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A numerical study of oil spill prediction in the Gulf of Thailand using ocean wave model

Satit Sriwichien[1,2], Kittisak Chayantrakom[1,2*] and Wattana Kanbua[3]

*Correspondence:
kittisak.cha@mahidol.ac.th
[1]Department of Mathematics, Faculty of Science, Mahidol University, Bangkok, Thailand
[2]Centre of Excellence in Mathematics, CHE, Bangkok, Thailand
Full list of author information is available at the end of the article

Abstract

Oil spill is the most important cause of marine pollution. It affects marine ecosystem, an economic system, and human society. The main chemical and physical properties are the so-called oil weathering processes; spreading is one of the processes. In this research, the spreading is mainly considered because it is the most dominant process at the beginning of an oil spill incident. A mathematical model for oil prediction, based on Fay's hypothesis and Lehr's formula, is used to simulate the spreading of oil spill. The model needs wind speed as the main factor. In this paper, the wave model, namely WAM, is used for simulation of atmospheric and oceanographic states. The wave model is based on the wave spectral balance equation. The numerical results from the oil spill model based on ocean wave modeling are shown to study oil spill incident at three different locations in the Gulf of Thailand.

Keywords: Fay's hypothesis; Lehr's formula; Oil spill; Spreading; WAM

1 Introduction

Oil spills occur with high risk after a collision or the sinking of oil tankers under bad weather conditions, and are especially dangerous in ports with dense maritime traffic. Moreover, they can cause several damages to ecosystem and losses to human society. In Thailand, oil spill incidents have occurred in the Gulf of Thailand. For example, the Visahakit tanker collided with the container vessel, releasing 2100 tonnes of diesel and fuel oil into the Chaophaya River mouth in 1974. For another case, a pipeline owned by PTTGC, Thai state-owned oil company, burst while oil was being transferred from an undersea well to a tanker. The accident caused more than 210 tonnes of fuel oil pouring into the sea at Rayong province in 2013 [1]. Oil spills can damage natural resources because of their physical and chemical properties. The main properties that spilled oil undergoes are collectively known as weathering processes. There are many types of weathering processes, namely spreading, evaporation, dispersion, emulsification, etc. At the beginning of an incident, such crude oil can spread by ocean waves, which is the main factor for spreading of oil spills, and the ocean waves are produced by wind. Nowadays, we can forecast the wave height and the wind speed by using wave models, e.g., WAM model which is a third generation wave model developed by WAMDI group [2]. There are many research works about prediction of ocean waves by WAM model and oil spill models. For instance, Wattana et al. [3] investigated wave fields during the approach of typhoon LINDA in 1997 in the Gulf of Thailand using hard and soft computing approaches. Firstly, they used the hard computing approach by the WAM cycle 4 model to simulate wave heights and periods distribution. Later the soft computing approach based on the General Regression Neural Network (GRNN) model was developed to predict the wave characteristics. The simulation showed that WAM model underestimates the wave height by 20%. The GRNN showed better forecasting results than the WAM model. Moreover, for short-term prediction within 24 hours, the data-driven model such as GRNN should be viewed as a strong alternative in operational forecasting. In 2018, Daming Li et al. [4] presented a simulation method for oil spills in a multi-island area. The simulation considered the weathering processes by using mathematical modeling. Their results showed that the transport of oil slick is mainly influenced by flood currents, whereas the wind plays a major role in the drift and thickness of oil slicks. In this research, we present the mathematical simulation for wave prediction using WAM model covering from 95°E to 105°E in longitude and 5°N to 15°N in latitude. Moreover, we use the results from the wave model to describe the weathering of oil spills.

