SAFE MOORING OF LARGE CONTAINER SHIPS AT QUAY WALLS SUBJECT TO PASSING SHIP EFFECTS

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SUMMARY

Container traffic and individual ships' sizes increased dramatically over the last decades, testing the existing harbour infrastructure to its limits. An important aspect regarding the safety of the berthed vessel is the quality of the mooring configuration. A case study is presented, where an 18000 TEU container vessel is moored at a quay. The motions of the moored vessel and the forces in its lines due to ship passages are simulated, using the potential software ROPES and the UGent in-house package Vlugmoor. Focus is on the mooring plan (operational parameter) and the characteristics of the individual lines (design parameter).

NOMENCLATURE

B	Beam (m)
C_B	Block coefficient (-)
D	Depth of the vessel (m)
F_{br}	Breaking load line (ton)
$F_{br,r}$	Maximum force in mooring line, relative to breaking load (-)
$F_{fen,br}$	Fender capacity (ton)
$F_{fen,r}$	Maximum load in fender, relative to fender capacity (-)
l	Length of the rope (m)
L_{pp}	Length between perpendiculars (m)
n	Number of lines (-)
$O_{x,y,z}$	Earth bound axis system (-)
T	Draft (m)
ukc	Under keel clearance (%)
x	Longitudinal position centre of gravity moored vessel in $O_{x,y,z}$ (m)
X_p	Passing ship force: longitudinal component (kN)
y	Transversal position centre of gravity moored vessel in $O_{x,y,z}$ (m)
y_a	Transversal position aft perpendicular in $O_{x,y,z}$ (m)
y_f	Transversal position fore perpendicular in $O_{x,y,z}$ (m)
Y_{pa}	Passing ship force: transversal component aft perpendicular (kN)
Y_{pf}	Passing ship force: transversal component fore perpendicular (kN)
Δ	Displacement vessel (ton)
Δx_{max}	Maximum longitudinal motion amplitude (m)
$\Delta y_{a,,max}$	Maximum transversal motion amplitude, at aft perpendicular (m)
$\Delta y_{f,max}$	Maximum transversal motion amplitude, at fore perpendicular (m)
$\Delta y_{m,max}$	Maximum transversal motion amplitude, at midship (m)
ε	Strain of the rope (%)
ε_{10}	Strain at 10% of the breaking load (%)
ε_{br}	Strain at breaking load (%)
ξ	Dimensionless x-position of the passing vessel in $O_{x,y,z}$
EN	Equipment number
HMPE	High Modulus PolyEthylene
IACS	International Association of Classification Societies
IMO	International Maritime Organisation
OCIMF	Oil Companies International Marine Forum
SIGTTO	Society of International Gas Tanker and Terminal Operators

1. INTRODUCTION

The container shipping industry has the biggest share in worldwide transport nowadays, combined with a substantial growth in container ship size (Lloyd's Register, QinetiQ, Strathclyde University, 2013), this leads to a congestion of existing channels and terminals. This paper addresses the safety of moored vessels in case of passing ship events, focussing on the mooring configuration itself, not on the parameters defining the passing event (ship speed, passing distance,…). The configuration consists of the mooring plan and the individual characteristics of lines and fenders. The discussion in this paper focusses on the properties of the lines (design parameter) and their spatial configuration (operational parameter).

Present regulatory bodies as IMO and the IACS, do not impose regulations with regard to the mooring plan and the stiffness of the individual lines. Only the required breaking strength and number of lines is imposed. This is in sheer contrast with the oil and gas industry, where OCIMF and SIGTTO implement requirements for mooring plans and characteristics of the individual lines. These requirements cannot be copied directly, as the force dynamics are different when vessels are moored at a quay. The bollard configuration also differs, as the bollard pattern must not interfere with the tracks of the gantry cranes.

For evaluation of the simulation results, criteria are required. For periodic loads (e.g. waves), maximum significant motions are defined by PIANC, as a result of a probabilistic study, demanding 95% efficiency of the terminal operations. As a passing event is limited in time, it hardly influences the overall efficiency over a larger time window. The attention shifts here to the safety of the (un)loading operation.

A case study is presented, considering 18000 TEU container vessels, based on experience on mooring studies in Flemish ports. Simulations are performed using the potential code ROPES to calculate the passing ship forces and the in-house tool Vlugmoor to evaluate the motions of the moored vessel and the forces in lines and fenders.

The case study is used to illustrate the shortcomings in international regulations, which were mentioned earlier. Having the reference case for comparison, the influence of design and operational aspects on the quality of the mooring operation is discussed. From a design perspective, different rope materials are investigated, focussing on main materials, rather than specialised (modified) brands of ropes. The importance of the elasticity of the lines is highlighted.

The mooring plan is discussed from an operational point of view, assuming that the positions of winches, fairleads and bollards are fixed. The reference mooring plan which is presented is a configuration which has been observed in practice. An optimisation of this configuration is discussed in this paper. The influence of an unbalanced pattern, resulting from a lack of available bollards due to reduced space in between two moored ships, is shown as well. The importance of providing pretension, and thus avoiding slack, is presented in a last discussion.

