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Dispersion Rate of Spilled Oil in Water Column under Non-Breaking Water Waves

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Abstract**—**The purpose of this study is to present a mathematical phrase for calculating the dispersion rate of spilled oil in water column under non-breaking waves. In this regard, a multiphase numerical model is applied for which waves and oil phase were computed concurrently, and accuracy of its hydraulic calculations have been proven. More than 200 various scenarios of oil spilling in wave waters were simulated using the multiphase numerical model and its outcome were collected in a database. The recorded results were investigated to identify the major parameters affected vertical oil dispersion and finally 6 parameters were identified as main independent factors. Furthermore, some statistical tests were conducted to identify any relationship between the dependent variable (dispersed oil mass in the water column) and independent variables (water wave specifications containing height, length and wave period and spilled oil characteristics including density, viscosity and spilled oil mass). Finally, a mathematical-statistical relationship is proposed to predict dispersed oil in marine waters. To verify the proposed relationship, a laboratory example available in the literature was selected. Oil mass rate penetrated in water body computed by statistical regression was in accordance with experimental data was predicted. On this occasion, it was necessary to verify the proposed mathematical phrase. In a selected laboratory case available in the literature, mass oil rate penetrated in water body computed by suggested regression. Results showed good agreement with experimental data. The validated mathematical-statistical phrase is a useful tool for oil dispersion prediction in oil spill events in marine areas.

Keywords**—**Dispersion, marine environment, mathematical-statistical relationship, oil spill.

I. Introduction

BESIDES being important ecosystems for a variety of organisms, marine environments are considered as one of the most crucial commercial areas all over the world. The presence of petroleum contaminants in marine waters is one of the events that severely affect these areas. Spilled oil dealing with waves and sea currents, experiences different physical, chemical and biological processes and finally disseminate in the marine area [1], [2]. One of the important processes in oil transport is vertical oil dispersion in the water column, and the present research has focused on oil penetration in water body [3]. In this regard, various scenarios were investigated using the multiphase numerical model, and the results are collected in a database. Afterward, the results were analyzed statistically. Considering the effective parameters in oil dispersion in the water column, a mathematical-statistical relationship is proposed for prediction of dispersed oil in marine waters. After verifying proposed relationship with experimental data, its performance is validated by a comparison of the numerical model results in some other scenarios.

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II. Numerical Multiphase Model

A Lagrangian multiphase numerical model is established to simulate marine waters. In the field of numerical analysis, Lagrangian methods are those that do not require a connection between the mesh of the simulation domain but are rather based on the interaction of each particle with all its neighbors. As a consequence, extensive original properties such as mass or kinetic energy are no more assigned to mesh but rather to the single particle. Lagrangian methods enable the simulation of some otherwise difficult types of problems, at the cost of extra computing time and programming effort. For this purpose, particle-based Lagrangian approach, which is suitable for computing complicated free surfaces, boundaries, and multiphase problems, is used.

In the applied model, two phases of oil and water can be simulated concurrently [4]. The numerical model has been developed to study spilled oil transport and fate in the marine environment with emphasis on oil dispersion in the water column.

The model was verified for different physical processes of oil transport in marine waters, and accurate performance of the numerical model was proved. For instance, the model was applied to simulate some oil processes like horizontal advection and surface spreading, and the ability of the numerical model was examined in oil distribution prediction [4].

III. Proposing Oil Dispersion Phrase

Since the main focus of this research is on the process of oil dispersion in the water column, in this step it is necessary to evaluate the applied numerical model performance in predicting the spread of oil in the water column in marine environments.

The numerical model has been implemented for a series of wave characteristics, specifications oil and sea conditions and the results were compiled into a database.

To create the database, the two-phase Lagrangian model frequently has been performed for several scenarios with different input data. Dispersion rate of spilled oil pouring into wavy channels and other obtained results includes 125 series of numerical experiments, were collected in a database.

Input information in this database can be categorized in three part: channel specifications (channel length, water depth), wave (amplitude and sweeping time of wave-maker) and spilled oil (density, viscosity and oil mass).

Since the analysis of large amounts of data and understanding their relationship is complex and time-consuming, to analyze and evaluate the results and confirm the performance numerical model, SPSS software is used. Which is one of the popular statistical software and able to perform various statistical calculations.

Using the results recorded in the database obtained by the numerical model, different variables that contributed to the dispersion of oil in the water column, have been identified. Then, to find the relationship between the dependent variable (in this case the oil dispersion rate in the water column) and independent variables (in this case the characteristics of flow, wave, and oil), SPSS software was used multiple regression functions. Finally, a relationship is presented to calculate the oil dispersion rate in the water column according to different variables.

In each numerical test, after about 10 seconds of performance, the amount of dispersed oil was measured and recorded in the database.

