3D Numerical Modeling of Dispersion Potential of Sewage Sludge at the Proposed Submerged Site off the Coast of Son-Tra Peninsula, Danang City

Quang Truong Nguyen[1,2](✉), Tuan Duc Ho[2,3], Quang Hung Phan[1,2], Hai Yen Tran[1,2], and Thong Nguyen[4]

[1] Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam
nqtruong@hcmut.edu.vn

[2] Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam

[3] Asian Centre for Water Research (CARE), 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam

[4] Faculty of Urban Infrastructure Engineering, Mien Tay Construction University, Vinh Long City, Vietnam

Abstract. Assessment of potential risk of sludge dispersion of Tho-Quang fishing port is essential to ensure compliance with the Technical Regulations on assessment of dredges and identification of dredged sludge areas in Circular No. 28/2019/TT-BTNMT dated December 31, 2019 of the Ministry of Natural Resources and Environment. However, there are still many discussion regarding the possibility of spreading waste after submerging in the proposed area and potentially affecting the natural ecosystem of the vicinity off the coast of Son-Tra peninsula. The results of this study will contribute to the scientific theoretical basis to be able to quantitatively evaluate the spread of sewage sludge extracted from the dredging of Tho-Quang boat lock. In this study, we will apply 3D numerical modeling to simulate dredged sludge waste propagation with different discharge scenarios in terms of submergence depth, submerged sludge discharge as well as other hydro-meteorological scenarios in order to evaluate the potential risks of sewage sludge spreading to the nature reserve in the Son-Tra peninsula, Danang city. The results show that the influence of tidal current plays a very important role in the spread of sludge. Under the effect of tidal currents, submerged sludge can spread up to 10 km from the discharge center with a concentration of 5 mg/l.

Keywords: TELEMAC 3D · TOMAWAC · Hydrodynamic · Waste dispersion · Danang coast

J. N. Reddy et al. (Eds.): ICSCEA 2023, LNCE 442, pp. 1807–1814, 2024.
https://doi.org/10.1007/978-981-99-7434-4_195

1 Introduction

There is an increasing demand for identifying locations that can receive dredging sludge from river and seaports, as well as for construction areas along the coast in Vietnam. However, the ability to find suitable locations, especially in coastal areas, is very limited [4]. One proposed solution is to safely dispose of the sludge by submerging it in coastal areas that are not far from shore. However, a major problem is the phenomenon of diluted sludge spreading and potentially contaminating sensitive ecologies or affecting areas that depend on tourism [8]. Sinking sludge typically consists of very fine particles that quickly dilute in the surrounding water environment and under the influence of dynamic flow regimes, this turbid sludge can spread to neighboring areas. There are many factors affecting the spread of sludge, including two main factors: the phenomenon of convection (mainly the average tidal flow) and the phenomenon of diffusion. In this study, the spread of submerged sludge from the dredging port of Tho Quang–Da Nang is estimated by calculating the sludge spreading at a position offshore of Son Tra peninsula about 12 km from the coast (as recommended by the specialized management agency). The simulation results will allow for an evaluation of the proposed discharge location and the potential impact of diluted sludge on the ecological areas that need protection around the Son Tra peninsula. This study used the numerical modeling, in which the phenomenon is studied by simultaneously applying the theory of hydrodynamic problems with the Telemac3D model, wave problems with the Tomawac model, and advection-diffusion problems describing the spread of diluted sludge in the area. All of the modules mentioned above have been developed by EDF (Electricité de France) in collaboration with European and American laboratories, and these open-source models are widely used worldwide [1, 3].

2 Study Area and Numerical Model

2.1 Study Area

The study area includes the north of Son Tra peninsula and the south to the Dai mouth of Hoi An city. It extends along the coast for about 55 km and has an average width of 45 km from the shore. The area is about 2374 km^2, described by 40573 unstructured triangular elements with the largest mesh of 4000 m (offshore element) whereas the smallest is 50 m for the elements in Thu-Bon river (see Fig. 1). The three-dimensional mesh, consisting of prisms cut into tetrahedrons, is automatically constructed by TELEMAC-3D from the two-dimensional mesh. The classical sigma transformation is set, resulting in a homogeneous distribution of 5 levels in the vertical direction.

