Current Forces on Moored Ships
affected by Land Reclamation for new JadeWeserPort

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Abstract

Port extension projects in tidal areas often lead to increase of tidal flow velocities in or near the port area. The new Container Terminal at Wilhelmshaven, Germany, called JadeWeserPort, will be one of several terminals within the so called North-Range of Europe. As the berthing face of the reclamation in Wilhelmshaven will be about 1100 m off the existing coastline, the tidal flow will be diverted. The ebb flow will cross an existing ship mooring facility at a piled jetty south of the proposed reclamation. Consequently, ships moored at the jetty will experience stronger transverse currents than in the existing situation. In order to determine the hydrodynamic forces in the given situation, numerical model investigations were carried out. The methodology included the representation of the design ship in the grid, the computation of the forces on the ship and a validation of the results against OCIMF-coefficients. For the situation under study, the project delivered a reliable prediction of the forces to be expected on the ship at the jetty. Furthermore it delivered an optimized mitigation measure to reduce the force to values that are lower than the forces considered as maximum allowable.

1 Introduction

Wilhelmshaven is one of three largest commercial ports at the German Bight. Today this harbour handles mainly bulk goods such as oil and oil products, chemicals and coal. Wilhelmshaven is located west of the mouth of the river Weser a tributary called Jade; see Figure 1. Figure 2 shows the layout of the project: a new land reclamation protruding from the existing shoreline accommodating a container terminal and a logistics zone.
The new Container Terminal at Wilhelmshaven, called JadeWeserPort, will be one of several terminals within the so called North-Range of Europe. A new container terminal in Wilhelmshaven is feasible because of two reasons:

1. It is expected that the container handling volume in the harbours to the east of the North-Range will grow by an averaged rate of 5.5 % every year during the coming years. This will lead to a growing demand of container handling capacity.

2. Because of being the major German Harbour for bulk goods, Wilhelmshaven’s existing navigation channel is fairly deep, allowing ships with a draught of 20 m to reach the existing oil terminals. Independent of tidal and navigational constraints, the maximum ship draught will be 16.5 m. This water depth will allow the reception of future generations of container vessels.

The project has been developed for the German State Lower Saxony (Wilhelmshaven belongs to Lower Saxony) and the Hanseatic City of Bremen by JadeWeserPort Realisierungs GmbH, that is currently responsible for all planning steps of the realization phase. The land reclamation planned consists of a total area of 360 ha. After construction, the quay wall will have a length of 1725 m. Under full operation the terminal will be able to handle about 2.7 million TEU per year. The construction phase of the terminal is expected to begin in late 2006. Operation of the terminal will start in 2010.

2 Problem Definition and Methodology

Port extension projects in tidal areas often lead to increase of tidal flow velocities in or near the port area. In the case of a seaward port extension like in Wilhelmshaven, the land reclamations cause deviation of the tidal flow, leading to a different flow pattern with locally stronger currents and other hydrodynamic effects. The modified tidal flow affects the operation of neighboring structures situated in the vicinity of
JadeWeserPort. One of these structures is an existing piled jetty, called “Niedersachsenbrücke”.

The berthing face of the reclamation will be about 1200 m into the channel from the existing coastline. Immediately to the south of the proposed reclamation this jetty, which is 300 m in length and 30 m in width, serves for unloading coal for a local power station. This pier is orientated parallel to the existing coastline and is also 1200 m distant from the west bank (see Fig. 2).

The existing flow conditions at the jetty induce only small forces, since the flow is well aligned with the ship. After construction of the reclamation, the flow under ebb conditions will be as indicated in Figure 3: off the shallow areas out towards the deep fairway passing through the piles supporting the deck of the jetty. Thus, ships moored at the pier will experience stronger transverse currents than in the existing situation.

The forces on a moored ship can be estimated using the coefficients as published by the OCIMF (Oil Companies International Marine Forum), but these are valid for open water only: the flow must be uniform in space, and the interaction between the ship and the environment must be limited. This method is not suitable for more complex situations, with strong flow gradients. In order to determine the hydrodynamic forces with more precision, JadeWeserPort Realisierungs GmbH commissioned its consultant, IMS Ingenieurgesellschaft mbH, Hamburg, to tender model investigations.