2. PRODUCTION OF MOORING LINES: A GLOBAL MARKET

The expertise in rope design and production is present worldwide and globalisation offers the possibility to ship-owners to seek the best ropes for their specific needs. IMO (IMO, 2005) and IACS (IACS, 2005) mention similar regulations with respect to the needed number of lines, their strength and the minimum length of each of the individual lines, based on the equipment number of the vessel (EN). This is discussed further in section 5.2. The elasticity of the lines is not regulated, which is a severe shortcoming, as the elasticity is a crucial aspect of the line as it defines the dynamic behaviour of the vessel.

The stiffness of the ropes is primarily a function of the main material which is used. Nylon lines are very flexible lines, whereas steel lines are extremely stiff. Production techniques offer possibilities to modify the specifications of these main materials (strength, elasticity, handling, UV and thermal resistance,…). Rope suppliers often dispose of their own certified ropes, which incorporate specialised production techniques. As the aim of the paper is to discuss the general behaviour of lines, without any commercial interference, the lines are subdivided based on the characteristics of the main materials. Table 1 shows the stress-strain behaviour of five main materials, based on the specifications obtained from six rope manufacturers.

Table 1: Stress-strain behaviour of mooring lines as a function of the main materials.

Base material	ε_{10} [%]	ε_{br} [%]
Steel	0.2	2
HMPE	0.5	5
Polyester	3	15
Polypropylene	4	20
Nylon	10	30

Table 1 shows the breaking strain (ε_{br}) of the lines and the strain of the rope at 10% of the breaking load (ε_{10}), which indicates the non-linearity in the lines. Steel and HMPE lines show a linear stress-strain curve, whereas the nylon ropes are denoted by a limited stress build-up for small loads.

3. SAFE MOORING OF CONTAINER VESSELS

The topic of ship safety involves two aspects. The safety of moored vessels can be increased by imposing regulations with regard to mooring configurations. In order to evaluate the safety of the moored vessel during (un)loading operations, safety criteria need to be defined. Both aspects are discussed from the perspective of passing ship events.

3.1 EXISTING REGULATIONS

For container vessels, there is general lack of clear regulations with an international significance, apart from the IMO and IACS cited earlier, which fail to incorporate regulations regarding the mooring plan and elasticity of the lines. For oil and gas tankers, OCIMF and SIGTTO, provide guidance on lines and mooring plans, which are in general practice translated into terminal guidelines. These rules do not cover container vessels, or more in general vessels moored at a quay wall. Not only are the force dynamics different, as is shown in section 5.3, the general layout of the terminal differs entirely, with regard to the bollard positioning. The case studies in this paper show that there is an urgent need to produce some sort of international recommendations or even regulations, in order to guarantee safe mooring conditions at quay walls, for ever increasing ship sizes.

3.2 DEFINING CRITERIA FOR SAFE MOORING

Defining criteria for safe mooring of large container vessels is a challenging matter, as it involves a good understanding of the parameters which are of interest (motions and forces). The forces in the ropes are limited by the breaking strength of the rope, but foremost by the holding capacity of the winches, which is usually around 60% of the breaking force of the lines. The forces which can develop in the fenders are a function of the properties of the individual fenders and fall outside of the scope of the current paper. In general, it is expected that the fenders start to show plastic deformation at around 90% of their maximum capacity.

Defining limits for ship motions is a more challenging field, as they are a function of the nature of the applied load, more specific of its periodicity and the evaluation procedure. PIANC WG 115 (PIANC, 2012) has published a dedicated report on this subject, focussing on a variety of environmental forces and determining criteria based on the results of a probabilistic study, demanding a 95% efficiency of the (un)loading operation. The focus on efficiency is understandable, when (mainly) periodic forces are acting on the moored vessel. An example here is a berthed vessel exposed to incoming swell. The result of the calculations is a significant motion. A passing event should however be seen as a stand-alone event, which only has limited influence on the long-term efficiency of the operation. The focus here is on the safety of the moored vessel, quay wall and shore-based equipment, passing vessel and not to forget the wellbeing of workers on board and on shore.

Regarding the safety aspect, the longitudinal ship motions, along the quay wall, are most critical. A catastrophic event would be a collision between a gantry crane (or its spreader) and the accommodation or funnel. As the shipping companies are forced to offer the lowest rates, due to international competition, they need to use each square metre of the vessel as efficient as possible. Often the distance between container and accommodation will be limited to 1.0 m, which means that this is a upper limit for longitudinal motions. Even at lower motions, dangerous situations may arise, thinking of accidents regarding gangways, damage to containers and injuries (or even casualties) amongst crew members.

4. SIMULATION OF PASSING EVENTS

Simulation studies are a fast and efficient method to execute a systematic mooring analysis, replacing expensive model testing. For this case study, the forces induced by the passing vessel are calculated using the potential code ROPES. The analysis of the motions and mooring line forces is performed using the in-house package Vlugmoor. As these models always incorporate a simplified representation of the real-life situation, the user needs to be aware of the opportunities and drawbacks of using a specific numerical tool.

