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# BERTHING VELOCITY OF LARGE SEAGOING VESSELS IN THE PORT OF ROTTERDAM

by  
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**Key words:** berthing velocity, berthing impact, berthing energy, marine structures, large seagoing vessels

## 1.1 Abstract

While ships evolve constantly, berthing velocity curves developed during the 1970s are still embedded in the design of marine structures. This paper discusses the interpretation of new berthing records of modern large seagoing vessels collected in the port of Rotterdam. Berthing velocities of several types of vessels at various berths and operational conditions were examined, resulting in an increased understanding of the relevant aspects and the establishment of new probability distribution functions. Navigation conditions were accounted for by differentiating factors such as vessel characteristics (size and actual draft), environmental conditions (currents, wind and waves) and the berthing policy (pilot and tug assistance). The measured berthing velocities are most sensitive to the general berthing policy and local experience of pilots. Due to newly acquired insights, some historically embedded hypotheses will need to be reconsidered. For instance, the assumption that berthing velocities are strongly correlated to the size of the vessels could not be confirmed for ships larger than 50,000 DWT. Also, no water cushion effect was observed. The manoeuvring of container vessels showed a high sensitivity to wind, but their berthing velocities were not correlated to lateral wind power at all. Extremely low berthing angles of large seagoing container vessels were observed at the moment of berthing impact. The results of this research are of added value to all ports with similar sheltered navigation conditions and berthing policy to Rotterdam. The key findings were discussed with marine engineers, asset managers, harbour masters and pilots. This type of validation provided a better understanding of berthing velocity to all experts. The lower design berthing velocities will be beneficial for future structural assessments and lifetime extension of marine structures.

## 1.2 Introduction

Marine structures, such as quay walls, jetties and flexible dolphins, have to ensure the effective, safe and efficient handling of ships during their service life. In the coming years, many marine structures will be upgraded as part of a lifetime extension programme in the port of Rotterdam. The actual performance and reliability of marine structures depend largely on the ratio between the actual loads acting on these structures, the original design values and the deterioration of the facility. The loads associated with berthing impact need to be taken into consideration in the structural analysis. Ueda et al. [13] showed that the contribution of berthing velocity to the uncertainty in kinetic berthing energy was approximately 85%, which provided an indication of the need for further investigation on berthing velocity.

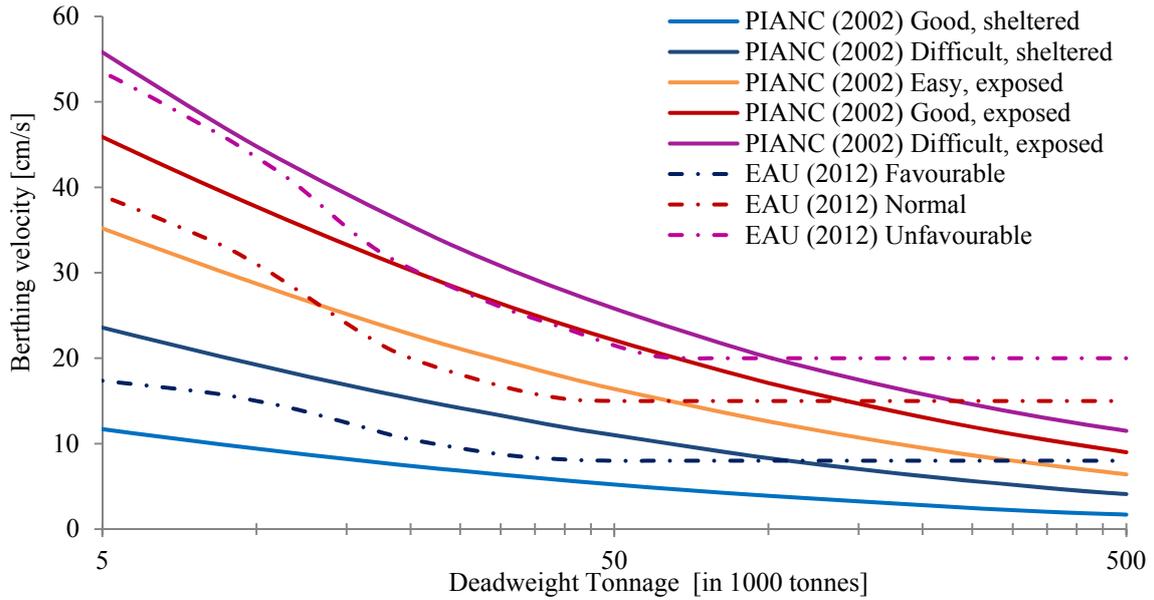
At the 1953 International Navigation Congress in Rome, Prof. A.L.L. Baker examined berthing velocity based on field observations of exposed locations in the UK and the Arabian Gulf. His work was extended by Saurin [12] and Brolsma et al. [3] and resulted in the so-called Brolsma curves. The Brolsma curves included in the design guideline of fender systems (PIANC, 2002) are shown in Figure 1.

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**Figure 1: Mean design value of berthing velocity PIANC (2002) and characteristic berthing velocity EAU (2012) as a function of navigation conditions and vessel size**

Brolsma collected field measurements from shore-based docking systems at three berths in Rotterdam and one in Scotland. The proposed mean design values of the berthing velocities were called normal berthings and represent a return period of 30 years based on 100 arrivals per year. Over time, Brolsma’s original curves were reproduced, slightly modified and published in PIANC (2002) and BS6349-4 (2015). The German recommendations for waterfront structures EAU 2012 [5] and the Spanish ROM 0.2-90 [9] both provide recommendations for characteristic values of berthing velocities. The berthing velocity of large seagoing vessels with a DWT greater than approximately 50,000 tonnes was assumed to be independent of the size and type of vessel. Three categories of navigation conditions were distinguished (Figure 1).

