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Technical Note

Numerical modeling of sediment transport patterns under the effects of waves and tidal currents at Pars port complex inlet

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ABSTRACT

This study aimed to investigate the sedimentation mechanism at Pars port complex inlet (petrochemical and services ports in Iran) under the effects of wind-waves and tidal currents and to provide solutions to reduce sedimentation by changing the port plan. For this purpose, at first, the modeling of changes in water level and tidal currents in the area was conducted. The results for the currents and waves were evaluated and validated using the measured field data. The one-dimensional sediment transport potential was calculated by about 33,000 cubic meters per year. The analysis of two-dimensional sediment transport phenomena within the ports and inlets showed that tidal currents patterns that are parallel to the coast and the waves in the region are the most important factors in sedimentation. Accordingly, to minimize sedimentation and to investigate the effect of the geometric shape of the port, three configurations were proposed for ports, and the patterns of sedimentation were evaluated in the new arrangements.

1. Introduction

Sedimentation has always been one of the main problems of the ports, which interfere with the movement of vessels. Thus, decreasing sedimentation has always been one of the main considerations in the design and layout of ports. Sedimentation and sediment transport in ports occur under the influence of waves and currents, which are, greatly influenced by the geometric shape of the ports. In many cases, lack of investigation of the sedimentation regimes in the construction of ports and coastal structures can impose high costs of operation over the project lifetime and even may become uneconomical and lead to the project closure. For example, the annual volume of dredging ports in the United States of America is over 200 million cubic meters, most of which are for maintenance and dredging of access channels at ports [1].

Therefore, identifying and investigating the factors affecting sedimentation and resolving this problem based on research and scientific calculations may contribute to the continued use of ports throughout the year and prevent the loss of national assets such as recurring dredging.

Recently, several studies have been performed relating sedimentation and its reduction in the ports' basin and inlet.

In a research project, Babu et al. [2] used a hydrodynamic mathematical model MIKE21 to simulate and verify tidal currents in the Gulf of Kutch in southwestern India. They validated the results of their model using different measured wind field data. The obtained results from the model were in agreement with the flow fields' data. Yüksek [3] studied and evaluated the effects of breakwater's location on sedimentation patterns in the ports and suggested some design criteria in the form of breakwaters dimensionless geometrical parameters. Yin et al. [4] performed studies on the exchange rate of rectangular ports with different geometrical shapes. According to the results, the port's length has a far greater effect on the exchange rate than its width and, the effects of tides on the horizontal exchange in narrow inlet ports are more severe. Van Maren et al. [5] conducted a study on one of the new basins of Antwerp port in Belgium, using field measurements and high-resolution numerical models. They showed that by increasing the length of the basin, the sedimentation rate decreases. Panigrahi et al. [6] assessed sediment dynamics in the Arklow coast in Ireland decide on the required equipment for the establishment of a wind turbine site. Leite et al. [7] used a mathematical model named "SisBAHIA" in the Itapocoroi Gulf on the east coast of Brazil to study the current patterns. Formation of circulating patterns of currents near the shoreline nose and eaves due to sediment transport of long-shore currents were part of their observations. Nakagawa et al. [8] examined the field measurements and provided a numerical model to calculate sediment transport processes near the seabed and fluid mud layer in Tokyo Bay.

Despite the importance and very high sensitivity of Pars Special Economic Energy Zone (PSEEZ), very few studies have been done on sediment transport in the region. Therefore, our aim in the first part of this paper was to simulate tidal currents and wind waves using numerical model and calculation of the subsequent sedimentation using empirical equations and the numerical model of LITDRIFT. The results of the simulation showed good agreement with the data measured in the field. In the second part, two-dimensional sedimentation was considered using a numerical model and three corrective plans to reduce sedimentation were studied.

2. Study Area

The area under study is located in the Pars Port Complex in PSEEZ, which includes both petrochemical non-petrochemical service ports (**Error! Reference source not found.**). It covers the rea of the Gulf of Naiband to Shirino. The complex is located 70 km southeast of Kangan, 37 km from East of Taheri Port on the Naiband Gulf between 27° 28' N altitude and 52° 37' E longitude. The maximum depth is 57 m in the southwest of the region, and the lowest is in the coastal area and is less than 1 meter.

Figure 1. Satellite illustration of Pars Port Complex [9]

3. Materials and methods

MIKE21 software and field measured data were used to simulate the deposition in the study area mathematically.

After the input information was determined, the tidal currents and then the pattern of wave propagation in the coastal area were simulated. Then, the one-dimensional sediment transfer potential and the two-dimensional sediment transfer pattern parallel to the shore were obtained, respectively.