4.1 ROPES

The ROPES software tool is a potential double body flow method, developed by PMH (Pinkster & Pinkster, 2014), which has been validated with model tests performed at several leading model test facilities (Van Wijhe & Pinkster, 2008), including Flanders Hydraulics Research in Antwerp, Belgium. The assumption of the flow being inviscid, irrotational and incompressible is valid, as long as no (large) flow separation zones are present. Flow separation typically occurs when ships pass with a non-zero drift angle (Talstra & Bliek, 2014) or in case of entering a narrow channel or lock (Toxopeus & Bhawsinka, 2016). The double body theory assumes a rigid surface, which means that no free surface effects are taken into account. This has two important consequences. Long waves, generated by the passing vessel, cannot be simulated (Pinkster, 2004). The passing ship's squat is also not incorporated in the model, which means that the effect on the under keel clearance (ukc) of the vessel is not taken into account. As a consequence the passing ship forces are under-predicted in shallow water at high passing speeds. A correction factor, based on the depth based Froude number, as proposed in (Talstra & Bliek, 2014), is included in Vlugmoor.

4.2 VLUGMOOR

Vlugmoor is the in-house tool, developed and used at the Maritime Technology Division of Ghent University to simulate the dynamic behaviour of a moored vessel. The calculations are performed in the time domain, evaluating the force equilibrium at each time step. The resulting motions are used as input for the next step. Vlugmoor has been validated in a non-published thesis work and is used frequently to perform mooring studies for Flemish ports.

5. CASE STUDY: MOORED 18000 TEU CONTAINER SHIP

Based on the experience gained by performing mooring studies for Flemish ports, a case study is presented in this paper. This chapter elaborates on the passing event and mooring parameters, which define the reference case.

5.1 PASSING EVENT

The passing event has been carefully selected, in order to represent a real-life case, without reaching the limitations of the software tools. Figure 1 shows the passing event at a busy container terminal, where the waterway section is restricted in width and depth, resulting in a limited passing distance and ukc value. The channel is modelled as a rectangular section with a width of 450 m and a uniform water depth of 18.24 m, which results in a 20% ukc. As the market share of ultra large container carriers increases, it is plausible that moored and passing vessel are 18000 TEU container vessels.

The quay wall is assumed to be a continuous structure, avoiding transitions in flow sections, which would call for the use of CFD or model tests. The passing distance, measured side-to-side is two and a half times the beam of the vessel. The ukc is 20%, which means that the correction factor for free surface effects needs to be applied. The 18000 TEU container ship passes at 6 knots, sailing both in- and outbound. The simulations of both passing events is necessary, because the mooring configuration is not symmetrical, due to the difference between the layout of fore and aft ship.

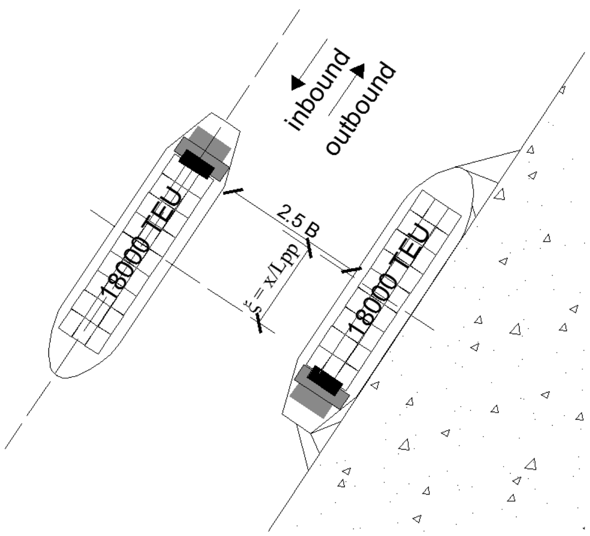

Figure 1: Case study: reference passing event at a congested container terminal. (inbound passing vessel is shown).

In Figure 1, the dimensionless parameter ξ expresses the relative position of the passing vessel with respect to the moored vessel during the passing event. Further insight regarding this parameter is given in section 5.3, where the forces acting on the moored vessel are given as a function of this parameter ξ.

5.2 MOORING LINES AND PLAN

The characteristics of the 18000 TEU container carriers are given in Table 2. The vessel is equipped with 16 polyester ropes, with a breaking strength of 140 tons. These values are chosen based on practical experience and exceed the demands of IMO and IACS. For the vessel defined in Table 2, the EN number is 9992, requiring 14 lines with a F_{br} of 75 tons. The total capacity of the lines, expressed as the product of the individual breaking strength and the number of lines is more than double the required value according to IMO.

The fenders, which are less of interest for this paper, have a capacity of 396 tons and a maximum compression of 0.24 m. It is assumed that the fenders deform in a linear way. A detailed study of the fender friction is outside of the scope of this paper, as there exists a variety in materials and coefficients. For this paper, a conservative approach is followed, limiting the friction to a constant value of 2% of the normal force on the fender. All bollards are aligned with the quay side, spaced 20 m apart and are designed as double bollards. Each individual bollard can support two lines with a F_{br} of 140 tons.