Often these types of investigations, involving 3D flow around complex structures, are carried out by physical scale modeling. However, the requirement of including a sufficiently large area around the ship and jetty, together with the requirement of working at a reasonable scale would lead to a very large scale model to be constructed, leading to a high price.

However, a promising approach based on numerical modeling was developed and carried out by WL | Delft Hydraulics, The Netherlands, as a cost-efficient alternative. Because of the innovative character of a numerical approach, the following steps were undertaken to prove its validity:

1. development and verification of a force integration routine, which computes the forces on a schematized ship from computed water levels and velocities. The
verification was done by comparison of computed forces with measured forces from generally accepted measurements (OCIMF, 1977) for a ship in open water;

2. set-up and verification of a flow model for the area around the land reclamation by comparison with modeling results from an existing, well calibrated model of the Jade Weser estuary. This model was developed by the Federal Waterways Engineering and Research Institute (BAW), Hamburg, to evaluate the large-scale effects of the land reclamation on all hydrodynamic processes (water levels, waves, morphology);

3. combination of the flow model and the ship schematization, and implementation of a jetty model for computation of the hydrodynamic forces on the moored ship.

The numerical modeling was carried out with WL | Delft Hydraulics’ flow modeling software Delft3D-Flow. Delft3D-Flow is a multi-purpose hydrodynamic non-steady flow solver based on the shallow-water equations in Boussinesq approximation. It solves the equations assuming a hydrostatic pressure distribution on a curvilinear grid. Additionally, the Horizontal Large Eddy Simulation (HLES) turbulence modeling technique was applied, which enables to adequately resolve large scale eddy motions in horizontal planes to a resolution just above the grid size. Unresolved two- and three-dimensional turbulent motions are respectively accounted for by a dedicated subgrid-scale model (Uittenbogaard & Van Vossen, 2003), and the $k-\varepsilon$ model. Particularly, the eddy resolving properties allow for a good representation of the eddy patterns and stagnation points, as well as points of separation of the flow around the ship. The stagnation and separation points, and the energy loss by the formation of eddies are important for estimating forces on the ship while moored.

3 Model Development

3-1 Development and Verification of Force Integration Routine

Representing the ship in Delft3D

In this study a 190.000 DWT bulk carrier was considered with characteristics as given in Table 1.

Delft3D-Flow makes use of a structured (curvilinear, orthogonal) grid. With this type of grid it is not possible to create a full boundary fitted description of its three-dimensional shape; a simplification is needed. The main simplification applied was to schematize the hull form to a shape with vertical frames (cross sections), and with the beam varying over the length of the ship. The draft of the hull form was assumed constant over the length of the ship. The resulting ship schematization and representation on the computational grid is depicted in Figure 4.

The volume of the ship is introduced by specifying a vertical displacement field, describing the depth of the hull form in each grid cell that is covered by the ship. In
this way, the water surface is shaped to represent the outline (both horizontal and vertical) of the ship. The computations used six layers in the vertical. All computational layers pass underneath the ship.

Table 1 Parameters describing the design ship.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>value</th>
<th>Parameter</th>
<th>unit</th>
<th>value</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all</td>
<td>m</td>
<td>300,00</td>
<td>Draft</td>
<td>m</td>
<td>17,50</td>
<td>14,33</td>
</tr>
<tr>
<td>Length perpendiculars</td>
<td>m</td>
<td>286,00</td>
<td>Displacement</td>
<td>ton</td>
<td>205,000</td>
<td>166,000</td>
</tr>
<tr>
<td>Beam</td>
<td>m</td>
<td>47,50</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 4 Ship’s hull representation (for a current angle of attack of 225°) on the computational grid. The red cells represent cells within the ship.
Computation of the forces on the ship

In the hydrostatic approach used in Delft3D-Flow, the pressure exerted by the water against the side of the ship can be computed at all locations from the water density and the water level elevations. By integrating all pressures over the sides of the ship, the total force that acts on the ship can be computed. However, due to this hydrostatic approach, the computation of water levels does not take into account three-dimensional effects. Therefore, WL | Delft Hydraulics developed a post processing tool to account for pressure losses not computed by Delft3D-Flow.