3.1. Used Data

In this study, various data, including data on bathymetry, wind and waves, were used as input data.

3.1.1. Providing the bathymetry file

Data needed to prepare the bathymetry file are land boundaries and model hydrograph with high accuracy and general hydrograph of the Sea of Oman and the Persian Gulf. The above information is based on ETOP01 hydrographic maps of the Persian Gulf and Oman Sea (Figure 2).

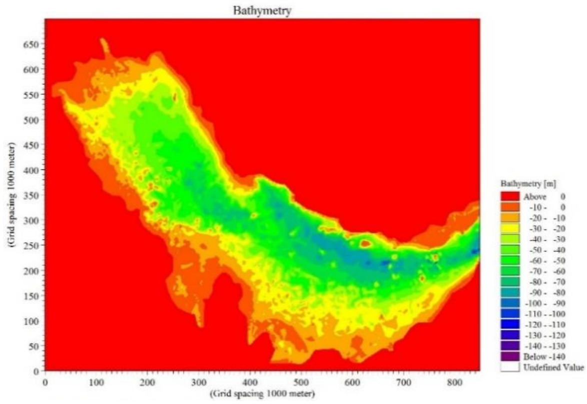

Figure 2. Bathymetry Data of ETOPO1 in the Persian Gulf used in the current model

3.1.2. Wind Data

Wind data include horizontal and vertical velocities as well as air pressure at the mean sea level. Wind velocity components are obtained from the global forecast system (GFS), which is a global numerical model for weather prediction developed by National Oceanic and Atmospheric Administration (NOAA).

The mathematical model was implemented four times a day, and in the advanced model, it was implemented 16 times per day. GFS wind field data were extracted from the 0.5 degrees net distance (0.5 degrees latitude in the north-south direction and 0.5 longitudes in the east-west direction) of the surface area of the National Centers for Environmental Prediction (NCEP) web site in GRIB files (Figure 3). Then, using GRADS software, files were converted to TXT format to be readable for the model.

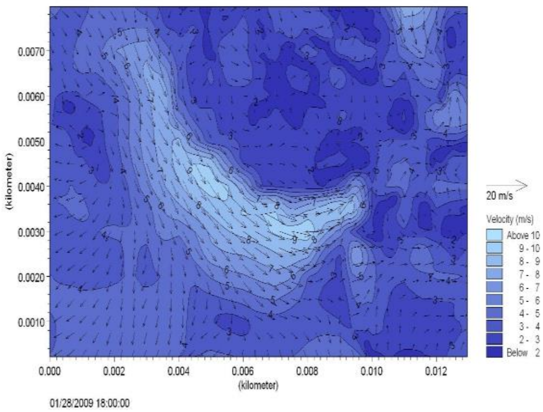

Figure 3. Example of GFS wind data for the Persian Gulf and Oman Sea, used in the wave and current model.

3.1.3. Water level (tides) data

Description of water levels and currents in open boundaries is important to determine the boundary conditions. Open boundaries model have been identified with a water level at variable times and fixed locations. Regional hydrodynamic model boundary conditions are chosen in a way that by the availability of accurate and reliable information in it and a sufficient distance from the target, characteristics extraction and the accurate regime of tidal currents in the area (which are reciprocating) is possible with high accuracy.

Because in modeling the Persian Gulf region, the only open border that needs to introduce information to the model is located in the Strait of Hormuz, to model water level fluctuations to simulate tidal currents in the Persian Gulf, the harmonic constants of national cartographic center in the Strait of Hormuz were used. The tidal level time series on Hormuz Island, was applied according to Figure 4 to allocate boundary information for modeling the region model.

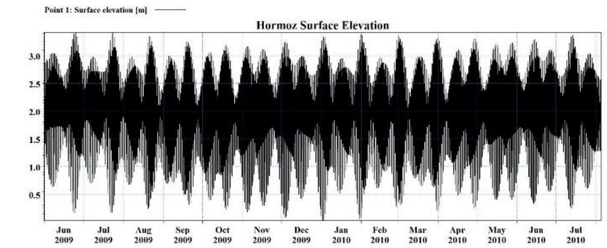

Figure 4. Time series of tidal elevation on the Hormuz Island used as an open boundary regional model.

3.1.4. Sediments grading

Sediment sampling in Pars services and petrochemical ports was undertaken by reviewing projects carried out by the Ports and Maritime Organization (PMO) of Iran.

Figure 5 shows, for example, one of the sediment grading done by the Port Maritime Organization (PMO) of Iran. Sediments in this area are often silt and fine-grained sand.

