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Safety of container ship (un)loading operations in the Port of Antwerp

Impact of passing shipping traffic

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Abstract

Purpose – Economies of scale drive container ship owners towards ordering larger vessels. Terminals need to ensure a safe (un)loading operation of these vessels, which can only be guaranteed if the mooring equipment is not overloaded (lines, fenders and bollards) and if the motions of the vessel remain below set limits, under external forces. This paper aims to focus on the passing vessel effect as a potential disturbing factor in the Port of Antwerp.

Design/methodology/approach – Motion criteria for allowing safe (un)loading of container vessels are established by considering the container handling process and existing international standards (PIANC). A case study simulation is presented where the behaviour of the moored vessel under ship passages is evaluated. Starting from a representative event, the effect of changes in passing speed and distance is discussed.

Findings – The study illustrates the influence of passing velocity and distance on the behaviour of the moored vessel, showing that when passing speeds are higher and/or distances lower than the reference event, safety limits are potentially exceeded. Possible mitigating measures, including the use of stiffer mooring lines and/or a change in arrangement, are discussed.

Research limitations/implications – This paper serves as a basis for future research on safety criteria and optimisation of the mooring equipment and configuration to deal with passing vessel effects.

Practical implications – The presented results can be used by ship and terminal designers to gain familiarity with passing vessel effects and adopt suggested best practice.

Social implications – By restricting the motions of the passing vessels, the focus and general well-being of the crane operator is enhanced, as is the safety of workers.

Originality/value – The paper provides a unique combination of container fleet observation, safety criteria establishment and case study application.

Keywords Ultra large container ship, Safety of container handling, Passing vessel effects, Mooring line arrangement, Mitigating measures

Paper type Research paper

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Symbols and abbreviations

6DOF = Six Degrees of Freedom;
IACS = International Association of Classification Societies;
IMO = International Maritime Organisation;
MBL = Minimum Breaking Load;
OCIMF = Oil Companies International Marine Forum;
PIANC = The World Association for Waterborne Transport Infrastructure;
ROM = Recomendaciones de Obras Marítimas;
SIGTTO = Society of International Gas Tanker and Terminal Operators;
ULCS = Ultra large container ship;
B = Beam of the vessel (m);
d_{pas} = Passing distance side-to-side (m);
L_{OA} = Length overall of the vessel (m);
$O_{-x,y,z}$ = Earth fixed axis system (–);
T = Draft of the vessel (m);
T_d = Design draft of the vessel (m);
V_{pas} = Passing velocity(m/s);
x = Longitudinal position centre of gravity moored vessel in $O_{-x,y,z}$ (m);
x_p = Position midship passing vessel in $O_{-x,y,z}$ (m);
X_p = Longitudinal force passing ship (ton);
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} = Transversal force aft perpendicular passing ship (ton);
Y_{pf} = Transversal force fore perpendicular passing ship (ton);
ε_{br} = Elongation of the line at break (percentage); and
ξ = Non-dimensional representation of x_p (–).

1. Introduction

The shipping industry forms an indispensable link in the global market chain. Nowadays, the seaborne trade accounts for 90 per cent of the worldwide trade (QinetiQ, Lloyd's Register and Strathclyde University, 2013). When focussing on cargo vessels, five main types are identified: container vessels, bulk carriers, tankers, RoRo's and general cargo vessels. These general cargo ships had the leading share in worldwide transport for decades, but have been largely replaced by container vessels. Nowadays, the general cargo fleet consists of small ships (< 10,000 dwt; SEA Europe, 2017). Containers can be easily stacked, which leads to effective use of cargo holds, and are loaded quickly, using gantry cranes. From a perspective of logistics, the containers are easily distributed over the hinterland, using trucks, trains and inland vessels, cutting in the delivery costs and times.

The container fleet evolves towards ultra large container ships (ULCS, > 12,000TEU), which nowadays account for 18 per cent of the total container capacity (SEA Europe, 2017). Ports and container terminals thus need to handle these sea giants on a daily basis. This puts pressure on ports, as they need to keep up with the growth in ship size. While ports and quays (civil works) are destined to past 100 years or more, ships only have projected lifetimes of 20 years, allowing the ship sizes to grow much faster than port and quay infrastructure. Dredging works, combined with terminal renovation, or even development of new quay infrastructure, allow good accessibility of the port. Many ports are faced, however, with limited expansion possibilities, as land becomes scarce, being a trade-off between industrial, demographic and ecological needs.

With more, larger container ships visiting ports, the number of potentially critical passages increases. The passing distance, side-to-side, decreases with increasing ship width. The larger displacement of the vessels adds to the passing force increment. It is thus needed to assess these effects on moored ships, which is the topic of the current paper. The passing vessel effect is discussed in general, citing relevant literature where the hydrodynamics are discussed in detail. The safety of the moored vessel is discussed extensively in the light of external load type and by looking at the container (un)loading process in detail. A set of ship longitudinal (surge) motion criteria is developed based on literature and the in-house experience of Ghent University. A case study, based on study work for the Port of Antwerp (Belgium), is presented, where the behaviour of the moored vessel is simulated numerically for varying passing distance and speed. The passing ship effect is simulated using potential software RoPES. The behaviour of the moored ship is calculated in the time domain using UGent's in-house tool Vlugmoor. As passing distance and velocity are often fixed due to channel restrictions and minimal manoeuvrability needs, mitigating measures, improving the safety of the moored ship at the quay wall, are presented.

2. Container fleet

2.1 History

Container shipping is a relatively new mode of sea transportation. The first vessels sailed in the 1950s, often being general cargo vessels with containers stowed on board. Two decades later, cellular container ships were developed, committing exclusively to container transport. The historical growth in container vessel sizes is largely defined by the size of the most important canals and locks. The Panama Canal, accompanied by two sets of locks on the Pacific and Caribbean sides of the Panamanian isthmus, connecting the Atlantic with the Pacific, is a well-known example. Vessels which could enter the canal, before its 2016 expansion, were called "panamax" (container) vessels, a term which is still around up to this date. These vessels have a maximum length (L_{OA}) of 294 m, a beam (B) of 32.2 m and a 12 m draft (T).

2.2 Present situation

The worldwide economic crisis of the past decade hit the shipping market hard. Despite the declining container freight rates (KPMG, 2016), shipping companies order ULCS, which cut the costs per unit, based on economics of scale. This creates an overcapacity, which led to record breaking scrapping, up to 197 vessels (or 435,000TEU) in the year 2013 (SEA Europe, 2017).

