SEDIMENT TRANSPORT BEHAVIOUR IN A STRAIT UNDER THE INFLUENCE OF CURRENTS

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ABSTRACT

The Madura Strait, one of the most congested shipping lanes in Indonesia has been an important shipping route since the 13th century until recent days. The problem that exists in Madura strait is excessive sediment supply from river. This condition has disrupted several infrastructure facilities in the Madura Strait as happened at the Petrokimia Gresik port that is experiencing massive sedimentation. As one of the main supporting facilities in the factory, the existence and continuity of the port is important to always be maintained. This is related to the shallowing that often occurs in turning basin area. To estimate the shallowing process due to sedimentation in the pier pool, an analysis using a numerical model approach was applied. Based on the analysis, the current velocity in the turning basin area ranged from 0.10 to 0.20 m/s. In some conditions, the current velocity tends to approach 0 m/s which indicates a sedimentation zone was formed. Further, the analysis of bottom sediment movement shows the density of sediment material around the turning basin area ranged between 0.03 and 0.06 kg/m^3. This condition leads seabed shallowing by 5.5 cm/month threatens navigability.

Keyword: sediment transport, numerical model, Madura strait, current velocity, port infrastructure

Introduction

The strait region is one of the unique and challenging locations because it has different hydrodynamic characteristics comparing to common ocean. Strait areas usually experience significant fluctuations in currents and waves due to the influence of two connected seas [1]. Problems that may arise due to the dynamics in the strait include sediment transport, erosion, sedimentation and even morphological changes. As experienced in the Bohai Strait where sediment transport occurs massively due to the influence of currents and sediment sources from the Yellow River that affect the coastline of the surrounding islands [2]. Sediment transport process in shoreline can be quite complicated as many parameters are involved. Waves, tidal current can be used as flow sediment transport model in seabed shear and sediment transport analysis as well [3]. Moreover, the behaviour of coastal morphology can be studied using the combination of wave, current and sediment material movement as input model [4].

The sediment transport model in coastal region can be done using 3D model thoroughly [5], [6], [7]. One of the 3D models that can be used as an approach in studying sediment transport in coastal areas is Delft 3D. The model is widely used to solve complex hydrodynamic problems with a fairly good level of accuracy [8].

This research aims to study the phenomenon of sediment transport that occurs in the Madura Strait where there is port infrastructure affected by the sedimentation process, thus disrupting the activities and safety of ship traffic. The study of longshore currents in the Madura Strait that has been carried out can be used as a basis for understanding the behavior of currents that affect the sediment transport process [9]. Through this study, the sediment rate around dock pool in Madura strait hopefully can be examined. Furthermore, the treatment and mitigation against the influence of sediment on ship traffic can be determined.

Methodology

The model used is Delft-3D with the average continuity equation with respect to depth for incompressible fluids as follows:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

With the kinematic boundary conditions on the water surface and seabed explained as follows:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial((d+\zeta)U\sqrt{G_{\eta\eta}})}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial((d+\zeta)V\sqrt{G_{\xi\xi}})}{\partial \eta} = (d+\zeta)Q \tag{2}$$

Where *U* and *V* are the average velocities with respect to depth for the velocity vector *u*, *d* is the depth below the reference point, ζ is the elevation of the free surface from the reference point. $\sqrt{G_{\xi\xi}}$ and $\sqrt{G_{\eta\eta}}$ are corrections to the curvilinear coordinates. Where ξ and η are the respective spatial directions for the curvilinear coordinate system. The momentum equations for the ξ and η directions are given as follows [10]:

$$\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial u}{\partial \eta} - \frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - fv = -\frac{1}{\rho_0\sqrt{G_{\xi\xi}}}P_\xi + F_\xi + M_\xi \tag{3}$$

and

$$\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}}\frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}}\frac{\partial v}{\partial \eta} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - fu = -\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta + F_\eta + M_\eta \tag{4}$$

With $P_{\xi,\eta}$ is the pressure gradient, $F_{\xi,\eta}$ is the force due to Reynolds stress and $M_{\xi,\eta}$ is the contribution from external forces (waves, source and sink). The sediment transport equation is distinguished according to the type of sediment to be modeled, non-cohesion sediment (sand) and cohesion sediment (silt and clay) [10]. The non-cohesion sediment transport equation is calculated based on the equation from Van Rijn for bed sediment transport, q_b:

$$q_b = 0.015\rho_s uh\left(\frac{d_{50}}{h}\right)^{1,2}\left(\frac{u_e - u_{cr}}{[(s-1)gd_{50}]^{0,5}}\right)^{1,5} \tag{5}$$

The sediment concentration provides using the empirical formula which is a function of the discharge as follows.

$$Qc = C\,Qw \tag{6}$$

Where Qc is sediment quantity, C is sediment concentration and Qw is flow discharge.