The Japanese OCDI [10] presented mean berthing velocities of approximately 5 cm/s related to single berthings of small seagoing vessels based on a survey by Moriya et al. The highest observed berthing velocity was 15 cm/s. A data collection published by Ueda and Shirashi in 1992 was also included. The measurements included in the dataset consisted of 738 berthing operations of oil tankers with a DWT around 200,000 tonnes at offshore berths, which showed a Weibull distribution:

$$F(x; \lambda, k) = 1 - e^{-\left(\frac{x}{\lambda}\right)^k} \quad (\text{Weibull distribution}) \quad (1)$$

in which:

- $\lambda$  Scale parameter Weibull distribution [m/s]  $\lambda \approx 0.04$  m/s
- $x$  Velocity [m/s]
- $k$  Shape parameter Weibull distribution [-]  $k \approx 2$

The highest record of the measured berthing velocity was 13 cm/s and a design value with a return period of once per 1000 arrivals of 14.5 cm/s was recommended.

Relatively few data on berthing velocity were collected since the 1970s and measurements of large seagoing container vessels were completely lacking [1]. PIANC therefore started a new working group, MarCom 145. The objective of this working group was to produce a report providing data on actual track records of vessel approaches for a range of environmental conditions and to present clear and uniform guidelines on the use of design berthing velocities. The Port of Rotterdam Authority supported this initiative of PIANC and decided to develop a measurement programme to collect new observations. This programme was extended to various ports in the USA [4]. A detailed description of the method can be found in Rath [8]. Similar initiatives were undertaken in Germany, South Asia and Japan as described by Hein [6] and Jamase et al. (2014). Berthing operations of ferry-class vessels

were conducted in the ports of Juneau and Seattle [7]. Typically, mean berthing velocities of 5 cm/s were found. The maximum berthing velocity measured was 13 cm/s.

The most relevant parameters that could influence berthing velocities were considered in this research. The historical assumption that berthing velocity is correlated to the vessel dimensions of large seagoing vessels is not supported by all design guidelines. Remarkably, the variety in type of vessels, installed propulsion systems, berthing policy and experience of pilots is not included in any guideline. For berths with a relatively low under keel clearance and/or a relatively closed type of marine structure, lower berthing velocities are to be expected due to the so-called water cushion effect. Hence, the main focus of the research was on the correlation between berthing velocity and ship dimensions, type of fendering, water cushion effect, type of marine structure, environmental factors, berthing policy and navigation aids. The main objective was to enhance the understanding of the landing procedures and berthing velocities. The probability distribution functions of berthing velocity were of particular interest in order to provide a solid base for future reliability-based assessments of marine structures. It was expected that the actual berthing velocities would most likely be lower compared to the current design guidance, because existing marine structures are still in good condition. The results of this investigation could contribute to new business opportunities, e.g. to allow larger vessels to berth onto existing marine structures and/or to extend the service life of new or existing marine structures.

### 1.3 Materials and methods

#### 1.3.1 Type of vessel and project location

Berthing velocities of small and large seagoing container vessels, tankers and bulkers were of interest. Unfortunately it was impossible to measure the berthing velocity of small vessels with limited freeboard. To acquire more insight into the correlation between berthing velocity and type of vessel, a differentiation was made between container vessels, tankers and bulkers. Subsequently, each of these vessel types was subdivided into specific vessel classes. The classification of vessels was largely based on the international Lloyds database. Various berth types were involved. All container vessels moored onto closed quay walls equipped with either hard buckling or soft cylindrical fender systems. Bulkers berthed onto closed quay walls where rigid timber beams were installed. At tankers berths, whereas flexible mooring dolphins with buckling fender systems were utilised adjacent to open jetties. The geographic location of the berths is indicated in Figure 2.



Figure 2: Berths at Maasvlakte associated with either PPU data, mobile or shore-based laser observations

### 1.3.2 Data collection

Several methods were used for collecting data on berthing velocities. Interviews and questionnaires appeared to be less efficient and the Automatic Identification System (AIS) of vessels did not provide enough accuracy. A berthing velocity accuracy of mm/s was preferred, with at least cm/s being required in this study. Container vessels were measured with a portable laser system provided by Trelleborg Marine Systems called the ‘SmartDock® laser LITE’. Using this mobile docking system, track records of actual berthing operations were collected during the windy season (Oct.– Dec. 2011). In total, 178 measurements of relatively large seagoing container vessels were recorded. These measurements were collected by the Port of Rotterdam Authority in close cooperation with the KRVE (the Royal Boatmen’s Association Eendracht in the Harbour of Rotterdam) and the Dutch Pilotage Service. This appeared to be an efficient and safe way to gather a large amount of data in a short period of time. Following this data gathering campaign, the developed method for data collection was also used in several ports in the USA.



Figure 3: SmartDock® laser LITE and software interface

A typical berthing operation recorded with portable lasers is illustrated in Figure 4. Firstly, the point of maximum fender deflection and zero (berthing) velocity was determined. Because the distance between the portable workstation and the fender line is known, the exact moment of impact and corresponding berthing velocity were established relatively easy. It should be emphasized that in this case the container vessel bounces back a little shortly after the first contact with the fender. A few moments later a second impact is visible. In this particular case, the first impact governed over the second impact. For small feeder, tanker and bulker berthings the berthing velocity of the second impact was often higher.