With the construction of the new Panama locks, vessels up to 366 m in length and 49 m in width are able to enter the Canal. They are defined as "neo-panamax" vessels. With the rapid increase of the Asian market, trade routes between Asia and Europe, as well as intra-Asian routes, are growing rapidly (QinetiQ, Lloyd's Register and Strathclyde University, 2013), not being limited to the Panama lock sizes. The Suez Canal, connecting the Mediterranean and the Red Sea, poses no restrictions to the current container vessel fleet. The maximum allowed air draught, as defined in Figure 1, is limited to 68 m. (Suez Canal Authority, 2015). Latest generations of container vessels have an air draught of around 64 m, which means that newer generation vessels might face restrictions.

Nowadays, the largest container ships have a length of 400 m and a beam of 59 m, allowing 23 container rows on deck, typically with ten tiers below deck and ten tiers above deck (see Figure 1 for definitions). These vessels are most known as 18,000TEU vessels. Some shipbuilders add one more tier of containers in deck and/or hold, increasing the capacity up to 22,000TEU. The largest vessel which visited the Port of Antwerp up to this date is the *Cosco Shipping Universe*, carrying around 21,000TEU containers (Figure 2).

2.3 Future perspective

From a structural perspective, ships with much larger dimensions and deadweight have been designed and constructed. The most known example here are the ultra large crude carriers, also called supertankers/mammoth tankers. As these tankers only call at a limited number of ports and often discharge offshore, there are no draft restrictions. Container vessels call at various ports and often need to reach quays located in shallow water areas, limiting the draft and overall dimensions of the container ships. The largest vessels on order at the moment are so-called MegaMax24 vessels (Louppova, 2017), with 24 rows, 24 tiers and 24 bins, having a length of 400 m and a width of 62 m. Their depth and air draught also increase to host 24 tiers (12 on deck and 12 below deck). Port development studies already take into account future ship dimensions. The study regarding the creation of extra container capacity in the Port of Antwerp considers container vessels with a length (L_{OA}) of 430 m and a beam of 62 m (Eloot *et al.*, 2017).

3. Passing vessel effects

When a vessel moves through the water, a pressure field develops around the vessel, causing a primary wave, followed by shorter wake waves. These secondary waves are denoted by short periods, which in most cases do not significantly affect the moored vessel. The effect of the primary wave can be assessed using empirical formula, numerical models and physical modelling, the latter also modelling the wake of the passing vessel. In general,

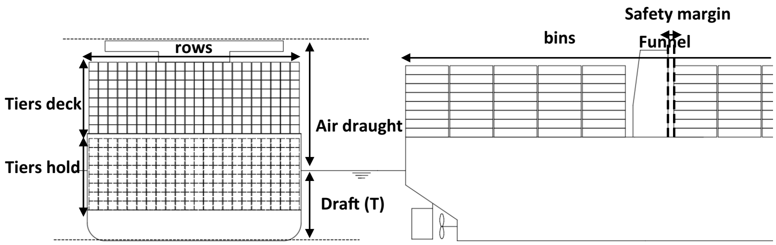


Figure 1.
Stern view (left) and side view (right) of a container vessel

Figure 2.
Approach to the Port of Antwerp of the COSCO Shipping Universe, © Sven Goyvaerts

the forces generated on the moored vessel scale with the speed squared, the displacement and the inverse of the passing distance (Talstra and Bliek, 2014). In a first assessment, analytical expressions can be used. These have been developed by Flory (2002), Varyani and Vantorre (2006) and Seelig (2001) amongst others. The application of these formula is of course limited because of the specific data set which has been used to perform the regression analysis.

When a quay is present, for example, the flow pattern around the moored vessel changes considerably, causing the surge force to nearly double and the sway force to decrease significantly compared to the open water case (Pinkster, 2004) (Denehy *et al.*, 2015) (Van der Molen *et al.*, 2011). The double-body potential package RoPES (Pinkster and Pinkster, 2014), the result of the RoPES JIP project, is used in the current paper, enabling to model the forces acting on the moored vessel when berthed at quay wall. It has been validated based on an extensive set of physical model test (Talstra and Bliek, 2014), as well as full-scale measurements (Wictor and van den Boom, 2014). It is a fast and user-friendly tool which can used to systematically model ship passages, where passing distance, speed and draft and water depth can be varied easily. Slopes and bathymetries can also be introduced as harbour parts, making it possible to model main channel and berthing zones with different water depths.

As with all numerical tools, there are some limitations to the usage of the software. In RoPES, the water plane is modelled as a fixed mirror plane. This means that squat of the passing vessel is not modelled, causing an underestimation of the passing vessel forces in confined and restricted waters (Talstra and Bliek, 2014). Free travelling waves, arising due to a variation in the pressure field (change in ship speed or change in section), are also not accounted for when using a fixed water surface. In general, when the geometry becomes complex, it is always advised to perform physical model tests. This also allows to model the fenders and lines, making it possible to evaluate the full dynamic behaviour of the system (Bhautoo *et al.*, 2015) (Cornett *et al.*, 2008).

Another interesting modelling technique concerns the use of computational fluid dynamics (CFD) to model complex (viscous) flow patterns, which cannot be modelled using potential codes and which suffer from scale effects when performing physical scale model tests. Some cases where CFD should be used is with changing flow sections (Toxopeus and Bhawsinka, 2016) and when vessels sail with a non-zero drift angle (Bunnik and Toxopeus, 2011).

4. Safety of moored vessels

A congestion of existing ports and an increase in ship dimensions (e.g. wind area of container and cruise vessels) drive the industry towards studying the origin and magnitude of external forces, as well as their effect on moored vessels. The safety of moored vessels is of prime importance to assure a smooth loading operation, with no delays and damage to any infrastructure and no casualties amongst workers. This discussion must be held in the light of the type of moored vessel and the (most prominent) external disturbances.

4.1 Cyclic loads vs singular load peaks

A key factor in the discussion concerns the nature of external load. A continuous wave action exhibits cyclic forces on the vessel, which cause the mooring system (lines and fenders) to suffer from cyclic loading. The creep induced by cycling loading in the lines can cause failure below the theoretical minimal breaking load (OCIMF, 2018). If the remaining lines cannot cope with the extra loading, a chain reaction will cause all the lines to break eventually, as the external force is continuously present. In case the mooring lines are able to resist the external forces, the motions of the vessel will negatively impact the efficiency of the process and the safety of the operation.