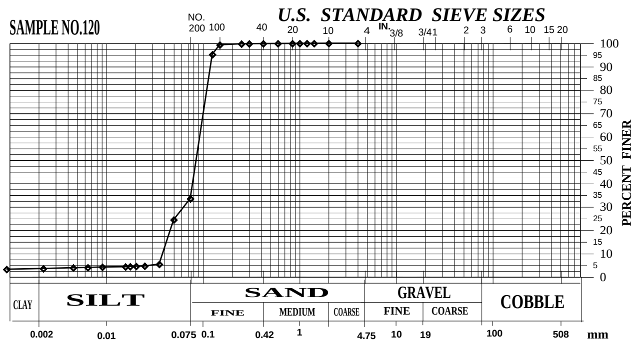

Figure 5. An example of a sediment grading chart done by the Port Maritime Organization (PMO) of Iran.

3. Results and Discussion

For the mathematical simulation of sedimentation in the studied area, MIKE21 software and measured field data were used. After identifying the input data, simulations of tidal currents were performed using the HD module. This module which is a stable module in MIKE21 software, provides a good platform for the majority of other modules. Then the pattern of waves in the coastal area was simulated by the SW module. Finally, using the modules LITDRIFT and ST, respectively, the potential for one-dimensional sediment transport and two-dimensional model of sediment transport along the coast were obtained.

3.1. Hydrodynamic modeling and simulation (HD)

To model the tidal currents, a regional model was designed, and the boundary conditions were imposed. Then outputs of the model were applied in a smaller model (local model) related to the shore in Pars ports. Tidal currents simulation with a time step of one hour was performed on an unstructured triangular grid in 2009 and 2010. Selected Grid and boundaries for this simulation are given in Figure5 and Figure 6. The grid has 4925 elements and an area of 600 square (in the area near the port) to 60 thousand square meters in offshore areas selected for elements. Boundary data were assigned to the model as of current velocities and tidal levels, which are derived from the regional model. Allocated data of open boundaries in deep water were like water levels, and southeast and northwest boundaries are selected as current flux.

In order to investigate the effect of viscosity coefficient on tidal levels and velocities on modeling results, the Smagorinsky formula with a constant value of 0.28, which is proposed in the software code, has been used to simulate these studies. The bed roughness coefficient is one of the parameters used in currents calculations as adjustable parameters in the calibration process. Concerning the applicability of the model results with the predictions, for different values of roughness coefficient, "37" is selected for the Manning coefficient and designed mathematical models are performed by this amount. To control the time step, one can define time step ranges. In this study, the minimum and maximum time steps are 1 and 3600 seconds, and the CFL number is equal to 0.8, so the stability of the numerical simulation be imminent.

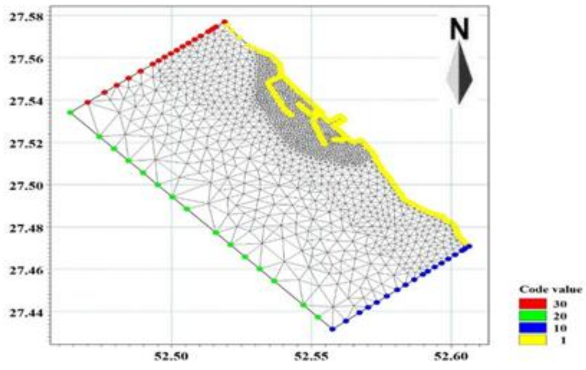

Figure5. The location and determined boundaries of the local model in Pars (open boundaries; blue line (Southeast), green (Southwest) and red (Northwest) and the closed boundary; yellow line (Northeast).

For example, the validation of the results for tidal water levels of the corresponding numerical values of the measurement field in a fixed period (January-February 2010) was conducted, which shows the compliance of the results of the numerical model with the measured data (Figure 7).

Figure 8, shows current rose from simulation results of the ports' inlet at a depth of 10 meters to the CD.

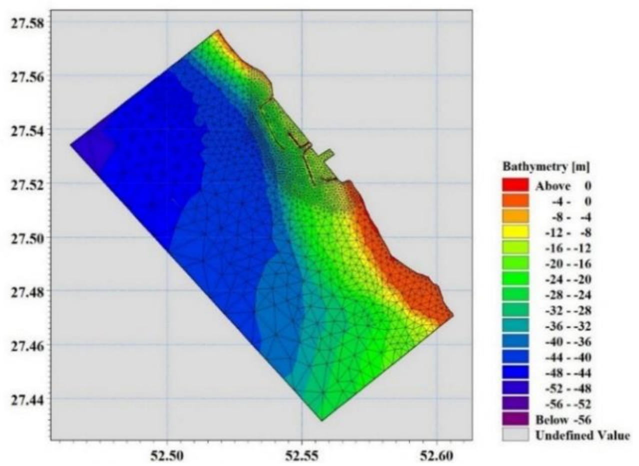

Figure 6. Final Grid used in the local model in Pars ports.