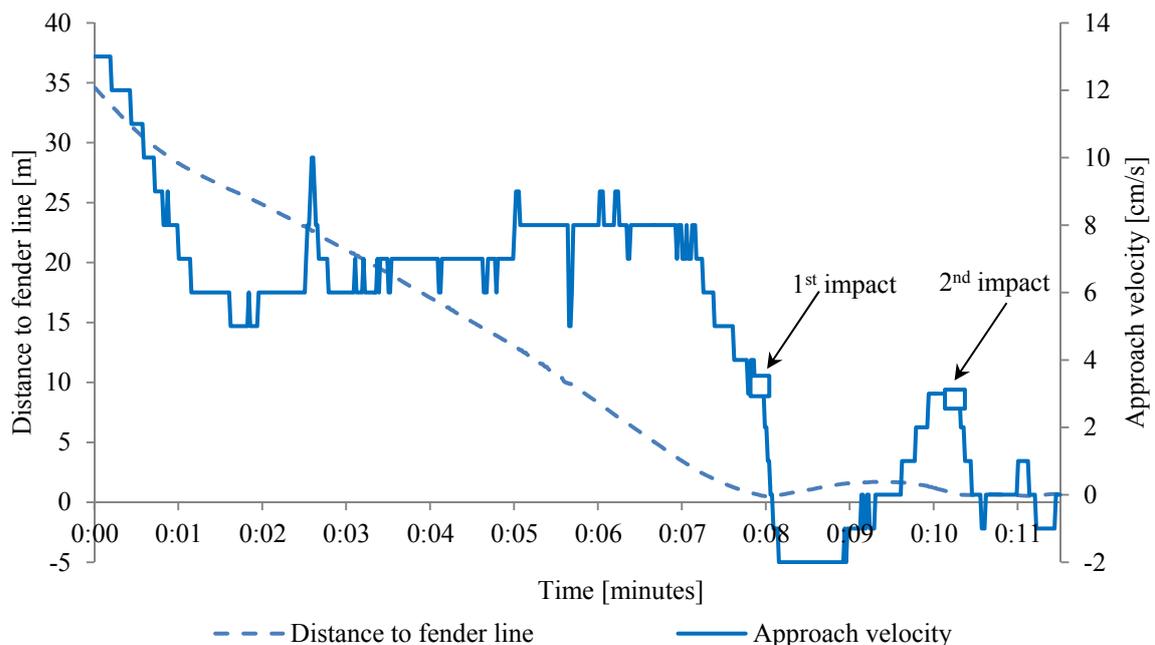


Figure 4: Approach velocity at moment of impact recorded with SmartDock® portable workstation of Post-Panamax container vessel

Besides the portable laser data, the Dutch Pilotage Service provided approximately 222 Portable Pilot Unit (PPU) track records and two terminals provided data from five jetties equipped with shore-based docking aid systems, amounting to approximately 161 berthings. The accuracy of these measurements was cm/s for the shore-based systems and mm/s for the PPU data. PPU's were only installed at vessels with a draft greater than 17m, because these vessels had to sail very accurately through the main port channels. A total of 225 and 144 measurements of tanker and bulker berthings were collected respectively.

According to the GPS track records, even moored vessels were always in motion. It was therefore extremely difficult to determine the berthing velocity at the moment of impact if fender systems are installed on flexible dolphins. The GPS position of the fender line could not be directly compared with the location of first impact, and a second berthing impact often governed over the first impact due to the yaw motion of the tankers. This was solved by finding the maximum berthing velocity within a range of 0.8 m (based on actual measured deformations of the dolphins). The extreme events deduced from PPU data are therefore most likely slightly conservative, especially the extreme events of bulk carriers. Verification showed that no correction was made for the PPU track records of bulkers, which were berthing onto closed quay walls equipped with rigid fender beams. The extreme berthing velocities of bulkers are therefore most likely overestimated, because there is negligible deflection of quay walls and rigid fender beams.

It was envisaged at the start of this test programme that a clear distinction had to be made between various berthing and navigation parameters. A large database was developed including all available and most likely relevant data which could influence berthing velocity. Besides observations of berthing velocity, the following data were collected:

- General data (date and arrival time)
- Measured data (berthing velocity and angle)
- Geometric conditions (type of terminal, number of bollards, type of waterfront structure, design depth/level of harbour bottom, berthing condition, type of fendering, exposed or sheltered).
- Vessel characteristics (name, type, length, width, maximum draft, actual draft, type of thrusters for main propeller, stern and bow thrusters, bow radius).

### 1.3.3 Data analysis

Several hypotheses, mainly regarding correlations between berthing velocity and other berthing parameters, were tested with linear regression analyses. This section provides an overview of the (statistical) methods used to acquire insight into the key parameters that influenced berthing velocity.

For various type of vessels the mean value, standard deviation and the maximum observed berthing velocity were established in order to verify the hypothesis that berthing velocity is correlated to the size of the vessel. All vessel classes were individually analysed with normal, lognormal and Weibull cumulative distribution functions, respectively. An important disadvantage of such a differentiation into populations of individual vessel classes is a significant decrease of the number of measurements within a certain population. The number of data within a population sometimes became too low for empirical data analysis. The following probability distribution functions are fitted to the datasets of the collected berthing velocities:

$$F(x; \mu, \sigma) = \frac{1}{2} \left( 1 + \operatorname{erf} \left( \frac{x - \mu}{\sigma \sqrt{2}} \right) \right) \quad (\text{normal distribution}) \quad (2)$$

$$F(x; \mu, \sigma) = \frac{1}{2} \left( 1 + \operatorname{erf} \left( \frac{\ln(x) - \mu}{\sigma \sqrt{2}} \right) \right) \quad (\text{lognormal distribution}) \quad (3)$$

$$F(x; \lambda, k) = 1 - \exp \left( - \left( \frac{x}{\lambda} \right)^k \right) \quad (\text{Weibull distribution}) \quad (4)$$

in which:

$F(\cdot)$	Probability distribution function [-]
$x$	Berthing velocity [cm/s]
$\mu$	Mean [cm/s]
$\sigma$	Standard deviation [cm/s]
$\lambda$	Scale parameter Weibull distribution [m/s ]

$k$  Shape parameter Weibull distribution [-]

It should be noted that, if a single extreme berthing velocity was measured in a small population, the Weibull fit could largely be influenced by a single extreme value, which could easily lead to unrealistic and unreliable extreme berthing velocities. The influence of the maximum observed berthing velocities was investigated with a Weibull fit for the data points with a Peak-Over-Threshold (POT) of 95%. These principles are illustrated in Figure 17. If the fit of the distribution had a lower coefficient of correlation than  $R^2 < 0.85$ , the results of the data analysis were carefully studied and should be neglected in future extreme value analysis. An adequate fit of the tail of the distribution functions to the dataset is of utmost importance. The dataset of the tanker berths was enlarged with the measurements of the tanker berths in Germany, which resulted in larger populations. This location had similar navigation conditions and berthing policy.