Table 2: Characteristics 18000 TEU container carrier.

L_{OA} [m]	399.00	**$F_{fen,br}$ [ton]**	396
L_{pp} [m]	376.00	**F_{br} [ton]**	140
B [m]	59.00	**ε_{br} [%]**	15
T [m]	15.20	**l [m]**	200
C_b [-]	0.73	**n [-]**	16
D [m]	30.20	**EN [-]**	9992
Δ [ton]	264343		

The lines pattern which is used is a function of design parameters (winch, fairlead and bollard positioning) and operational considerations (available space, influence of tide / changing draft, skill of the crew). In this paper, it is assumed that the design parameters are fixed, in order to focus on the operational parameters which affect the mooring plan. Figure 2 shows the mooring plan which is used as reference in this case study. This mooring plan has been defined based on plans of an existing ultra large container vessel. It is indicated as mooring plan A. The earth bound axis system $O_{x,y,z}$ is also defined, with as origin the initial centre of gravity of the moored vessel. The x-axis is defined parallel with the quay wall. A right-handed coordinate system is used. The lines are modelled between the bollard on the quay and the fairlead, considering an equivalent breaking strain to account for the line section between the winch and the fairlead.

The spatial configuration shown in Figure 2 is an example of a well-balanced mooring plan, which is able to cope well with passing ship forces, when the ship is moored at a quay wall.

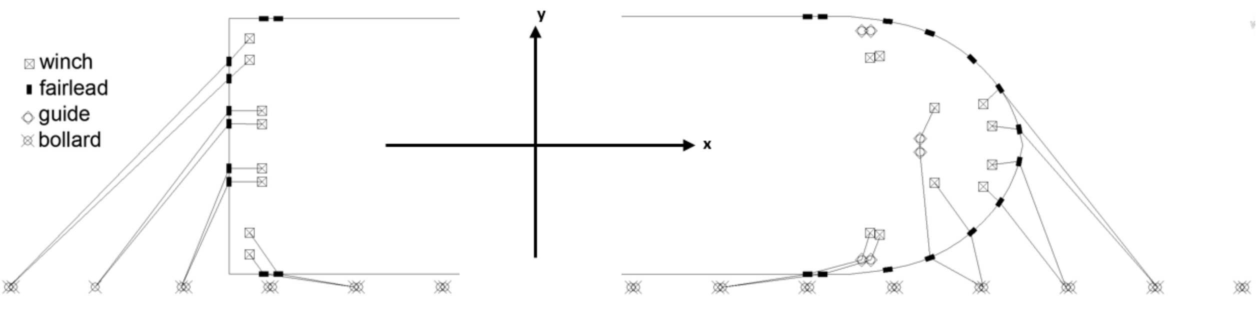

Figure 2: Mooring plan A, with indication of bollards, winches, guides and fairleads on the vessel and bollards on the quay. Definition of right-handed, earth-bound coordinate system $O_{x,y,z}$.

5.3 RESULTS REFERENCE MOORING SIMULATION (MOORING PLAN A)

Based on the defined case study parameters, the mooring simulation is performed, consisting of the ROPES and Vlugmoor calculations. The results of the ROPES simulation are given in Figure 3. The vertical axis shows the passing ship forces and the horizontal axis the relative position of passing and moored vessel, as defined in Figure 1 , with x (and thus ξ) according to the earth bound axis system $O_{x,y,z}$. (Figure 2). All the graphs shown in this paper have ξ as abscissa. The results are expressed as longitudinal forces (X_p) and a transversal force fore (Y_{pf}) and aft (Y_{pa}).

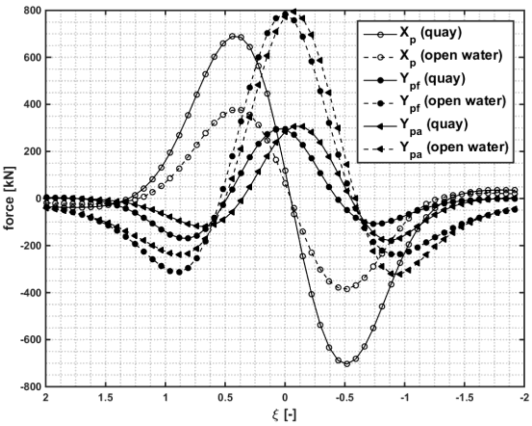

Figure 3: Passing ship forces (X_p, Y_{pf}, Y_{pa}): quay wall and open water case; inbound passing vessel.