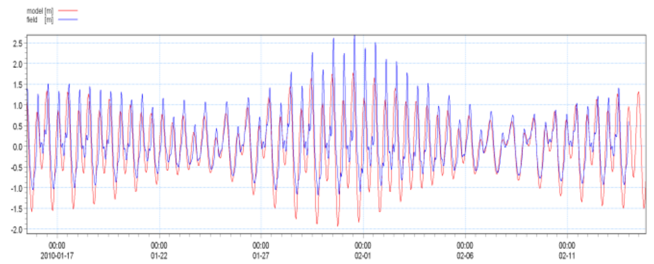

Figure 7. Comparison of the results of numerical modeling for local fluctuations in water level in the inlet of Pars ports in the depth of 10 m to the CD (January-February 2010).

As the figure shows, the tidal currents are reciprocating. The dominant current direction is along the northwest-southeast. The maximum prevailing tidal currents rate in this direction is 17.5 meters per second. Therefore, the current is almost perpendicular to the entrance and along the coastline. The current rose is according to the distribution pattern of tidal currents in the inlet ports.

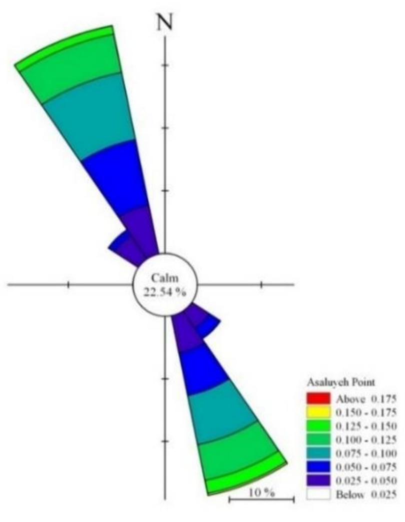

Figure 8. Currents rose from simulation results of the ports' 270 degrees inlet at a depth of 10 meters to the CD (meters per second).

Here, the current vectors of the local model for ports at a depth of 10 meters to the CD, are also presented. In Figure 9, the dominant current direction is along the southeast to the northwest and reciprocating. The tides currents play an important role in sediment transport.

Due to the fact that the entrance of Pars ports is in the southeast direction, sedimentation can be expected inside the port as well as in the port access channel. The simulation results in the next stage as one of the factors affecting the sedimentation of the sediment model is being used.

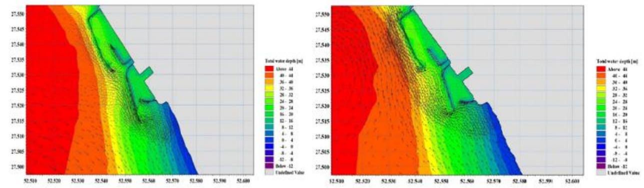

Figure 9. Current vectors in Pars port: low tide (left) and high tide (right).

3.2. Modeling and simulation of wave (SW)

Usually, in studying the design parameters of marine structures and also studying the sedimentation phenomenon in coastal areas, it is necessary to calculate and determine the characteristics of the waves on the beach, because of the main characteristics of entering waves to shore changes due to the effect of phenomena such as shoaling, reflection, and refraction [11].SW module is a mathematical model to study wave propagation in offshore (deep) and the coastal (shallow) [12]. Mathematical equations used in this module are the survival density wave spectrums, which are resolved in the frequency range of zero-order and first-order wave energy spectrum, by using the finite-difference techniques with Alternating Direction Implicit (ADI). Like the current model, the wave model defined with a minimal step setup time of 1 s and a maximum 3600 s for 2009 and 2010. Also, the Grid used in the model is the same as the current model.

The wind field is obtained from the GFS data. To produce waves based on wind parameters, the spectral shape and stationary formulation are used. Because modeling is done in shallow water and deep water, so discretization in the frequency environment must be logarithmic. Also, the discretization direction should be concerning all directions and be divided into 16 different directions. Because of the special importance of the quadruplet wave-wave interaction of produced waves, this process is activated. For the break of depth, decrease relationships, Jansen and Battjes equations are used, and bottom roughness effect is also applied [13], [14].