Numerical performed using a nesting system, where regional nesting is done to obtain current patterns while local models are used to simulate sediment and temperature. The regional model grid is shown in Figure 1. In advance, the model parameter settings that are used in numerical model can be seen in Table 1.

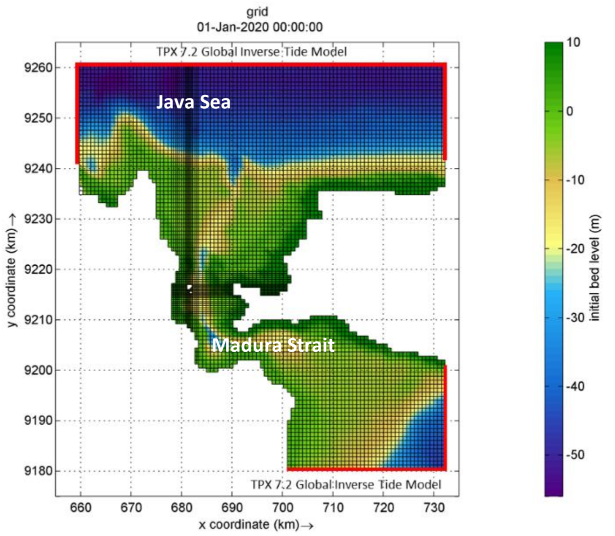

Figure 1. Regional grid model

Table 1. Numerical model parameters

Numerical scheme	Finite difference
Grid size	Max ∆x = 50 m; Min ∆x = 50 m Max ∆y = 50 m; Min ∆y = 50 m
Eddy viscosity coef.	1 m^2/s
Friction coef.	65 $m^{1/2}/s$
Simulation time	31 days
Time step	60 s
Tide	TPXO Global Tidal Models V 7.2
Wind	ECMWF Reanalysis 6 hourly wind speed & direction year 2018

Bathymetry data taken from both BIG (Badan Informasi Geospasial) and direct measurement (primary data). Meanwhile, the boundary condition data are consisted of tide and wind which sourced from TPXO Global Tidal Models V 7.2 and European Centre for Medium-Range Weather Forecast respectively. Model validation and verification is conducted using tide data from BIG (Badan Informasi Geospasial).

Result and Discussion

The tidal conditions in the Madura Strait are influenced by the tidal dynamic in the north and south of Madura Island which have quite different characteristics. North tidal conditions tend to be diurnal with 1 high tide and 1 low tide, while the south tidal tends to be a semi-diurnal mixture. This condition affects the current velocity pattern in the Madura Strait due to the combination of the two types of tides.

To ensure tidal behavior, the observation was conducted as seen in Figure 2. The tidal conditions at the observation point are dominated by diurnal tides, when approaching high tide, the water level decreases before high tide occurs. The results of the model verification show that the water level elevation that occurs is in accordance with the predictions from BIG (Figure 2) and there is no significant difference in the results of the local and regional models. The root mean square error (RMSE) value of model validation provides 0.63 which indicates the good result of model.

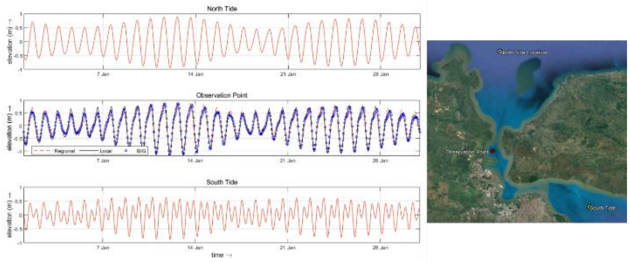

Figure 2. Tide model verification

In advance, the tidal constituent provides the Formzahl value with 3.3 scale of scale. This value reflects the tidal type at the study location is a mixed type with a tendency towards a single type. It means in one day there will be one high tide and one low tide as seen as in Figure 3.

