in the upper part can be considered as constant (Boufadel *et al.*, 2006; Tkalich and Chen, 2002). An empirical relationship for the initial penetration depth of oil droplets in a water column due to wave breakage was presented by Nilsen *et al.* (1985). In some relationships, the depth of the mixing layer has been considered to be directly proportional to wave height. Delvigne and Sweeney (1988) and Li and Garrett (1998) estimated the proportionality coefficient as being about 1.5 and between 1.2 and 1.6, respectively.

Another important topic is the oil resurface rate. Tkalich and Chan (2002) parameterized the effect of wave breakage on vertical mixing. They presented relationships for calculating the volume of oil which returns to the surface and the amount which remains submerged in lower layers as a function of the size of the oil droplets. In their analytical model for oil semi-equilibrium distribution between a surface slick and water column, they obtained an estimate for the amount of oil entering the water column under breaking waves. They introduced a non-dimensional mixing coefficient as the ratio of downward oil flux due to mixing and upward oil flux due to buoyancy. They calculated the oil entrainment rate from the surface slick to the water column as:

$$\lambda_{ow} = K_e \omega \gamma H / 16 \alpha L_{ow} \tag{11}$$

Where λ_{ow} is the entrainment rate, K_e is a coefficient between 0.3 and 0.5, γ is the non-dimensional coefficient of energy dissipation, ω is the wave frequency, H is the wave height, α is the mixing coefficient and L_{ow} is the vertical length scale.

Boufadel *et al.* (2007) introduced non-dimensional parameters to describe the horizontal spreading rate and vertical distribution of an oil slick in the presence of waves, buoyancy and turbulent diffusion. An experimental study by Johansen *et al.* (2015) produced a new semi-empirical model for oil droplet size distribution generated by a single breaking wave event. They presented the theoretical and empirical foundations for their model based on dimensional analysis with contained two non-dimensional groups, the Weber and Reynolds numbers, as:

$$D/_{h} = A\ We^{-a}\ (1 + \acute{B}\ Vi^{a}) \tag{12}$$

Where D is the characteristic droplet size (m), h is the the oil film thickness (m), We is the Weber number and equals $h\rho gH/_{\sigma}$, Vi is the viscosity number and equals $\mu\sqrt{gH}/_{\sigma}$, ρ is the oil density (kg/m^3), σ is the interfacial tension (N/m), g is the gravity acceleration (m/s^2), H is the wave amplitude (m), μ is the dynamic viscosity (kg/ms) and $A, \acute{B}$ and a are constants to be determined. When this relationship was fitted to the experimental data, the coefficients were found to be $A = 2.251, \acute{B} = 0.02$ and $a = 0.6$.

In conclusion, the comparison and analysis of analytical and empirical relationships reviewed in this section show that most of these models were developed to calculate the overall oil dispersion rate in a water column. These methods estimate only the total amount of oil which enters the water column. Relationships which consider interaction with wave breakage and turbulent flow (i.e. Delvigne's work) are closer to the actual physics of the phenomena and have been applied more than other methods. In addition, oil droplet size is an important criterion for better dispersion prediction, as was considered by Mackey *et al.* (1980) and Reed *et al.* (1989). In practice, these two approaches have been extensively applied and almost overshadow the other formulas.

No analytical or empirical relationship has been presented thus far to predict the oil concentration in a water column as a function of space and time. It can be said that the available relationships are only appropriate for 2DH models and cannot calculate oil distribution in a water column. Theses empirical equations cannot be used in 2DV or 3D models. Further research is needed to identify relationships for calculation of the oil concentration in water at different times and space intervals under different climate conditions.

Dispersants are globally and routinely applied as an emergency response to oil spills in marine ecosystems with the goal of chemically-enhancing dispersion and dissolution of oil in the water (Kleindienst *et al.*, 2015). Recently, the interaction between oil, dispersants and sediment and their role in developing oil spill countermeasures in deep water environments have been reviewed by Gong *et al.* (2014). A lack of well-organized studies on the effect of dispersant on vertical oil dispersion, however, justify the need for more research in this area and its consideration in mathematical prediction formulas (Li *et al.*, 2009a,b; Reed *et al.*, 2004; Wrenn *et al.*, 2009).

