Optimizing Pier Structures using Dynamic Mooring Forces Modelling

by

Oliver Stoschek[1], Stefan Leschka[2], Christian Hein[3] **and Anja Brüning**[4]

1. INTRODUCTION

Existing mooring facilities in Ports were usually planned several years or even decades ago and were focusing on small ships, when compared to ship sizes seen today. Ship sizes have increased considerably in the last and recent years. We are now facing ship length >400m. Thus, formerly planned mooring facilities were often not designed for these kind of Post New Panamax ship sizes. The existing international guidelines (PIANC, OCIMF) and local guidelines (e.g. EAU in Germany) do not particularly account for the latest ship sizes. Applying them can lead to considerably overestimated mooring facilities.

To assess the real capabilities of existing or new planned mooring facilities on piers and in harbors, dynamic mooring simulation should be performed. Such methods will in general lead to more realistic loads. As a first step, they help determining the priority for updating the infrastructure. Such analyses can further be used to expand the lifetime of existing mooring facilities.

DHI developed a new software to calculate dynamic mooring forces (MIKE 21 Mooring Analysis (MA), DHI, 2017). Compared to other dynamic mooring analyses software, two-dimensional flow fields (incl. infra gravity seiching waves) can be incorporated. Their consideration can be of evidence in ports. The software and its predecessors were already applied in several port studies worldwide. Three examples from the German North Sea coast, namely in Bremerhaven, Wilhelmshaven and Hamburg, will be presented here. Their location is indicated in Figure 1.

In Bremerhaven, special ship forms and passing ships requested a dynamic mooring force assessment. In Wilhelmshaven, wind, passing ships and currents are determining the mooring forces. In Hamburg mainly wind forces on Post New Panamax Plus ships demand for detailed mooring force assessment. By using dynamic mooring analyses methods in these examples, the safety of the investigated berths could be re-evaluated. In this paper, the dynamic mooring analysis method is briefly described, followed by a description of the aforementioned examples.

[1] DHI WASY GmbH, Branch Office Bremen, Knochenhauerstr. 20-25, 28195 Bremen, ost@dhigroup.com
[2] DHI WASY GmbH, Branch Office Bremen, Knochenhauerstr. 20-25, 28195 Bremen, sle@dhigroup.com
[3] Bremenports GmbH & Co. KG, Am Strom 2, 27568 Bremerhaven, christian.hein@bremenports.de
[4] Sellhorn Ingenieurgesellchaft mbH, Teilfeld 5, 20459 Hamburg, anja.bruening@sellhorn-hamburg.de

Figure 1: Location Overview

2. DYNAMIC MOORING ANALYSIS

The hydrodynamic interaction between the fluid and the floating body is assumed to be well described by linear potential flow theory. This approach is valid as long as the parameter $\frac{kA}{tanh(kh)} \ll 1$, in which A is the wave amplitude, k is the wave number and h is the water depth. It is further assumed, that the body motion remains small (ensured by the mooring system) and estimates for the neglected hydrodynamic effects can be included via empirical coefficients.

Under these assumptions, the equation of motion can be solved in the time domain and reads

$$\sum_{k=1}^{6}\left(M_{jk} + a_{jk}\right)\ddot{x}_k(t) + \int_0^t K_{jk}(t-\tau)\dot{x}_k(\tau)d\tau + C_{jk}x_k(t) = F_{jD}(t) + F_{jnl}(t) \qquad (1)$$

The first term at the left-hand side describes the inertia forces, the second term the hydrostatic forces and the third term the hydrodynamic forces to first order in the body motion and the wave steepness (Bingham, 2000). They are referred to as impulse-response functions (IRF's). The matrices M_{jk}, C_{jk} and K_{jk} are 6 x 6 matrices of the floating body system. M_{jk} and C_{jk} are the inertia restoring matrix and the hydrostatic restoring matrix, respectively. a_{jk} are impulsive (added mass) contributions, originating from the t = 0 limit of the radiation problem. The forces due to radiated waves generated by the body's motions are expressed as a convolution of the radiation IRF's, K_{jk}.

The right-hand side summarizes all non-linear external forces, such as those from the mooring system and viscous and frictional damping (Froude-Krylov force), $F_{jnl}(t)$, and the wave exciting forces due to scattering of the incident waves $F_{jD}(t)$.

The position and angular rotation of the body in six rigid-body degrees of freedom (DOF) $x_j(t)$ are expressed in Cartesian coordinates, where $x_1 = x$ is aligned with the longitudinal ship axis pointing forward. The translations are indicated as x_1 = surge, x_2 = sway and x_3 = heave. The rotational motions are x_4 = roll angle, x_5 = pitch angle and x_6 = yaw angle. The over-dot indicates differentiation with respect to time t (Bingham, 2000).

The second term in equation (1) makes deriving of the matrices $K_{jk}(t)$, $a_{jk}(t)$ inefficient in the time domain due to the convolution with time t. Therefore, these hydrodynamic calculations are performed in the frequency domain. The hydrodynamic coefficients in the frequency domain, the frequency response functions (FRF's)

$$\sum_{k=1}^{6}\left\{-\omega^2\left[M_{jk} + A_{jk}(\omega)\right] + i\omega B_{jk}(\omega) + C_{jk}\right\}\tilde{x}_k(\omega) = \tilde{F}_{jD}(\omega),\ j = 1,2,\ldots,6 \qquad (2)$$

$\tilde{F}_{jD}(\omega)$ are the exciting forces as a function of the wave frequency ω, $\tilde{x}_k(\omega)$ is the unit vector for the six degrees of freedom (DOF). A complete radiation analysis of the structure is performed by computing the added mass coefficient matrix $A_{jk}(\omega)$ as real part and the damping coefficient matrix $B_{jk}(\omega)$ as the imaginary part of the radiation potential $\varphi_j(\omega)$ at evenly spaced frequencies over the entire significant domain of frequencies (including $\omega = 0, \infty$).