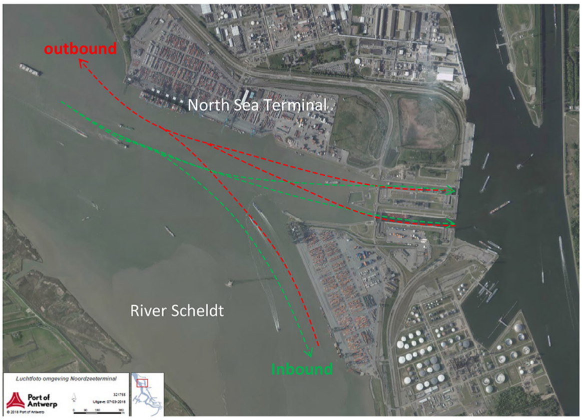
A transient load (passing vessel) causes a reaction in the mooring system, which disappears shortly after the passage because of damping present in the system. Due to the magnitude of the peak load, one or more lines could break. The aforementioned cascade effect could also be present; however, because of the fact that the load is singular, the possibility exists that the ship remains moored using the remaining lines. In all cases, breaking of lines is dangerous and could cause injuries or even fatalities amongst crew members (DMA, 2006).

For the Port of Antwerp, there were 14,473 port calls of seagoing vessels in 2016 (Port of Antwerp, 2017), leading to 28,946 passages a year at the most downstream container terminal (North Sea Terminal, Figure 3). Most of these passages only have a marginal effect on the moored vessel, with occasionally a potentially critical event. These few passages do not influence the daily efficiency, as they do not occur on a daily basis.

4.2 Tankers vs dry cargo vessels

The unloading process is characterised by the vessel type and the equipment on the quay. From the perspective of vessel type, there is a big difference between tankers, using pipes for gas/fluid transfer and dry cargo vessels, needing conveyor belts or cranes (on board or on the quay). Tank terminals, including oil and LNG/LPG, operate under uniform guidelines issued by OCIMF and SIGGTO. If the moored vessel moves with respect to the loading arm, an alarm is triggered as a first warning. In next stages, the discharge operation is interrupted and eventually the arm is decoupled. Limits are thus imposed based on mechanical limits of equipment.

For container ships, and dry cargo vessels in general, ship motions could have various safety implications, including damage to ship and infrastructure and casualties amongst workers. These limits, however, are not strictly mechanical and follow from considerations and in-depth analysis of all the processes involved. For container vessels, such analysis is made in the next chapter, serving as a basis for more extensive research and debates to be held in an international context. This falls within the scope of PIANC WG186 and WG212, which are discussed below.



Notes: Red: outbound; green: inbound
Source: Eurosense, commissioned by Port of Antwerp'

Figure 3.
Passing shipping traffic at North Sea Terminal, Port of Antwerp

5. (Un)loading process container vessels

The biggest advantage of container vessels over general cargo vessels is that the time that the ship spends at the berth is limited because of the fast loading and unloading operations. Terminals want to attract shipping lines by offering fast and reliable operations. To achieve this, the time that loading needs to be paused (downtime) needs to be limited. The operation can only be reliable if high safety conditions are fulfilled, even in the presence of high, singular loads, such as passing vessels.

The vessel moves in six degrees of freedom (6DOF), three translations and three rotations (Figure 4). The hoisting system is able to account for limited roll, yaw and pitch. Heave motion does not affect the operation, as it is along the hoisting direction. The sway motion can be corrected by moving the trolley along the rail (Figure 5). Correcting for the surge motion, however, is impossible, as this requires the whole crane to move along the quay.

5.1 The handling process

The containers are handled using spreaders, connected to a trolley, which moves laterally over the arm of the gantry crane (Figure 5). A detailed image of a dual-hoist system is given in Figure 6. During operation, the operator is located directly above the trolley, looking downwards, which limits the vision, making it impossible to anticipate passing vessel events. Each time that the ship moves substantially, the focus and general mental state of the operator are affected. The current topic thus also considers the general well-being of the operator.

5.2 Efficiency of the operation

Existing recommendations focus on ensuring a required minimal efficiency of the operation. A contribution regarding this issue was made by PIANC WG24 (PIANC,

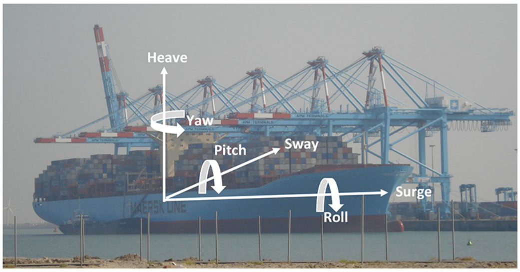


Figure 4. Moored container vessel, definition 6DOF

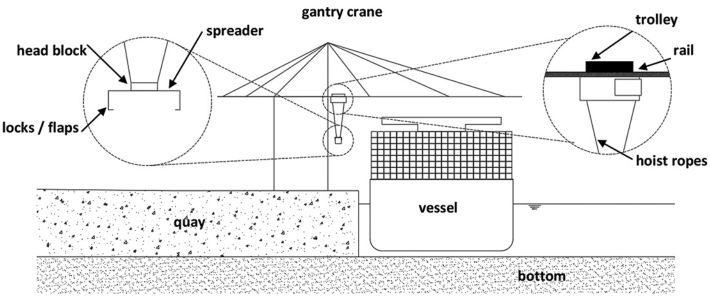


Figure 5. Handling of containers: different parts of gantry crane set-up

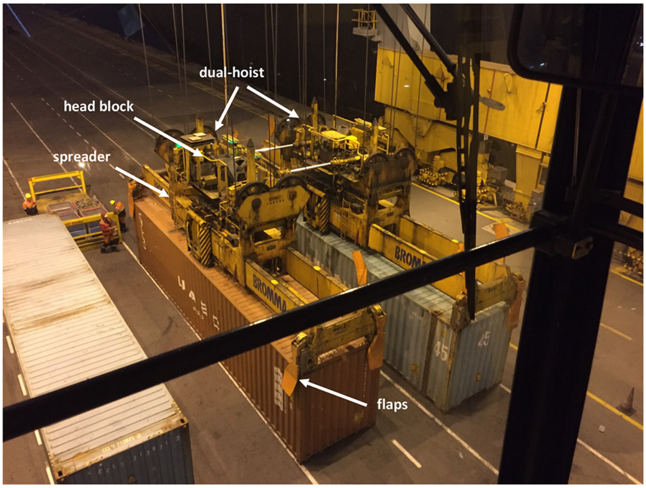


Figure 6.
Detail of dual-hoist trolley system

1995), giving criteria for peak-to-peak motions (50 and 100 per cent loading efficiency) based on numerical studies (Ueda and Shiraishi, 1988) and interviews with ship crews and operators (Jensen *et al.*, 1990). PIANC WG 115 (PIANC, 2012) focusses specifically on criteria for (un)loading container vessels, citing work from, amongst others, D'Hondt (1991). Tabular values mentioned in both reports are still widely used as design criteria, despite the fact that some sources might be considered outdated and the presence of subjectivity in determining some limits. WG 115 rightfully focusses on the surge motion, defined as significant motion amplitude along the quay wall. This is not just from the perspective of the crane operation, which cannot react to surge motion and would have to reposition each time. The large passing vessel surge forces when moored at a quay wall add to the problem. In this paper, all motions are expressed as amplitudes or maximum excursions relative to a starting equilibrium position.