Before the water levels were used to calculate the forces on the ship, the head loss caused by the sudden enlargement of the flow cross-section was computed analytically by the Borda-Carnot equation. The procedure results in a time and place dependent head loss at the downstream side of the ship. This head loss is added to the computed water level elevation around the ship. With this corrected pressure (water level) field, the forces on the ship could be computed.

Verification of the Method of Force Computation

The report ‘Prediction of wind and current loads on VLCC’s published by OCIMF presents coefficients for computing current loads on Very Large Crude Carriers (VLCC’s), i.e. tankers in the 150,000 to 500,000 DWT class. The OCIMF coefficients were used to test the validity of the method used in the present study.

The model tests forming the basis for the OCIMF publication were performed in a towing tank, as used to test ship models on (for example) their resistance and propulsion characteristics. Current forces and moment coefficients are presented in non-dimensional form for a moored vessel in various draft and under keel clearance conditions, and for current angles of attack between 0° (bow on) and 180° (stern on) turning clockwise, see Figure 5 on the next page. The non-dimensional lateral current coefficients are defined at the aft and forward perpendiculars as follows:

\[
C_{Y,A} = \frac{2F_{Y,A}}{\rho v_c^2 TL_{BP}} \quad \text{and forward:} \quad C_{Y,F} = \frac{2F_{Y,F}}{\rho v_c^2 TL_{BP}}
\]

(1)

In the above equations \(F_{Y,A}\) and \(F_{Y,F}\) are the hydrodynamic forces [N] exerted on the ship at aft and forward perpendicular respectively, \(\rho\) is the density of the water [kg/m³], \(v_c\) is the undisturbed current velocity [m/s] averaged over the draft of the vessel, \(T\) is the draft of the vessel [m] and \(L_{BP}\) is the length of the vessel [m].

In the model basin test upon which the OCIMF-coefficients are based, the width-draft ratio of the ships was typically between 2.2 and 2.6 (based on fully loaded ships). The present design ship falls in the same range. The undisturbed current velocities used in these tests were 2.0 and 3.0 knots which are similar values to those at the project location. Computations were done for three current angles of attack of 120°, 135° and 150°. The results of these computations are presented in Figure 5 in the form of the lateral current coefficients at the aft and forward perpendicular.
In Figure 5 the comparison is presented between the results from the computations and the values as published by OCIMF. As can be seen from the figure, all computed values show a deviation from OCIMF values of less than 20%. From this it is concluded that the method delivers adequate results in oblique flow situations, provided that a similar schematization and a similar grid resolution is used.

![Lateral current coefficient at aft and forward perpendicular depth to draft ratio = 1.20](image)

Figure 5 Lateral current coefficients at aft (blue) and forward (red) perpendicular for a depth to draft ratio of 1.20. The dots are from computations, the lines from OCIMF. The dashed lines represent the OCIMF values plus and minus 20%.

### 3-2 Set-up and Verification of the Flow Model

As an important next step, the local hydrodynamics in the vicinity of the Niedersachsenbrücke and the future land reclamation had to be well represented in a detailed flow model. To this aim a numerical three-dimensional model (Delft3D) of a part of the Jade-Weser estuary in the vicinity of the Niedersachsenbrücke was set up, with a high resolution at the location of the moored ship. Its boundary conditions were obtained from the Jade-Weser model of BAW.
The model should perform optimally for the second half of the ebb phase, because the flow is expected to exert the largest forces on the moored ship during this phase of the tide. This meant that it was not required to set-up a model that covers the complete tidal cycle, and that operation in quasi-stationary state would be adequate. In this approach a specific set of stationary (time-independent) boundary conditions is applied for a certain moment on the tidal cycle. After convergence of the model solution, the computed flow fields should be comparable with the time-dependent flow field, computed by BAW's model, occurring at that same phase of the tidal cycle. This verification of the model was done by comparison of main flow characteristics with results obtained by BAW.

The model covered the complete width of the Jade: from the shore to the west, well up onto the tidal flats in the east. The southern boundary was located about 3 km south of the ship, the northern boundary at the northern limit of the land reclamation.