In the other hands, the tidal current velocity pattern which influenced by water level shows different value. It generates the ocean current pattern to move from north to south both in one high and low tide cycle as well. This condition is likely caused by the tidal pattern in the southern region of Madura Island which experiences double mixed tides. The current velocity in the study location is quite high and can reach 2 m/s. The pattern of current velocity during west and east seasons is shown in Figure 4.

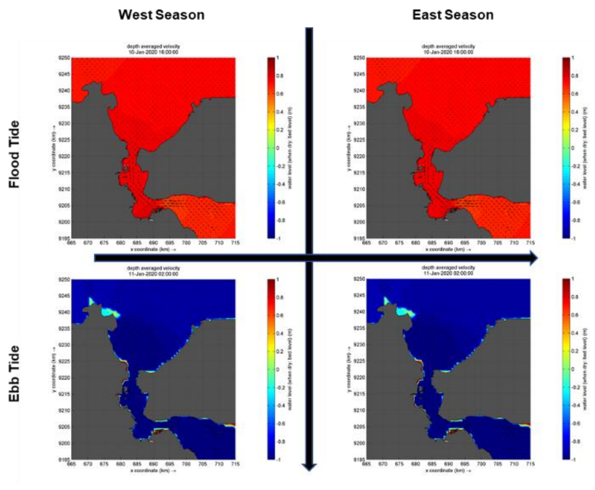

Figure 3. Water level during spring tide

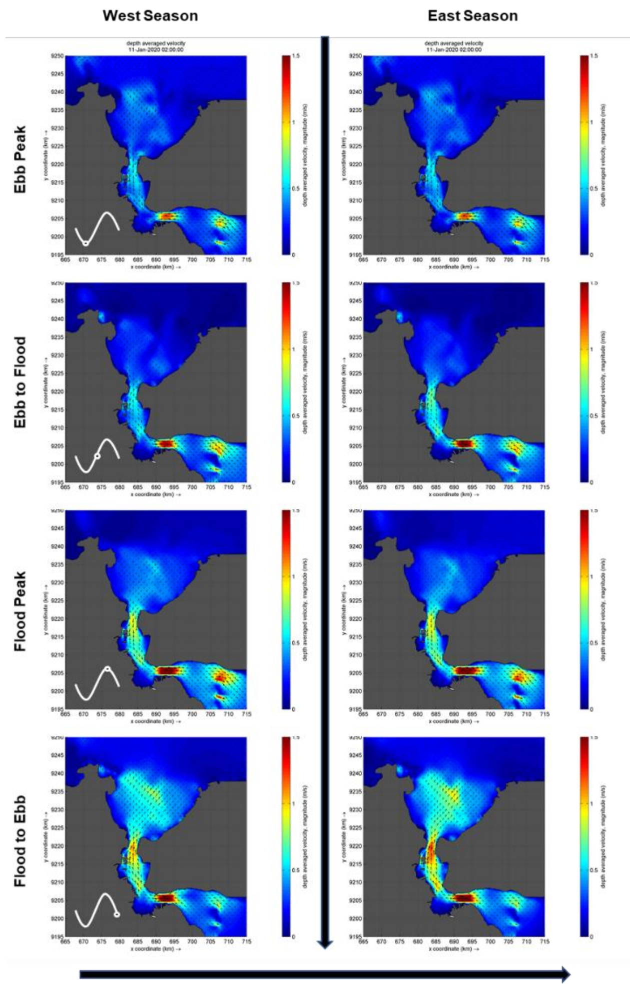

Figure 4. Current velocity during west and east seasons

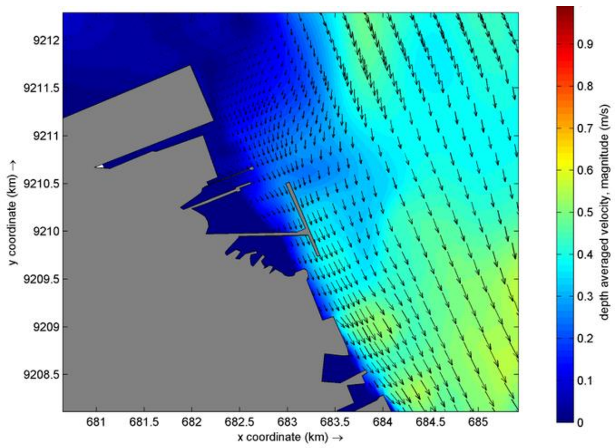

Figure 5. Current velocity distribution during high tide

In advance, the current model is focused on the area near the port infrastructure. The current pattern around the study location is shown in Figure 5 and Figure 6. The current velocity distribution at high tide in the middle of the shipping lane reaches 0.60 m/s, while in the turning basin area is around 0.20 m/s.

During the high tide, the relative current moves from north to south (Java Sea to Madura Strait). Conversely, during the low tide where the current moves from Madura Strait to the Java Sea, the current velocity around the port infrastructure ranges from 0.30 – 0.80 m/s. Furthermore, to determine the effect of wind and tides on current