Selecting a time step is done according to the smallest size of the grid elements and the Courant number, selecting the frequency step according to the selected frequency accuracy required in the computational domain and selecting directions numbers according to the spectral wave change rate and according to DHI based on the experience of similar projects done. Coefficients obtained from calibration that was used in the final model waves are shown in Table 1.

Table 1. The values of the parameters used in the final calibration mode of waves.

Parameters	Values used in calibration
White Capping for wave height	$C_{dis}=4.5$
White Capping for wave period	$\delta=0.8$
Wave breaking parameters	$\alpha=1, \gamma=0.8$
Roughness coefficient parameter	$k_n=0.002$

After setting up a local model and simulating a wave propagation in ports, the wave rose of this area has been extracted according to local models. Given the wave rose presented in Figure 10, it is observed that 61 percent of waves are below 0.5 meters and have calm conditions (Calm) had the dominant waves are close to the port from the West. Also, in Figure 11, wave height time series for the simulation period of 2009 and 2010, is given in the port's inlet.

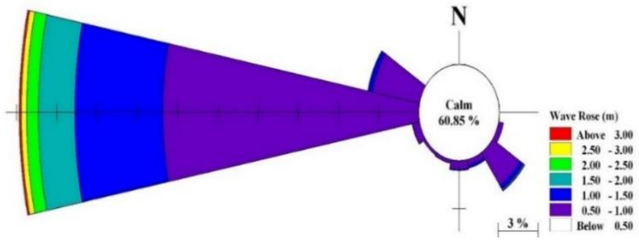

Figure 10. The extracted wave rose of simulated results derived from the local model of wave in the inlet at a depth of 10 meters to CD.

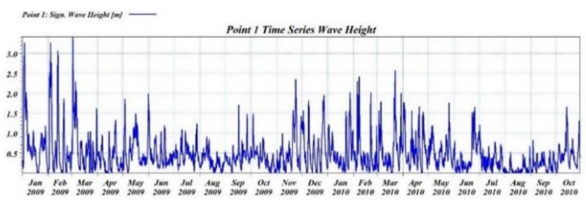

Figure 11. Wave height time series of the simulation model extracted from the wave local model results.

In Figure 12, the validation for wave height changes of the numerical model simulation with the measured field values for the period of 10/09/2009 to 29/12/2009 in Asaluyeh buoy is presented for comparison. As we can see, the overall change in wave height at different times is simulated by the model. In the period from 04/11/2009 and 15/12/2009, the peak height for measured wavefield data is above the simulated one. The reason may be the accuracy of wind data. We can say that 10% of errors in wind speed lead to a 20 percent error at the simulated height of waves. In general, the model simulated the condition well.

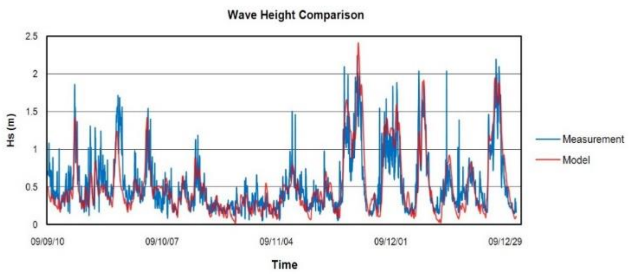

Figure 12. Comparison of measured and modeling of wave height change results in Pars ports (the period of 09/2009 to 12/2009).

Figure 13 shows the comparison of the wave peak-period variation of the numerical model and the measured field values of Asaluyeh buoy for the period from 12/09/2009 to 31/12/2009. As can be seen, the difference is about 1 to 1.5 seconds. It can be observed that the average wave peak period is about 6 seconds, and changes are from 2.5 to 7 seconds.

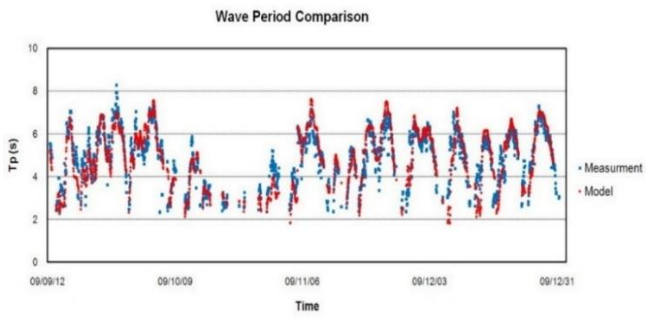

Figure 13. Comparison of the measured wave period peak series with results of numerical modeling in the Pars ports (09/2009 to 12/2009).