Most of the data that could influence berthing velocity were public or already registered within the Port of Rotterdam Authority (e.g. actual draft, water levels, wind power and direction, type of berth, etc.). The methods used to collect those data were all relatively basic and reliable. Because the actual draft, actual bottom level and actual water level are known, a regression analysis between the under keel clearance (UKC) of container vessels was carried out in order to measure the water cushion effect adjacent to closed quay walls.

$$UKC = h_w - h_{bottom} - d_{act} \quad (5)$$

in which:

$UKC$	Under keel clearance [m]
$h_w$	Actual water level [m + MSL]
$h_{bottom}$	Actual bottom level [m + MSL]
$d_{act}$	Actual draft [m]

The influence of wind speed and wind direction on the berthing velocity of container vessels was examined during the windy season. The position of the berth relative to the wind direction was registered in a central database [2]. Logically, the windage area of a vessel strongly depends on the actual draft of the vessel. The lateral wind force acting on the vessels was quantified in order to find out whether wind was influencing berthing velocity by using the following equations:

$$P_{Lat} = q A_{act} \sin(\alpha) = \frac{1}{2} \rho v_w^2 \sin(\alpha) \quad (6)$$

$$A_{act} = A_{min} + (T_{max} - T_{act})LBP \quad (7)$$

in which:

$P_{Lat}$	Lateral wind force [kN]
$q$	Dynamic pressure [kN/m <sup>2</sup> ]
$A_{act}$	Actual windage area [m <sup>2</sup> ]
$A_{min}$	Minimum windage area [m <sup>2</sup> ]
$\alpha$	Angle between wind and the hull [°]
$\rho$	Air density [kg/m <sup>3</sup> ]
$v_w$	Wind velocity [m/s]
$T_{act}$	Actual draft [m]
$T_{max}$	Maximum draft [m]
$LBP$	Length between perpendiculars [m]

In the Rotterdam datasets of tankers and bulkers both fore and aft velocities of the berthing records were listed. Those data included a combination of translational and angular velocity just before the first moment of impact. At the moment of maximum fender compression the translational berthing velocity at the contact point becomes zero and the ship maintains angular momentum. During the manoeuvre, tugs may change the angular position of the vessel. A model based only on translational velocities of

the centre of mass of vessels seemed inaccurate, especially at low velocities and low berthing angles. Although low angles seemed to be favourable, greater approach angles could contribute to a reduction of the amount of energy to be absorbed by the fender system. If vessels are berthed in a direction perpendicular to the line connecting the centre of gravity of the ship and the point of contact of the fender system the amount of energy absorbed by the fender will be reduced. A negative rotation of the vessel during the final landing procedure will also reduce the berthing impact. This type of berthing could be efficient in case of berths with high currents. The berthing angle during this type of landing must be larger in order to have enough time to reduce the rotational velocity of the vessel. Else the 2<sup>nd</sup> impact could be more severe than the 1<sup>st</sup> impact. The following formula is included in the EAU 2012 [5]:

$$E_{kin} = 1/2 m v C_m C_s C_c C_E \quad (8)$$

$$E_{kin} = \frac{m C_m C_s C_c (v^2 (k^2 + r^2 \cos^2 \phi) + 2v\omega r k^2 \sin \phi + \omega^2 r^2 k^2)}{2(k^2 + r^2)} \quad (9)$$

Before the first impact the measured fore and aft perpendicular velocities include rotational effects. During evaluations of the Rotterdam measurements, the maximum of the fore and aft velocities were conservatively treated as translation velocities perpendicular to the berthing line. Only a part of the ship's energy is absorbed by the fender during the 1<sup>st</sup> impact. The first impact was mainly dominated by translation movements of the vessel. The 2<sup>nd</sup> impact was mainly dominated by rotation and contains angular momentum. The 2<sup>nd</sup> impact could be more severe compared to the 1<sup>st</sup> impact. Typically the translational velocity of the 1<sup>st</sup> impact was close to the mean berthing velocity, while the velocity of the 2<sup>nd</sup> impact was approximately 2 a 3 cm/s higher. This depends on the type of landing, direction of vessels movements and the rotational component. The  $C_E$  factor of the rotational component is smaller and the landing will generally be smoother compared to the impact of translation [14].

$$C_E = \frac{k^2 + r^2 \cos^2 \phi}{k^2 + r^2} + \frac{\omega r}{v} \cdot \frac{2k^2 \sin \phi}{k^2 + r^2} + \frac{\omega^2 r^2}{v^2} \cdot \frac{k^2}{k^2 + r^2} \quad (\text{translation and rotation}) \quad (10)$$

$$C_E = \frac{k^2 + r^2 \cos^2 \phi}{k^2 + r^2} \quad (\text{translation only}) \quad (11)$$

$$C_E = \frac{k^2}{k^2 + r^2} \quad (\text{rotation only}) \quad (12)$$

The estimate of the radius of gyration was obtained from the OCDI [10]:

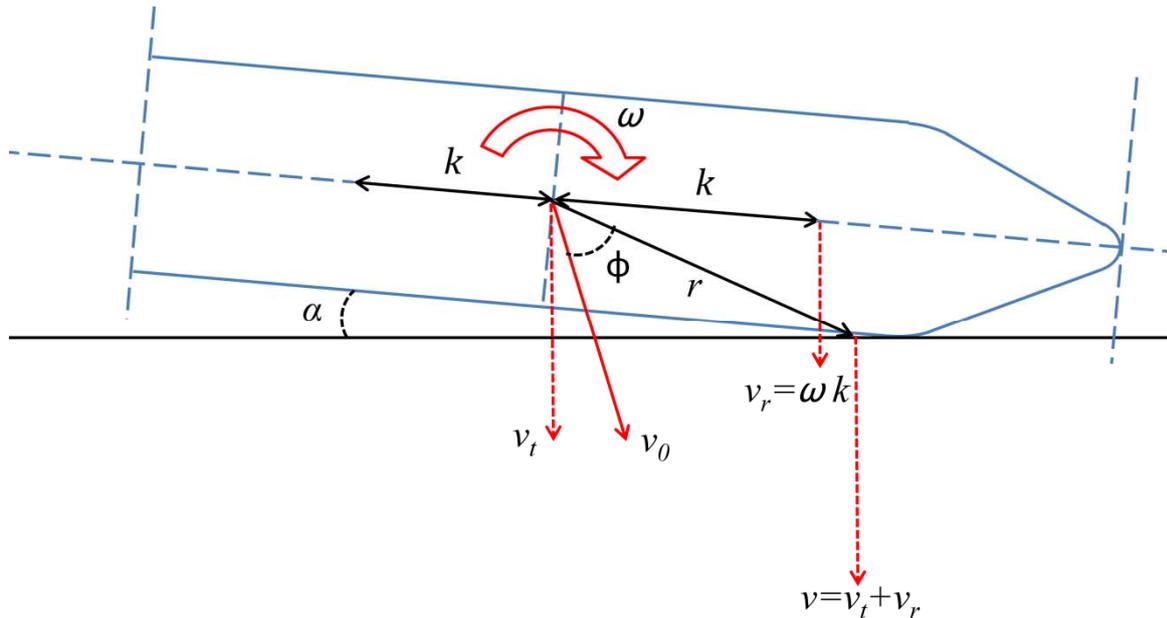
$$k = \frac{\sqrt{I}}{L} = \frac{L}{\sqrt{12}} = 0.29 L \quad \text{with } B < \frac{1}{6} L \quad (13)$$

$$k = L (0.19 C_B + 0.11) \quad \text{for } C_B < 1 \quad (14)$$

in which:

$E_{kin}$	Kinetic energy [kJNm]
$m$	Mass of vessel/water displacement [tonnes]
$k$	Radius of gyration of ship [m]
$r$	Distance of ship's centre of gravity from point of contact with marine structure [m]
$v$	Total translation velocity of centre of mass at time of first contact (includes component parallel and perpendicular to berthing line) [m/s]
$v_t$	Component of the translation velocity perpendicular to the berthing line [m/s]
$v_r$	Perpendicular velocity due to vessel rotation considered at a distance equal to the radius of gyration from the ship's centre of gravity [m/s].
$\omega$	Ship's angular velocity at time of first contact with fender [rad/s]
$\phi$	Angle between velocity vector $v$ and distance $r$ [°]

$\alpha$	Berthing angle [°]
$L$	Length of vessel [m]
$B$	Width of vessels [m]
$C_B$	Block coefficient, $C_B \approx 0.72-0.85$ for bulkers or $C_B \approx 0.85$ for tankers [-]
$C_m$	Virtual mass factor [-]
$C_s$	Ship flexibility factor [-]
$C_c$	Waterfront structure attenuation factor [-]
$C_E$	Eccentricity factor, $C_E \approx 0.4-0.6$ for quarter and $C_E \approx 0.6-0.8$ third point berthing [-]



**Figure 5: Principles of translational and angular velocity during 1<sup>st</sup> impact**

An overview of typical design berthing velocities was developed for various design vessels in order to compare the new measurements with the currently recommended design guidance. Logically these values were established by a desk study of the programme of requirements and relevant design reports. The desk study was limited to the most important berths realised between 1990 and 2015. All marine structures involved were owned by the Port of Rotterdam Authority.

## 1.4 Results

Measurements of various berths in several port basins were collected. In an attempt to develop an increased understanding of the recorded berthing velocities, differentiating factors were accounted for by vessel characteristics, environmental aspects and berthing policy. The key findings are further presented in this section.

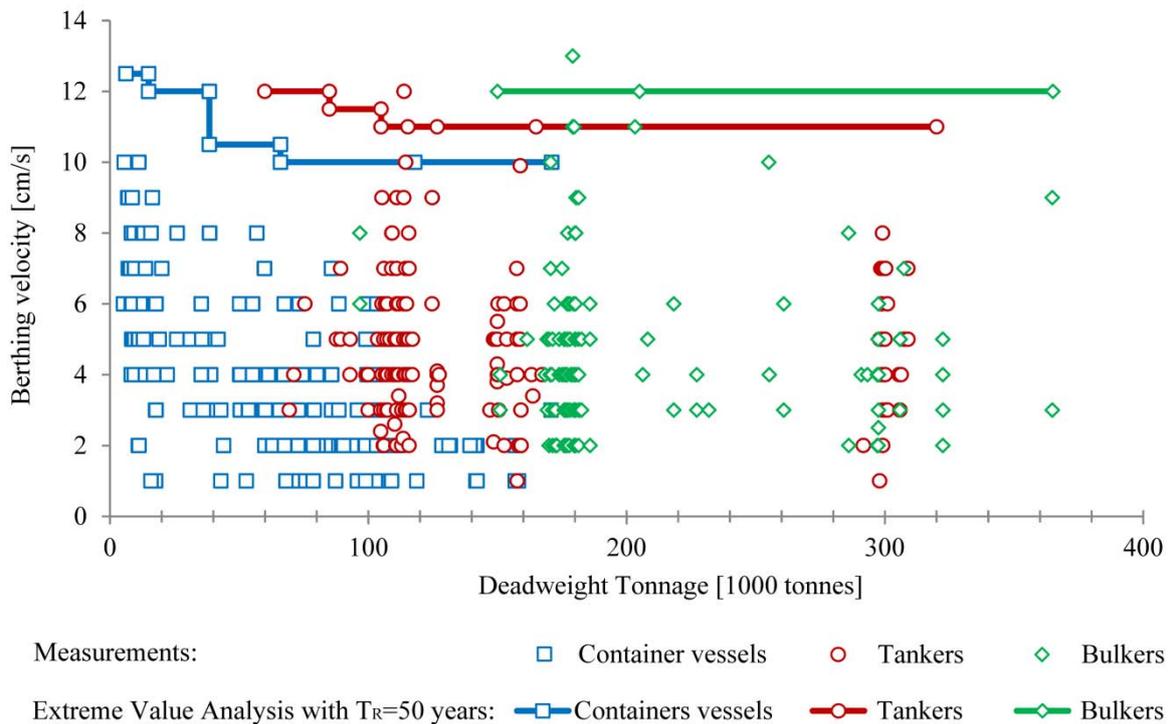
### 1.4.1 Ship dimensions and characteristics

The mean berthing velocity of large seagoing vessels was approximately 4 cm/s and the maximum measured berthing velocity out of 555 berthings was 13 cm/s (Table 1). Almost all arrivals were assisted by tugs and guided by pilots.