2 Mathematical models

2.1 Wave model development

Many research works have been carried out using wave models because waves are a serious danger to life and property in various maritime and coastal activities. Thus, it is necessary to develop the ability to forecast wave conditions to reduce the damage of life and property. The first wave forecasts were made in preparation for the Normandy invasion of World War II by Sverdrup and Munk in 1946 and 1947. They obtained relationships for the growth and decay of waves by considering the energy transfer from wind to waves during growth and the reversing transfer from waves to atmosphere during decay. The first computer-generated wave forecasts for the National Weather Services (NWS) were made in July 1956. However, these models produced a single wave height and period at each grid point. Originally, only wind sea or significant wave height (H_s), which is defined as the average height of 33% of the waves that are highest, generated by local and recent wind speeds were calculated. Later, a single H_s for the combined sea state was added. This prediction is the so-called representative wave approach. However, this approach takes into account the inherent complexity of the wave field on the ocean surface because the sea state consists of complex properties, e.g., superposition of wavelengths and propagation in different directions. Hence, the energy spectrum $F(f,\theta)$ is used to describe the behavior of waves. This spectrum represents the distribution of wave energy over wave frequency f and wave propagation θ. The significant wave height can be calculated by

$$H_s = 4\left[\int F(f,\theta)\,\mathrm{d}f\,\mathrm{d}\theta\right]^{\frac{1}{2}}, \tag{1}$$

and the wave energy spectrum is governed by the energy balance equation

$$\frac{DF}{DT} = S = S_{\mathrm{in}} + S_{\mathrm{nl}} + S_{\mathrm{ds}}, \tag{2}$$

where S is a combination of nonconsecutive sources and sinks of wave energy including the wind input (S_{in}), the transfer of energy due to nonlinear interactions between the spectral wave components (S_{nl}), and the dissipation due to wave breaking (S_{ds}). The term S_{nl}

only exchanges energy between spectral components, but does not change the total wave energy. The first spectral model was developed based on the treatment of the nonlinear interaction term (S_{nl}), but S_{nl} was not modeled explicitly so that all spectral components evolved independently. Later, the second generation wave model was introduced such that nonlinear interaction was a simple approximation. Later, it was found by SWAMP group in 1985 [5] that the second-generation wave model suffers from limitation in the parameterization of the nonlinear transfer. Moreover, these models gave defective results in rapidly changing wind and wave conditions. From the above reason, the wave modeling group (WAM) [2] was established to improve the models. The WAM group developed a simple procedure to estimate S_{nl} in an economical manner.

2.2 Ocean wave model

The WAM model, a third generation wave model, was developed by WAMDI group [2] and improved by Komen et al. [6]. The WAM model solves the wave energy balance equation without any a priori assumptions on the shape of the wave energy spectrum. The wave energy balance equation together with the propagation speed is given by

$$\frac{\partial F(f,\theta;x,y,t)}{\partial t} + \nabla \cdot (c_g F) = S(f,\theta;x,y,t), \tag{3}$$

where F is the spectral energy density, f denotes wave frequency, θ is wave direction, c_g represents the propagation speed of wave energy, and S is the net source function describing the rate of change of wave spectrum and is given by

$$S = S_{\mathrm{in}} + S_{\mathrm{nl}} + S_{\mathrm{ds}}, \tag{4}$$

where S_{in}, S_{nl}, and S_{ds} represent wind input, wind wave interaction, and dissipation due to white-capping, respectively. These source terms are described in the following subsections.

2.2.1 Wind input (S_{in})

The wind input is based on Miles's theory [6] and is given by

$$S_{\mathrm{in}} = \gamma \cdot F, \tag{5}$$

where F is the spectral energy density and γ is the growth rate of waves. The growth rate of waves depends on two parameters, which are

$$x = \left(\frac{u_*}{c}\right)\cos(\theta - \phi) \quad \text{and} \quad \Omega_m = \frac{\kappa^2 g z_0}{u_*^2}, \tag{6}$$

where κ^2 is the von Karman constant, u_* represents the friction velocity, c is the phase speed of the waves, ϕ denotes the wind direction, θ is the wave direction in which the waves propagate, and z_0 is the roughness length. The growth rate of the waves is defined by

$$\frac{\gamma}{\omega} = \epsilon\beta x^2, \tag{7}$$

where γ is the growth rate, ω is the angular frequency, ϵ denotes the air-water density ratio, and β is Miles's parameter. In terms of wave and wind quantities, μ is given by

$$\mu = \left(\frac{u_*}{\kappa c}\right)^2 \Omega_m e^{\kappa/x}. \tag{8}$$

For the dimensionless critical height, $\mu = kz_c$ where k is the wave number and z_c is the critical height such that $U_0(z = z_c) = c$. Then Miles's parameter can be written as

$$\beta = \frac{\beta_m}{\kappa^2}\mu \ln^4(\mu), \quad \mu \le 1, \tag{9}$$

where β_m is a constant.

