A NUMERICAL INVESTIGATION OF MULTIPHASE FLOW AND OIL SPILL IN ISTANBUL STRAIT

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Abstract: Istanbul Strait is a globally important inland sea region connecting two continents. It is the most crowded and dangerous strait succeeding Strait of Malacca. Istanbul Strait's traffic density is 3 times of Suez Canal, 4 times of Panama Canal because of international sea traffic and this density is increasing every day, so it is becoming more dangerous. To decrease this danger, the flow in the strait must be investigated in a realistic way by using present opportunities.
In this study, a part of Istanbul Strait is modeled by a commercial CFD code and investigated numerically. The multiphase flow in the strait is analyzed and also oil spill is simulated for the same model. During the analyses, the currents in the strait and the sheer force caused by the wind are taken into account.

Keywords: Istanbul Strait, multiphase flow, oil spill, CFD.

Introduction

Istanbul Strait is 31 km long and approximately 50000 ships are passing through the strait every year. And average depth of the strait is 35, 8 meters. Winds coming from Black Sea and Mediterranean Sea are effective on the strait. The transition of the strait is difficult due to the waves and strong currents forced by these winds (Can, 1988).

The lack of vaporization in the Black Sea causes a level difference between the Black Sea and the Marmara Sea. This difference causes a pressure difference, so in Istanbul Strait, there is an up current from Black Sea to Marmara and there is a down current from Marmara to Black Sea. The reason of the down current is that the densities of the fluids are different (Baydar, 1994). The salinity of the up current is ‰ 18 and down current is ‰ 21.

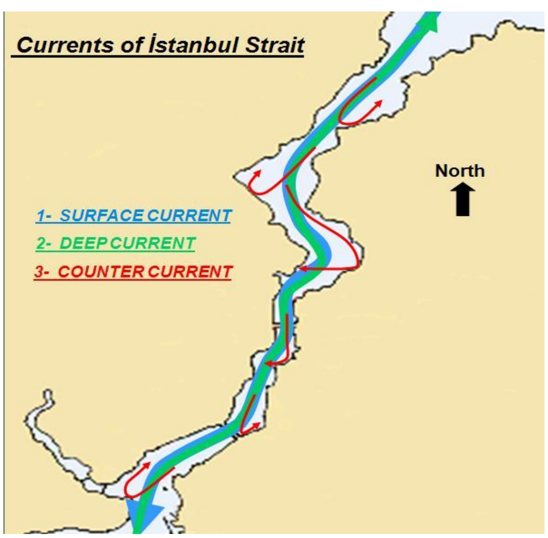


Figure 1. Currents in Istanbul Strait.

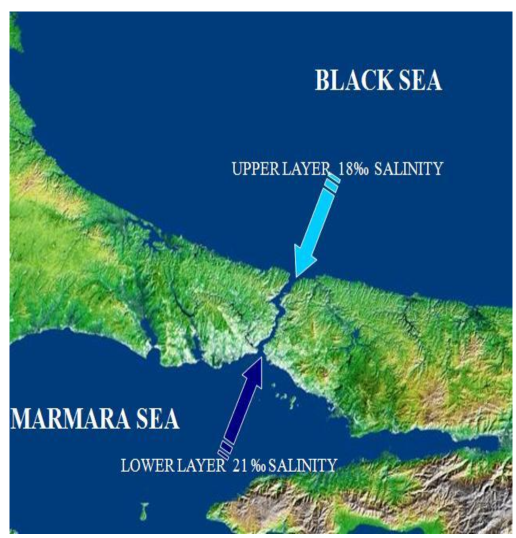


Figure 2. Salinity of Istanbul Strait.

The traffic in the strait is increasing so the amount of oil transportation is also increasing. In oil transportation Istanbul Strait is important because it is the only opening gate for the countries which have sea borders to Black Sea. For this reason the risk of pollution in Istanbul Strait is becoming more important. Oil is the most important

factor in sea pollution. Main reasons of sea pollution caused by oil are: tanker accidents, oil production in the sea, oil refineries, discharging of ballast water into the sea (Güven et al., 1998).

In fact, many accidents occurred in recent years in Istanbul Strait. And especially tanker accident had important effects on the strait.