The radiation potential is derived using the Boundary Element Method. The wave exciting forces are expressed by means of the radiation potentials from Boussinesq wave fields via the Haskind relation. All transformations from the frequency domain to the time domain are done by performing Fast Fourier Transformation. 2nd order wave drift forces are calculated using Newman's approximation (Newman, 1977). For further details, please refer to Babarit & Delhommeau (2015) and DHI (2018).

MIKE 21 MA accounts for

- Two-dimensional fields of waves, currents and wind and its combinations or, if not available,
- Time series, which can be derived from spectral information.
- The elastic behavior of mooring lines and fenders are considered via working curves, available from the software installation or from manufacturers
- The real ship hull and it's frequency response (Eigenfrequency) is used.

This allows for detailed investigation of realistic causes and their effects. Figure 2 presents a typical situation, in which MIKE 21 MA is applied.

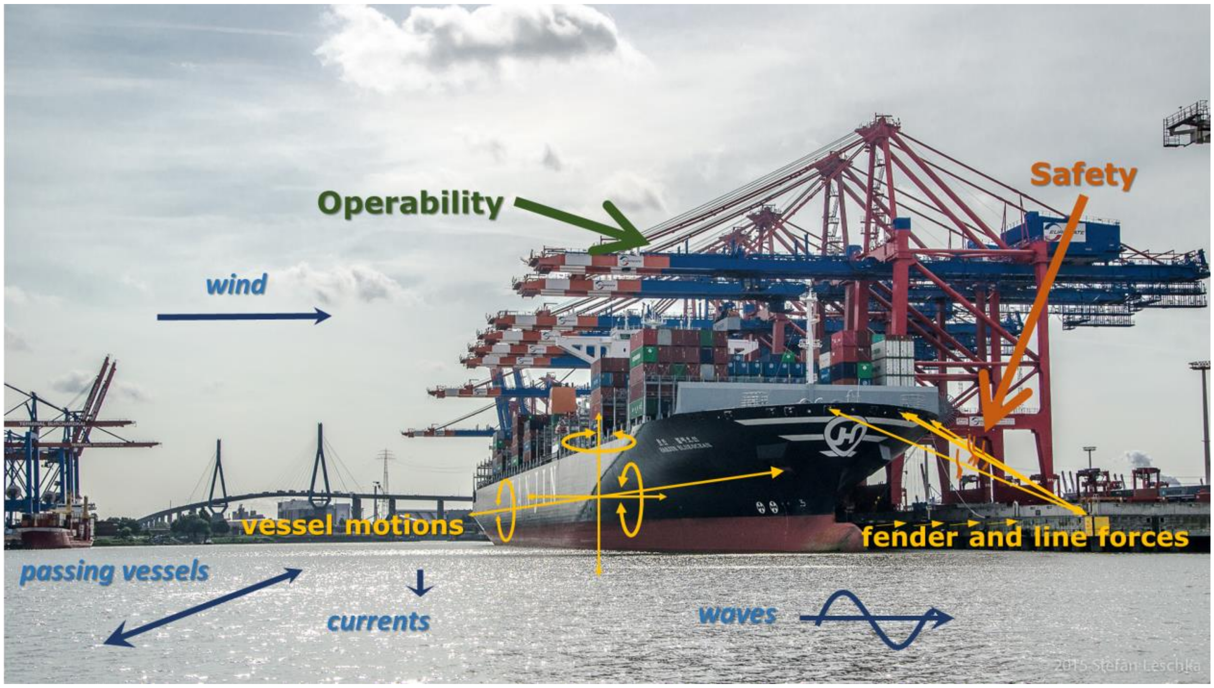

Figure 2: Typical application of MIKE 21 MA.

3. OFFSHORE TERMINAL BREMERHAVEN

To manifest its leading position as one of the main ports for the offshore wind industry in North Germany, Bremerhaven started the development of the former “Fischereihafen”. To support this industrial developing area with best infrastructural connection, a new offshore terminal (OTB) located in the “Blexer Bogen” - a bend of the Weser River right before the estuary mouths into the Wadden Sea - is planned for shipment of offshore components. The location is presented in Figure 3 and Figure 4.

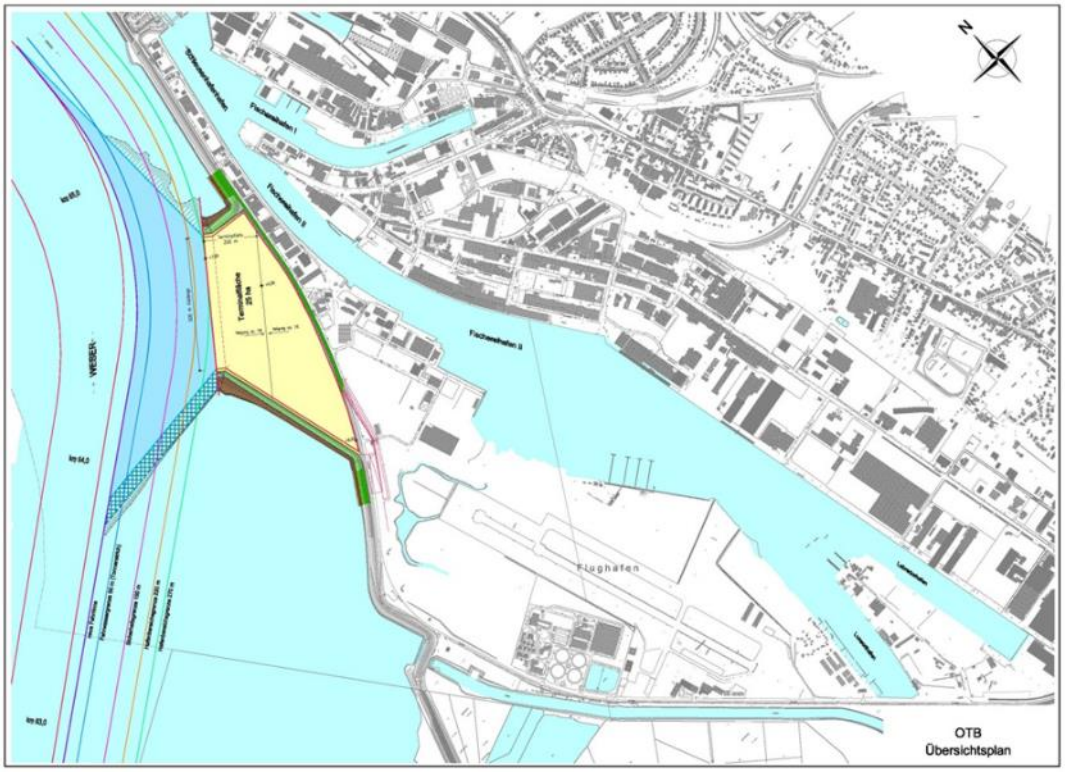

Figure 3: Location of the planned OTB at the "Blexer Bogen"