In regard to climate, this site belongs to the tropical climate zone, which is affected by the cold northern wind and has only two main seasons: rainy and dry. The average rainfall ranges from 2000 to 2500 mm, but it is unevenly distributed over time and space. The rainy season mainly occurs between September and December (representing about 80% of the total annual rainfall) and coincides with the tropical typhoon season.

2.2 Numerical Model

The 3D hydrodynamics field is computed with the 3D hydrodynamics code belonging to the open source TELEMAC-MASCARET system (TMS), TELEMAC-3D [2]. The

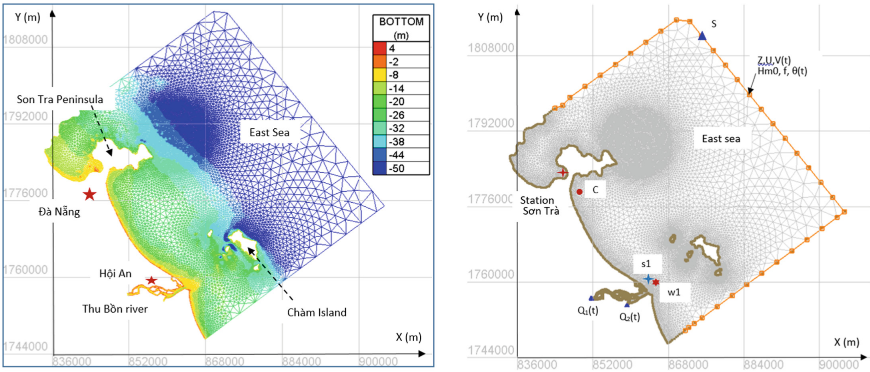


Fig. 1. Numerical mesh with bathymetry in the study area (left) and hydrodynamic boundary conditions (right)

TMS is currently developed by the R&D department of Electricité de France (EDF) and TELEMAC Consortium members. TELEMAC 3D solves the 3D Navier-Stokes equations with a finite element discretization under a non-hydrostatic approximation.

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\Delta(U) + F_x \tag{2}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\Delta(V) + F_y \tag{3}$$

$$\frac{\partial W}{\partial t} + U\frac{\partial W}{\partial x} + V\frac{\partial W}{\partial y} + W\frac{\partial W}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - g + \nu\Delta(W) + F_z \tag{4}$$

$$p = p_{atm} + \rho_0 g(Z_s - z) + \rho_0 g\int_z^{Z_f}\frac{\Delta\rho}{\rho_0}dz + p_d \tag{5}$$

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial y} + W\frac{\partial C}{\partial x} = \mathrm{Div}[\nu \mathrm{Grad}(T)] + Q \tag{6}$$

wherein: U, V, W (m/s) are three-dimensional components of velocity; T (g/l) is passive or active (acting on density) tracer; p is pressure; v (m^2/s) is velocity and tracer diffusion coefficients; Z_s (m) is free surface elevation; Z_f (m) is bottom depth; p_0 is reference density; F_x, F_y, F_z (m/s^2) are source terms; Q is tracer source of sink.

Wave propagation with TELEMAC was modelled using TOMAWAC. By means of a finite-element type method, TOMAWAC solves a simplified equation of evolution of the directional spectrum of wave action written in the following form:

$$\frac{\partial N}{\partial t} + \frac{\partial \ddot{x}N}{\partial x} + \frac{\partial \ddot{y}N}{\partial y} + \frac{\partial \dot{k}_x N}{\partial x} + \frac{\partial \dot{k}_y N}{\partial y} = Q(k_x, k_y, x, y, t) \tag{7}$$

wherein $N\left(\vec{x}, \vec{y}, \vec{k}, t\right) = N(x, y, k_x, k_y, t)$ is directional spectrum of wave action density; $\vec{k} = \left(k_x, k_y\right) = (ksinsin\theta, kcoscos\theta)$ is wave number vector for directional spectrum discretization, θ denoting the wave propagation direction and Q designating the source and sink terms.