In Figure 14, the validation of wave direction changes is presented by comparing numerical model results with the values measured by the wave buoy of Asaluyeh for the period 12/09/2009 to 31/12/2009. As you can see, most of the wave's directions are about 270 degrees. The major changes are in the range of 270° to 295°. A small fraction of the waves are emitted from the South East between 135° to 180°. The results obtained by the model agree with the measured directions. As you can see, the difference between the directions of the model and measuring is about 10° to 20°.

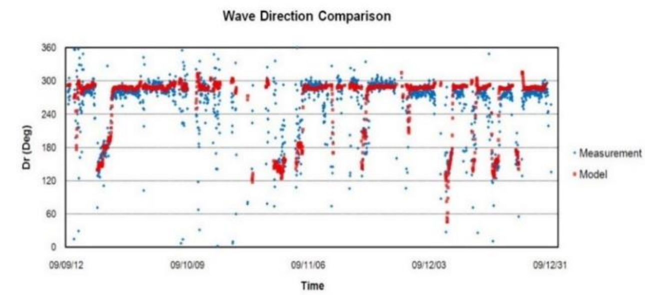

Figure 14. Comparison of time series of measured wave's directions by numerical modeling of the Pars ports (the period 09/2009 to 12/2009).

3.3. Sediment transport simulation

Long-shore currents are the main cause of transport of 80 to 90 percent of sediments in this area, which are separated from the bed and are immersed in water. They are called long-shore sediment.

In many cases, the trend of changes perpendicular to the shore is not noticeable and the use of models that consider only parallel shore transfer (one-dimensional modeling) leads to logical results. For this purpose, in this study, first the transfer potential of parallel coastal sediments has been calculated and then the two-dimensional sedimentation pattern has been studied using the ST model.

3.3.1. Calculating the long-shore sediment transport rate (one-dimensional)

Long-shore sediment transport rate is usually in the form of the annual transferred sediment volume. In this study, to estimate annual volume of long-shore sediment transport rate, the mathematical model and the empirical relationship are used according to the region wave characteristics.

At first, to study the sedimentation and the one-dimensional sedimentation process, mathematical model LITDRIFT of

LITPACK software was used. Concerning the phenomenon of refraction, shallow depths and wave transmission, specifications for the wave's breakpoint are calculated. By applying the appropriate sediment transport formulas for each component, sediment transport potential is determined for each component of the waves. Finally, by putting together the various components of wave-induced sediment, the lateral distribution of sediment from the sea coast will be defined. The input data are properties of waves and characteristics of the coastal strip. The outputs of this model are shown in Figure 15, and Figure 16. According to Figure 15, the cumulative gross annual sediment transport rate is 33,000 cubic meters per year. Graphs of potential sediment transport from the North-West to South-East (-ve) and South East to North West (+ ve) is presented in Figure 16. It shows that most of the littoral sediment transports (peak in the chart) occur at a depth of -6 m CD.

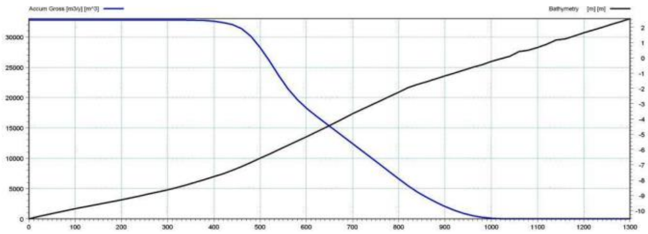

Figure 15. Graph of cumulative gross sediment transport rate in Pars Ports.

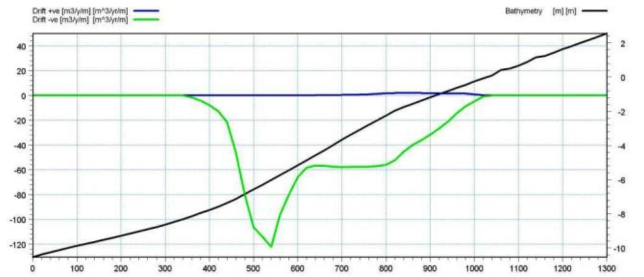

Figure 16. Graphs of the transport rates from North-West to South-East (- ve) and South East to North West (+ ve) in Pars ports.

Rates of sediment transport of the numerical model were compared with the experimental method of Kamphuis [15], who presented the results of laboratory investigations by the following equation:

$$Q = 6.4 \times 10^{4} H_{sb}^{2} T_{p}^{1.5} m_{b}^{0.75} D_{50}^{-0.25} Sin^{0.6}(2\alpha_{b}) \qquad (1)$$

Here, Q is alongshore sediment transport rate, H_{sb} is significant breaking wave height, T_p is the peak period, m_b is beach slope in the breaking zone ($= d_b \lambda_b$) that d_b is the breaking depth and λ_b is the distance from still water line to the breaker, D_{50} is median grain size and α_b is the wave angle in a breaking point.