Figure 4: Areal overview of the planned OTB at the "Blexer Bogen"

At the "Blexer Bogen", large Bulkers are passing this planned terminal in close distance. Therefore, interplay of ship traffic and mooring forces of ships with special size and forms will occur. The main objective of this study was to prove that the drawdown generated by passing vessels does not endanger the applied mooring systems.

DHI's mooring assessment tool in combination with the hydrodynamic module was used to analyze the mooring forces for special offshore installation vessels. The methodology is depicted in Figure 5.

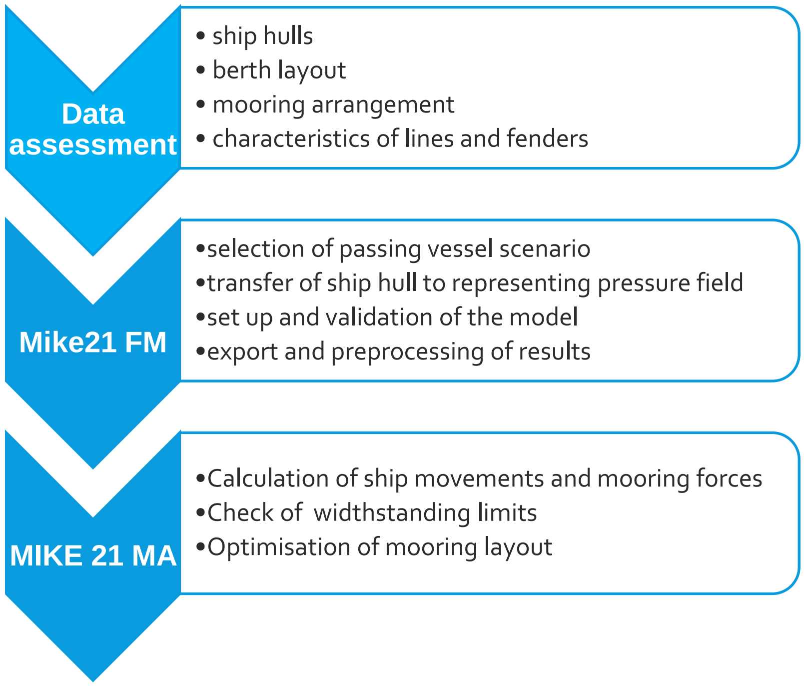

Figure 5: Study methodology

A significant effort was made to achieve and process the data (e.g. ship hulls, berth layout, characteristics of mooring lines). The second and very important aspect was to set up and validate the MIKE 21 Flexible Mesh (FM) Hydrodynamic Model (HD) based on a selection of passing ship scenarios. In the process of assessing the drawdown induced ship motions and mooring forces, the initial mooring arrangement was improved by iteration.

Since most of the empirical formulae include neither the effects of bathymetric changes nor the effect of a river bend or varying distances to the shore, DHI's approach of using a moving pressure field within a MIKE 21 FM HD was applied to reproduce the underlying physics within the numerical model. The model approach uses a flexible mesh (FM) based on unstructured triangular or quadrangular elements and applies a finite volume numerical solution technique. For further information it is referred to DHI (2017).

The characteristics of different passing vessel, its pathway and maximum speed were transferred into the model domain. The resulting drawdown waves were compared to in situ measurements to proof the reliability of the model results.

The moving ship was represented by a moving pressure field that represents the submerged vessel hull. The left part of Figure 6 shows a close up of the mesh, revealing several resolutions, in the vicinity of the OTB. The right part of the figure presents a snapshot of the drawdown wave.

For the identification of the most dangerous ship passage affecting moored vessels at the berth, nautical simulations have been revised regarding the effective vessel speed over ground (SOG), trough water (STW) and their pathway with regards to the passing distance to the quay. The highest vessel speed (SOG or STW) derived from the nautical simulations were used as a conservative approach within the MIKE 21 FM HD model. As a second step, these first order ship (drawdown) waves and its corresponding current speeds in the vicinity of the terminal area were coupled to the mooring analysis software.