3.2. Numerical models for dispersion calculation

Many numerical oil spill models have been developed recently to predict oil slick transport in coastal waters. These models range from simple tracking or particle-based models to 3D simulations which include many fate processes. Interaction between fate processes and biological effects have also been included.

Spilling oil in water is a 3D phenomenon; however, for simplicity, sometimes it is assumed to be either 1D or 2D. In 2D vertical models, the sequence of operations usually starts with the use of empirical relationships in each time step to compute the rate of oil decrease due to processes such as evaporation, dissolution and dispersion (Qi *et al.*, 2011). The effect of these processes should also be considered on changes in oil characteristics such as viscosity and density. In most 2D depth-averaged models, the improved Mackey *et al.* (1980) or Delvigne and Sweeney (1988) equations (see previous section) are used to separate the amount of oil entering the water from the total volume of spilled oil and calculation is then carried out for the remaining oil volume. By solving the appropriate equations, the spreading rate of the surface oil slick can be calculated. The displacement of this slick under mechanical forces and turbulent diffusion can then be determined. The new position of the oil surface after a time step is computed in the last step. Note that as the oil slick approaches the shore or icy covers, its interaction with them should also be considered.

This description makes it clear that 2D horizontal models can predict oil slick transport with some simplification through the integration of the flow parameters and oil processes as a function of depth. In addition, the oil penetrating the water column can be calculated using empirical equations. The 3D hydrodynamics models provide a better representation of currents, which allows more precise representation of oil processes in the water body.

An overview of the 2D and 3D numerical oil spill models developed during the last decade shows that models by Yapa *et al.* (2001, 2004) and Dasanayaka and Yapa (2009) have been developed specifically to simulate oil and gas blowouts from the sea bed. Once the oil plumes originating from underwater blowouts reach the ocean mixed layer, its near-surface dispersion is influenced heavily by wind and wave-generated turbulence. In this regard, Yang *et al.* (2015) applied the LES approach to model oil dispersion in an ocean mixed layer and conducted statistical analysis on mean plume dispersion.

In other 2D or 3D models, the transport and fate processes of advection, spreading, turbulent diffusion, evaporation, dissolution, emulsion, natural dispersion, shoreline interaction, oxidation and degradation are simulated. Most recent models are 2D or are only 3D in the hydrodynamic part of the model. Examples are those developed by Al-Rabeh *et al.* (2000), Arkhipov *et al.* (2007), Brandvik and Faksness (2009), Chao *et al.* (2001), Chen *et al.* (2007), Elhakeem *et al.* (2007), Elliott (2004), Gjosteen (2004), Hibbs *et al.* (1997), Hibbs and Gulliver (1999), Janeiro *et al.* (2008), Korotenko *et al.* (2004), Koziy and Maderich (2003), Martino and Peybernes (2007), Nagheeby and Kolahdoozan (2008, 2010), Ohshima and Simizu (2008), Papadimitrakis *et al.* (2006), Peishi *et al.* (2011), SabbaghYazdi (2006), Sarhadizadeh and Hejazi (2009), Sebastiao and Soares (2007), Shen and Yapa (1988), Wu and Wang (2010) and Dominicis *et al.* (2015). A large number of these models disregard oil dispersion in a water column. In most, hydrodynamic conditions are first simulated and calibrated before the estimated surface oil slick trajectory is compared with real oil spill data. In other cases, only the transport and spreading of the oil slick on the sea surface is estimated over time and then verified with field data.

Chao *et al.* (2003), Tkalich *et al.* (2003, 2006), Chen *et al.* (2004) and Wang *et al.* (2005) focused on oil dispersion as a function of water depth. In their models, water depth is divided into two or three surface and sub-surface layers. After calibration of the hydrodynamic model, the oil concentration suspended below the water surface is estimated. Due to a shortage of field and laboratory data, no comparison has been made with these measurements.

