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Development of a statistical oil spill model for risk assessment☆

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ABSTRACT

To gain a better understanding of the impacts from potential risk sources, we developed an oil spill model using probabilistic method, which simulates numerous oil spill trajectories under varying environmental conditions. The statistical results were quantified from hypothetical oil spills under multiple scenarios, including area affected probability, mean oil slick thickness, and duration of water surface exposed to floating oil. The three sub-indices together with marine area vulnerability are merged to compute the composite index, characterizing the spatial distribution of risk degree. Integral of the index can be used to identify the overall risk from an emission source. The developed model has been successfully applied in comparison to and selection of an appropriate oil port construction location adjacent to a marine protected area for *Phoca largha* in China. The results highlight the importance of selection of candidates before project construction, since that risk estimation from two adjacent potential sources may turn out to be significantly different regarding hydrodynamic conditions and eco-environmental sensitivity.

1. Introduction

Oil spills have been of major concern and are regarded as one of the most critical forms of marine pollution, causing serious impacts to wildlife and their habitats. It is estimated that approximately 5.72 million tons of oil have been discharged into the ocean as a result of tanker incidents from 1970 to 2015 (ITOPF, 2016). With rapid economic growth, massive oil demand motivates oil port constructions along the China coastline, which brings high oil spill risks to the surrounding coastal seas. It is encouraging to observe downwards trends in total oil spill accidents, but the occurrence of a relatively small number of comparatively large spills can still cause severe environmental damage. The Dalian New Port accident in 2010 and the Penglai 19-3 oilfield leakage event in 2011 are significant events in terms of both local damage to the environment and financial loss (Xu et al., 2012; Zhu et al., 2014). The need for improving oil spill assessment and contingency plan has promoted the development of numerical oil spill models during the past three decades (ASCE, 1996; Reed et al., 1999; Spaulding, 2017). Most published oil spill modelling research has been concentrated on the influence under specified conditions, neglecting the uncertainty of conditions when actual discharge occurs (Azevedo et al., 2014; Cucco et al., 2012). Even for a fixed pollution source, if emissions occur at different moments, their consequences and scope of damage may vary drastically. Hence, the oil spill prediction for the newly built oil port, where no leakage accident has occurred, should be statistically handled.

Despite late emergence and low concern, research on statistical oil spill model has made a remarkable progress. Lo (1991) developed a statistical model that could generate an oil influence probability map considering the oil-slick movement. McCay et al. (2004) estimated the potential impacts and natural resource damages of oil spills running probabilistic model numerous times. Guillen et al. (2004) combined geographic information system (GIS) and multivariate statistical methods in the post-processing of trajectory output for identifying risk to an area from a group of spill sources. An ensemble map of thousands of simulated oil spill trajectories over many years of wind and ocean current input data was generated for the Gulf of Mexico (Price et al., 2004), producing estimate of the probabilities of oil spill influence. Kankara and Subramanian (2007) carried out sensitivity analysis of probable oil spill trajectory and fate analysis from an integrated numerical simulation model generated in order to set the priority conservation objectives in the oil spill event. The reliability of a statistical oil spill model has been validated by means of actual oil slick observations and trajectories of drifting buoys during the Prestige accident (Abascal et al., 2010). Díaz et al. (2008) and Guo et al. (2016a) managed to run a

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probabilistic particle model in multiple scenarios for determining damage result of a real oil spill pollution event. The risk around marine protected area (MPA) was investigated by oil trajectories, which tracked Lagrangian tracers backwards from the receptor points to multiple sources (Ciappa and Costabile, 2014). Oil spill hazard maps were presented by integrating ship traffic data, oil spill model and atmosphere-ocean forecasting system (Liubartseva et al., 2015). Valdor et al. (2015) developed an environmental risk analysis method in port areas on the basis of a manageable number of hypothetical scenarios. Alves et al. (2015, 2016) presented numerical models, linked with bathymetric, oceanographic and meteorological data, to simulate a series of virtual oil spill scenarios in the Eastern Mediterranean Sea for assessing surrounding susceptibility to spilled oil.

Although these statistical oil spill models provided a series of mappings of space variables, including space affected probability, concentration, temporal duration etc., these quantities are used to estimate environmental risk individually. For further impact analysis, these dimensions, potentially relevant to assessing the oil spill risks, should be integrated synthetically. A dilemma in selecting an appropriate oil port location drives us to develop a method of comprehensively evaluating oil spill risk. In this study, we attempt to synthesize these dimensions as a joint function, which can be employed to judge risk with respect to all of them. To maintain objectivity in the assessment, a quantitative analysis should be incorporated which was absent in existing models. When selecting proper sites for oil port, we unify the statistical variables together with regional vulnerability into one index for ease of comparison.