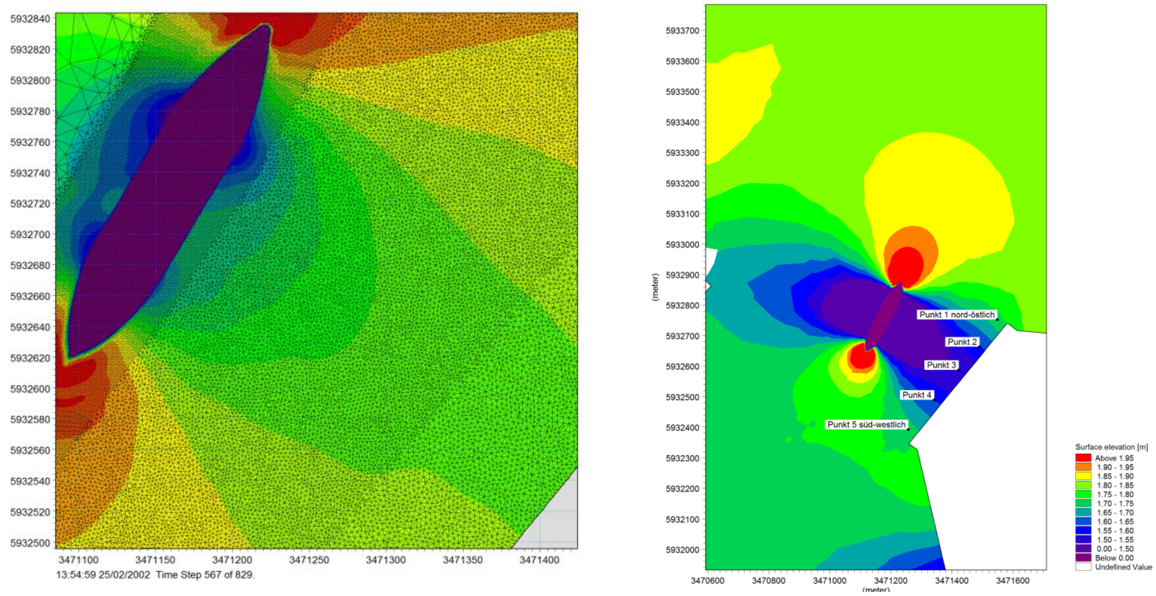

Figure 6: Passing ship hull included in the mesh and the calculated drawdown in front of the OTB

Different cargo ships and Jack up barges were investigated. As one example, the P2-Class cargo ship was investigated with two mooring arrangements, which are shown in Figure 7. Since the initial number of eight synthetic mooring lines was judged insufficient, an additional optimized mooring set up with two more spring and two more breast lines was examined. As the number of mooring winches of this ship was limited, too, it was assumed that an onshore system, such as shore tension devices, could be installed to assure the pretension.

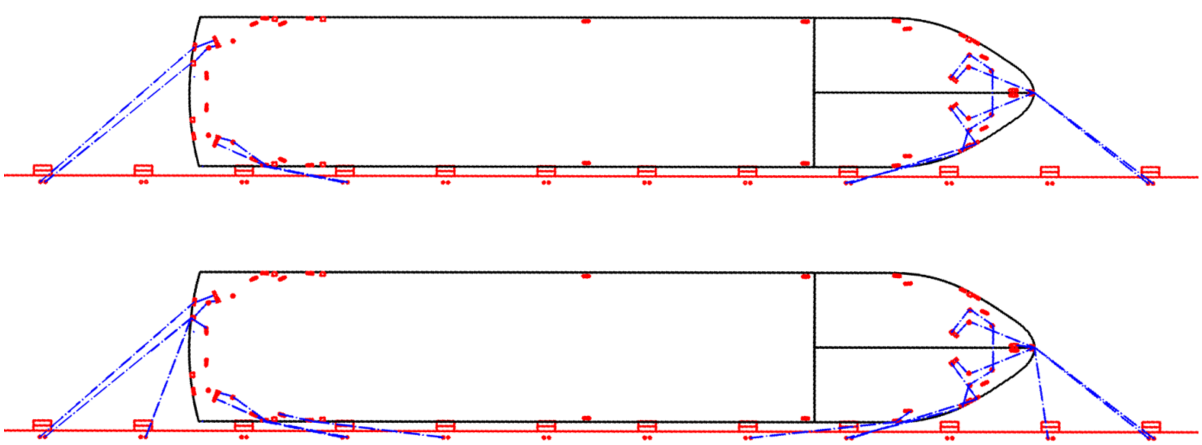

Figure 7: Mooring arrangements of the cargo ship P2-800. Upper panel: Initial mooring arrangement, Lower panel: Optimized set up with additional mooring lines.

Exemplarily, the highest mooring forces and the rate of line usage obtained in this study are summarized in Table 1. The results show that for some cases additional mooring lines were required to withstand the external load induced by the drawdown waves of passing vessels. The maximum absolute ship motions occurring within the simulations are summarized in Table 2.

Ship type	**MBL [kN]**	**Reduced MBL [kN]**	**Max. Force [kN]**	**Initial set up**
Cargo ship P2-class (8 Lines)	480	240	291	**121 %**
Cargo ship P2-class (8 + 4 lines with shore tension)	480	240	203	84 %
Pontoon (ballasted)	990	495	144	29 %
Pontoon (loaded)	990	495	280	56 %
Jack-Up ship 1 (initial set up 6 lines)	511	230	263	**114 %**
Jack-Up ship 1 (6 lines + 2x spring lines)	511	230	180	78 %
Jack-Up ship 2 (initial set up 12 lines)	850	425	277	65 %

Table 1 : Max mooring forces per line occurring during dynamic load assessment. Exceedance of MBL are indicated red.

Ship type	Surge [m]	Sway [m]	Heave [m]	Roll [°]	Pitch [°]	Yaw [°]
Cargo ship P2-class (8 Lines)	4.49	0.06	0.40	1.62	0.19	0.16
Cargo ship P2-class (8 + 4 lines with st)	2.72	0.05	0.40	0.60	0.19	0.14
Pontoon (ballasted)	0.19	0.03	0.39	0.11	0.18	0.08
Pontoon (loaded)	0.94	0.17	0.41	0.34	0.20	0.51
Jack-Up ship 1 (initial set up 6 lines)	2.40	0.12	0.40	0.21	0.21	0.40
Jack-Up ship 1 (6 lines + 2x spring lines)	1.58	0.12	0.40	0.13	0.19	0.32
Jack-Up ship 2 (initial set up 12 lines)	0.94	0.17	0.39	0.22	0.20	0.14

Table 2 : Max motions absolute values assessed from ship motion simulations. Exceedance of motion limits are indicated red.

As a reference for safe operations, the max. allowable ship motions during loading and unloading conditions after PIANC (1995) were applied. The guideline is based on experience and investigations and provided a good guidance for different vessel types.

In general, the simulation results are significantly lower than the recommended thresholds. Still, the surge motion is critical in some cases. For example, the P2-Class Cargo ship with optimized mooring layout and shore tension devices is not able to reduce the motion into an acceptable range and the threshold for surge of 2 m is exceeded by 36%. However, it must be stated that this situation would rarely occur, and operations can be stopped during the passage of such vessel. The exceedance of surge motions for both Jack up vessels is assumed to be not critical since loading operations will most probably take place in a jacked position. Detailed project information can be found at Brüning et al (2014).