Table 1. Statistical data of ships passing Istanbul Strait (2009) (www.turkishpilots.org).

MONTHS	TOTAL	TOTAL GT	TRANSIT	TANKER		
				TTA	LPG-LNG	TCH
JANUARY	3949	36,435,114	2149	482	75	156
FEBRUARY	4029	36,594,659	2239	478	63	178
MARCH	4904	42,905,410	2636	582	75	190
APRIL	4890	43,233,610	2671	556	65	157
MAY	5014	44,366,542	2726	573	72	171
JUNE	4909	42,625,497	2761	576	59	187
JULY	5064	46,119,645	2975	588	66	186
AUGUST	4988	46,415,009	3140	549	55	164
SEPTEMBER	4570	43,710,510	2812	508	55	138
OCTOBER	4479	47,154,955	2798	575	61	140
NOVEMBER	3816	41,245,600	2367	518	62	157
DECEMBER	3784	42,829,063	2488	579	56	151
TOTAL	54396	513,635,614	31762	6564	764	1975

Table 2. Statistical data of ship accidents in Istanbul Strait, (Örs and Yılmaz, 2003).

YEARS	TOTAL	TANKER	CRASH	FIRE	LANDING	TOTAL
1996	49952	4248	2	0	5	7
1997	50942	4303	2	0	9	11
1998	49304	5142	3	0	8	11
1999	47906	4452	4	3	6	13
2000	48079	4937	5	0	4	9
2001	42637	5188	15	0	5	20
2009	54396	9303	39	11	27	77

Studies have been made for oil spill simulation around the world for years. Some researchers use their own CFD codes and methods instead of commercial ones. Reed et al. (1999) has given brief information about many models used in studies between 1990 - 1999. One of them is the dispersion model based on the experimental work of Delvigne and Sweeney which has now become a standard. This method estimates the entrained oil mass per unit area as well as unit time, and is used by plentiful researchers.

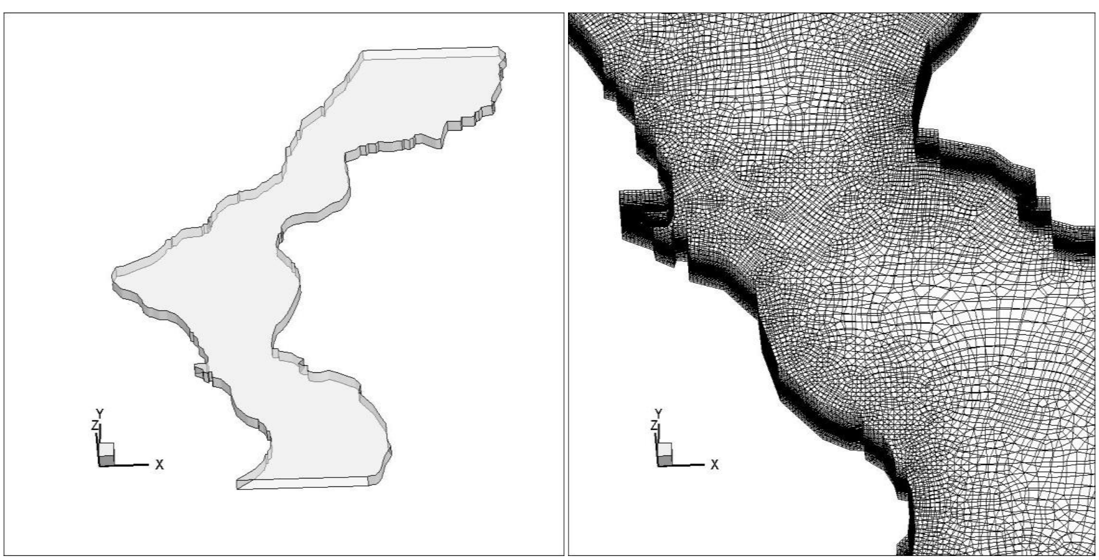
Nakata et al. (1997) presented the equations for a two-layer, two dimensional system for a Nakhodka tanker oil spill by using the model developed by Yapa et al. (1994). Sugioka et al. (1999) investigated the tanker accident "Diamond Grace" with "Lagrangian discrete panel" method. Skognes and Johansen (2004) simulated oil spill given from a point with the help of StatMap model which is including wing data of the region. Elliott and Jones (2000) simulated the oil spill in Liverpool Bay with "particle tracking" model in three dimensions. Hansen and Ditlevsen (2003) solved oil spill problem occurred after tanker accidents with the program GRACAT (Grounding and Collision Analysis Toolbox). The GRACAT program is an integrated software package developed at the Technical University of Denmark from 1998 to 2001. Wang et al. (2005) used particle method for two dimensional oil spill problem. Sebastiao and Soares (2007) tried to calculate the instabilities in oil spill prediction.