This study involves a computational process encompassing the subsequent stages: (i) Setting up the model by generating a mesh and implementing boundary conditions; (ii) Calibrating and validating the model using monitoring data; (iii) Employing the model to investigate the dispersion problem. These calculation steps will be presented in the following sections.

3 Simulation of 3D Hydrodynamics in the Coastal Area of Da Nang

3.1 Boundary Conditions

Hydrodynamic. The study area includes 2 discharge boundaries on two major tributaries located at about 12 km towards the upstream of Cua-Dai estuary: a large branch near Cau-Lau bridge and a small branch in the upstream of Cua-Dai bridge. The stage on the open boundary in the East Sea is from the astronomical tides with the 9 main waves (S_2, N_2, K_2, M_2, K_1, O_1, P_1, Q_1 and M_4) extracted from the OTIS database with a resolution of $1/30^0$ [6].

Waves. The spatial-temporal variations of wave and wind data during the simulation period are from the NOAA's database [5]. Typical wave height in the offshore area ranges from 1.5 m to 2.5 m and gradually decreases to about 1m in the estuary area (see Fig. 2).

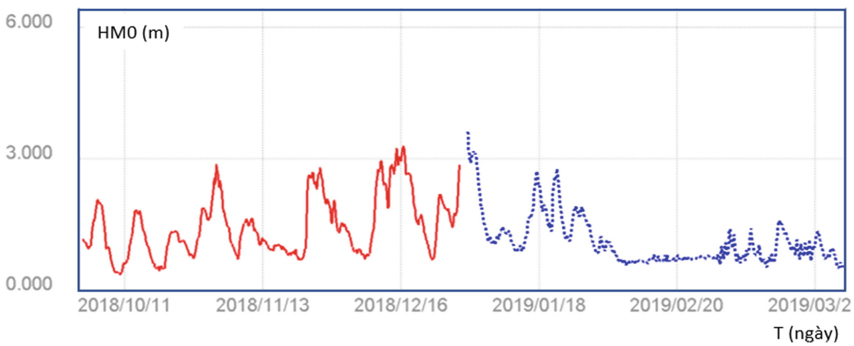


Fig. 2. Wave height evolution at boundary during the simulation period

Winds. The influence of wind (variations in space and time) on the flow is also taken into account. The following image shows the wind chart in March 2019 at the coastal area of Da Nang. The maximum wind speed of 12.7 m/s occurred during the time period affected by the Northeast monsoon.

3.2 Model Calibration and Validation

Hydrodynamic: The model is calibrated from 5/1/2019 to 12/1/2019 and then validated from 12/4/2019 to 18/4/2019 using the monitoring data at the Son Tra marine station. Figure 3 represent the comparison between the observed and simulated stages in January 2019 (model calibration) and in April 2019 (model validation). By measuring the Nash Sutcliffe (NSE) parameter at 0.91 and Root mean square error (RMSE) at 0.0005–0.06 to compare the observation with the simulation (see Table 1), one can infer that the simulation results accurately represent the monitoring value and the numerical model is reliable.

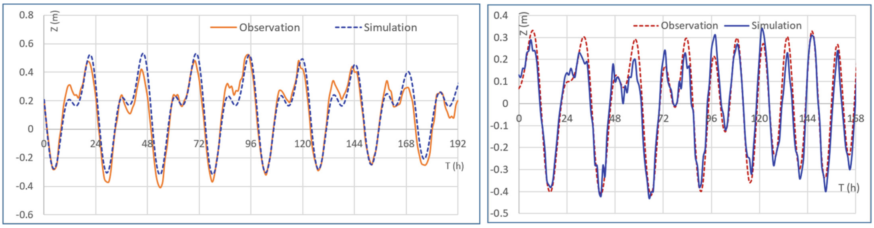


Fig. 3. Observed and simulated stages at the Son Tra station, from 5/1/2019 to 12/1/2019 (left, calibration) and from 12/4/2019 to 18/4/2019 (right, validation)

Table 1. Agreement between observation and simulation for the calibration and validation process