Fang and Johnston (2001), Zhu and Strunin (2002), Boufadel *et al.* (2006), Violeau *et al.* (2007), Nazir *et al.* (2008) and Valizadeh and Shafieefar (2009) developed 2D vertical models in which estimation of the concentration of oil dispersed in a water column due to wave breakage is also included. Only qualitative graphical results were presented for these models. Imanian (2012) developed a multi-phase Lagrangian numerical model for marine environments to study dispersion of spilled oil under different wave conditions. She proposed a mathematical relationship for dispersed oil concentration through statistical analysis and validated the results using experimental data.

Wang *et al.* (2008), Guo and Wang (2009) and Guo *et al.* (2010) developed a full 3D model in which, in addition to estimating the spread and advection of an oil slick on the sea surface, determines the vertical distribution of oil concentration versus water depth. Following 3D hydrodynamic simulations, the fate processes are simulated using empirical relationships and the surface oil slick trajectory and changes in its thickness are predicted over time. Finally, the concentration of dispersed oil in water column is estimated by solving the advection-diffusion equation and the results are reported without comparison with field data or laboratory measurements. No general results are reported in this model for fate processes related to the oil droplet entering a water column.

Although, there is a wide range of numerical models available, the vast majority are not comprehensively calibrated because of lack of reliable experimental and field data. This is especially true for prediction of the vertical oil concentration distribution both over time and in space. It can be concluded that 1D or 2DH oil spill models are in their last stage of development, while 2DV and 3D models require further development to accurately predict oil penetration as a function of water depth and time. Recent advances in oil spill models have focused on application on large-scale real cases, which assures development of a wide-ranging oil spill prediction model with high accuracy in the near future.

3.3. Laboratory modeling for dispersion calculation

Many studies have been conducted to better understand oil dispersion in water and to provide data for calibration of numerical models. Most of these experiments have been carried out to determine the variation in oil concentration in the water column over time. Artificially fated oil is often used in the laboratory in which evaporation or dissolution has already occurred; thus, the density and viscosity have already increased. In addition, only dispersion, and not the biological process of the oil fate, can be studied in short-term experiments. A laboratory setup typically consists of channels with a wave inducer at one end and a wave absorber or inclined beach at the other. According to the protocols of EPA standards for chemical extraction and separation of water and oil, the samples are mixed with the chemical solvent dichloromethane.

Riazi *et al.* (1999) conducted limited experiments to determine oil mass flux into water over time and presented a semi-analytical model. Page *et al.* (2000) experimentally studied the efficiency of dispersants on oil spills in the surf zone. Bonner *et al.* (2003) analyzed the results of Page *et al.* (2000) and formulated the weighted equilibrium of oil among the water column, water surface and channel walls.

Li *et al.* (2007) experimentally analyzed the role of sediment particles on oil dispersion in a water column. Li *et al.* (2008, 2009a-c) conducted additional experiments to evaluate the effect of chemical dispersants on oil spills. Li *et al.* (2010) studied the effect of temperature on the efficiency of the oil dispersant. In another laboratory investigation, Sun *et al.* (2014) studied the role of mixing energy on oil aggregation and its significance to oil dispersion. Because oil-in-water dispersion is also a critical step during underwater blowouts and droplet size is a determining factor in the vertical migration of oil, Aman *et al.* (2015) experimentally measured oil droplet size for plumes under deep water conditions.

In a recent study, Parsa et al. (2015) experimentally investigated vertical oil dispersion of surface oil spills in a regular wave field. The purpose was to determine the trend of oil concentration variation related to natural oil dispersion and formulate the magnitude and time of maximum oil concentration. These two are the most vital parameters in oil pollution management and for test protocol determination. Previous research has mainly focused on the total amount of oil submerged in a water column; therefore, no information is available regarding the oil concentration in a water column. Because no prior equation previously existed to estimate the parameters in a water column, this was a pioneering study. The correlation between oil concentration and important parameters such as wave characteristics, amount of oil spilled into the water and the sampling distance from the spilling location was assessed and the variation in oil concentration was quantified.