In Figure 3, the starting position of the vessel is ξ = 2.0 and it sails towards the end location, given by ξ = - 2.0. As the inbound sailing vessel approaches the moored vessel (2.0 > ξ > 0.5), the moored vessel is pushed towards the quay and rotates clockwise (ξ = 1.0) . This is confirmed by a Y_{pf} which is more negative than $Y_{pa,}$ indicating a clockwise rotation. The moored vessel is pulled towards the approach direction of the passing vessel (positive X-force), reaching the maximum force around ξ = 0.5. When the vessels' midships are in the same (longitudinal) position (ξ = 0), there is no longitudinal force. There is however a strong suction force in the direction of the channel, indicated by a positive transversal force. For (-2.0 < ξ < - 0.5), the moored vessel wants to follow the passing vessel (negative X-force, maximum at ξ = -0.5) and the vessel is pushed towards the quay (ξ = 1.0).

In figure 3, the forces acting on the moored ship with and without the presence of the quay wall are given, to emphasize the difference between the open water case and mooring a vessel at a quay wall. When a quay wall is present, the longitudinal force increases, whereas the transversal force decreases, compared to the open water case (Varyani, 2008).

Vlugmoor simulates the behaviour of the moored vessel during the ship passage, giving the forces in lines and fenders and the motions of the moored vessel, as functions of time. The pretension, which is equal to 10% of F_{br}, is applied at the start of the simulation in all lines. The forces are slightly redistributed to attain a reference equilibrium position. This equilibrium is reached before the passing ship forces affect the moored vessel.

Figure 4 shows the motions of the moored vessel during the passage. The vertical axis gives the longitudinal position of the moored vessel's centre of gravity, in the $O_{x,y,z}$ system and transversal position of the fore and aft perpendicular. It can be observed that the longitudinal motions (difference in x-positions) are significant, whereas the transversal motions (difference in y-positions) are limited.

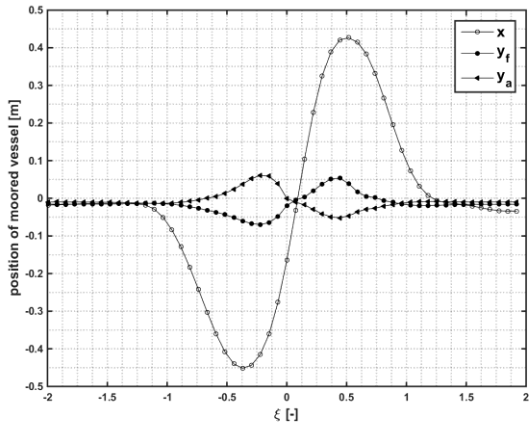

Figure 4: Position of the moored vessel (x, y_f, y_a) as a function of the position of the passing vessel relative to the moored vessel; outbound passage.

Table 3 : Results mooring analysis (mooring plan A).

$F_{br,r}$ [-]	0.23	Δx_{max} [m]	0.46	$\Delta y_{f,max}$ [m]	0.09
$F_{fen,r}$ [-]	0.11	$\Delta y_{m,max}$ [m]	0.02	$\Delta y_{a,max}$ [m]	0.07

Table 3 gives an overview of the simulation results, displaying the maximum forces and motions, resulting from either inbound or outbound passing events, depending on whichever is the highest. The maximum force in lines and fenders is expressed relative to the breaking strength of the lines and the capacity of the fenders, respectively. The motions are expressed as motion amplitudes, relative to the equilibrium position, which is reached after applying pretension in the lines. The maximum longitudinal motion amplitude is given by $\Delta x_{max.}$ The transversal motions at the midship, the fore and aft perpendicular, are given by $\Delta y_{m,max}$, $\Delta y_{f,max}$ and $\Delta y_{a,max}$, respectively. The results show that the forces are limited, whereas the longitudinal motion reaches 0.46 m. The transversal motion is limited, which follows from the decrease in transversal forces when mooring at a quay wall, compared to the open water case (Figure 3).

6. INFLUENCE OF MOORING LINE CHARACTERISTICS (DESIGN PARAMETER)

Container ships are equipped with varying types of mooring ropes. All ropes within the range defined in Table 1 are found on large container vessels. A change in elasticity of lines, alters the behaviour of the moored vessel substantially, as is shown in Table 4. It is assumed that the breaking load of the lines is 140 tons for all lines, despite varying strengths (N/mm) of the main materials. In practice, these lines will have different diameters. A nylon line with a diameter of 104 mm, with a weight of 6.66 kg/m has the same strength as a 48 mm HMPE line, with a weight of 1.27 kg/m. This will have consequences for the handling, but has no influence on the simulation results.

Table 4 shows that the longitudinal motions, which are the most critical motion because of safety reasons, vary between 0.17 m for very stiff HMPE lines, over 0.46 m for common polyester lines, to 0.84 m for highly elastic nylon lines. This means that whereas the ship hardly moves when using stiff lines, the motions become unacceptable when elastic lines are used. It is thus very important that ropes are not only categorised according to breaking strength, but that the stress-strain properties should be taken into account as well when imposing regulations.

We can conclude that for the specific case of a passing container vessel, the use of stiff lines is recommended. One must keep in mind that stiff lines lead to a high eigenfrequency of the system, which means that it is susceptible to (short) waves (Varyani, 2008). This can be solved by working with medium stiff lines (polyester), or by adding nylon tails to the stiff lines to increase the flexibility and lower the eigenfrequency.

