Ocean Engineering 130 (2017) 385–397

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Hydraulic modelling of oil spill through submerged orifices in damaged ship hulls

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ARTICLE INFO

Keywords:
Oil spill
Ship accident
Stratified flow
Hydraulic model
Discharge coefficient
Genetic Algorithm

ABSTRACT

Hydraulic models for one- and two-layer flows are combined in different oil spill scenarios for tanker accidents. Four oil spill model versions are used to determine oil-leak quantities in six test cases. Five test cases are verified by comparison to the laboratory results of Tavakoli et al. (2011). One test case is presented as a demonstration of the modelling approach developed here. In the hydraulic modelling, it was found that a descending oil surface in the leaking tank yields a unidirectional flow, while an ascending oil-water interface shows a bidirectional flow. Oil spill volumes and durations confirm that oil outflow depends strongly on flow separation and mixing at the submerged orifices. As a corollary of this work, discharge coefficients are determined from the experimental verification of the hydraulic models. An optimisation algorithm was employed to determine the head losses of a stratified flow through the double-hull tank hole.

1. Introduction

Ship collisions and groundings are major accident types in maritime transportation (EMSA, 2010, 2014). Depending on the ship type and extent of damage, such accidents can result in human causalities, adverse environmental effects and/or financial loss. Oil slick in offshore regions, such as the Gulf of Mexico, the Strait of Sicily, the Baltic and the Mediterranean Sea, can reveal complicated dynamics. Due to the distances to the shore where civil protection teams and clean-up equipment are located, oil spills are difficult to manage (Cucco et al., 2012; Soomere et al., 2014; Melaku et al., 2015). According to Alves et al. (2015), oil slick movement in the Eastern Mediterranean Sea is strongly affected by bathymetric, meteorological, oceanographic, and geomorphological conditions. Accidents involving oil tankers can result in adverse environmental effects if structural damage to the ship hull occurs at such a location that compartments containing oil are breached, leading to significant spills (Soomere et al., 2010, 2014; Alves et al., 2014, 2015, 2016; NEREIDs Project). Thus, to assess potential environmental risks, it is essential to understand possible consequences of accidental breaches in tanker hulls. Furthermore, in addition to the typical trajectories of oil slick movement it is necessary to be able to predict the amount of potential oil spilt for different hull configurations and breach points. The oil spill model presented here is a part of the accidental damage and spill assessment model (ADSAM), which was devised to estimate rapid oil spill scenarios for hull collisions and grounding damage. The ADSAM model predicts structural damage and evaluates the spill volume and duration in situations where only limited data are available for ships involved in maritime accidents. In this regard, the ADSAM model is well suited for a risk analysis approach whereby large numbers of scenarios can be analysed using limited available data. An integrated model of this kind is proposed in Tabri et al. (2015).

When modelling oil-outflow dynamics from a leaking tank, it is essential to use tools that are capable of modelling flow to density variations, hydrostatic driving pressure, viscosity and mixing and hull-damage characteristics (e.g., orifice location, size and shape). Oil emulsification plays a significant role in modelling oil slick trajectory (Alves et al., 2015), as emulsion with 80% water content may end up with a volume that is five-times the spilled volume of parent oil (Xie et al., 2007). In the formation of emulsions resulting from the physical mixing promoted by turbulence at the sea surface, the density and viscosity of a liquid is constantly changing. Nevertheless, such investigations of oil outflows from leaking tanks (e.g., Simecek-Betty et al., 2005; Tavakoli et al., 2011) are scarce. Published models are limited to calculating the final outflow (i.e., oil spill) volume, with little or no consideration of variations in the outflow dynamics with time. An engineering modelling tool based on the internal-flow hydraulic formulae (Sergejeva et al., 2013) can be applied to determine integrated parameters in oil spill scenarios. However, a Computational Fluid Dynamics (CFD) tool for rapid assessment of oil spill accidents

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http://dx.doi.org/10.1016/j.oceaneng.2016.11.032
Received 18 December 2015; Received in revised form 20 November 2016; Accepted 21 November 2016