There are also some studies for oil spill simulation in Istanbul Strait. Örs and Yılmaz (2003) developed a numerical model for oil spill problem in the strait. This model solves shallow water equations in accordance with finite element method. Can (2007) also simulated oil spill for the strait and determined critical regions. Ertürk and Yonsel (2002) analyzed oil spill problem with Dirichlet boundary conditions by using ADAM model. Beji et al. (2008) investigated the two phase flow in Istanbul Strait numerically. The two phase flow was examined by Can (1988). An oil spill with multiphase flow and exhaust simulation are made by Dogrul (2010).

In literature, generally simulations are made in two-dimensional. Present study differs from previous studies by analyzing a local part of Istanbul Strait (Rumeli Kavağı – Beykoz) for oil spill with two-phase flow in 3-dimendional. Firstly the multiphase flow is analyzed and the interaction between the currents is observed. After that an oil spill is simulated with multiphase flow in the strait. In these analyses, wind effects and currents on the sea surface are taken into account.

Mathematical Model

3-D working domain (Fig .3b) was meshed by GAMBIT, the preprocessor of FLUENT. This domain represents a local part of the strait, Rumeli Kavağı - Beykoz, as seen in Fig. 4. Mostly dangerous part of the strait is around Rumeli Kavağı - Beykoz region.



(a) (b)

Figure 3. 3-D geometry (a), mesh structure applied to the model (b).

As can be seen from Fig. 3, unstructured mesh elements have been generated for the simulations. Because of multiphase flow in the strait, a fine mesh structure is used near the plane between two phases. Mesh element number is about 1.3 million.

Both sides of the strait are specified as wall type and bottom surface of the whole domain is considered as wall, too. Uniform velocity, turbulent kinetic energy (k) and turbulent dissipation rate (ε) are given at the inlet surfaces, while pressure outlet is specified at the outlet surfaces. The solver considered here uses finite volume method as discretization scheme. The flow is unsteady, incompressible, and three-dimensional. With the help of unsteady simulations, interaction between two phases is observed and later oil spill is simulated.

For the mathematical model the time-averaged, three-dimensional, unsteady-state mean flow equations of continuity and momentum can be written in Cartesian tensor notation as;

$$\frac{\partial \rho}{\partial t} + div\left(\rho.\vec{V}\right) = 0 \qquad (1)$$

$$\rho \frac{DU_i}{Dt} = -\delta_{ij}\frac{\partial P}{\partial x_j} + \mu \frac{\partial^2 U_i}{\partial {x_j}^2} \qquad (2)$$

As turbulence closure, standard k-ε (SKE) turbulence model with standard wall-function is used. The SKE turbulence model is one of several two-equation models that have developed over the years. It is probably the most widely and thoroughly tested of them all. As it is well known that SKE is a semi-empirical model based on model transport equations for the turbulence kinetic energy, k (Eq.3) and its dissipation, ε, (Eq. 4)

$$\frac{\partial \rho k}{\partial t} + \frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\Pr_k}\right)\frac{\partial k}{\partial x_i}\right] + \mu_T G - \rho\varepsilon + S_{k,p} \qquad (3)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_T}{\Pr_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + \frac{\varepsilon}{k}\left(C_1\mu_T G - C_2\rho\varepsilon\right) + S_{\varepsilon,p} \qquad (4)$$

where C1 and C2 are additional dimensionless model constants; Prk and Pre are the turbulent Prandtl numbers for kinetic energy and dissipation, respectively; Sk,p and Se,p are source terms for the kinetic energy and turbulent dissipation; and the turbulent production rate (G) is defined in Eq. 5:

$$G = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} - \frac{1}{\rho^2}\frac{\partial \rho}{\partial x_j}\frac{\partial \rho}{\partial x_J} - \frac{2}{3}\left(\frac{\rho k}{\mu_T} + \frac{\partial u_i}{\partial x_J}\right)\frac{\partial u_J}{\partial x_j} \qquad (5)$$