Table 4: Results mooring analysis – influence of the elasticity of the mooring lines (mooring plan A).

Line	**HMPE**	**ε_{10} [%]**	**0.5**	**ε_{100} [%]**	**5**
$F_{br,r}$ [-]	0.23	Δx_{max} [m]	0.17	$\Delta y_{f,max}$ [m]	0.06
$F_{fen,r}$ [-]	0.09	$\Delta y_{m,max}$ [m]	0.02	$\Delta y_{a,max}$ [m]	0.03
Line	**Polyester**	**ε_{10} [%]**	**3**	**ε_{100} [%]**	**15**
$F_{br,r}$ [-]	0.23	Δx_{max} [m]	0.46	$\Delta y_{f,max}$ [m]	0.09
$F_{fen,r}$ [-]	0.11	$\Delta y_{m,max}$ [m]	0.02	$\Delta y_{a,max}$ [m]	0.07
Line	**Nylon**	**ε_{10} [%]**	**10**	**ε_{100} [%]**	**30**
$F_{br,r}$ [-]	0.24	Δx_{max} [m]	0.84	$\Delta y_{f,max}$ [m]	0.11
$F_{fen,r}$ [-]	0.13	$\Delta y_{m,max}$ [m]	0.03	$\Delta y_{a,max}$ [m]	0.11

7. INFLUENCE OF THE MOORING PLAN (OPERATIONAL PARAMETER)

In this section, we discuss the mooring arrangement from an operational point of view, which means that the position of bollards, winches and fairleads (design parameters) is assumed to be fixed. The aim is to show the importance of achieving, and most importantly maintaining an optimal mooring configuration. Providing terminal guidelines, combined with training and supervision of crew, are vital to ensure a safe mooring operation.

The following topics are addressed:

- Optimising the mooring plan (section 7.1);
- Consequences of an unbalanced mooring configuration (section 7.2);
- Importance of providing pretension (section 7.3).

7.1 OPTIMISING THE MOORING PLAN

The biggest drawback of using ropes to moor a vessel, is that they need to stretch before they can take up loads, which means that the ship must move to start generating reaction forces. Certainly for stiff lines, it is critical that the lines have similar lengths, so that they are all loaded simultaneously. In general, fore and aft lines are longer lines, which will thus build up less forces than spring and breast lines. They are also less suited to cope with pure longitudinal or transversal forces. These shortcomings are counteracted by allowing lines to cross each other, as is shown in Figure 5. This configuration leads to a more efficient use of all the lines. The simulation results are given in Table 5. The results for mooring plan A are repeated, to allow direct comparison between the results.

Table 5 : Results mooring analysis – crossing fore and aft lines (mooring plan B).

Mooring plan A					
$F_{br,r}$ [-]	0.23	Δx_{max} [m]	0.46	$\Delta y_{f,max}$ [m]	0.09
$F_{fen,r}$ [-]	0.11	$\Delta y_{m,max}$ [m]	0.02	$\Delta y_{a,max}$ [m]	0.07
Mooring plan B					
$F_{br,r}$ [-]	0.22	Δx_{max} [m]	0.40	$\Delta y_{f,max}$ [m]	0.03
$F_{fen,r}$ [-]	0.06	$\Delta y_{m,max}$ [m]	0.01	$\Delta y_{a,max}$ [m]	0.02

When the optimised mooring plan is considered, the transversal motion of the vessel becomes next to nothing. The longitudinal motion decreases with 13% with respect to mooring plan A (Figure 2). It is important to remark that the configuration shown in Figure 5 can only be obtained if the fairleads are positioned higher than the bollards at the quay at all times. This could be problematic at tidal terminals and with vessels having a smaller freeboard.

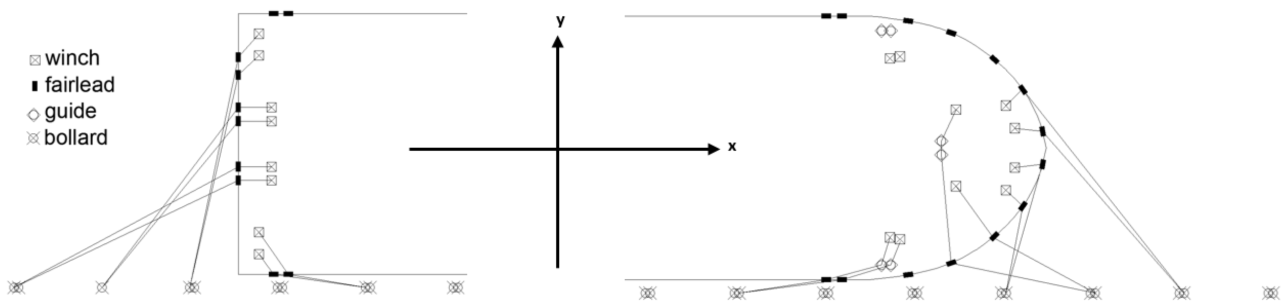

Figure 5: Mooring plan B: optimising plan A, by implementing crossing fore and aft lines.