For periodic motions, a statistical analysis can be performed based on significant exciting forces (e.g. due to waves) and the resulting significant motions. The allowed motion before operation needs to be halted depends on several factors. When locks are used, motions of 0.1 m are permissible, and the use of spreader flaps allows motions of 0.2 m (PIANC, 2012). The human factor, being the skill and focus level of the operator, plays an important role as well, but is hard to take into account in models. Disregarding the human factor, significant surge motions up to 0.2-0.4 m (locks) (spreader flaps) lead to an acceptable handling efficiency of 95 per cent (PIANC, 2012).

5.3 Safety of the operation

When the moored vessel moves along the quay due to passing vessel effects, it will have a marginal effect on the overall efficiency, as (critical) ship passages are limited over the stay of the vessel at the berth. Large motions, however, pose potential safety issues for the moored vessel. From a statistical point of view, significant values are transformed to the (most probable) maxima by multiplying them by a factor of 1.7, assuming a Rayleigh distribution of the variable. Significant motions of 0.2 and 0.4 m correspond with maximum motions of 0.34 and 0.68 m, respectively. The big downside of using this approach is that it still builds on efficiency considerations.

PIANC WG 186 (active since 2016), which two of the authors are part of, focusses on the safety of large vessels at a quay. A big safety issue for container vessels involves contact between crane and vessel, as this affects both the quay infrastructure and the safety of the ship, crew and workers. As the container market operates on narrow margins, the deck space available for containers is maximised. This leads to limited space between the containers and both the accommodation (bridge) (Figure 7) and the funnel (Figure 1). Additionally, there is an increase in container tiers on deck (12 for MM24 vessel), leading to a larger air draught, beyond the expectations of the terminal operator at the time of the terminal's design. This leads to situations where the bridge of the vessel is located above the level of the crane arm (Figure 4), which creates potentially dangerous situations when the moored vessel starts to move along the quay.

Collisions not just lead to large repair works and inaccessibility of the terminal, the possibility of human casualties is even more worrisome. In addition, the crane operator feels uncomfortable in this condition, leading to loss of concentration, even if no damage occurs. A good mental condition of the operator is an important factor in the overall (long-term) safety of the process.

5.4 Motion criteria passing vessel events

Ghent University has been involved in several mooring studies, involving passing vessel effects. To evaluate the results, motion criteria have been established. They take into account the proposed values in WG24 (based on numerical simulations and crew experience) and WG115 (detailed efficiency considerations), as well as clearance between ship structure and cranes. The criteria have also been discussed with the terminal operators, confirming that 0.40 m surge motion is acceptable during loading operation in case of a passing event. There are currently two limits used to evaluate the mooring analysis. The critical motion amplitude is set at 0.5 m, which coincides with the surge limit according to WG24 for 100 per cent efficiency and holds the middle between the values from WG115 for 95 per cent

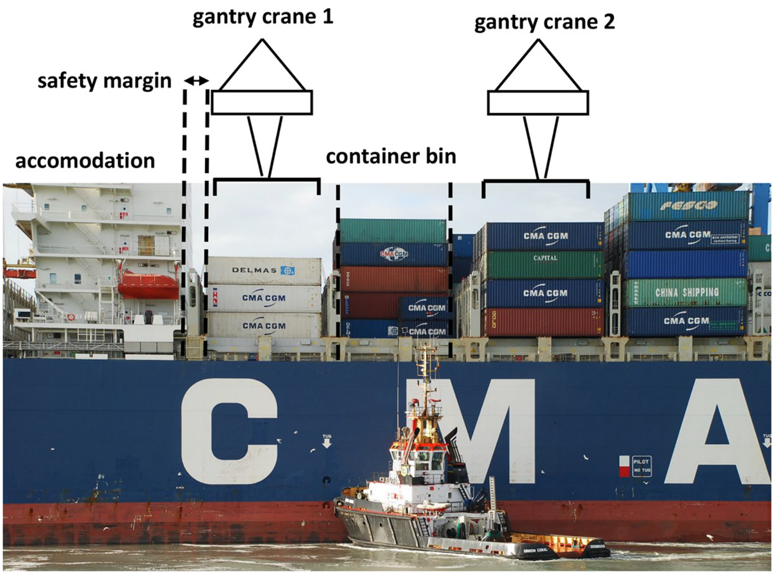


Figure 7.
Safety clearance between accommodation and container bin

efficiency (0.34 m and 0.68 m in function of the spreader system). The maximum limit is set at 1.0 m, referring to the 50 per cent efficiency limit of WG24.

5.5 PIANC WG212

In the previous discussion, a hard distinction was made between efficiency and safety considerations with respect to ship motions, which is certainly the correct approach to follow. There is, however, a need for a document to extensively discuss these categories (and maybe add more nuances in the process). PIANC clearly recognised this issue by launching a new working group entitled “Criteria for acceptable movement of ships at berths” in 2018. In the terms of reference, the terms “safe mooring” and “loading efficiency” are defined and express the need for different governing criteria.

6. Case study

The influence of passing vessels on moored container ships is explained using an exemplary case, based on study work for the North Sea Terminal (Figure 3) in the Port of Antwerp, which is representative for a passing event in a large container port. As the prime interest for mooring studies are large vessels, both the moored and the passing vessel are neo-panamax container vessels, carrying around 13,000TEU. The characteristics of both vessels are given in Table I; L_{oa} is the total length of the vessel, B is the beam, T_d is the design draft and T is the draft of the vessel during the simulation.

6.1 Governing parameters passing event

Passing vessel events can lead to complex effects on moored vessels (e.g. generation of free waves, Section 3). In this case study, the event is simplified to a parallel passage in a uniform section with constant speed and no drift angle, for which the potential package RoPES has been extensively validated. As indicated previously, the forces acting on the moored vessel are proportional to the inverse of the passing distance (d_{pas}^{-1}) and the speed squared (V_{pas}^{2}). For shallow and confined water, the dependency between speed and passing vessel force is more than quadratic. A correction factor to account for this is proposed by Talstra and Bliek (2014). If the terminal is located along a main fairway, significant passing velocities (V_{pas}) are expected. A minimal passing velocity is needed to manoeuvre the vessel, in strong wind and current, and to ensure a good traffic flow in the port.