4. BULK TERMINAL NIEDERSACHSENBRÜCKE, WILHELMSHAVEN

The Jade-Weser Port of Wilhelmshaven provides a deep access channel and is focusing on large container, general cargo and bulk carriers. The so-called "Niedersachsenbrücke" is the main pier for coal import for northern parts of Germany. The terminal is a pile founded pier located about 1100m offshore of the mainland. Two coal-fired power plants are directly picking up the coal from this pier. It was originally planned in the late 60's of the last century, having a berth on the landside for feeder bulk carriers and another berth on the seaside for Post Panamax bulkers of more than 300m length. The terminal can also be used for transferring cargo directly between two simultaneously moored ships.

After the construction of the Jade-Weser Port north of the Niedersachsenbrücke, modifications to the existing bulk terminal were necessary. Consequently, currents and current-induced loads were changing. Re-assessments of the mooring forces (CES, 2002) took static design loads (wind, current) into account. As part of a more recent assessment of expected operational conditions by WK Consult, it turned out that the static forces on both sides of the Pier can take values close to the maximum allowed static load of the pier. A simplified static analysis showed critical loads in some parts of the structure. No information was available for simultaneously moored ships and for the condition of vessels passing the pier. Other dynamic loads, e.g. due to waves, were not considered. This was seen critical, particularly in the light of future requirements, where two large Bulk Carriers are to be hosted simultaneously at the pier.

To get a comprehensive and more realistic overview of mooring forces, dynamic mooring force calculations, which combined wind and currents (from measurements) and passing ships (from a hydrodynamic simulation) were carried out by DHI. The analyses were performed in cooperation with Manzenrieder und Partner, who performed water level and current measurements, and Nautisches Büro Bremen, who performed AIS data analyses to derive a representative passing vessel situation.

The ships, mooring lines and fenders are characterized in Table 3. An exemplary mooring configuration is presented in Figure 8.

Berth	**Outer**	**Inner**
Vessel type	**Bulk carrier**	**Bulk carrier**
DWT	250,000	40.000
LOA	323.5 m	220 m
LPP	310 m	210 m
Beam	52 m	28 m
Draft	18.5 m	11.5 m
Loading condition	75 %	100 %
Freeboard	9.5 m	4.5 m
Transversal windage area	1600 m²	1200 m²
Longitudinal windage area	6500 m²	4000 m²
Mooring lines	**HTTP**	**HTTP**
Line number	16	12
Diameter	72	60
Min. breaking load	84 t	60 t

Berth	**Outer**	**Inner**
Vessel type	**Bulk carrier**	**Bulk carrier**
Fenders	**Super Cone SCN 1100**	**Cylindrical fender 2000x1200**
Max. reaction force	2348 kN	2000 kN
Max. deflection	1.65 m	1.2 m
Longitudinal windage area	6500 m²	4000 m²

Table 3: Ship parameters (Voss, 2008; Albrecht 2011; CES, 2011; Salzgitter Colsult, 1989)

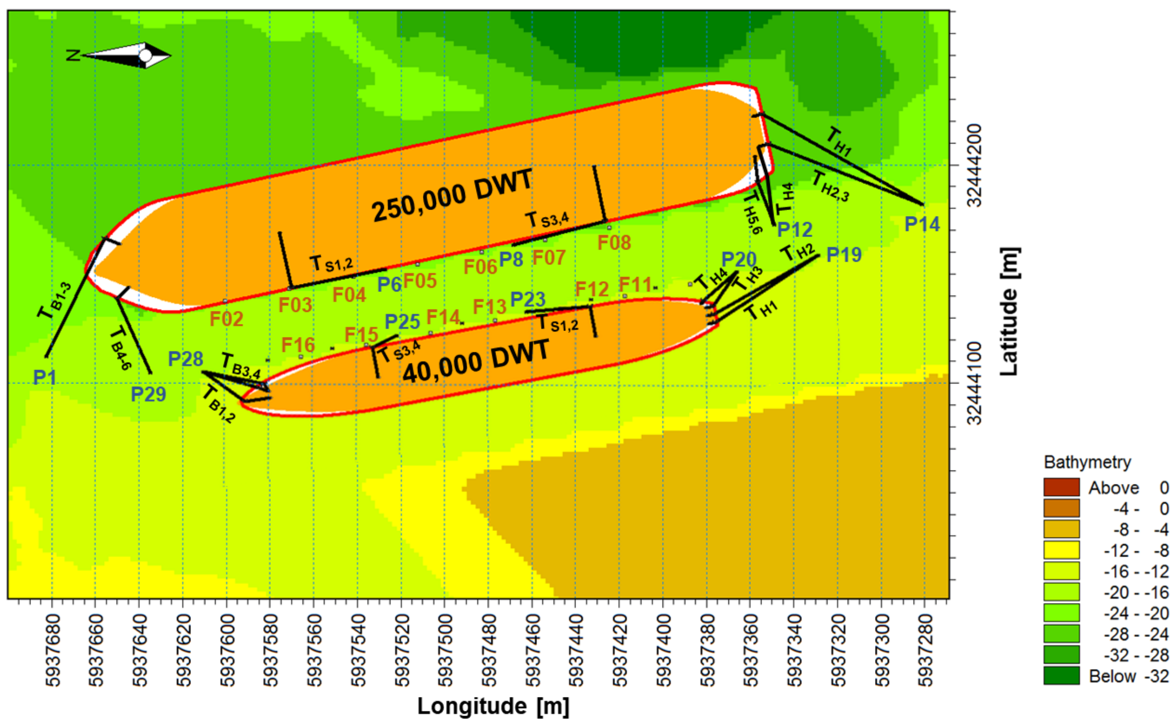

Figure 8: Exemplary mooring configuration at the Niedersachsenbrücke in Wilhelmshaven (coordinates in ETRS 1989 UTM 32N), “F” = fenders, “P” = bollards, “T” = mooring lines (based on Albrecht, 2011).