Calibration			Validation	
Stage (m)	Observation	Simulation	Observation	Simulation
Mean	0.106	0.11	−0.012	0.000
Max	0.520	0.533	0.340	0.331
Min	−0.410	-0.318	−0.430	−0.417
	NSE = 0.9057 RMSE = 0.0005		NSE = 0.918 RMSE = 0.059	

Wave: The model is also calibrated from 16/10/2014 to 12/11/2014 and then validated from 19/10/2016 to 25/10/2016 (see Fig. 4) using the wave monitoring data at the location s_1 and w_1 (see Fig. 1). The result from the Fig. 4 shows that, in general, the time series of the observed values is quite smooth (less fluctuated) than the simulation results. This is reasonable because in practice, the data monitoring time step is 1 h, much larger than the calculated time step in the model (10 s). The waves in November 2014 was quite larger than those in the previous month, which is in line with the natural tendency of the area.

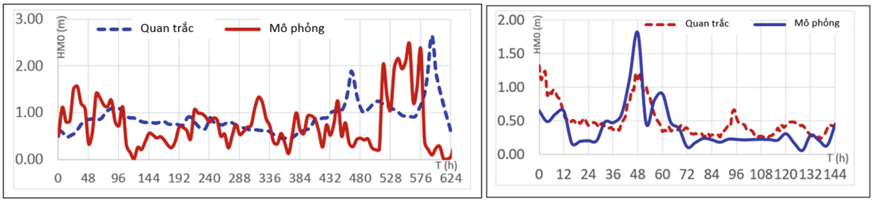
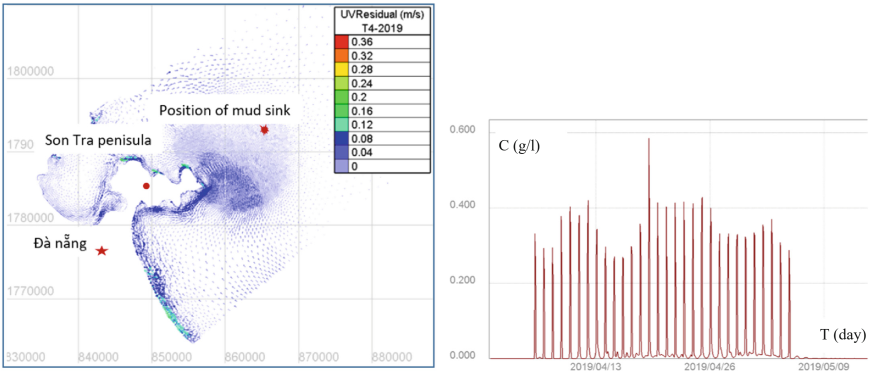


Fig. 4. Comparison between observed and simulated wave height HM_0, from 16/10/2014 to 12/11/2014 (left, calibration) and from 19/10/2016 to 25/10/2016 (right, validation)

4 Dispersion of Sewage Sludge

To assess the extent to which slude is spreading in the study area, a simulation was conducted using a hypothetical scenario involving the submergence of a mass of 100,000 m^3 of mud for three hours a day between April 5, 2019, and May 5, 2019, over a 30-day period at a location approximately 12 km from Son Tra peninsula (refer to Fig. 5a). The selected discharge intensity caused the suspended sludge concentration at the surface to fluctuate around 0.3 g/l at the submergence site, as illustrated in Fig. 5b. Notably, the concentration did not increase over time, indicating rapid sludge dilution.



(a) (b)

Fig. 5. Scenario of submerged sludge at a position of about 12 km from Son Tra peninsula in April 2019, **a** The mean tidal currents in the study area, **b** Suspended sludge concentration from April 5, 2019 to May 5, 2019

The simulation results show a very clear impact of convection and diffusion of sediment in both space and time. Under the influence of the tidal flow, the high-concentration mud will oscillate mainly in the northwest-southeast direction during the simulated period. As shown in Fig. 6, the area with a sediment concentration of 5 mg/l can spread up to 10 km away from the sinking position in the southeast direction due to convection. Overall, the results show that the suspended sludge tends to move away from the Son Tra Peninsula, which is a positive factor to consider when preventing sediment (pollution) from invading the ecologically sensitive areas around the peninsula as planned.