**Table 1: Collection of berthing velocity survey from measurements**

Ship type	$n$	$V_{50\%}$ [cm/s]	$V_{max}$ [cm/s]	berth type	aids	wind	waves	current	
Container	□	178	4.0	10	closed quay	None	high	sheltered	low
Tankers	○	225	4.3	12	jetty / dolphin	Portable pilot units / shore-based docking aids	high	sheltered	low
Bulkers	◇	144	4.4	13	closed quay	Portable pilot units	high	sheltered	low

The frequency of arrivals was set at 100 berthings of the design vessel per year, in line with the recommendations of Brolsma et al. [3]. The berthing velocity corresponding to a return period of 50 years was derived by extrapolating the Weibull distribution fit of individual vessel classes (Figure 6)



**Figure 6: Field measurements of berthing velocity against extreme berthing velocities with a return period of 50 years**

The berthing velocities of individual vessel classes with a return period of 50 years are compared to the design curves of EAU 2012 [5] and PIANC 2002 [11] in Figure 7. The values in the EAU graphs are characteristic values, with a return period of 50 years [9]. The curves of PIANC 2002 represent a return period of 30 years.

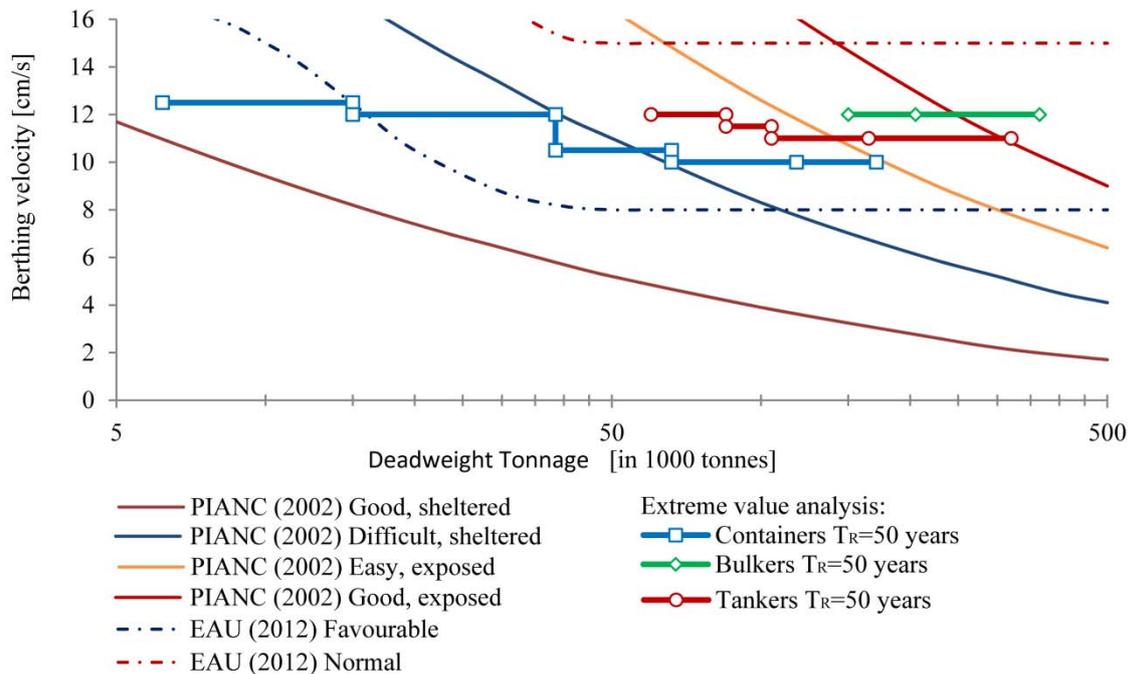


Figure 7: Berthing velocities with a return period of 50 years against EAU 2012 and PIANC 2002

According to the new measurements, tankers showed a very small correlation between berthing velocity and mass of the tankers. Large seagoing bulkers did not show any correlation. A gentle correlation was found only for container vessels. It should be stressed that for some vessel classes the number of data was too small to draw a final conclusion. Furthermore, no difference was found between the actual water displacement and the maximum water displacement of the vessel.

The ratio between the actual draft and maximum draft was further studied by linear regression analysis. The dataset showed high degree of dispersion and no real correlation was found. In spite of the fact that the datasets were too small to draw strong conclusions, the trend suggests that berthing velocity does not vary for different drafts within the considered range. The under keel clearance for e.g. Post-Panamax arrivals is illustrated in Figure 8. The median value of the under keel clearance of all container vessels was approximately 6 m and the water cushion effect did not significantly influence the berthing velocity of container vessels. Also, for bulkers and tankers no correlation was found between berthing velocity and under keel clearance.