3.4. Analysis of experimental results

Some experimental studies on oil spill dispersion have published data showing the variation in oil concentration in the water column (c) according to time (t), water depth (h) and distance from the spill location (d). The most important of these are Page *et al.* (2000), Li *et al.* (2008, 2009), Wang *et al.* (2015) and Parsa *et al.* (2015). The following results were extracted from these experiments to explain the physical reality of phenomena and the main reasons for the incompatibility of the results in some cases.

Under both spilling and plunging breaking wave conditions, the oil concentration below the spill is very low and increases slowly over time. Also, the vertical gradient of concentration below the spill is small (Figure 2a). Further away from the spill, a sharp gradient begins to develop near the surface and is progressively diffused to the lower layers (Figure 2b) (Li *et al.*, 2008).

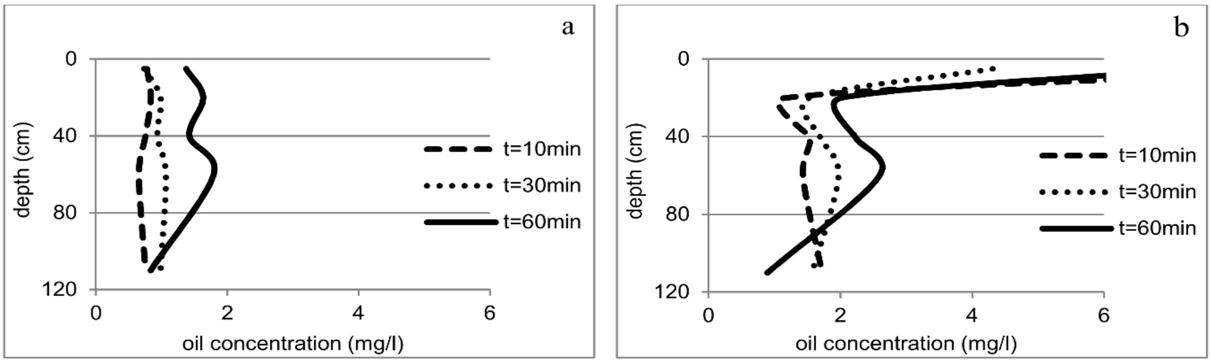

Figure 2. Comparison of oil concentration changes at different times and locations at depths of: (a) 1.5 m from spill point (near spill point); (b) 4 m from spill point (far from spill point) (Li et al., 2008).

It is known that opposing factors compete during oil dispersion. Wave turbulence causes oil penetration into the water column and the buoyancy force caused by the difference in density between the oil and water causes oil to resurface. As mentioned, the concentration below the spill is low. It appears that, close to the spill, dispersion is low and, moving away from the spill, the turbulence is sufficient to transport the oil downwards (overcoming the buoyancy force). This confirms that dispersion requires time to evolve and evolves in a diffusive process vertically from the water surface to the bottom. These issues are demonstrated along with other experimental measurements in Figure 3 (Li *et al.*, 2009a).

Figure 4 shows that the oil concentration increases in sections further away from the spill location for both breaking wave types at all depths and times (Li *et al.*, 2008). Similarly, at a depth of 75 cm from the water surface, the oil concentration increases as the distance from the spilling location increases (Figure 5) (Li *et al.*, 2009a). In contrast, at a depth of 140 cm, the oil concentration does not follow the same trend and initially changes quickly and then more slowly as the distance increases (Figure 5). Furthermore, near the shore, the oil concentration was reported to be higher than offshore at any time (Figure 6) (Page *et al.*, 2000).