2.2.2 Nonlinear transfer interaction (S_{nl})

The nonlinear source function is represented by the discrete interaction approximation [7]. Normally, this source function is developed for deep water using the appropriate dispersion relation in the resonance conditions [8]. For the finite-depth water, the computation of S_{nl} needs a scaling factor as follows:

$$S_{\mathrm{nl}}(\text{finite depth}) = R(\bar{k}h) S_{\mathrm{nl}}(\text{infinite depth}), \tag{10}$$

where $\bar{k}$ is the mean wave number and h is the depth of water. This scaling is valid when $\bar{k}h > 1$ with the scaling factor

$$R(x) = 1 + \frac{5.5}{x}\left(1 - \frac{5x}{6}\right)e^{-5x/4}, \tag{11}$$

with $x = 0.75\bar{k}h$.

2.2.3 White-capping dissipation (S_{ds})

The dissipation source term is given by

$$S_{\mathrm{ds}} = C_{\mathrm{ds}}\bar{\alpha}^2\bar{\sigma}\left[\delta_1 \frac{k}{\bar{k}} + \delta_2\left(\frac{k}{\bar{k}}\right)^2\right]F, \tag{12}$$

where F is the spectral energy density, C_{ds} is a non-dimensional constant, δ_1 and δ_2 are weight parameters. The mean wave number is determined by

$$\bar{k} = \left[\frac{\int k^p F \,\mathrm{d}\theta}{\int F \,\mathrm{d}\theta}\right]^{1/p}, \tag{13}$$

where p is a constant power. The mean frequency is defined by

$$\bar{\sigma} = \left[\frac{\int \sigma^p F \,\mathrm{d}\theta}{\int F \,\mathrm{d}\theta}\right]^{1/p}, \tag{14}$$

so that the mean steepness is $\bar{\alpha} = E\bar{k}^2$, where E is the total wave variance [9].

2.3 Oil spill model

According to Fay's hypothesis [10], the spreading of oil spill is horizontally expanded. He estimated the size of spreading area as follows:

$$A = k\left[gV^2 t^{3/2} \nu_w^{-1/2}\left(\frac{\rho_w - \rho_0}{\rho_0}\right)\right]^{1/3}, \tag{15}$$

where A is the area of oil slick in a square meter, g is gravitational acceleration, V represents the total volume of an oil spill in barrels, t is time in minutes, ν_w is oil density, ρ_o, ρ_w denote oil and water density, respectively, and k is a constant. Later, Lehr [11] found that Fay's formula greatly underestimated the slick growth. Moreover, the oil slick expands and covers in the elliptical shape, whose large diameter is in the direction of wind. He developed a relationship based on Fay's study as follows:

$$L_{\min} = 53.76\left[\frac{\Delta\rho}{\rho_0}\right]^{1/3} V_{\text{oil}}^{3/4} t^{1/4}, \tag{16}$$

$$L_{\max} = L_{\min} + 0.95 U_w^{3/4} t^{3/4}, \tag{17}$$

$$A = 2270\left[\frac{\Delta\rho}{\rho_0}\right]^{2/3} V^{2/3} t^{1/2} + 40\left[\frac{\Delta\rho}{\rho_0}\right]^{1/3} V^{1/3} U_w^{4/3}, \tag{18}$$

where $L_{\max}$ and $L_{\min}$ are the length in meters of the major and minor axes of an ellipse, respectively, $\Delta\rho = \rho_w - \rho_o$ and U_w is the speed in knots. Furthermore, the center of the elliptical shape can be obtained as follows:

$$\begin{aligned} \frac{\mathrm{d}X}{\mathrm{d}t} &= V, \\ X(t_0) &= X_0, \end{aligned} \tag{19}$$

where X is the position of center of an ellipse, V is the velocity of wind, and X_0 is the position of oil spill at the initial time.