A test matrix comprising of 22 scenarios was set up. The scenarios addressed combinations of loads due to wind, current, wave and passing vessels. AIS data revealed a minimum passing distances of 200 m (inbound), which was combined with a bulker of 166.7 m length, 25 m width and 14 m draft, which was moving through water with 8 knots (Meyer, 2017). The study methodology follows the one shown in Figure 4.

The most critical environmental condition was characterized with wind speeds of 32.4 m/s from west, waves of 1.6 m significant height and a peak period of 4.5 s from east-northeast and ebb current of 0.9 m/s. The wind induced wave was combined with a long period wave of 0.5 m significant height and a peak period of 12 s from north, which was derived from scatter analyses of wave data, extracted from DHI’s Northern Europe Hindcast (1979-2016), available from https://waterdata.dhigroup.com/octopus/home.

The following conclusions were formulated:

- The highest loads in the spring lines occur when tidal currents are directed towards the stern of the ship.
- Loads due to waves are small due to the small period of wind-induced waves and the orientation of the berth, resulting in a small approaching angle of long waves.
- The highest bollard loads occur due to wind from westerly direction on the outer berth (similar to previous studies)
- Expected loads due to passing vessels are small.

It could be confirmed that the construction of the bulk terminal Niedersachsenbrücke provides safe mooring conditions for the investigated design ships also under the condition of changed current fields and dynamic conditions due to waves and passing vessels. No modification to the pier construction was necessary.

5. ULCV BERTH FINKENWERDER PFÄHLE, PORT OF HAMBURG

The Hamburg Port Authority (HPA) is planning to enforce mooring facilities along the Elbe at the port entrance to mainly host Ultra Large Container Vessels (ULCVs) in case that a suitable berth inside the port cannot be approached. The existing facilities are detached from the river bank and located near the fairway in Finkenwerder. They were designed for Panamax size ships. The following considerations were taken into account:

- It is planned to use the mooring facility for Bulk Carriers up to 250m length and for the next generation ULCV (up to 450m).
- The existing facilities should be reused.
- Mainly wind induced loads are to be taken into account. Wind forces on ULCVs were evaluated for different load conditions in model tests in a wind test facility.
- Different mooring configurations are to be investigated for the ULCVs.
- Assessment of fender forces for land going wind events for the existing dolphins.
- Upgrade of the berth with additional dolphins

Using standard guidelines (e.g. the German EAU), would lead to the requirement of large pile groups to host the mooring facilities. Since the berths are mainly used by ULCV’s, wind and currents play an important role. HPA decided to use the dynamic mooring software from DHI to assess the operational limits of the existing mooring facilities in order to prevent any damage to the infrastructure. Additionally, dedicated piles were set to cover some critical situations identified by the dynamic mooring simulations.

5.1 Baseline situation

The length of the mooring facility “Großschiffsliegeplatz Finkenwerder” is limiting the mooring capabilities. Only 2 dolphins at each berth are located outside the ship length which can host bow and stern mooring lines. With the existing hooks, up to 4 lines can be hosted at each dolphin. Only 4 lines at the bow and at the stern and 2 spring lines can be used, as shown in Figure 9, but the general mooring configuration of ULCV’s includes 6 lines at bow and stern.

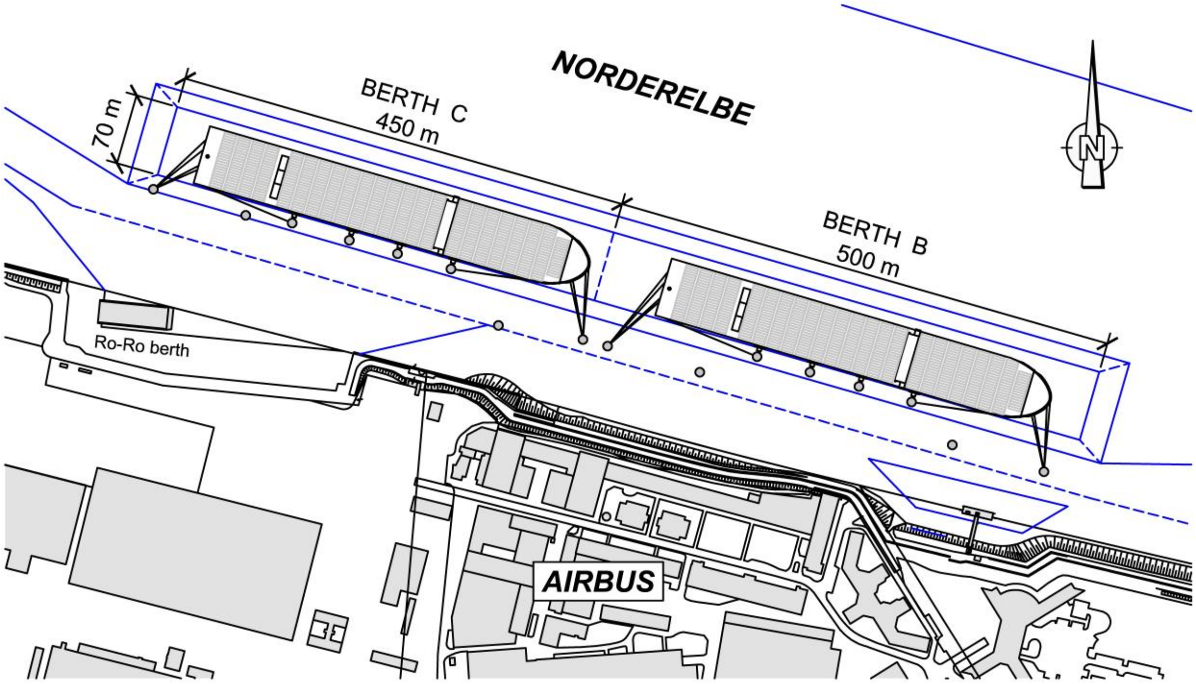

Figure 9: Existing mooring facilities in Finkenwerder, Hamburg

5.2 Bounding conditions

As a first step, the bounding conditions for the expansion of the mooring facilities were defined. There are geometrical limitations due to the Ro-Ro berth of Airbus, located onshore. The height and diameter of the planned dolphins must be similar to existing ones.