The oil concentration will decrease over time at any point. (Figure 6) (Page et al., 2000). Wang et al. (2015) experimentally measured the oil concentration under different wave patterns in a laboratory wave channel. They reported a down trend (Figure 7) similar to that on the Figure 6. In contrast, Li et al. (2008) reported that the oil concentration increased over time for both types of breaking waves at all sections and depths (Figure 8) (Li et al., 2008).

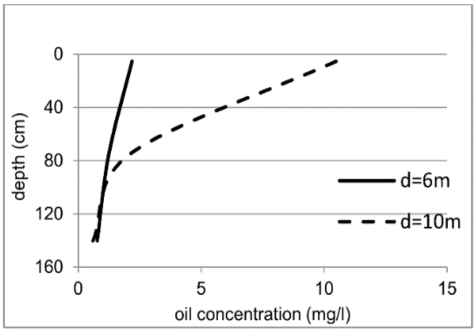

Figure 3. Comparison of oil concentration changes in two locations at depths of: (a) 6 m from spill point (near spill point); (b) 10 m from spill point (far from spill point) (Li et al., 2009)

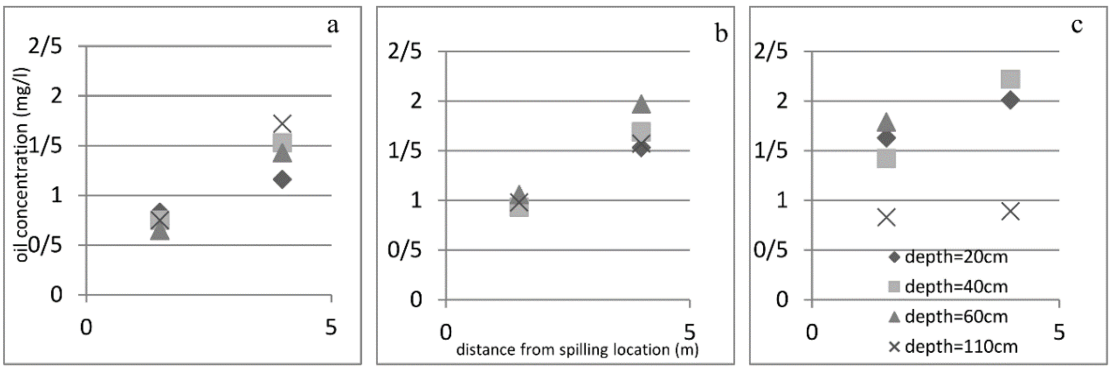

Figure 4. Increasing trend of oil concentration at different distances from spill point and different water depths at: (a) 10 min; (b) 30 min and; (c) 60 min after oil spill (Li et al., 2008)

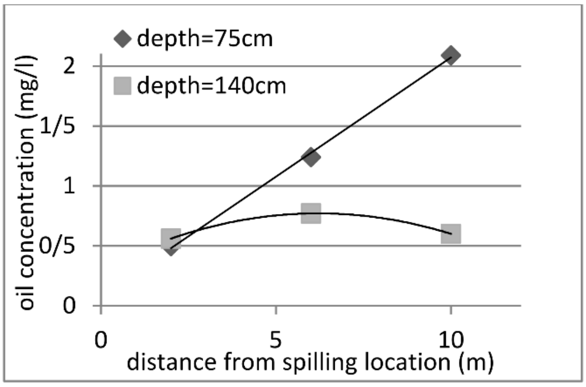

Figure 5. Oil concentration trend versus distance from spill point near water surface and near channel bed (Li et al., 2009). Note that the trend is not consistent with those of Figures 2, 3 and 4.