velocity, a residual current velocity analysis was conducted. The difference between the model with wind influence and the model that only considers tides is interpreted as residual current velocity. It can be concluded that the effect of wind is not significant to the current with the value of residual current velocity not exceeding 5 cm/s as seen in Figure 7.

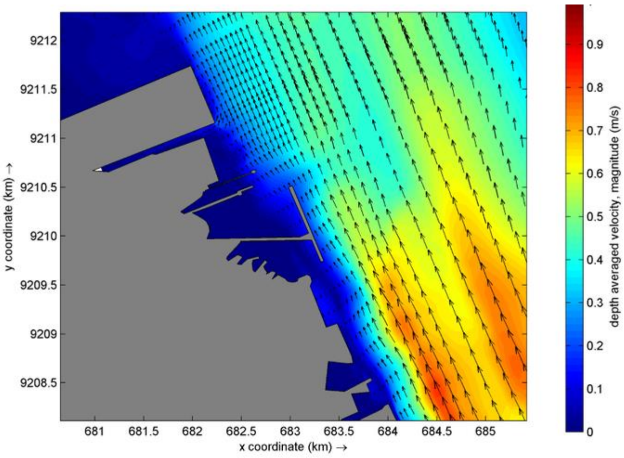

Figure 6. Current velocity distribution during low tide

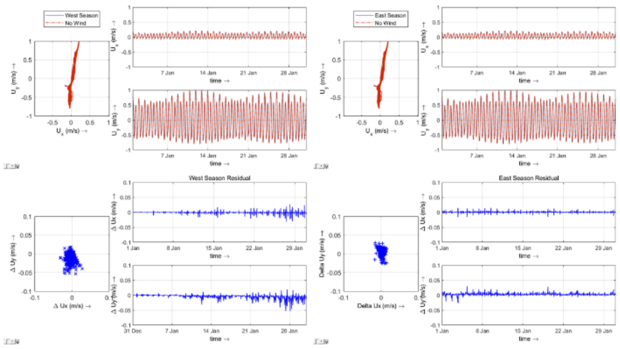

Figure 7. Residual current velocity during west and east seasons

According to current model analysis, the distribution of sediment then carried out to determine the effect of current velocity to the sediment distribution around the port infrastructure.

The simulation of fine sediment distribution is carried out by considering flow and sediment sources to the Madura Strait from the surrounding rivers. The sediment source is the result of the discharge function as shown in Formula (6). Other sedimentation parameters are the settling velocity of suspended sediment and the critical shear stress value with 0.80 mm/s and 0.50 N/m^2 of value respectively.

Table 2. Flow and sediment concentration from several rivers as model input

River/Canal	Discharge (m^3/s)	Sediment concentration (mg/l)
Mireng	63	129
Lamong	45	96
Mas	12	30
Petro	9	24
Sememi	105	200
Kandangan	64	129
Balong	69	140
Greges	12	30
Tambak Wedi	61	124
Tambak Kenjeran	4	12