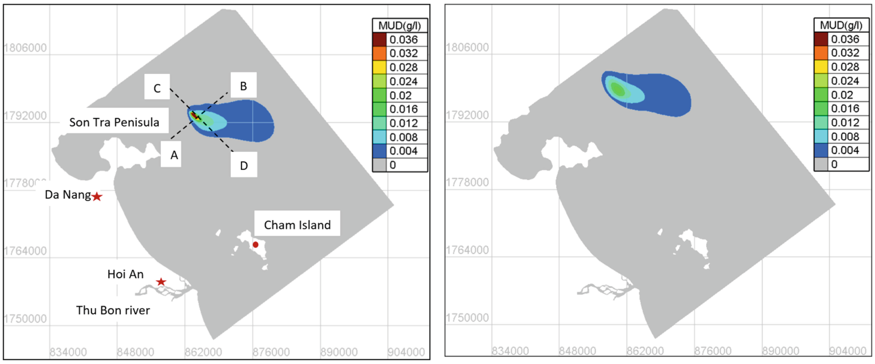


Fig. 6. Simulated suspended sludge concentration at the water surface at 9 am (left) and 8pm (right), April 26, 2019

Under the effect of diffusion phenomenon, the concentration of sediment at the sinking site will quickly dilute within a day. The Fig. 7 illustrates the distribution of sediment concentration along the vertical axis at two representative cross-sections A-B and C-D passing through the location of the sediment discharge. The shape of the high-concentration sediment distribution is generally in the form of a cone with increasing cross-sectional area in depth. The results show that the sediment concentration in depth under the effect of gravity on the sediment waste is consistent with the laws of physics [7]. The position of the plume shifts over time under the effect of the tide. The results also demonstrate changes in concentration over time under the effect of substance diffusion.

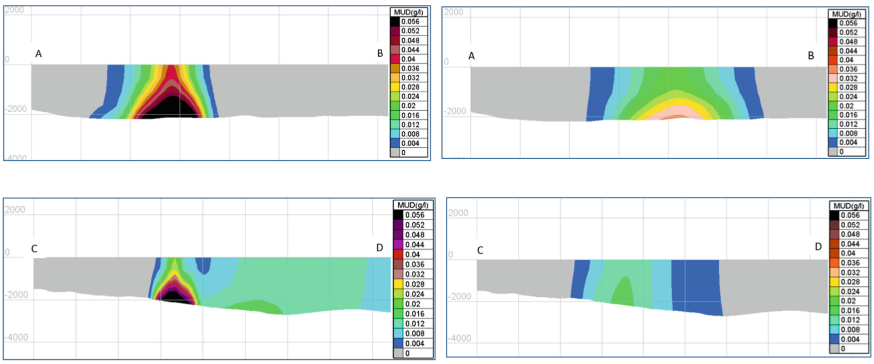


Fig. 7. Simulated sludge concentration distribution in April 25, 2019 along the A-B cross-section at 9 am (upper left) and 8 pm (upper right); and along the C-D cross-section at 9 am (bottom left) and 8 pm (bottom right).

5 Conclusion

The spread of submerged sludge concentration about 12 km from Son Tra peninsula to the sea is significantly affected by two main factors: convection and diffusion. Convection, which is caused by tidal currents, can cause sludge to spread up to 10 km to the Southeast from the discharge site horizontally, as shown during the simulation period from April 5, 2019 to May 5, 2019, with a discharge of 100,000 m^3/month. However, the concentration of sewage sludge is quickly diluted by the surrounding water under the effect of diffusion. It is important to note that the results obtained from the simulation are for reference only, and their accuracy may improve with real monitoring data collected from implemented projects. At the considered location, the concentration distribution in the vertical direction is conical, with the concentration increasing rapidly with depth. The position of the cone will shift with the tidal current, and the sludge concentration will decrease over time due to substance diffusion.

Acknowledgements. The simulations have been performed at the High Performance Computing Center (HPCC), Ho Chi Minh City University of Technology. We acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

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