According to the programming results from this formula in Microsoft Excel, the sediment transport rate obtained 35,000 cubic meters per year, showing the fit and proper compliance of the mathematical model with the experimental method.

3.3.2. Two-dimensional erosion and pattern of sedimentation

In this study, to estimate sediment transport rate and bed level changes, according to the effects of sea waves and currents, the ST module from MIKE 21 ST application is used. The performance pattern of the module is in a way that the sediment potential is evaluated in each region using the input data. The input data are hydrographs of the area, water depth, sediment size and characteristics of waves and currents. The rate of erosion and sedimentation in the model region is calculated according to the sediment transport rate potential. The water depth and currents data should be conducted in other modules and should be ready before running the ST module. So, the relationship between water depth and currents is evaluated through the HD module, and the wave condition is determined through the SW module.

The first step to use these modules is providing Sediment Transport Table. This table is the first input data in the ST module. Extending the sediment transport table is not known due to a lack of sufficient data and period hydrographs for calibration and also the validation of the model before the simulation. But one can estimate it scientifically according to the boundary conditions, information about the area and previous experience. The lowest error tolerance to stop repeating the calculations is 0.0001, and the shields parameter is 0.05. The relative sediment density is ۲/۶۵; water temperature is 25 degrees, the median grain size is 0.1 mm (D_{50}), sediment grading is 1.1, and porosity is 0.4 and wave breaking parameters are $\gamma_1 = 1$, and $\gamma_2 = 0.8$.

Equations used to calculate the suspended and bed sediment are Engelund and Hansen [16] by a bed load factor and suspended load equal to 1. Bed roughness is equal to a manning coefficient of 37 (from the hydrodynamic model calibration). The sediment numerical model for a time step period of the first quarter of 2009 is 30 min time step. Sedimentation and erosion changes amount specified in the five positions around the arms of the breakwater, and their inlet has been measured (Figure 17).

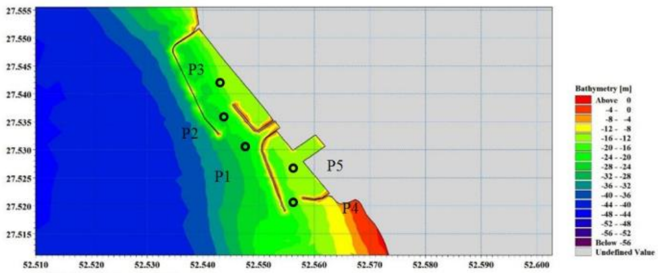

Figure 17. The status of five selected points in the model's output to investigate bed level changes.

Figure 18 shows the bed level changes from erosion and sedimentation in the vicinity of port; and in Table **2**, bed level changes are demonstrated in five selected points in the model's output. As in Table **2**, in most of the ports selected areas, sedimentation is the dominant phenomenon.

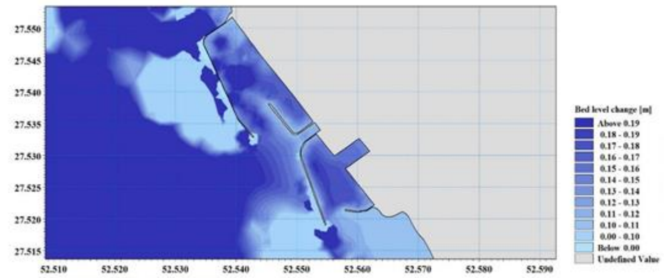

Figure 18. Bed level Changes caused from sedimentation and erosion by the sediment model for simulation of the first quarter of 2009.

Table 2. Bed level Changes at five selected areas at the end of the quarter simulation.

Point	Bed Level Change [cm]
P1	15.8
P2	17.6
P3	15.4
P4	11.4
P5	16.7

3.3.3. Strategies to deal with sedimentation problem

As already mentioned, one of the aims of this study is to plan strategies for the reduction of sedimentation in the ports. To deal with sedimentation problem in the access channel and ports inlet, three plans were proposed (Figure 19).