Four reference vessels were identified for the assessment of the mooring forces. The reference vessel data base includes the past development of vessels, feeder ships (8,000 TEU, 335 m length), actual classes (15,000 TEU and 19,000 TEU) and future classes of container vessels up to 24,000 TEU (450 m length).

Natural wind speeds were taken from measurements provided by the Deutschen Wetterdienst (DWD). It contains a statistical analysis of the 2% exceedance probability (50 year return period) 10 m above ground. The wind sector discretization was 30°.

A height-averaged wind speeds were defined at the center point of the reference ships. It was assumed that all reference ships have a height of approximately 64 m. The variation in the vessel height found in Hamburg was < 3% and considered too small for consideration. The relevant wind speed used in the calculations is summarized in Table 4. A local influence (shelter) of the Airbus buildings on the wind can be noted during southwesterly wind events (120°N to 270°N).

Richtung		30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°	0°-360°
LP B 1)	$v_{w,2\%}$ [m/s]	22,1	25,6	27,9	15,1	11,6	13,9	22,1	23,2	32,5	33,7	17,4	15,1	34,9
LP C 2)	$v_{w,2\%}$ [m/s]	22,1	25,6	27,9	20,9	16,3	18,6	27,9	32,5	33,7	33,7	17,4	15,1	34,9

1) LP B = Liegeplatz B; 2) LP C = Liegeplatz C

Table 4: Local height averaged windspeed (m/s) for a 50 year return period divided by sectors of 30°. Height of the reference vessel 64 m.

Table 5 shows the minimum requirements for lines and winches. The values base on a questionnaire of the Hamburg Pilots and experiences of the Oberhafenamt, the body responsible for policing the harbor.

Bezeichnung	Bulker	Handy New Panamax	New Panamax	Post New Panamax	Post New Panamax Plus 2)
Schiffstyp	Bulker	Container	Container	Container	Container
Baujahr (ab)	-	2000	2008	2006	Zukunft
DWT/ TEU	230.000 T	8.000-12.000	12.001-14.500	14.501-21.500	21.501 +
Material der Leinen1)	PP/PE oder PA	PP/PE oder PA	PP/PE oder PA	PP/PE oder PA	PP/PE oder PA
min. Leinenanzahl (ausgelegt)	12 (4,2 vertäut)	8 (3,1 vertäut)	12 (4,2 vertäut)	16 (6,2 vertäut)	22[3] (8,3 vertäut)
Minimum Breaking Load MBL	siehe New Panamax	90 t	110 t	130 t	150 t
zul. Regelbeanspruchung PA =45% / PP/PE =50%	siehe New Panamax	40,5 t/ 45 t	49,5 t/ 55 t	58,5 t/ 65 t	67,5 t/ 75 t
SWL Winden (≈ min MBL)	siehe New Panamax	90 t	110 t	130 t	150 t
Designlast Bremse (≈ 80% MBL)	siehe New Panamax	72 t	88 t	104 t	120 t

1) PP/PE = Polypropylene/ Polyester; PA = Polyamid (Nylon)
2) Werte basieren auf Grundlage von [4] und Abschätzungen
3) Annahme auf Basis einer Lastabschätzung

Table 5: Minimum conditions for mooring ropes and winches for the selected reference vessels

Selected design parameters for the mooring analysis

It is assumed that 16 nylon lines are used by default (6-2 mooring). The minimum breaking load (MBL) of the lines is 150 t. The safe working load (SWL) of the winches is equal to the MBL of the line used.

As allowed line tension, 45 % of the MBL is considered (67.5 t) for a single line and 135 t for a double line.

Due to the defined design condition (storm) it is considered that these limits cannot be maintained. As during storm events, the given rule states that winches shall operate “on breaks” instead automatically, a modification of the safety thresholds is recommended.

For the result evaluation, in subsequent analyses a limit of 80 % of the minimum breaking load (MBL) for all lines was assumed. This is to ensure at least 20 % elongation reserve during “break” operation of the winches. As an exception, the limit for the 19,000 TEU ship was selected equal to the design load of the winch break of 120 t x 80 % = 96 t (192 t for double winches). This limit is in accordance with the design load of the slip hooks, which is stated to be 1,000 kN (~100 t) per hook. It is also noted, that the design load of 96 t means a usage of 64 % of the MBL (150 t). Thus, the load reserve in the lines is 36 %.

5.3 Recommendations

The analyses lead to the following recommendations for operating the berths B and C of the ultra large vessel terminal Finkenwerder:

1. During wind speeds of 6 Bft or higher, highly increased ship motions are to be expected. This information is to be transferred to the captains.
2. Additional mooring lines can be used. This is to be understood as temporal solution and requires special caretaking, because the lines need to be taught and growed slack manually using the winch head. Otherwise, changing tides lead to slack or too tight lines.
3. If the number of lines on the ship is not sufficient or the lines are too small, or resulting ship motions lead to uncertainties, then for southern and southwesterly winds of 8 Bft and higher, the captains shall demand for tug boat assistance, so that the lines do not exceed 80 % of the MBL.

5.4 Summary of results

Baseline situation

The results of the mooring analyses show that the existing berth Finkenwerder Pfähle does not suffice for hosting recent ship generations with lengths of 400 m. 6 to 8 bow and stern lines cannot be moored on with the existing dolphins due to geometrical reasons. At least two dolphins are missing.

The analyses of line and dolphin forces show that the existing situation, where the airbus hangars lead to wind shading for berth B, a 4-2 mooring configuration of a 19,000 TEU ship is sufficient to host the vessel during a design storm event. Horizontal design loads of 3,000 kN on the dolphin heads were not exceeded. In case of seaward wind of 6 Bft and higher, the ship can lose the contact with the fenders.