The passing distance (d_{pas}), defined side-to-side (Figure 13), is a function of the beam of the vessels and the channel width. Based on experience, the cases given in Table II are denoted by passing distances with values of approximately two, three and four times the

Table I.
Characteristic parameters moored and passing 13,000 TEU vessel

L_{oa} [m]	B [m]	T_d [m]	T [m]
366.0	48.2	15.2	13.6

Table II.
Passing distance and velocity for modelled passing events

		V_{pas} [m/s] ([knots])		
		3 (5.8)	**4 (7.8)**	**5 (9.7)**
d_{pas} [m]	**100**	-	✓	-
	150	✓	✓	✓
	200	-	✓	-

ship's beam. The reference event is chosen based on the maximum passing speed (4 m/s or 7.8 knots) and minimum passing distance (150 m), logged in the period January-February 2018 at the North Sea Terminal (Figure 3). Starting from this event, a variation in passing distance (100-200 m) and in passing speed (3-5 m/s) has been considered to simulate milder and more severe passing events.

6.2 Mooring line arrangement

The mooring line arrangement or mooring plan is defined based on quay and vessel design. The mooring plan is the end responsibility of a ship's captain. The quay wall equipment (fenders and bollards) are fixed with the bollards placed close to the vertical quay side so as to not obstruct the gantry crane rails (Figure 8). The bollards are positioned every 21.5 m, with sufficient capacity to connect two lines to each bollard. High impact fenders are positioned at every bollard position. The hull makes contact with 11 fenders based on the parallel middle body of the ship. The fenders have a capacity of 396 tons, modelled as linear deflecting, reaching maximum reaction force at 0.25 m of displacement. The friction is assumed to be negligible (0.02 friction coefficient), which is a conservative approximation when the surge motion is investigated.

The vessel's equipment includes mooring winches, bitts, roller guides and fairleads and is also fixed during the design phase of the vessel (Figure 9). These elements cannot be moved around the deck easily, as the anchoring structure is part of the main structural design of the ship's hull. The equipment itself is not elaborated on in this paper but should be a topic for future research. Winch design, operation and regulation, for example, have a significant impact on the safety of the moored ship in mooring operations.

Mooring lines are part of the ship equipment as well, but they need to be replaced every so often due to wear. The line type and properties could thus still be altered (Section 7) when the lines are replaced. Important parameters here are the minimum breaking load (MBL) of the line and the elongation at break (ε_{br}). For the reference case, the MBL of each line is 160 tons and the elongation at break is 20 per cent with linear stress-strain behaviour. This coincides with a good quality synthetic mooring line, which is showing considerable

[redacted]

Figure 8.
Quay wall: fender, bollard, crane rail and ship: fairlead

Source: Image courtesy of Antwerp Port Authority

Figure 9.
Ship: winch, bitt and roller guide

elongation at break. Its behaviour is in between the polyester and nylon curve in the MEG4 (OCIMF, 2018) (Figure 10).

A pretension level of 10 per cent MBL is assumed. This coincides with good practice, where pretension should be between 5 and 10 per cent MBL. Lack of pretension causes large motions, as has been shown in Zwijnsvoorde *et al.* (2018). Where the motions are limited to 0.46 m with pretension in lines, the motions increase to 0.87 m (no pretension in springs) and 1.47 m (with 1.0 m slack in spring lines prior to the ship passage (Van Zwijnsvoorde and Vantorre, 2017))!

Large motions are caused by the highly elastic response of the line at low tension and the build-up of vessel momentum during initial movement. Note that maintaining appropriate pretension in the lines is a labour intensive task, certainly when tidal differences and

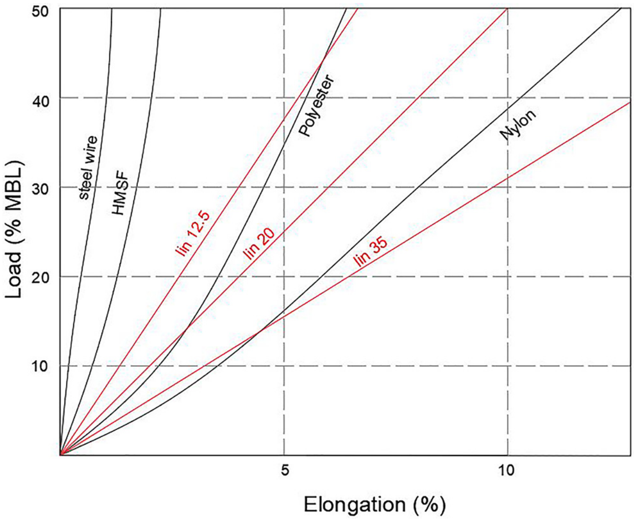


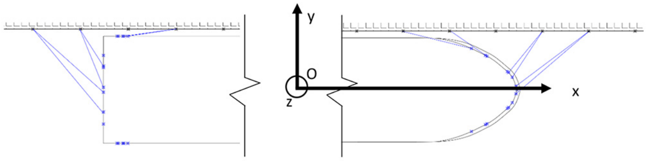
Figure 10.
Mooring line characteristics OCIMF MEG4 (Figure 1.9, p17; OCIMF, 2018), with added linear lines modelled in this paper

changes in draft are present. For container vessels, the change in draft is generally limited during the stay at the berth. For bulk carriers, however, which usually arrive in ballast and leave fully loaded or vice versa, the change in draft is significant and needs to be compensated by active mooring line management. All vessels moored in a tidal environment (with water level changes, as well as currents) and need to manage their lines carefully during the stay at the berth.

The mooring line arrangement consists of a number of lines in a certain geometrical configuration, which should be well-balanced at all times. Port authorities will often impose a minimum number of lines to be used; a fixed mooring plan from the side of the terminal operator is, however, rather rare. This differs from tankers and particularly LNG carriers, where mooring configurations need to be approved by the local port authority. A good mooring plan for the study at hand is given in Figure 11.