The recorded data was entered in SPSS as independent variables (inputs) (wave height, wavelength, wave frequency, oil density, oil viscosity and oil density) and dependent variable (output) (dispersed oil mass). Using multivariate regression function, the relationship between independent and dependent variables are expressed.

After statistical analysis, regression summary, analysis of regression and regression coefficients are presented in the Table I-III.

TABLE I
SUMMARY OF DISPERSION REGRESSION

R	R Square	Adjusted R Square	Std. Error of the Estimate
.799	.638	.629	.5105320

Predictors: (constant), ln t, ln ro o, ln M0, ln nu o, ln Lw, ln Hw, ln Tw; Dependent Variable: ln M-d.

R column in Table I states multiple correlation coefficient and R Square column states multiple determination coefficients. In this case, the regression coefficient is about 80% and explains about 64% of the variance.

TABLE II
ANALYSIS OF DISPERSION REGRESSION

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	132.455	7	18.922	72.598	.000
Residual	75.065	288	.261		
Total	207.520	295			

Predictors: (constant), ln t, ln ro o, ln M0, ln nu o, ln Lw, ln Hw, ln Tw; Dependent Variable: ln M-d.

Column Sig. expresses the significant level of regression in Table II. In this case, assuming "no significant regression" is rejected with 99.9% confidence and it can be concluded that that regression is significant with high confidence.

TABLE III
REGRESSION COEFFICIENTS OF DISPERSION MODEL

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-21.747	3.405		-6.387	.000
ln Hw	.211	.086	.135	2.457	.015
ln Tw	-3.294	.861	-.493	-3.826	.000
ln Lw	3.429	.410	.925	8.355	.000
ln nu o	-.411	.125	-.128	-3.278	.001
ln ro o	2.530	.504	.181	5.020	.000
ln M0	.862	.059	.564	14.511	.000
ln t	-.125	.066	-.068	-1.898	.059

Table III shows the estimated values in the regression. Column Sig. states the significance level of each parameter. So that:

Assuming "presence of wave height is not significant in the regression" with 98.5% confidence, assuming "presence of wave period is not significant in the regression" with 99.9% confidence, assuming "presence of wavelength is not significant in the regression" with 99.9% confidence, assuming "presence of oil viscosity is not significant in the regression" with 99.9% confidence, assuming "presence of oil density is not significant in the regression" with 99.9% confidence, assuming "presence of spilled oil mass is not significant in the regression" with 99.9% confidence and assuming "presence of passed time is not significant in the regression" with 94.1% confidence is rejected.

Since assuming "all the parameters were not significant" with is rejected high confidence, it can be concluded with high confidence all parameters are significant and must be present in the regression. According to estimated values of parameters, regression function is as follows:

$$M_d = 3.5925 * 10^{-10} \ * {H_w}^{0.211} {T_w}^{-3.294} {L_w}^{3.429} {\nu_o}^{-0.411} {\rho_o}^{2.53} {M_0}^{0.862} t^{-0.125} \tag{1}$$

where, H_w wave height, T_w wave frequency, L_w wavelength, ν_o oil viscosity, ρ_o oil density, M_0 spilled oil mass, t the time after the oil spilling and M_d mass of dispersed oil in the water column caused by waves.

For each linear regression model, there are a few underwritings prove them properly; regression analysis is valid. This can be equivalent with "errors follow a normal distribution" [5].

To evaluate the assumption of normal errors in a linear model, Histograms, P-P diagrams and Kolmogorov test can be used.

The histogram displays the density of the observed values (regression errors here) and compares with a normal distribution. The average error is zero, indicates the correctness of the first underwritings.

P-P plot is used to determine following a variable (the regression errors here) from a specific distribution (normal distribution here). Observed cumulative probability values (regression errors here) are plotted versus the expected cumulative probability values (normal distribution here). The points have closer to the bisecting line, indicates further adherence of desired distribution.

In order to verify the proposed regression, histograms, and P-P in Figs. 1 and 2 have been plotted.

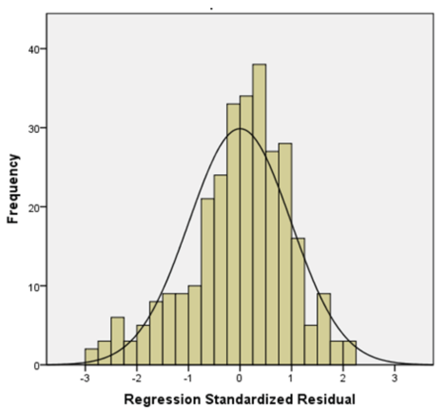

Fig. 1 Histogram of standardized error of regression model

In Fig. 1, mean is zero and standard deviation of the observed values (regression errors here) is 0.988, which is very close to the mean and standard deviation of the standard normal distribution (zero and 1, respectively).