In FLUENT 6.2, the governing equations are discretized using a first-order upwind interpolation scheme, and the discretized equations are solved using PISO algorithm. As the multiphase model, "mixture" is chosen. Typical relaxation factors used here is 0.3, 0.7, 0.8, 0.8 and 0.2 for pressure, momentum, turbulence kinetic energy, turbulence dissipation rate and volume fraction. The related equations are solved for flow, turbulence and volume fraction. The solution is seen converged when the continuity residual is lower than 10-7 and residuals of other variables are lower than 10-6.

As the boundary conditions; mostly same conditions are applied to both models; multiphase model and oil spill model. Boundary conditions are given in Table 3 and 4.

Table 3. Boundary conditions applied to multiphase model.

Up current	Black Sea inlet	Velocity Inlet
	Marmara inlet	Pressure Outlet
Down current	Black Sea inlet	Pressure Outlet
	Marmara inlet	Velocity Inlet
	Side walls	No Slip Wall
	Bottom	No Slip Wall
	Surface	Slip Wall

Table 4. Boundary conditions applied to oil spill model.

Up current	Black Sea inlet	Velocity Inlet
	Marmara inlet	Pressure Outlet
Down current	Black Sea inlet	Pressure Outlet
	Marmara inlet	Velocity Inlet
	Side walls	No Slip Wall
	Bottom	No Slip Wall
	Surface	Slip Wall
	Oil inlet	Velocity Inlet

In all analyses, lower level depth and upper level depth is considered as 20 and 30 meters respectively. Up current velocity is 0.3 m/s and down current velocity is 1.3 m/s. Density of the up current is 1018 kg/m3 while down current density is 1021 kg/m3 as shown in Figure 2. For all simulations, the wind is considered as coming from north and its velocity is accepted as 1 m/s. So the surface shear force caused by the wind is calculated as 0.0006925 Pa (Eq. 6) and applied to the sea surface.

$$\tau_w = 1.25 c_d W^2 \quad (6)$$

The density of the oil used in the analysis is 960 kg/m3. It is considered that totally 50000 m3 oil is spilled to the sea during the analysis. Oil inlet velocity is 0.01 m/s. So the oil is spilled for 1600 seconds, then the dispersion of the oil is observed for some time.