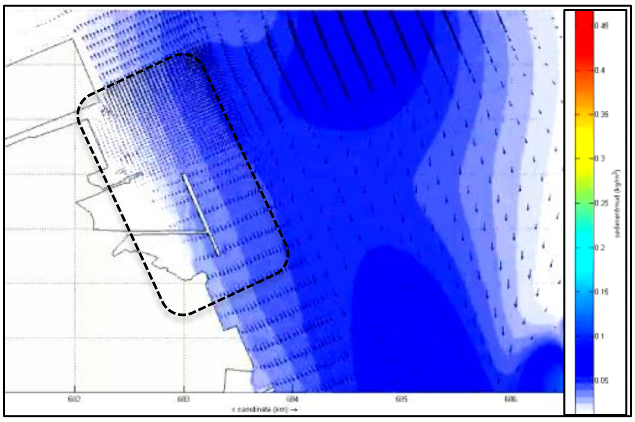

Figure 8. Sediment distribution pattern around port infrastructure

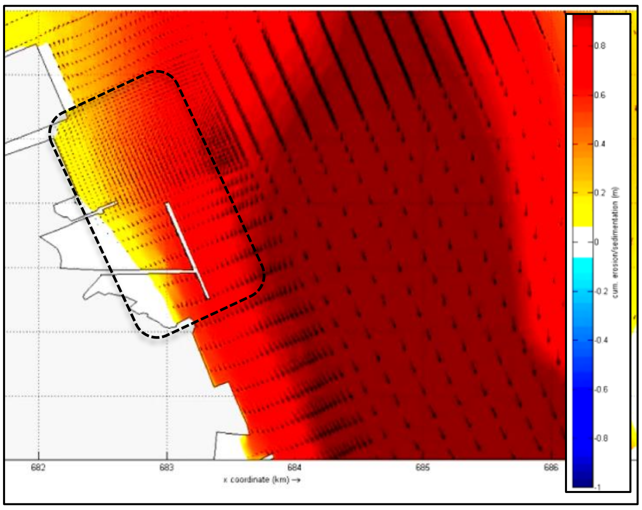

Figure 9. Changes of port bottom after 4 months sedimentation processes

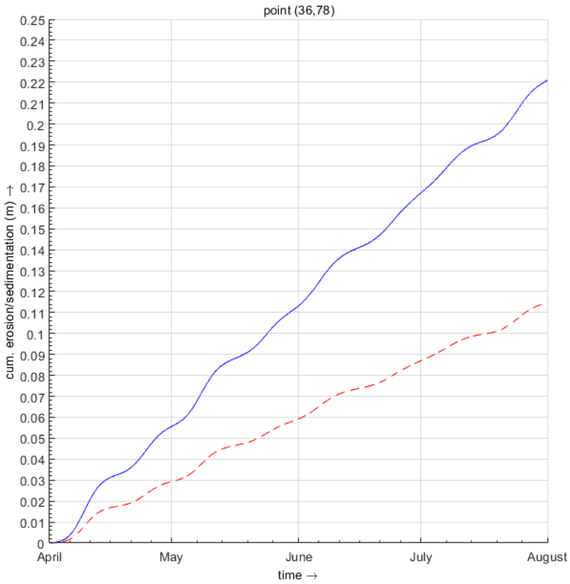

Figure 10. Sediment accumulation between April and August period

Based on the data and parameters above, the numerical model was conducted for 4 months from April to August. The simulation result shows the distribution of sediment especially around the turning basin between 0.03 and 0.06 kg/m^3 as seen as in Figure 8. In detail, changes in the bottom of the turning basin as a result of sedimentation process provide a total value of material accumulation between April and August of 22 cm or 5.5 cm/month in average as shown in Figure 9 and 10. The sediment accumulation is mainly concentrated around turning basin which has the lowest current velocity.

According to the sediment model result, it can be seen that the turning basin severe significant sediment accretion. This situation reflects the excessive impact of sediment distribution from several rivers around Madura Strait. Furthermore, the sedimentation will impact shipping lane in Madura strait in a large scale. Therefore, the maintenance of sediment can be determined based on this result (i.e. sediment dredging schedule).

Conclusion

The current pattern that occurs in Madura strait cause sedimentation around port infrastructures. During high and low tide, the current carries the sediment material from several rivers and provides the sedimentation especially in the low velocity area. These phenomena lead to the shallowing of turning basin which has the lowest current velocity. Due to this situation, seabed morphology will change and cause disruption to the port infrastructure activities. In the future, the mitigation of sediment problems near port infrastructure needs to be conducted to ensure the safety and sustainability of ship traffic in Madura strait.

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