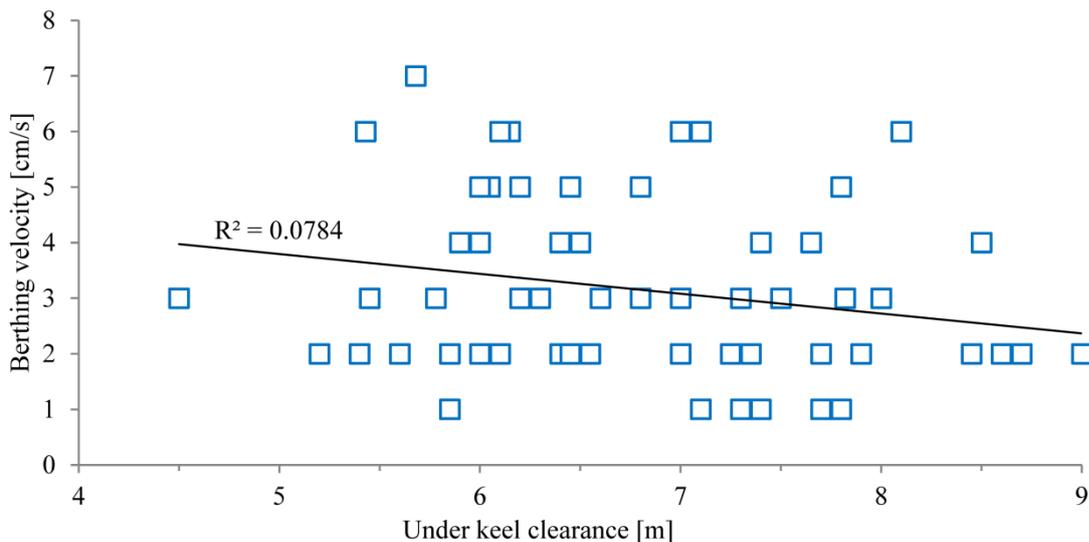


Figure 8: Relation between UKC and berthing velocity for container class Post-Panamax

A comparison of the various locations showed that the distribution of berthing velocity for container vessels was more or less constant for the port basins involved at the Maasvlakte. The geometric conditions of port basins (wide or narrow port basins) does not show an effect on the distribution of the berthing speed. The occupancy of the surrounding berths also had no significant influence. Typical distributions of container vessels are shown in Figure 9.

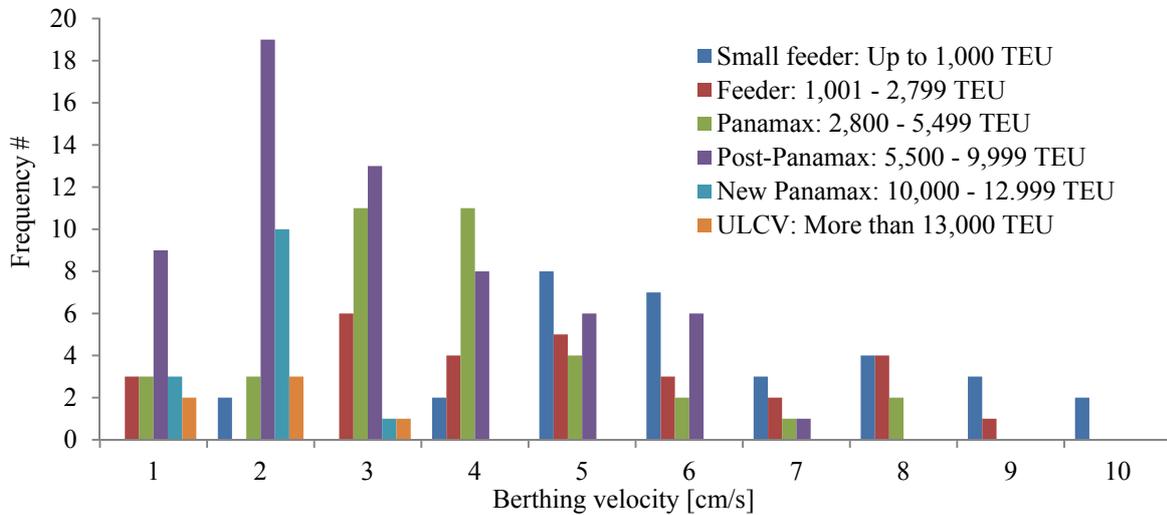


Figure 9: Histogram of berthing velocity of individual container vessel classes

#### 1.4.2 Environmental conditions

The considered berths in the port of Rotterdam are classified as sheltered with respect to currents and waves (Figure 2). However, manoeuvring with large container vessels with a high freeboard and numerous containers on deck will potentially show a high sensitivity to wind. Almost all nautical experts agreed on this. For several types of container vessels the lateral wind force acting on the vessel was calculated. The results of the Panamax and Post-Panamax classes are illustrated in Figure 10. Generally, the coefficient of correlation was negligible or small for container vessels. No real correlations were found for Small-Feeders and Panamax vessels, but Post-Panamax vessels show a small correlation.

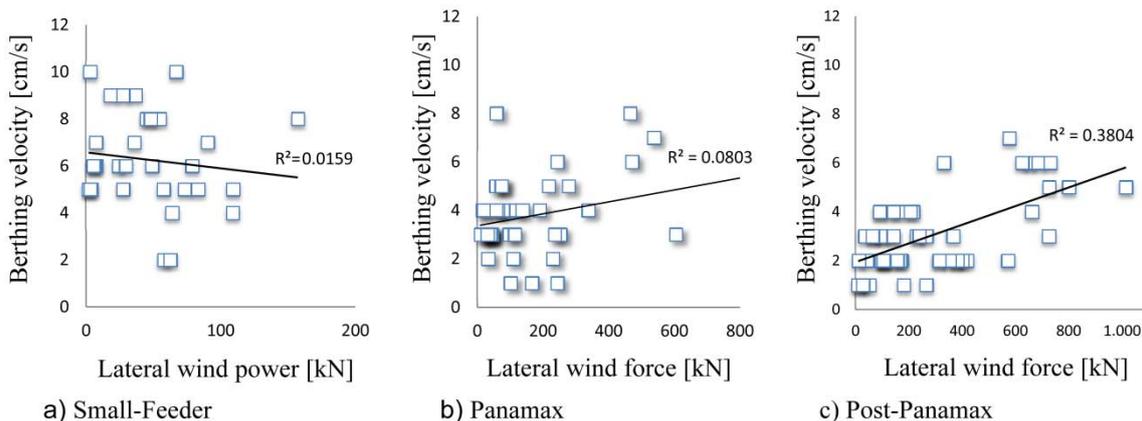


Figure 10: Lateral wind force against berthing velocity Small Feeder (a), Panamax (b) and Post-Panamax (c)

Figure 11 shows that wind does not have a major influence on berthing velocity. In this figure measurements of container vessels are divided into 3 categories according to weather conditions: favourable (wind speed < 7 m/s), normal (wind speed 8–12 m/s) and unfavourable (wind speed > 12 m/s) conditions. It should be noted that tankers and bulkers may not enter the port of Rotterdam when wind speeds exceed Beaufort 8 (< 20.7 m/s) and in the case of a favourable wind direction with speeds in excess of Beaufort 9 (< 24.4 m/s). Container vessels may not enter the port when wind speeds exceed Beaufort 6 (< 13.8 m/s). No clear distinction between categories was observed.