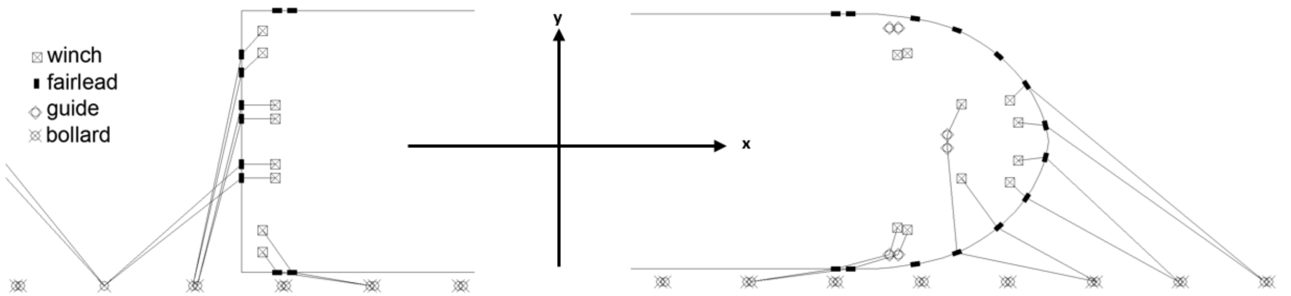

Figure 6: Mooring plan C: unbalanced mooring line configuration.

7.2 UNBALANCED CONFIGURATION

Existing container terminals accommodate as many container vessels as possible, in order to maximize the terminal occupation. As the main dimensions of these vessels have increased drastically in the last decades, existing terminals need to decrease the space in between moored container vessels, which leads to a shortage of bollards to moor the vessel adequately. An example of an unbalanced mooring configuration is given in Figure 6.

In Figure 6, the number of bollards which is available for the aft lines is restricted, due to the presence of another container vessel at the terminal. To make to situation even worse, the fore lines are almost parallel to the quay, resulting in a lack of fore breast lines. The simulation results are shown in Table 6, together with the results for plans A and B.

Table 6: Results mooring analysis – unbalanced mooring configuration (mooring plan C).

Mooring plan A					
$F_{br,r}$ [-]	0.23	Δx_{max} [m]	0.46	$\Delta y_{f,max}$ [m]	0.09
$F_{fen,r}$ [-]	0.11	$\Delta y_{m,max}$ [m]	0.02	$\Delta y_{a,max}$ [m]	0.07
Mooring plan B					
$F_{br,r}$ [-]	0.22	Δx_{max} [m]	0.40	$\Delta y_{f,max}$ [m]	0.03
$F_{fen,r}$ [-]	0.06	$\Delta y_{m,max}$ [m]	0.01	$\Delta y_{a,max}$ [m]	0.02
Mooring plan C					
$F_{br,r}$ [-]	0.26	Δx_{max} [m]	0.61	$\Delta y_{f,max}$ [m]	0.54
$F_{fen,r}$ [-]	0.23	$\Delta y_{m,max}$ [m]	0.19	$\Delta y_{a,max}$ [m]	0.16

Table 6 shows a hefty increase of the motions of the moored vessel. The imbalance of the configuration not only causes an increase in longitudinal motions, it also leads to a transversal motion which is six times higher than in the reference case, due to the yaw motion of the moored vessel. Figure 7 shows the longitudinal motion and the transversal motion of the fore perpendicular, with as abscissa the position of the passing vessel.

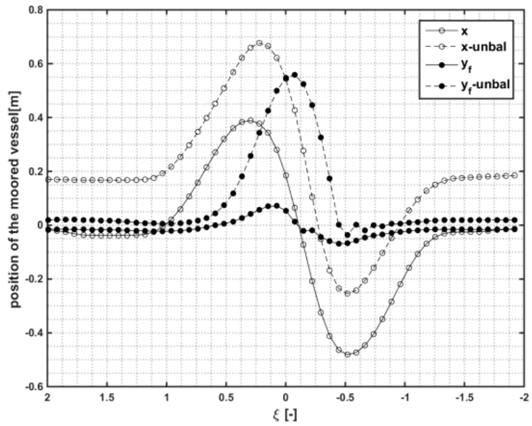

Figure 7: Comparison of x and y_f between the reference configuration (mooring plan A) and the unbalanced configuration (mooring plan C); inbound passage.

7.3 SLACK IN THE SPRING LINES

Even when a good mooring plan is delivered and executed in a satisfying way, maintaining this configuration, with emphasis on the pretension in the lines, is a demanding job. For a start, sufficient highly trained crew members are needed. Additionally, supervision by terminal operators or port authorities is recommended. The captain of the ship must be involved in this process.

As the longitudinal motions are the most critical, we assume in the following example that the pretension in the springs is absent. A possible cause is a change in draft during the (un)loading process and/or a change of water level due to tide. Table 7 shows the simulation results in case pretension is missing in the springs and in case a slack of 1.0 m is present.

Table 7: Results mooring analysis – no pretension and slack in spring lines (mooring plan A).