3 Numerical results

This section presents the simulation of oil spill incidents in the Gulf of Thailand located at (7.3678°N, 102.6005°E), (8.0162°N, 102.5126°E), and (9.6898°N, 101.4068°E), starting at the location of South Bongkot 5, South Bongkot 23, and Platong oil drilling rigs, respectively. These positions were in path of the Cyclone Pabuk on 4 January 2019, as shown in Fig. 1. In each case, it is assumed that 10 million barrels of crude oil with 0.965 $\mathrm{g \cdot cm^{-3}}$ in density were spilled into the sea. The wave speed and wind direction are obtained from prediction of WAM model. In this study, it is assumed that both wave speed and wind direction do not vary with time.

Figures 2–4 depict the simulation of three cases of the oil spill incidents starting at South Bongkot 5, South Bongkot 23, and Platong oil drilling rigs, respectively. The simulation shows that, for each case, the oil slick moves along the direction of Cyclone Pabuk and tends to reach Thailand's eastern coast at different locations.

Tables 1–3 show the size in ellipse and the position of oil spill incidents. In Table 1, it is assumed that there is some crude oil spilled at (7.3678°N, 102.6004°E) which is the location

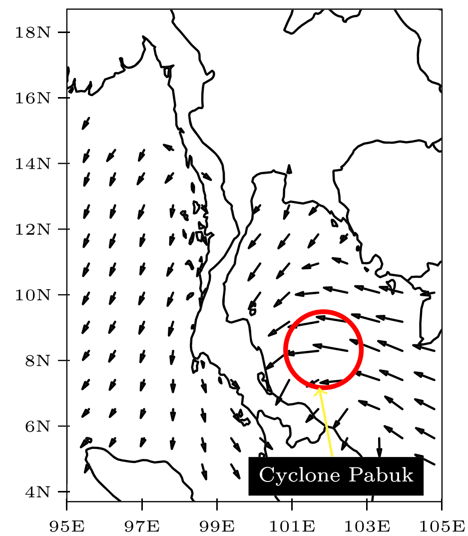

Figure 1 Gulf of Thailand. Wind direction on 4 January 2019 in the Gulf of Thailand at 07:00 am (local time) when Cyclone Pabuk moved toward Thailand's eastern coast.

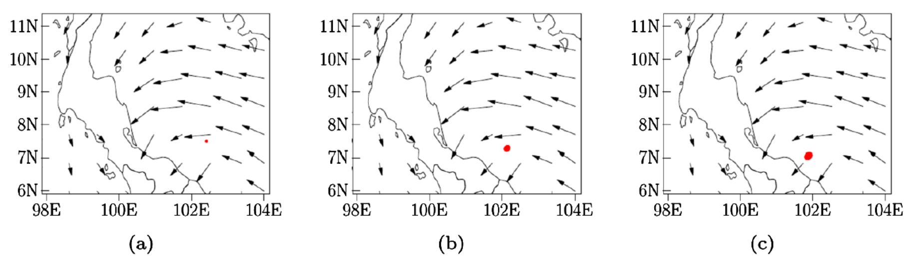

Figure 2 Movement of oil at Bongkot 5. The movement of oil slick (red dots in elliptical shape) at South Bongkot 5 oil drilling rig. (**a**) at the beginning of incident, (**b**) 30 minutes later, and (**c**) 60 minutes later.

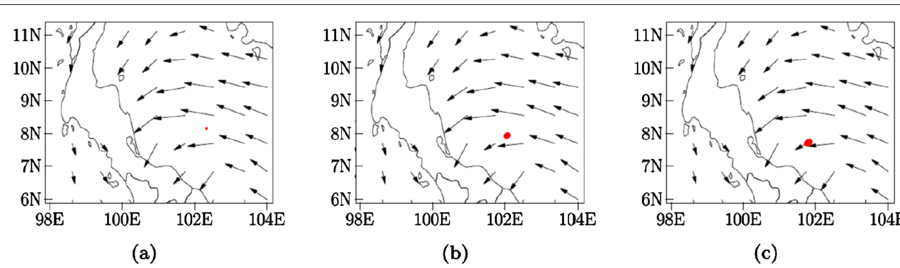

Figure 3 Movement of oil at Bongkot 23. The movement of oil slick (red dots in elliptical shape) at South Bongkot 23 oil drilling rig. (**a**) at the beginning of incident, (**b**) 30 minutes later, and (**c**) 60 minutes later.