6.3 Mooring simulation

Assessing the behaviour of a moored vessel requires dedicated dynamic time domain simulation software, such as Ghent University's in-house mooring tool Vlugmoor. An overview of the simulation process and the required numerical input is given in Van Zwijnsvoorde and Vantorre (2017). The passing ship forces are calculated using RoPES. For the reference case (4 m/s, 150 m), the passing ship forces are shown in Figure 12. The surge force (X_p) and lateral forces at fore and aft perpendicular (Y_{pf} and Y_{pa}) are displayed in function of the position of the passing vessel's midship relative to the moored vessel, expressed as ξ:



Notes: Aft and fore of vessel are displayed; earth fixed axis system O-$_{x,y,z}$ is indicated

Figure 11.
Reference mooring plan (Plan I)

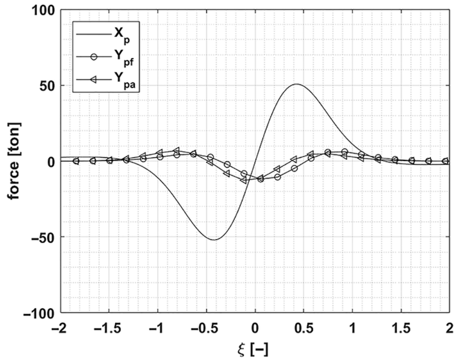


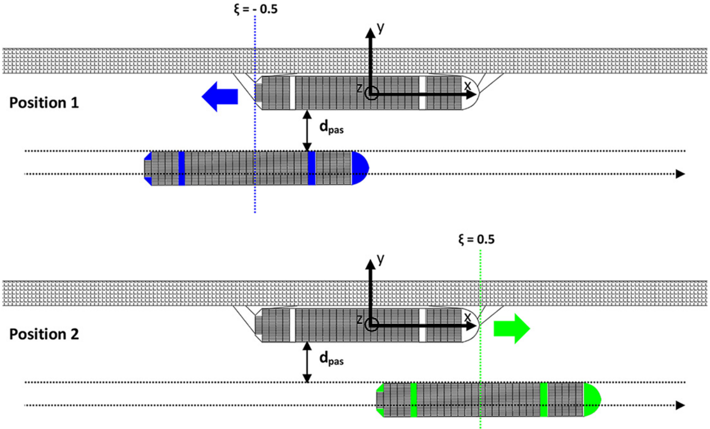
Figure 12.
Passing ship forces calculated with RoPES for the reference passing event (V_{pas} = 4 m/s, d_{pas} = 150 m)

$$\xi = \frac{x_p}{L_{oa}}$$

At $\xi = -0.5$, the passing vessel's bow reaches the moored vessel's stern (Figure 13 [top], Position 1). Around this moment, the negative surge force is maximal. Around $\xi = 0.5$, (Figure 13, bottom, Position 2), the positive surge force is maximised. It is confirmed that the surge force (X_p) is significantly higher than the lateral forces (Y_{pf}, Y_{pa}) when the ship is moored at a quay wall.

The Vlugmoor simulation results are time series for forces (mooring lines and fenders) and motions (in 6DOF). The results for all cases, given in Table II, are summarised in Table III. The line and fender force are given relative to their maximum load ($F_{br,r}$ and $F_{fen,r}$, respectively). The motions are expressed relative to the equilibrium position of the ship after pretension is applied in the lines. They are given as absolute values of longitudinal motion (x) and transversal motion fore, midship and aft (y_f, y, y_a), relative to the equilibrium position reached after pretension in lines has been applied.

Table III confirms that the surge motion (x) is the most critical parameter to assess the passing ship effects. Figure 14 shows the moored vessel's motion along the quay wall for the passing events defined in Table II. The critical and maximum motion limits are indicated as Limit 1 and Limit 2, respectively. The line forces only reach 16 per cent MBL in the reference event and 22 per cent MBL at higher passing speed. The maximum force in all lines for the



Notes: Position 1 (blue): negative surge force on moored vessel
Position 2 (green): positive surge force on moored vessel

Figure 13. Passing event

Table III. Simulation results for the passing events described in Table II

V_{pas} [m/s] ([knots])	3 (5.8)			4 (7.8)			5 (9.7)		
d_{pas} [m]	100	150	200	100	150	200	100	150	200
$F_{br,r}$ [-]	-	0.13	-	0.21	0.16	0.13	-	0.22	-
$F_{fen,r}$ [-]	-	0.04	-	0.19	0.06	0.04	-	0.19	-
|x| [m]	-	0.23	-	1.04	0.54	0.32	-	1.16	-
|y| [m]	-	0.00	-	0.07	0.00	0.00	-	0.06	-
|y_f| [m]	-	0.01	-	0.11	0.02	0.01	-	0.11	-
|y_a| [m]	-	0.01	-	0.26	0.02	0.01	-	0.23	-

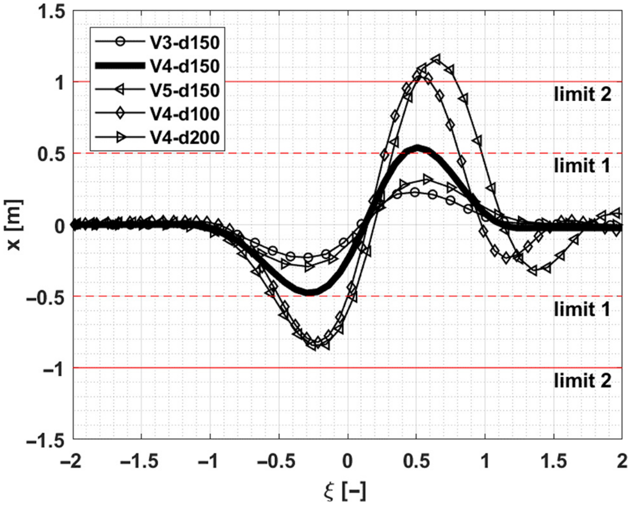


Figure 14.
Surge motion x [m] moored vessel for the passing events described in Table II

reference case are given in Figure 15, along with the OCIMF limit of 50 per cent MBL. The fender forces are very limited as are the transversal motions, certainly when comparing to the surge motions.

Table IV is a condensed version of Table III, only giving the longitudinal motions in function of passing distance and velocity to assess the effect of both parameters on the surge

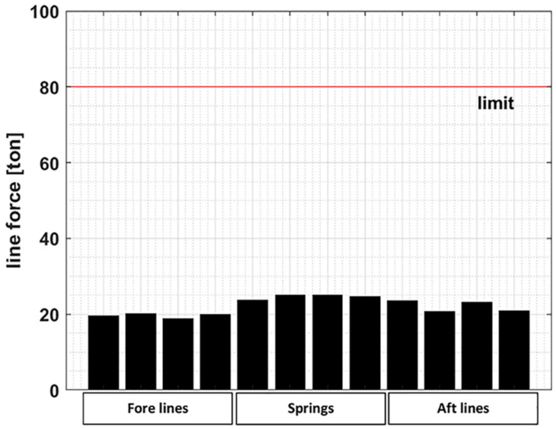


Figure 15.
Forces (ton) in the mooring lines of the vessel – reference passing event

Table IV.
Surge motion |x| [m] for the passing events described in Table II

		V_{pas} [m/s] ([knots])		
		3 (5.8)	4 (7.8)	5 (9.7)
d_{pas} [m]	100	-	🟥 1.04	-
	150	🟩 0.23	🟨 0.54	🟥 1.16
	200	-	🟩 0.32	-

motion of the moored ship. At the reference passing event (4 m/s at 150 m), which is the combination of maximum passing speed and minimum passing distance measured at North Sea Terminal, the lowest limit of 0.50 m is marginally exceeded (marked in yellow). Still, this could potentially lead to an unsafe situation. If the passing distance decreases to 100 m or the velocity is raised to 5 m/s, the motions are 1.04 and 1.16 m respectively, exceeding the second motion limit of 1.00 m (marked in red). These motions pose direct safety threats and are thus unacceptable.