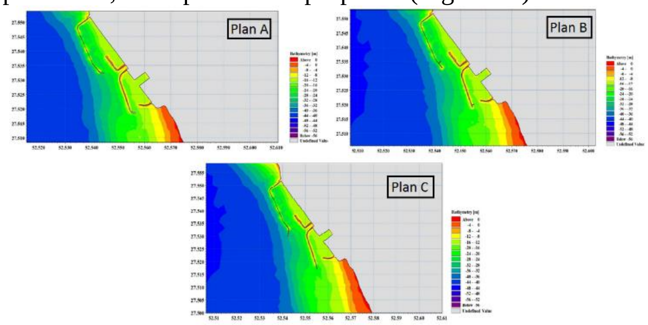

Figure 19. The proposed plans to review the sedimentation condition and its reduction in Pars ports.

In plan (A), an arm of the main (West) in both ports is rotated 100 meters to the inside. The plan significantly reduces the inlet of the port. With this change, it is expected that the amount of sedimentation at the entrance and inside the ports be significantly reduced. However, this change will harm navigation in harbors. Plan (B), adding a picket on the western arm of the breakwater in the 100 meters at both ports, reduces the height of the waves before entering the mouth of the main arm and creates the right environment for sediment storage. However, with this plan, navigation is less affected compared to the first option. With this change, it is expected that the sedimentation amount at the entrance and inside the ports will be significantly reduced.

In plan (C), Western breakwater pickets (main arm) at both ports are increased 150 meters to the outside. This plan does not change the inlet of the port and will not have a negative effect on navigation. With this change, the region is expected to have a calm area in the port east side and sediments from the West, however have less opportunity for transfer into ports. With this change, we expect a significant reduction in sediment transport rates. Although, the only factor considered in this study is sedimentation, it can be inferred that plan (C), due to the increased length of the main breakwater in deep water is the most expensive plan. In assessing the effect of proposed solutions for each of these plans, the model is simulated for one and a half months beginning in 2009, with a half-hour time step. And finally, the sedimentation pattern was provided for each one (Figure. 20).

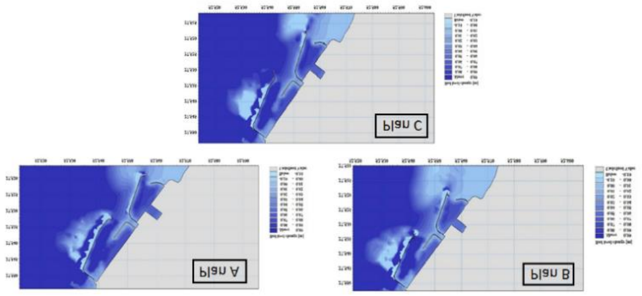

Figure. 20. Bed level changes caused by sedimentation and erosion of the plans.

Bed level changes at specified points in the ports' inlet were studied, and the rates of bed elevation at corresponding points in the current status (new plans) were compared. According to the results obtained from the model in Table 3, the rate of sedimentation in plans (A) and (B) are reduced and in plan (C), it is increased. It is also concluded that the plan (B), has caused the greatest reduction in sedimentation.

Table 3-Changes of bed level at five selected point at the end of the simulation for three months.

Point	Bed Level Change [cm]-Original Plan	Bed Level Change [cm]-Plan A	Bed Level Change [cm]-Plan B	Bed Level Change [cm]-Plan C
P1	7.9	8.1	8.1	8.5
P2	8.8	7.3	7.1	9.2
P3	7.7	6.8	6.5	8.5
P4	5.7	4.7	4.3	6.9
P5	8.3	7.5	7.2	8.7

4. Conclusions and remarks

In this study, the sedimentation mechanism at the entrance of Pars Port Complex (service and petrochemical ports) was investigated under the influence of tidal currents and wind waves, and in summary, the following results were obtained:

1. In pars ports, at high tide, the tidal currents are from the South East to North West, and at low tides, it is from the North-West to South-East.
2. In ports inlet, tidal currents rate of about 17.5 cm/sec is simulated.
3. The speed of the tidal currents at Pars Petrochemical and services ports increases.
4. The results of the simulation show agreement between the wave pattern direction and winds.
5. Simulated waves show acceptable convergence with the results of fieldwork, which indicates the correct choice of bed roughness coefficients in the shallows.
6. Based on the results obtained from the modeling of wave transport in coastal waters, the maximum wave height is at a

depth of 10 meters in the studied area with a height of about 3 meters and was estimated at 270 degrees. The dominant wave is in the North West.

7. The pattern of sediment transport in the region is as in the tidal currents at low tides from the South East to North West, and at high tides, it is the opposite.

8. A one-dimensional sediment model shows estimated sediment transport from the North West to South East at about 33,000 cubic meters per year.

9. Three proposal plans were assessed, and among of the three proposed options, the first and second plans, in which the port entrance was reduced, lead to a reduction of sedimentation in ports**.**

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