of South Bongkot 5 oil drilling rig. It moved about 39.48 kilometers to the second grid (7.1556°N, 102.3150°E) according to wave speed and wind direction from WAM model within 30 minutes after the incident and 39.67 more kilometers to the third grid (6.9412°N, 102.0290°E) within 60 minutes after the incident. It would take a few hours for the oil slick to land on the eastern coast of Thailand. The lengths of major and minor axes of an elliptical shape of the oil slick show that the oil spill could cause a huge damage to more than 10 kilometers of coastline. The results in Table 2 and Table 3 can be described in the same manner as those in Table 1.

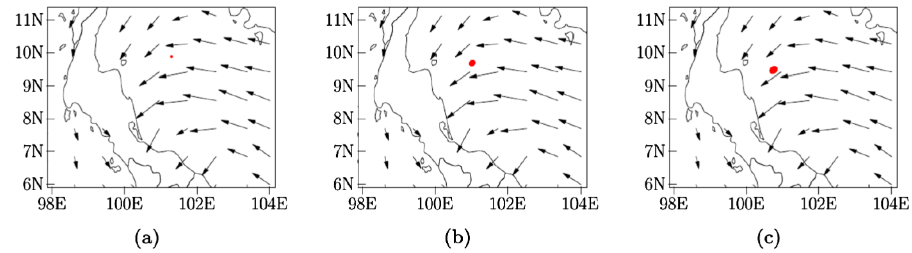

Figure 4 Movement of oil at Platong. The movement of oil slick (red dots in elliptical shape) at Platong oil drilling rig. (**a**) at the beginning of incident, (**b**) 30 minutes later, and (**c**) 60 minutes later.

Table 1 The size in ellipse and position of oil slick starting at South Bongkot 5 oil drilling rig at different times.

Time	Center	Distance (km)	Major axis (km)	Minor axis (km)
Beginning of incident	(7.3678°N, 102.6004°E)	–	–	–
30 minutes later	(7.1556°N, 102.3150°E)	39.48	10.80	8.97
60 minutes later	(6.9412°N, 102.0290°E)	39.67	13.76	10.67

Table 2 The size in ellipse and position of oil slick starting at South Bongkot 23 oil drilling rig at different times.

Time	Center	Distance (km)	Major axis (km)	Minor axis (km)
Beginning of incident	(8.0162°N, 102.5126°E)	–	–	–
30 minutes later	(7.8003°N, 102.2261°E)	39.82	10.76	8.97
60 minutes later	(7.5924°N, 101.9421°E)	39.08	13.66	10.67

Table 3 The size in ellipse and position of oil slick starting at Platong oil drilling rig at different times.

Time	Center	Distance (km)	Major axis (km)	Minor axis (km)
Beginning of incident	(9.6898°N, 101.4068°E)	–	–	–
30 minutes later	(9.4923°N, 101.1174°E)	38.89	10.78	8.97
60 minutes later	(9.2914°N, 100.8252°E)	39.36	13.76	10.67

4 Discussion and conclusion

In this paper, we use the prediction of wave speed and wind direction from WAM model based on the wave spectral balance equation to simulate the size and position of oil slick in the Gulf of Thailand. The spreading of oil is determined using Fay's hypothesis and Lehr's formula. It is assumed that wave speed and wind direction do not vary with time and the volume of crude oil is preserved, so that there is no loss of oil spill amount when spreading. The numerical results show that oil slicks tend to move towards the eastern coast of Thailand. Furthermore, the area of an oil spreading can be roughly approximated by the shape of an ellipse.

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Competing interests
The authors declare that they have no competing interests.

Authors' contributions

SS simulated, analyzed simulation results, and wrote the research paper. KC designed the research work, analyzed and interpreted simulation results, and wrote the research paper. WK analyzed, interpreted simulation results, and revised the research paper. All authors read and approved the final manuscript.

Author details

[1]Department of Mathematics, Faculty of Science, Mahidol University, Bangkok, Thailand. [2]Centre of Excellence in Mathematics, CHE, Bangkok, Thailand. [3]Marine Meteorological Center, Thai Meteorological Department, Bangkok, Thailand.

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