When only considering passing ship impact, there are two options to restrict the motions to values below 0.50 m. An increment in passing distance to 200 m or a decrease in passing speed to 3 m/s lead to motions of 0.32 and 0.23 m, respectively (marked in green). As discussed before, changing these parameters is in most cases not possible or desirable. Assuming that the passing parameters (ship, velocity and distance) are fixed, there are still several measures which can be taken. This paper elaborates on the elasticity characteristics of the lines and the mooring line arrangement, as well as suggests line tension monitoring to ensure pretension in the lines.

7. Mitigation measures

In this final section, three possible mitigating measures are discussed. In a first part, the benefit of using stiff mooring lines is shown. For completeness, the effect using highly elastic mooring lines is given. Optimising the mooring line arrangement for specific environmental conditions, passing vessel effects in this case, is an option. At all times, unbalanced mooring plans need to be avoided. Insufficient pretension or slack in the lines will always result in large motions. For this reason, the pretension in the mooring lines is regularly controlled by the dock masters in the Port of Antwerp. However, a good system to monitor the loads in the lines constantly could support the mooring management during the stay at the berth.

7.1 Use of stiffer lines

A rather simple and intuitive option to influence the behaviour of the moored ship is to change the properties of the mooring lines of the vessel. As the winches and fairleads are designed based on the vessel's MBL, a stronger line cannot be used. The elasticity of the lines, however, can change in function of the line type (polyester, HMPE, nylon, … [Figure 10]), which is adopted. As previously indicated, all simulated lines are assumed to have a linear stress-strain curve up to the breaking load in the current study. Next to the reference line, which has an elongation at break of 20 per cent, a much stiffer line with ε_{br} of 12.5 per cent is selected (Figure 10), which coincides with a polyester line of high quality. Unfortunately, vessels are also in some occasions outfitted with highly elastic nylon lines, which have ε_{br} of 35 per cent (or even higher!). These lines are less appropriate to moor large container vessels.

The results of the simulations are summarised in Table V. It is seen that the mooring line and fender forces are again limited, as are the transversal motions. It is interesting to see

Table V. Simulation results for the reference passing event (V_{pas} = 4 m/s, d_{pas} = 150 m), three line elasticities

ε_{br} (%)	12.5	20	35
$F_{br,r}$ [-]	0.15	0.16	0.16
$F_{fen,r}$ [-]	0.06	0.06	0.06
$\|x\|$ [m]	0.31	0.54	0.97
$\|y\|$ [m]	0.00	0.00	0.00
$\|y_f\|$ [m]	0.02	0.02	0.02
$\|y_a\|$ [m]	0.02	0.02	0.02

that the change in stiffness does not significantly influence the maximum line forces, where intuitively a stiffer system would attract more forces. In these cases, the stiffer lines restrict the motion, however, which means that less motion energy is present in the dynamic system. In these cases, both factors seem to balance out. It is premature to generalise this conclusion here; in addition, there are other reasons why elasticity in the system is needed. Stiff short lines would overload quickly, leading to breaking of the lines. Through stretching, the lines also helps to dampen out peak loads, which could lead to snapping of lines. Furthermore, the presence of hysteresis in elastic lines is beneficial for energy dissipation. A last aspect here concerns the dynamic reaction of the whole system. A stiff system will resonate at higher frequencies, which may be close to swell wave excitation frequencies.

The time series of the longitudinal motions is given in Figure 16. When stiff lines are used, the motion lowers to 0.31 m (−43 per cent with respect to reference case!), which is well within the critical limit. The motion reaches 0.97 m when highly elastic lines are used, which is close to the maximum limit. It should be borne in mind that all alternatives considered above are in line with guidelines issued by IMO/IACS. These recommendations fail to incorporate line elasticity as a design parameter, as they only formulate guidelines for MBL and required numbers of lines [see Van Zwijnsvoorde and Vantorre (2017) for discussion on the 2005 rules and IACS (2016) for the updated 2016 regulation]. For oil tankers, the line elasticity is indirectly covered by OCIMF guidelines (OCIMF, 2018), where steel wires or synthetic lines with higher stiffness (e.g. HMSF) are recommended for use on large tankers.

7.2 Optimised mooring line arrangement

The mooring operation influences the behaviour of the vessel to a large extent and is always the end responsibility of the captain, who is often assisted by the pilots, the linesmen ashore and port authority/terminal operator. For tankers, the mooring plan is usually fixed, according to a terminal manual, as these berths are designed as dedicated jetties and constructed for a design vessel (or a known range of design vessels) based on OCIMF standards (OCIMF, 2018). Container vessels are often moored at various locations along the quay depending on the occupation of the berth and do not follow an obligatory mooring line arrangement. The minimal number of lines which needs to be used is in some ports regulated by the harbour captain. For the 13,000TEU vessel at hand, Antwerp Port Authority demands the use of at least 12 lines (4 fore lines, 2 fore and 2 aft springs and 4 aft lines) (Havenkapitiensdienst, 2017).

Figure 17 shows the mooring plan which was already presented in Figure 11, which is noted as “Plan I” or the reference plan. Plan II is an example of an optimised configuration to

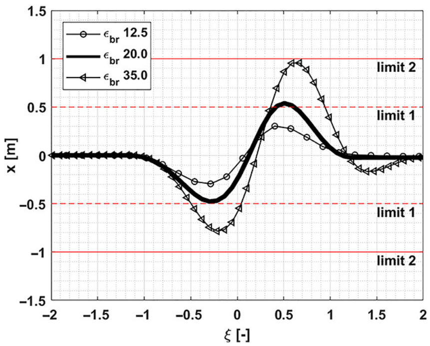


Figure 16.
Surge motion x [m] for the reference passing event (V_{pas} = 4 m/s, d_{pas} = 150 m), three line elasticities

cope with surge forces due to passing vessels by aligning the lines with the quay face, in line with the external surge force. In Plan III, the line arrangement is very compact, with fore lines which have an orientation more perpendicular to the quay, which limits their capability of generating a reaction force in the surge direction.