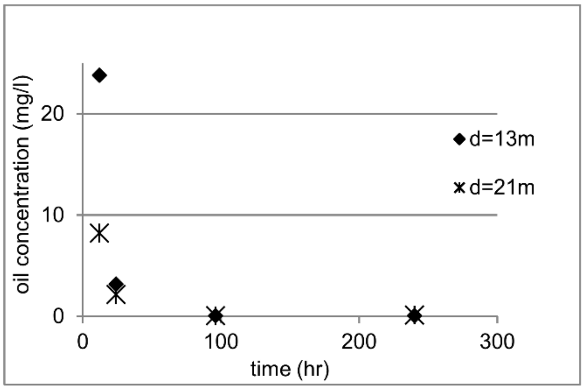

Figure 6. Decreasing trend of oil concentration over time since oil spill at depths of: (a) 13 m and; (b) 21 m from spill location (Page et al., 2000).

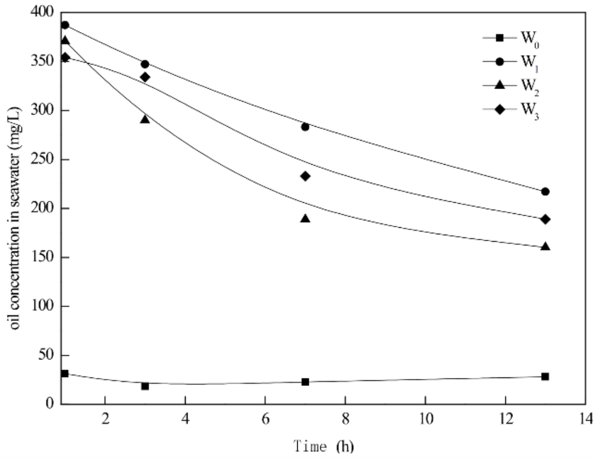

Figure 7. Decreasing trend of oil concentration over time since oil spill for different wave patterns (Wang et al., 2015).

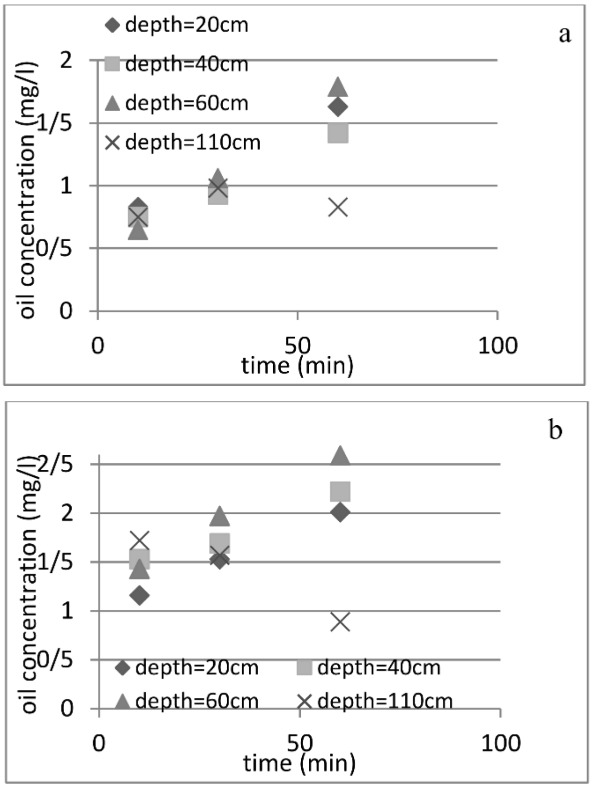

Figure 8. Increasing trend of oil concentration over time since oil spill at water depths of: (a) 1.5 m and; (b) 4 m from spill location (Li et al., 2008). Note that the trend is not consistent with those in Figures 6 and 7.

Inconsistency was observed among the different experimental results on oil dispersion in a water column described previously. It is therefore necessary to analyze these tests to determine a general trend for dispersed oil distribution. Examination of the test setups, especially their dimensions and time scales, indicate that the experiment by Page *et al.* (2000) was large-scale and the one by Li *et al.* (2008) was small-scale. From these two sets of experimental measurements, it can be concluded that for small-scale tests, the oil concentration increased over time and for a large-scale model, the trend is the reverse.