A 4-2 mooring configuration for 19,000 TEU ships is not sufficient under design wind conditions **without** airbus hangar shading. The loads exceed 45 % of MBL and, partly, MBL. Furthermore, horizontal loads at the dolphin heads are doubled (approximately 6,000 kN). The horizontal ship motions (surge, sway and yaw) lead unacceptable values (surge of approximately 8 m).

Extension for 400 m ships

In order to ensure mooring with a 8-2 configuration (or a 6-2 mooring at berth B) during storms, the preferred options (VB5-1 and VC10 OST/ VC10-1 WEST) for both berths show the demand for two to three additional dolphins for re-assessment case of the 19,000 TEU ship without wind shading from the Airbus hangars. All dolphins shall be designed for loads of approximately 3,500 kN. This is shown in Figure 10.

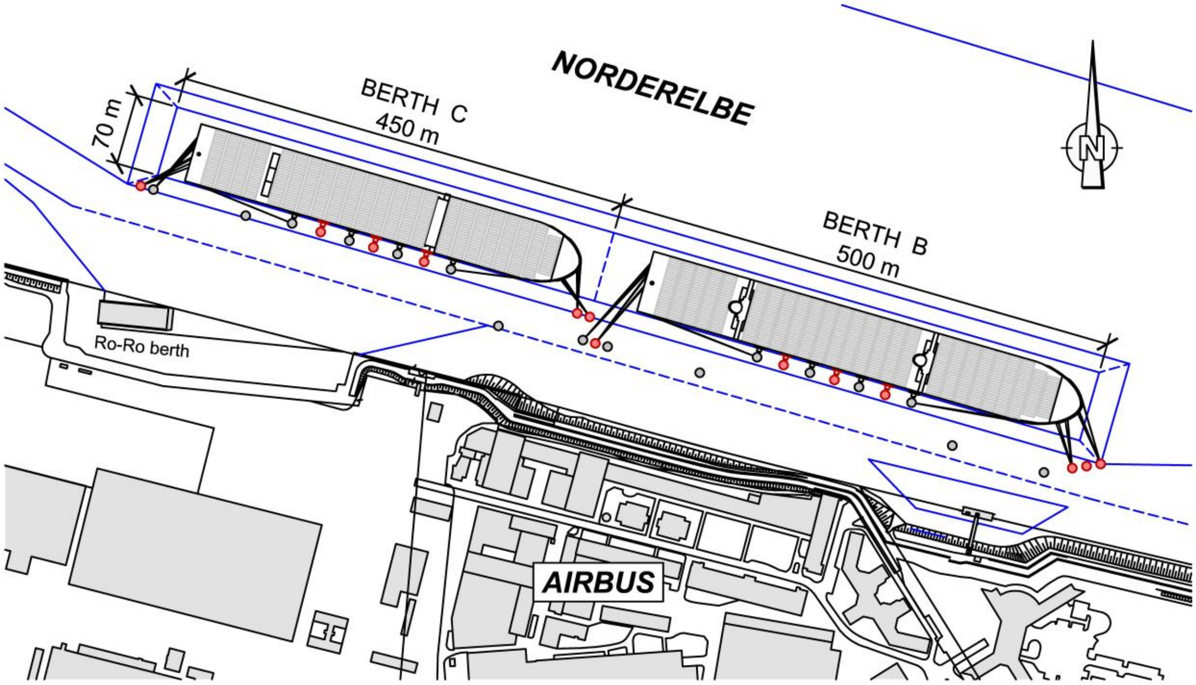

Figure 10: Extended mooring facilities in Finkenwerder, Hamburg

The loads from the spring lines do not exceed the design loads of the existing dolphins. The fenders on these dolphins are able to take the wind loads from ships of up to 400 m length of 2,800 kN. This is due to the load reserves in additional dolphins, which leads to load redistributions. Additional bollards furthermore improve the berthing situation for container carriers with smaller fender contact areas.

The estimated loads confirmed that smaller ships (bulkers, handy new Panamax) are not relevant for the design as they comprise of smaller windage areas and carry less lines. They can be moored with less lines (e.g. 4-2 mooring) also during storm events. It should be ensured that the lines used are appropriate for the here derived mooring forces.

Future ship generations – Confirmation of initial estimated by dynamic mooring analyses

Future ship generations (Post New Panamax Plus, e.g. design ship "Tomorrow") come with windage areas of more than 20,000 m³. This will lead to roughly 30 % higher loads in the dolphins. It is assumed that such ships are moored using an 8-3 configuration.

The re-assessments of mooring forces for 24,000 TEU ships (VB5) confirmed the estimated values stated above. The design loads for the first dolphin in berth B were exceeded for ships of LOA > 400 m. This demands for constructing another bollard. Furthermore, increased line numbers (e.g. 12-4 moorings) shall be considered. Therefore, another dolphin in berth B should be constructed.

Increasing line numbers as a consequence of increasing ship sizes will, as shown in table 7, comes along with increasing MBL of the lines used. As shown in the dynamic mooring analyses results, the existing slip hooks will reach its design loads.

A general renewal based on static load assumptions could be avoided.

6. CONCLUSIONS

This summarizes three applications of dynamic mooring analyses with the purpose to reassess safety and efficiency of pier structures. The mathematical background is briefly described and the most important assumptions are outlined. The example of dynamic mooring analyses for the Offshore Terminal Bremerhaven showed the ability of the applied methods to assess impacts from passing vessels in constrained waters. In Wilhelmshaven, an existing pier structure was re-analyzed under changing conditions and, additionally, dynamic wave loads. Compared to static methods, the more detailed dynamic method verified the safety of the existing structures also for dynamic conditions. Recommendations for increased safety were derived. In Hamburg, the method was applied to the largest container vessel classes. The analysis revealed necessary amendments to the existing berth. Furthermore, recommendations on the operations were given.

In all applications, dynamic mooring analyses lead to an improved understanding of the processes allowing for less conservative designs. Thereby, the applied method can lead to improved safety and reduced construction costs for pier structures.

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