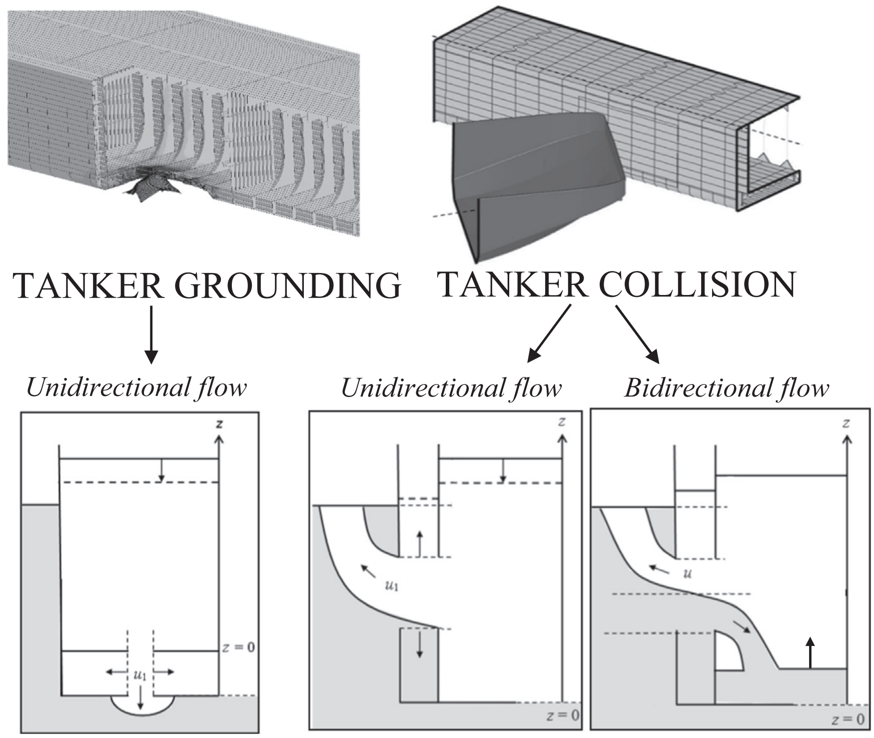

Fig. 1. Oil spill scenarios of grounding and collision for a double-hull tanker.

can be computationally demanding (Tavakoli et al., 2012). Thus, the use of stratified-flow hydraulic models is justified for the fast prediction of multiphase flow quantities. CFD analysis can be useful in validating more complicated spill cases where decision-based models are uncertain (e.g., due to the dynamics of a multiphase flow process).

Oil spills encompass the flow of two immiscible liquids in a complex geometric system that involves a wide range of length scales. Hydraulic formulae relevant for a stratified *unidirectional* flow through a hole can be readily obtained by considering the density difference between the liquids and excess hydrostatic pressure as the main driving forces. However, a realistic oil outflow rate can also be estimated by using the coefficient of discharge. Without excess hydrostatic pressure, a *bidirectional* flow occurs, whereby oil flows out from a leaking tank and seawater flows in the opposite direction (Fig. 1). Two-layer flow dynamics are predominantly solved numerically because no analytical solutions for non-rectangular holes are readily available for particular applications. However, hydraulic models can be adapted to the changing hydrostatic pressure and they provide satisfactory results in quasi-stationary conditions (Cuthbertson et al., 2006).

In the present study, a novel analytical solution for an exchange flow through a circular hole (orifice) is introduced. We emphasise that the oil-water exchange flow rate at the hole depends on the flow separation at the edges of the hole and the dynamical interaction of superimposed layers (e.g., mixing). The following hypotheses are proposed for the modelling of oil spills:

- discharge formulae allow the determination of oil outflow volumes;
- continuity formulae allow the determination of oil outflow durations;
- *unidirectional* oil outflow can be characterised by a quasi-stationary condition;
- *bidirectional* flow with oil outflow can be characterised by a stationary condition;
- a transitional stage between a *unidirectional* and a *bidirectional* flow is absent without a tank lift;
- discharge coefficients can be determined from available experimental data;
- the Genetic Algorithm predicts density and viscosity variations for a *bidirectional* flow associated with an oil outflow.

Results obtained from the physical modelling of oil outflows from the single- and double-hull test tank allow for the validation of the hydraulic models in terms of their geometric, kinematic and dynamic similarity with ship accidents (Tavakoli et al., 2011). In particular, the experimental conditions of different Tavakoli's lab tests can be used to build different versions of oil spill models. Changes in the oil surface (i.e., air-oil interface) and oil-water interface level in a leaking tank, with a fixed water level outside the tank, can be directly used to validate the results of the proposed hydraulic models. The dynamical interaction between immiscible liquids can result in changes of outflowing liquid density and viscosity. The aim of this study is to use hydraulic models to help interpret the complicated nature of oil-outflow dynamics from a tank. However, in different accident scenarios the fluids will still behave in a similar way. It should be mentioned here that the proposed internal-flow hydraulic models can be further used to determine the mixed-layer depth (associated with the emulsification of an outflowing liquid) and can be implemented to complement the oil spill mitigation procedures compiled for NEREIDs (Alves et al., 2015).

This paper is organised as follows. First, the hydraulic framework based on the quasi-steady flow equations for one- and two-layer hydraulic modelling is introduced together with the internal hydraulic formulae for *unidirectional* and *bidirectional* flows through orifices. Four oil spill models corresponding to oil outflow through the side or bottom orifice of single- or double-hull tankers are presented for two scenarios: grounding and collision. Next, modified and novel analytical formulae are used to determine the discharge coefficients, according to the experiments by Tavakoli et al. (2011). An optimisation algorithm is employed to determine the internal-flow head losses from the flows