The data from these experiments show that after the oil spills into the water, at any point in the water body, the oil concentration increases up to a specific time, after which it decreases. This can be explained because it takes time for the oil to reach that specific point in the water body away from the spill location. During this period, the oil concentration increases; later, the combination of flow and wave cause dissipation of the oil at that point and the oil concentration decreases.

It appears that the time at which the oil concentration is at a maximum (maximum oil dispersion time) is a function of oil advection in the water body and oil slick motion on the water surface. During the maximum oil dispersion time, oil slick likely travels on the surface and reaches a point above the water column. Figure 9 shows the variation in oil concentration in one experiment from Li *et al.* (2009) at a point 10 m away from the injection location at a depth of 75 cm. This test demonstrates the increase and decrease of oil concentration over time.

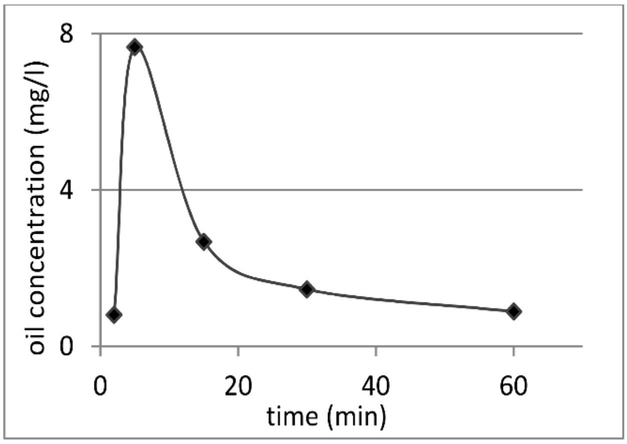

Figure 9. Ascending and descending trends of oil concentration over time since oil spill at depths of: (a) 75 cm and; (b) 10 m from spill location (Li et al., 2009) Note that the trend is not consistent with those in Figures 6, 7 and 8.

Note that, for oil spill tests that consider flow velocity and oil diffusion in water, the sample locations and time should be selected accurately. Temporal and spatial changes in oil concentration, maximum dispersion time and critical sections should be specified to capture the overall trend of oil dispersion in a water body. In other words, experiments should be designed so that the sampling period covers both ascending and descending parts of the concentration curves. Researchers who analyze experimental results should also consider this.

The following study addresses the inconsistency of results on the trends of dispersed oil concentration. A recent laboratory study by Parsa *et al.* (2015) performed in a 12-m wave channel investigated vertical oil dispersion of surface oil spills. They assessed the oil concentration variation at two sampling stations over time. It was found that the oil concentration caused by vertical oil dispersion followed an ascending trend to reach a maximum value and then decreased while the oil slick passed the sampling location at both sampling stations (Figure 10). Moreover, the results indicate that the increase in the curve slope was steeper than the decrease. This confirms the previously-mentioned temporal and spatial considerations for assessment of all-around variation in oil concentration caused by vertical dispersion over time.