P-P standard error of regression is plotted in Fig. 2. In this case, the dots are in good agreement with the line bisecting the regression error values indicating that adherence to the normal distribution.

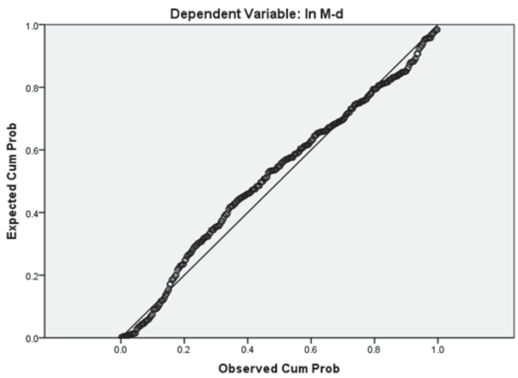

Fig. 2 Normal P-P Plot of regression standardized residual of regression model

One of the goodness of fit tests is Kolmogorov-Smirnov test. The method relies on differences in the frequency of partial accumulation of observations (regression errors here) and the expected value (normal distribution here).

Kolmogorov-Smirnov test results are presented in Table IV. Normal Parameters row in Table IV shows the parameters of a normal distribution (mean and standard deviation). In this case, the average error is zero, and standard deviation equals to 0.413.

In Table IV, row Asymp. Sig. shows the significant test level. In this case, assumption "observations (regression errors here) follow a normal distribution" is rejected with 92.1% confidence. Therefore, it cannot be confirmed with certainty that the observations follow a normal distribution.

TABLE IV
KOLMOGOROV-SMIRNOV TEST OF DISPERSION MODEL

		Unstandardized Residual
N		296
Normal Parameters[a,b]	.0000000	.0000000
	.50443845	.41272818
Most Extreme Differences	.074	.065
	.048	.045
	-.074	-.065
Kolmogorov-Smirnov Z		1.272
Asymp. Sig. (2-tailed)		.079

Test distribution is Normal.

IV. VALIDATION

In order to check the validity of the proposed relationship of oil dispersion in the water column, it is necessary to apply suggested regression in the different conditions.

For this purpose, two oil spill events are considered. Wave and oil specifications are reported in Table V. At first; these two events are simulated applying the two-phase numerical model.

TABLE V
WAVE AND SPILLED OIL SPECIFICATIONS IN VALIDATION EVENTS

Example	Wave Height (cm)	Wave Period (s)	Wave Length (m)	Oil Density (kg/m^3)	Oil Viscosity (m^2/s)	Spilled Oil Mass (kg)
1	38.52	1.98	4.01	850	0.085	1.90
2	28.81	2	3.70	900	0.085	5.58

Then, using proposed regression (1) for both of the considered events, the mass of entered oil in the water column is calculated.

The mass of entered oil in the water column calculated by the numerical model, and values derived from proposed regression relationship (1) are compared in Fig. 3.

Fig. 3 shows dispersed oil obtained from proposed statistical relationships (1) is close to the results of the applied numerical model; such that the trend of dispersed oil entered in water column calculated by the numerical model is in good agreement with proposed relationship (1).

In the first example, the difference between these two methods is 1.7%, and this difference arises to 4.9% in the second example. This indicates that the proposed relationship (1) can estimate the mass of penetrated oil in the water column accurately; in a way that there is not required to numerical simulation and its computational costs.

V. CONCLUSION

One of the most important processes in oil transport is vertical oil dispersion; a multiphase numerical model is applied to simulate oil penetration and resurfacing rate under non-breaking waves. The numerical model is performed for some scenarios, and the outcomes are collected in a database.

The database is analyzed statistically and realizing effective parameters; a mathematical-statistical relationship is suggested to predict oil dispersion in marine waters. The proposed correlation is verified and validated to apply in other oil spill scenarios.

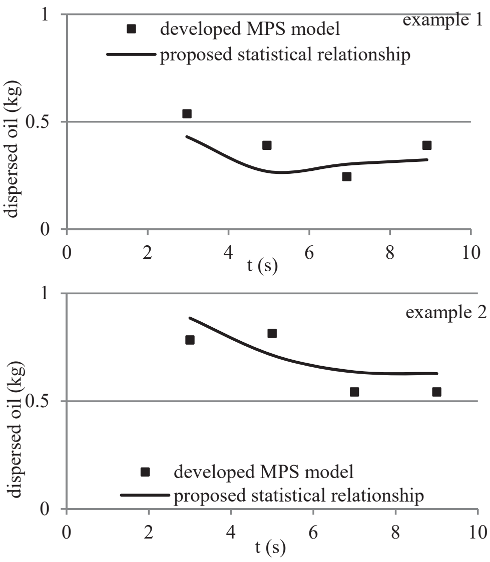

Fig. 3 Validation of proposed relationship of oil dispersion under waves

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