3-3 Schematization of the Jetty

The jetty configuration of piles, fenders and mooring dolphins of the Niedersachsenbrücke (see Figure 6) affects the passing flow by extracting energy due to friction and turbulence. Although at a different scale, these effects are similar to the effects on flow of vegetation. Therefore, in the numerical modeling the effect of the jetty could be accounted for by the so-called “vegetation routine” of Delft3D-Flow. The main parameters of this routine are the number of obstructions per unit area and their typical diameter and friction coefficient.

The implementation of the jetty in the numerical model has been based on drawings from the jetty construction. The piles all have a diameter of 0.75 m and a drag coefficient of 1.0, related to their shape, and have been modeled by means of a pile-density field, that describes distinctive areas where a specific type of construction was applied.

Figure 6 Photograph of the jetty “Niedersachsenbrücke” towards south-east.
4 Current Forces on Moored Ships

4-1 Simulations

Simulations have been carried out for the four distinct moments of the tide for which the boundary conditions have been derived and calibrated i.e. from 17:00 hr (maximum ebb velocity) till 20:00 hr (near Low Water) every hour. In order to capture effects of bottom friction and three-dimensional turbulence upon the vertical velocity profiles and thereby on the forces on the ship, the simulations have been performed with six layers in the vertical.

Results of the simulation for 17:00 hr are presented in Figure 7. The figure shows the water levels (left) and the flow velocities (right) around the ship and the jetty. Note that the velocities within the ship’s contour represent the flow underneath the ship.

Figure 7 Results of the computation for 17:00 hr (maximum ebb flow): water level (left) and flow velocities (right).

The computations show water level differences over the ship which vary between about maximum 10 cm in the 17:00 hr case, and 2 cm in the 20:00 hr case. All water levels show an elevated stagnation point near the aft of the ship, so that, like in the open water case, the highest forces will be exerted on the aft of the ship. A relatively large water level gradient is observed in the narrow passage between the ship and the land reclamation, where the flow crosses a dense area of piles underneath the jetty with a high speed.

The characteristics of the computed flow fields gave confidence for application of the developed method to compute the forces on the ship.

Figure 8 presents the forces as computed for the distinct phases of the tide: the mean value and the maximum and minimum values during one hour of simulation after model convergence (applying stationary boundary conditions as described). The Figure shows that the highest force is computed for the aft perpendicular in the 17:00 hr case; the moment with highest flow velocities. Since the flow velocities will be lower and the under keel clearance will be larger before this time, these values are the largest for the tidal cycle.
Figure 8 Mean, maximum and minimum computed forces at both bow (red) and stern (blue) of the ship and the corresponding water levels (green line).

4-2 Consistency of Results

The consistency of the methodology has been checked by WL | Delft Hydraulics through a series of computations with/without the ship and with/without the jetty. These calculations have been done for the tidal condition at 18:00 hr. Table 2 shows the essential results.

<table>
<thead>
<tr>
<th>Computation without ship:</th>
<th>without jetty</th>
<th>with jetty</th>
</tr>
</thead>
<tbody>
<tr>
<td>flow velocity at centre of ship</td>
<td>0.9 m/s</td>
<td>0.6 m/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Computation with the ship:</th>
<th>without jetty</th>
<th>with jetty</th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse force at the bow</td>
<td>740 kN</td>
<td>960 kN</td>
</tr>
<tr>
<td>transverse force at the stem</td>
<td>1880 kN</td>
<td>1880 kN</td>
</tr>
</tbody>
</table>

The influence of the jetty on the velocities is very clear: it leads to a reduction of the
flow velocity to about 0.6 m/s. The influence of the jetty on the forces turns out to be quite different: contrary to what might be expected, the jetty does not deliver a reduction of the largest force on the ship, the force at the stern. Near the bow the forces even increase.

This influence of the jetty on the forces can be explained by the fact that the ship is the major cause for the stagnation point near the stern of the ship. Near this stagnation point the velocities are relatively low. As a consequence, the jetty piles near the stern of the ship have a limited influence on the flow. Near the bow the increase in force can be explained by the resistance to the flow caused by the dense area of piles in the corner of the jetty. This leads to a higher water level, causing a larger force on the bow.