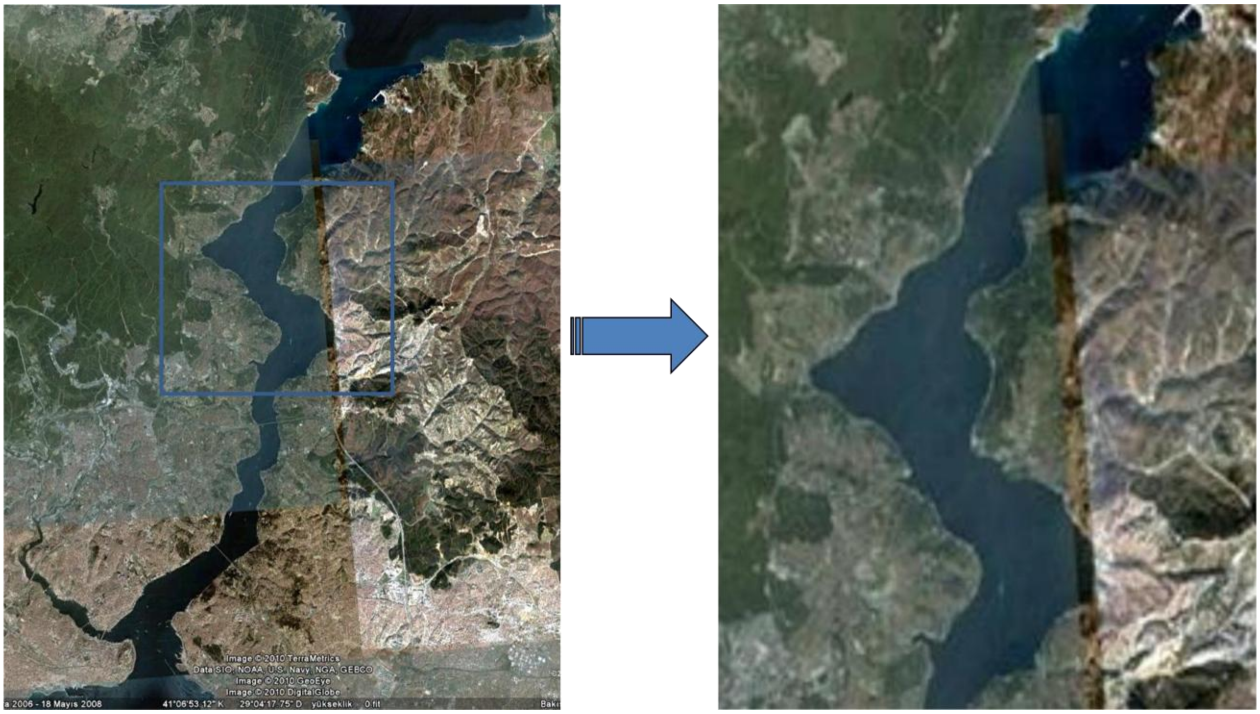


Figure 4. Investigated part of the strait.

Results

As mentioned above, the main goal of this study is to simulate multiphase flow and oil spill in Istanbul Strait. To achieve this goal series of computational analyses are performed on a personal computer of four dual-cores of 2.8 GHz with 6 GB RAM. After reaching the convergence criteria some results are obtained in following figures.

Figure 5 and 6 show counter currents as mentioned above.

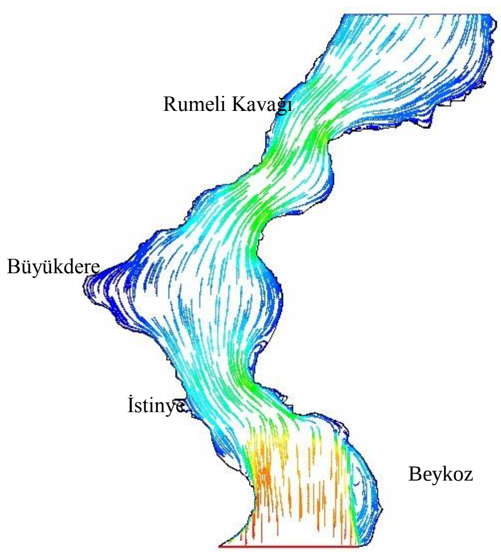


Figure 5. Counter currents on the surface.

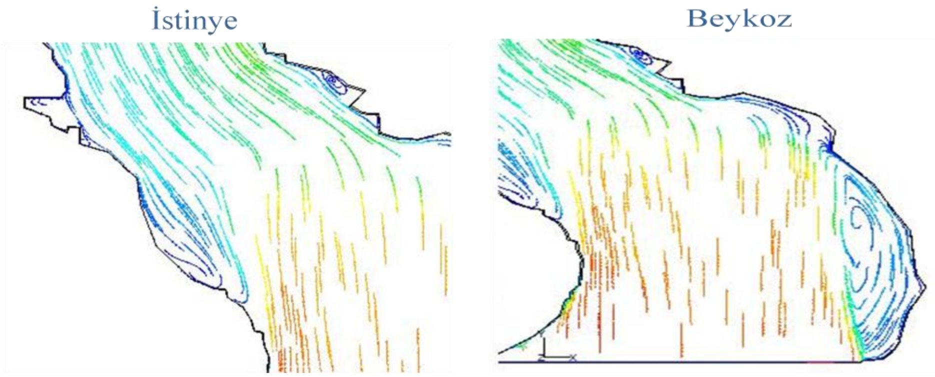


Figure 6. Counter currents in İstinye and Beykoz.

Volume fraction of oil on the surface is investigated in oil spill simulation and all analyses are made with transient calculation to obtain the behavior of spilled oil. The counter currents are seen in Figure 5 and 6.