The remainder of this paper is organized as follows: the descriptions of engineering background and model structure are given in Section 2, Section 3 presents modelling results for a concrete scheme comparison, and Section 4 summarizes the main conclusions of this study.

2. Methods and material

2.1. Study area

To supply crude materials to oil refineries, the local government decided to construct a new oil port along the Changxing Island coastline for docking vessels of 300,000 deadweight tonnage (DWT) supertankers. Changxing Island is located in northeastern Bohai Sea of China, where the half-life of water exchange time is over 2 years (Guo et al., 2016b). Changxing Island is located at the mouth of Liaodong Bay, a shallow mesotidal bay of Bohai Sea, with tidal elevation range about 1.9 m and 0.9 m at mean spring and neap tides, respectively. The hydrodynamic pattern is mainly dominated by tides and winds, which generate currents up to 1.6 m/s in the open seas. With the proximity to the coast, the intensity of tidal currents decreases from the north to west side of the island. Surf zone circulations existing at small scales, are primarily driven by northeast wind waves and southwest west swell and strongly impact pollutant dispersion processes. Due to the shallow depth and wave mixing, the stratification is quite weak, especially in winter or windy day. The study area is under the control of the eastern Asia moon; mean wind directions from northeast to north-northeast prevail in winter, whereas favoured wind direction is from west-southwest in summer. The annual mean wind speed is 6.4 m/s, while the frequency of speed over 10 m/s reaches 26.2%. The local strong wind direction appears from north-north-east, along which the mean value reaches 11.1 m/s.

In close proximity to this island is a national MPA that was designated by the Chinese government for *Phoca largha*, one of the endangered marine mammals in the Bohai Sea. *Phoca largha* is the only existing pinniped mammal that can reproduce in the China seas. It is at the top of the food chain and is directly bound up with surrounding marine environment. The MPA covers an area up to 6700 km^2. For its vast scale and convenient management, the MPA is divided into five subzones, whose boundaries are tagged with different colours in Fig. 1b. These sub-zones are further classified into three classes according to the extent of multiple uses: core zone, buffer zone and experiment zone representing the vulnerability of the area from high level to low. The two core zones (red boundaries in Fig. 2b) are established for there are the *Phoca largha*'s main habitats. They are regarded as sanctuaries for high conservation values, where disturbing uses are prohibited. The buffer zone (blue boundaries in Fig. 2b) surrounds the core zones and is designed to safeguard the area from encroachment, where several selective scientific research and observation activities with few ecological impacts can be permitted. Tourism in MPA may be compatible with conservation in other less ecologically sensitive area if properly managed. Two experiment zones (orange boundaries in Fig. 2b) are mapped between core zone and coasts, where more liberal, but still controlled, scientific activities, tourism and artificial domestication of rare birds and animals can be operated.

No preventive measures can absolutely eliminate oil spill accident occurrence. The oil port construction will inevitably bring high-risk to the surrounding marine environment, so it is essential to choose a suitable site with the minimum influence of leakage accidents. The harbor designers offered two alternative locations suitable for constructing future crude oil dock from the perspective of engineering feasibility (Fig. 1b). The final decision should be guided by the environmental advice. Purely from an environment perspective, both available sites have their advantages or disadvantages. The intensity of flow at Location A is weak, which may contribute to oil clean-up actions. However, it is located approximately 1000 m from the core zone of MPA. Once spill happens, the leakage can quickly damage the high sensitivity area, and the effects on *Phoca largha* may be catastrophic. Location B is a relatively distant location away from the core zone. On the other hand, there are strong currents which tend to transport spilled oil to offshore regions, resulting in more pollution scope and treating difficulties.

2.2. Computational frame of numerical model

The statistical risk assessment model used in this work was developed based on the combination of a wave-current coupled model, a deterministic oil spill model and a probabilistic methodology. The model flow chart is shown in Fig. 2.

A Monte Carlo simulation approach is adopted for each potential spill location. For a typical trial, the model predicts the risk map of a certain location during oil spill accidents adopting seven steps:

1. Confirming the oil properties of leaking oil (density, viscosity, surface tension, volatility, solubility, etc.) and the spill size;
2. Selecting the initial moment when the spill happens, assuming spill accidents occur independently and uniformly in time;
3. Providing accurate information of temporal environmental conditions (temperature, currents, waves, and winds);
4. Simulating the processes of oil-slick transport and fate, recording relevant information (each grid cell will be polluted or not throughout the spill scenario, the duration of each cell exposed to slicks, the maximum of slick thickness on each cell during every scenario, etc.);
5. Repeated running abundant times of independent oil-spill events to obtain steady probability distribution;
6. Statistical analysis of data from every hypothetical spill event;
7. Development of a final index by combining these dimensions with environmental sensitivity.