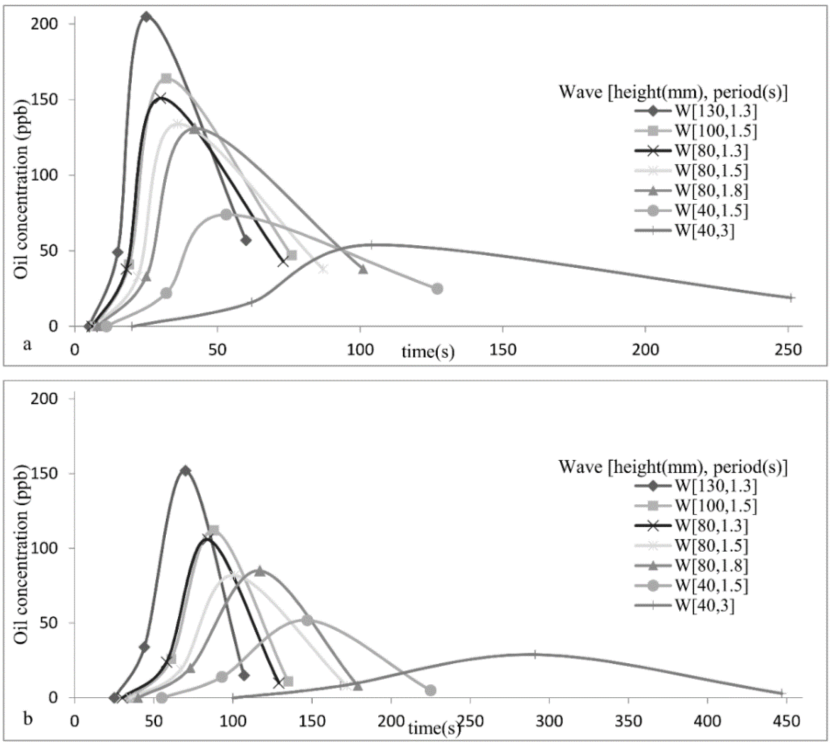

Figure 10. Trend of oil concentration over time since oil spill at mid-depth in different sections with different wave patterns at: (a) 2 m and; (b) 4 m from spill point (Parsa et al., 2015). Note that this graph shows an upward curve that reaches a maximum and then turns downward as the oil slick passes the sampling location, which is in contrast to Figures 6, 7 and 8 and is similar to Figure 9.

Because limited studies have been performed using real measurements, especially in a water column, field observations should also be considered in future oil spill studies as benchmarks for implementation of models (Xia *et al.*, 2010; Klemas, 2010). Environmental issues must be accounted for by using contention barriers or other techniques.

4. Discussion

This review reveals some critical research gaps in the area of vertical oil dispersion. The nature of dispersion is complex and a range of factors are involved; this configuration should be known in detail. It is recommended that explicit physically-based formulations rather than empirical oil concentration relationships be used. The 1D and 2DH numerical oil spill models have reached the ultimate level of development. In their place, 2DV and 3D models require further development. They should consider intricate and convoluted hydrodynamic patterns of oceanic turbulence or residual currents to accurately predict oil penetration into a water body.

The inconsistency of published experimental results show that smart selection of space and time sampling intervals which can cover maximum oil variation will lead to proper understanding of the temporal and spatial oil concentration distribution in water bodies. Little is known about how dispersants affect biodegradation and a comprehensive assessment of the impact of dispersants on vertical dispersion is required to evaluate the planning and use of dispersants during upcoming responses to oil spills. Extensive oil spill field measurement, especially in a water column, should be addressed in advanced studies to be applied in numerical models as a reference point for calibration.

5. Conclusion

Some key knowledge gaps impose significant limitations and uncertainty when determining vertical dispersion in oil spill transport and fate models. This paper reviewed different empirical relationships used to calculate oil natural dispersion in a water column, followed by a complete review of numerical models on oil spills, including vertical oil dispersion. The penetration rate of oil into a water column has been calculated in numerical models using experimental relationships and less attention has been paid to oil concentration distribution as a function of depth. It is recommended that future studies should focus on the gradient of oil concentration throughout the water column. It is also recommended that future models use explicit physically-based formulations rather than empirical oil concentration relationships.

Oil dispersion experiments were reviewed and analyzed as well. The published findings are controversial and contradictions appeared when comparing the results of different laboratory tests. Deficiencies and limitations in the application of these results have been highlighted and an explanation is advanced based on the limited number of samplings. It should be noted that selection of appropriate space and time intervals for sampling is quite important for proper understanding of the temporal and spatial oil concentration distribution in water bodies.

In conclusion, development of oil dispersion prediction models, especially in a water column is a challenge that continues to face hydro-environmental researchers. Developments can be achieved by precise observation of these phenomena in the laboratory as well as in the field and by accurately identifying the relevant processes. It is then necessary to establish models that can accurately reproduce these processes.

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