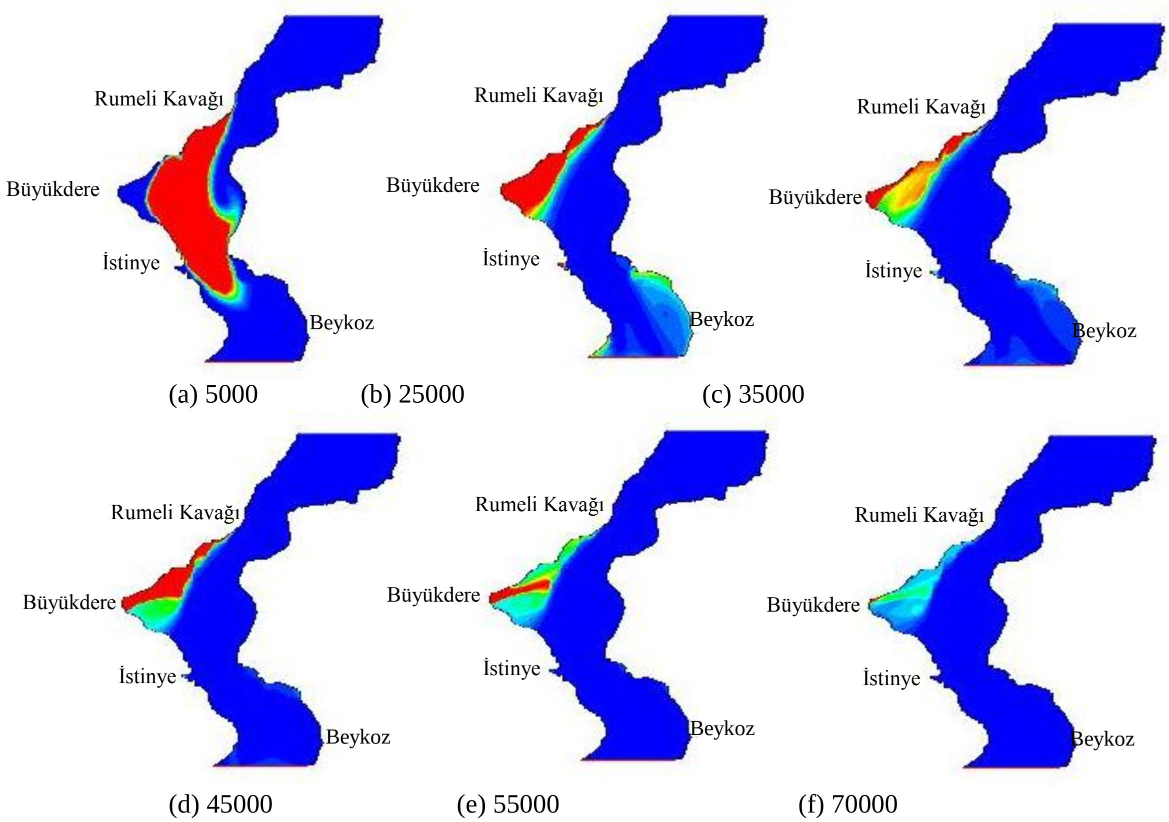


Figure 7. Behavior of spilled oil at time steps 5000, 25000, 35000, 45000, 55000, 70000 s.

In Figure 7, the results of simulation are given. In this simulation, which oil started to spill from Rumeli Kavağı, it is seen that at about 5000 s the oil started to collect in Büyükdere area. And between 5000 and 25000 s, the spilled oil flowed to the south direction due to the wind and currents.

But even in 70000 s some oil still collected in Büyükdere area. The simulation showed that in case of an accident in Rumeli Kavağı, the oil is collected in Büyükdere area.

The present study can be considered as an initial study for the preparation of the contingency plan of Istanbul Strait. similar oil spill simulations can be carried out for different areas of the strait to guess the risks in Istanbul Strait in case of sea pollution due to accident scenarios.

Conclusion

Istanbul Strait is important in oil transportation and the safety of the strait is also important. In this study, an important area of the strait is investigated for an oil spill in case on a tanker accident with two-phase flow in 3-dimensional. Unlike the previous studies, the domain is simulated in 3-dimensional and all the currents in the strait are taken into account. Also wind effects are simulated in the analyses.

According to the results, a tanker accident in Rumeli Kavağı area can be dangerous for the strait and city of Istanbul. So by using these simulations, an emergency plan should be made for the safety of Istanbul.

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