Pretension in all lines					
$F_{br,r}$ [-]	0.23	Δx_{max} [m]	0.46	$\Delta y_{f,max}$ [m]	0.09
$F_{fen,r}$ [-]	0.11	$\Delta y_{m,max}$ [m]	0.02	$\Delta y_{a,max}$ [m]	0.07
No pretension in the spring lines					
$F_{br,r}$ [-]	0.22	Δx_{max} [m]	0.87	$\Delta y_{f,max}$ [m]	0.27
$F_{fen,r}$ [-]	0.20	$\Delta y_{m,max}$ [m]	0.08	$\Delta y_{a,max}$ [m]	0.21
1.0 m slack present in the spring lines					
$F_{br,r}$ [-]	0.27	Δx_{max} [m]	1.47	$\Delta y_{f,max}$ [m]	0.58
$F_{fen,r}$ [-]	0.32	$\Delta y_{m,max}$ [m]	0.19	$\Delta y_{a,max}$ [m]	0.63

Table 7 shows that the performance of the mooring configuration, can be severely jeopardised by a lack of pretension and in worst case the presence of slack in the springs. Figure 8 shows a comparison of the forces in one of the fore spring lines. The vertical axis shows the force in the line.

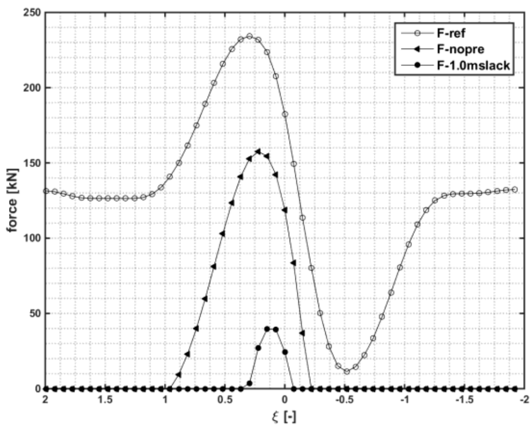

Figure 8: Force in one of the fore springs (mooring plan A): with pretension (F-ref), without pretension in the springs (F-nopre) and 1.0 m slack in the springs (F-1.0mslack); inbound passing vessel.

Figure 8 shows that in the absence of pretension, the spring line is activated in a later stage during the ship passage, which is even more clearly visible when slack is present in the line. The later reaction leads to a smaller total force in the spring. As the total force of the passing vessel on the moored vessel is of equal magnitude for the three cases, the fore and aft lines need to take up more load, when the springs show less response due to slack. As the fore and aft lines are less effective in taking up longitudinal forces, they show large elongations, resulting in substantial transversal motions as well, despite the slack only being present in the spring lines. This case yet again shows the importance of attaining a well-balanced mooring configuration, as slack in four lines, affects the entire configuration.

8. CONCLUSIONS

This paper focusses on the influence of passing vessels on large container vessels moored at quay walls. Simulations, using ROPES and the in-house tool Vlugmoor are performed, calculating the motions of the moored vessel and the forces in the lines and fenders. The paper focusses on the ship motions, as their presence can jeopardize the safety of the (un)loading process.

A reference passing event is presented, where an 18000 TEU container vessel passes a vessel of similar dimensions, in a restricted channel. The mooring plan and ship characterises, including mooring equipment, are given. The breaking strength of each individual line is 140 tons, which is almost twice the IMO/IACS requirement. The regulating bodies also only demand the use of 14 ropes, compared to the 16 lines used for the simulations.

The effect of the elasticity of the ropes, as a design parameter, is investigated, keeping the breaking strength constant. Simulations with very stiff lines (HMPE), elastic polyester lines and very flexible nylon lines, show that the motions of the moored vessel increase substantially with the use of more flexible materials. As motions of the moored ship endangers the safe (un)loading, there is a need to impose regulations by IMO and/or IACS, disallowing the use of very flexible lines for large container vessels.

The mooring plan is investigated from an operational point of view, assuming winches, fairleads and bollards have fixed positions. Ensuring a safe mooring situation comprises of implementing a well-balanced mooring configuration and maintaining it during the stay at the terminal. Crossing the fore and aft lines, leads to a decrease of the movement of the moored vessel, due to an increased efficiency of the lines. An imbalance in the configuration, due to limited bollard availability on the quay, leads to large longitudinal and transversal motions, even when the quality of the individual lines is assured. Again, there is a lack of international regulations, enforcing the use of well-balanced configurations. An approach similar to OCIMF/SIGTTO is suggested, where clear rules are defined and translated into terminal manuals.

The simulation with no pretension in the springs, due to draft or water level changes, shows an increase in longitudinal motion, as can be expected. Because the springs react slower to the passing vessel, the fore and aft lines need to take up more longitudinal forces, causing them to elongate more and generating significant transversal motions as well. This shows that a lack of pretension, only in the spring lines, affects the balance of the entire configuration. A simulation with a one meter slack in the springs magnifies the described effect. Maintaining the mooring configuration must not be neglected, as it can nullify the efforts put into regulating the individual ropes and the mooring plan.

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