4-3 Mitigating Measures

The results indicate that current forces on the ship moored at the Niedersachsenbrücke will exceed the allowable forces of 81 tons at the bow and 73 tons at the stern as defined by JadeWeserPort Realisierungs GmbH. The numerical computations predict maximum forces fluctuating around 118 tons at the bow and 230 tons at the stern. These results imply that impact reducing measures will be required in the future situation, after construction of the land reclamation.

As mitigating measure, a sheet pile wall along the western side of the jetty, that is upstream of the ship during ebb tide, was selected. The length and position of this sheet pile wall were to be optimized.

For investigating the effects of sheet piles placed along the jetty on the flow, the computational grid was adapted such that the grid lines at the western side of the jetty (at screen locations) run parallel with the jetty. Figure 9 shows a detail of the adapted grid, with dry cells that represent the screen (initial configuration) in bold red. The use of dry cells implies that the modeled sheet piles induce a 100% blocking obstruction over the total water depth.
In order to reduce the values below the criteria, the sheet pile wall would have to be extended to the south, beyond the jetty and beyond the two fenders panels at the western side of the jetty. The extension would therefore be placed along the walkway, extending further south from the jetty.

During the simulations it was found that with increasing length of the sheet pile wall the difference between the mean values and the maximum or peak values of the forces increase. For a certain case this fluctuation is close to 40% of the mean value at the stern and 67% at the bow. This increase of peak forces is due to a process of vortex shedding from the stern of the ship: vorticity from the shear zone departing from the south tip of the screen starts feeding the shear zone leaving the aft of the ship and a vortex slowly builds up in lee of the ship. At a certain moment this flow pattern in the lee of the ship becomes unstable, and vortex shedding takes place. This causes a sudden increase followed by a strong decrease of the recorded force.

![Figure 10 Results of the computation for 17:00 hr (maximum ebb flow) with optimized mitigating measure: water level (left) and flow velocities (right).](image)

In order to avoid this behavior, the experts recommended to use two smaller separate sheets with 7.5 m width instead of one bigger extension to induce some instability in the shear zone coming from the southern screen tip: the energy spectrum of instabilities leaving the screen tip will be less “peaked”, which should lead to smaller fluctuations of the forces on the ship. The forces computed for the optimized configuration are well below the design criteria. A snap shot of the flow situation for the 17:00 hrs situation (maximum flow velocities) is presented in Figure 10.

Despite the improvement achieved, the force signals still show quite a large variation. This is illustrated in Figure 11. This figure shows that the variations on the force are quite random: there is not a clear vortex shedding period to be recognized. This is typical for real-life turbulent flow processes. Also the figure shows that the forces are well above the mean values for a considerable period of time, which confirms that the peak values, not the mean values, should be considered when comparing with the allowable values.
5 Results and Conclusions

The presented method allows for the optimization of mitigating measures in a cost-effective way. Due to the eddy resolving characteristics of Delft3D-Flow, the resulting forces include important time-dependent behavior, as follows from the generation of turbulence by the obstruction up-stream of the ship. The computation of the time-dependent forces on the ship is of great importance in the evaluation of the mitigating measures. All in all, the method developed by WL | Delft Hydraulics provides a good approach to this type of problem: determination of time dependent forces on a ship in situations with a non-uniform flow field and/or situations where the flow around the ship is influenced by near-by structures, including land reclamations and piled jetties.

For the situation under study, the project delivered a reliable prediction of the forces to be expected on the ship at the jetty “Niedersachsenbrücke”. Furthermore it delivered an optimized mitigating measure to reduce the force to values that are lower than the forces considered as maximum allowable: a sheet pile wall along the western side of the jetty, that is upstream of the ship during ebb tide.

The design of the sheet pile wall has been elaborated by JadeWeserPort Realisierungs GmbH. The sheet pile will extend to the south, beyond the jetty, with separate sheets as recommended to induce some instability in the shear zone coming from the southern screen tip. The design accounts for a further extension of the wall for the case that in-situ measurements of the mooring forces prove its requirement.
6 Acknowledgements

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7 References