The results of the mooring simulation are summarised in Table VI, with the motion time series given in Figure 18. When considering the most efficient mooring Plan II, the motions are reduced by nearly 20 per cent, to 0.44 m, compared to Plan I. If the plan is compact (Plan III), the surge motion increases to 0.68 m. It should be noted that due to high occupancy rates, Plan II, which requires significant space between the moored vessels, might not be feasible. However, line arrangement like shown in mooring Plan III should still be avoided when significant passing vessel effects are expected. When looking at the line forces in Table VI, it is seen that the maximum line force also increases with Plan III. Taking care of the mooring arrangement is thus necessary to limit both motions, as well as line forces.

Recommendations concerning minimum free space in between ships are available. An example can be found in the Spanish ROM (ROM, 2007). These deterministic approaches, however, focus on manoeuvring space needed during berthing of a vessel and thus need to be treated with care within the current context. The case presented here displays the need to come up with guidelines for needed mooring space, as an inferior mooring line arrangement could ruin all the efforts made in the design phase.

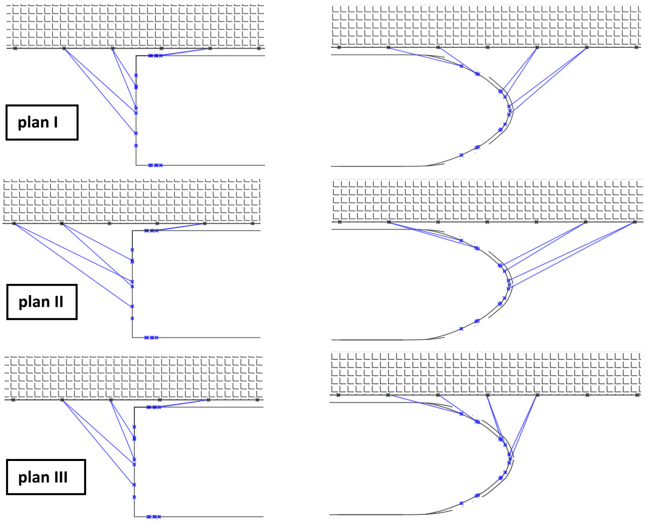


Figure 17.
Mooring plan I (reference); optimised mooring plan (II) and compact mooring plan (III)

Mooring plan	I	II	III
$F_{br,r}$ [-]	0.16	0.15	0.22
$F_{fen,r}$ [-]	0.06	0.05	0.08
$\|x\|$ [m]	0.54	0.44	0.68
$\|y\|$ [m]	0.00	0.00	0.02
$\|y_f\|$ [m]	0.02	0.01	0.04
$\|y_a\|$ [m]	0.02	0.02	0.08

Table VI.
Simulation results for the reference passing event (V_{pas} = 4 m/s, d_{pas} = 150 m), three mooring plans

7.3 Mooring line tension measurement

In Section 6, the importance of ensuring an appropriate pretension level and the operational difficulties to maintain this level have been discussed, referring to simulation studies showing the effect of absence of pretension on the motion of the moored vessel. The largest difficulty in maintaining a suitable tension level is that the tension in the lines is a priori unknown. A tension measurement system, with feedback to the captain and crew, would greatly support the operation.

At oil and gas terminals, mooring hooks are in some cases equipped with load cells, which are part of an integrated system. Such systems are already well-established and available in the market. Some examples here are MoorAlert (Strainstall, 2018) and SmartHook (Trelleborg Marine Systems, 2018).

These load monitoring systems, however, rely on the easy installation on mooring hooks, which are installed at fixed positions. Container vessels use different sets of bollards, making it harder to install such a system on each bollard on the quay. An elegant solution here would be to incorporate the load measuring device in the mooring line. This is already a well-known practice for deep sea mooring [Inter-MPulse (Prentice, 2013) and LCM (LCM, 2017)]. These measuring units are, however, voluminous and heavy, which make it hard to use them in everyday mooring operations. Wilhemsen (World Maritime News, 2018) has made some progress in merging the unit with the ropes, making it easier to handle. This system would allow ships to improve their line management, avoiding low pretension levels (or high tension in lines) and slack.

8. Conclusion

The effect of a passing ship on a container vessel moored at a quay wall in a restricted channel is investigated using numerical packages of RoPES and Vlugmoor (in-house UGent). A representative case study for a big container port with limited fairway width, as is the Port of Antwerp, is discussed. The simulations, including some worst case scenarios, show potential critical longitudinal ship motions (surge, along the quay), with mooring line forces being low to moderate. Specific motion criteria for moored container ships under passing ship forces are not found in literature. An attempt is made to come up with criteria, starting from existing literature (PIANC WG24, 115). This is combined with feedback from terminal operators and safety considerations based on possible contact between crane and ship. The critical and maximum surge motion (amplitude) limits are set at 0.5 and 1.0 m,

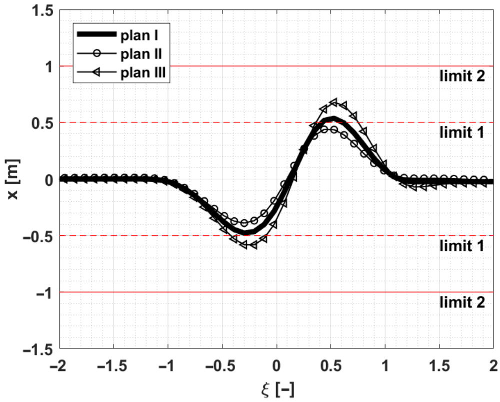


Figure 18.
Surge motion x [m], for the reference passing event (V_{pas} = 4 m/s, d_{pas} = 150 m), three mooring plans

respectively. Future work includes further research on these limiting motion criteria, which will also be done in the scope of PIANC WG212.

Lowering passing vessel speed and maximising passing distance results in a significant reduction in motion, but is in most cases not possible due to channel width restrictions and/or not desirable from the viewpoint of ship manoeuvrability and traffic flow. Mitigating measures are proposed to increase the safety of moored container vessels during the (un)loading process:

- Use of stiffer mooring lines leads to lower motions (−43 per cent compared to reference), with no increase in line forces.
- Aligning lines with the quay side increases the efficiency to cope with surge forces (−20 per cent motions compared to reference).
- Ensuring adequate pretension is critical. A load monitoring system can aid in the mooring management process.

It should be noted that some elasticity is always needed, however, to dampen peak loads, to avoid breaking of short lines and to consider the dynamic mooring system response in waves (cfr. the use of tails with steel wires).

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