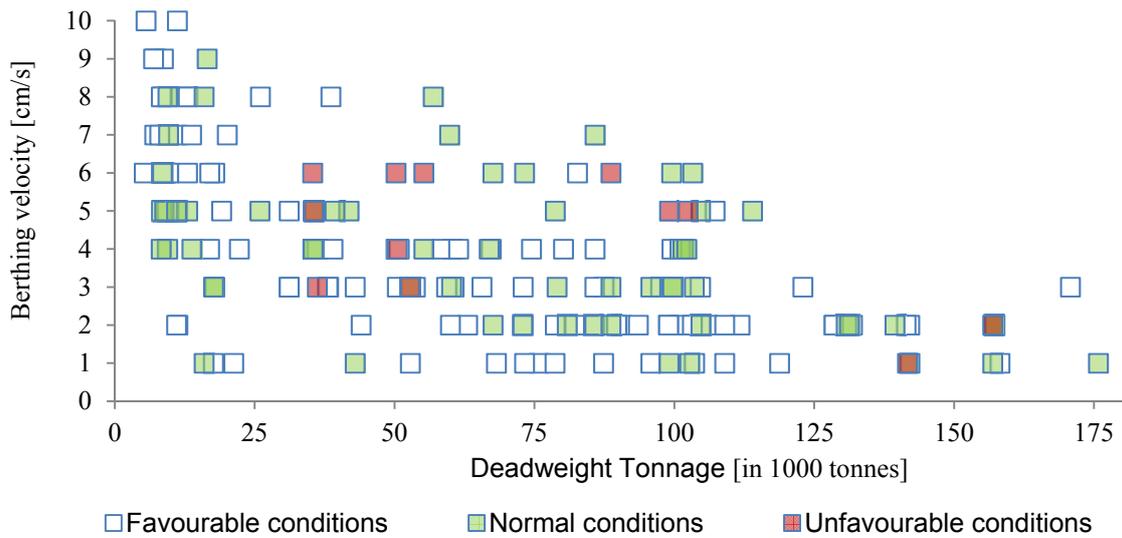


Figure 11: Influence of wind on the berthing velocity of container vessels

### 1.4.3 Tug assistance

The individual container vessel classes were compared with tug assistance (Table 2). Generally, the required number of tugs depends on the type of vessel (size, actual draft), navigation conditions (occupancy of the berths) and environmental conditions (lateral wind force). Although there were not enough data to derive reliable correlations between number of tugs and all these parameters, some trends became visible:

- The number of tugs does not have an effect on berthing velocity;
- A significant change between the small feeders and feeders was also found (Figure 12).

The track records were studied in more detail in order to explain this. This significant change was caused by a different type of landing procedure.

Table 2: Number of tugs for individual container vessel classes and mean value of berthing velocity (cm/s)

Vessel type	Without tugs			With 1 tug			With 2 tugs			With 3 tugs		
	n	v	DWT	n	v	DWT	n	v	DWT	n	v	DWT
Small feeder	29	6.1	9004	2	8.5	7617						
Feeder	12	5.7	16250	11	4.5	21771	3	3.3	36583			
Panamax				15	3.8	42424	22	3.6	55120	2	5.5	55170
Post-Panamax	1	3.0	104696	13	2.8	87340	37	3.1	90029			
New-Panamax				4	3.0	114327	18	3.1	114277	2	3.0	116733
ULCV							5	1.8	153552	4	1.5	153140

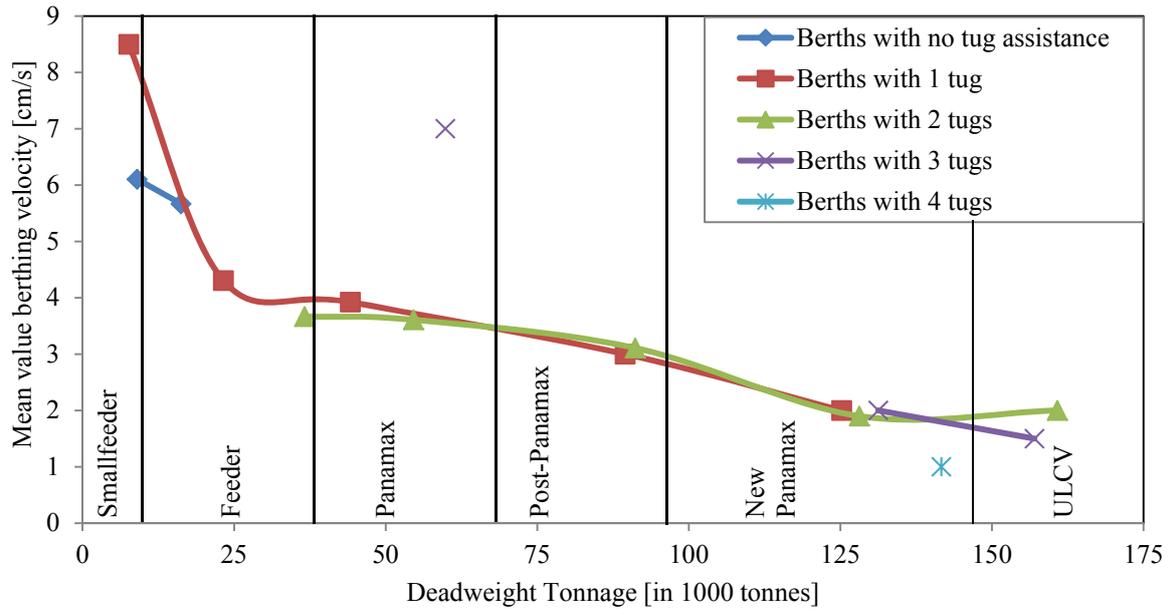


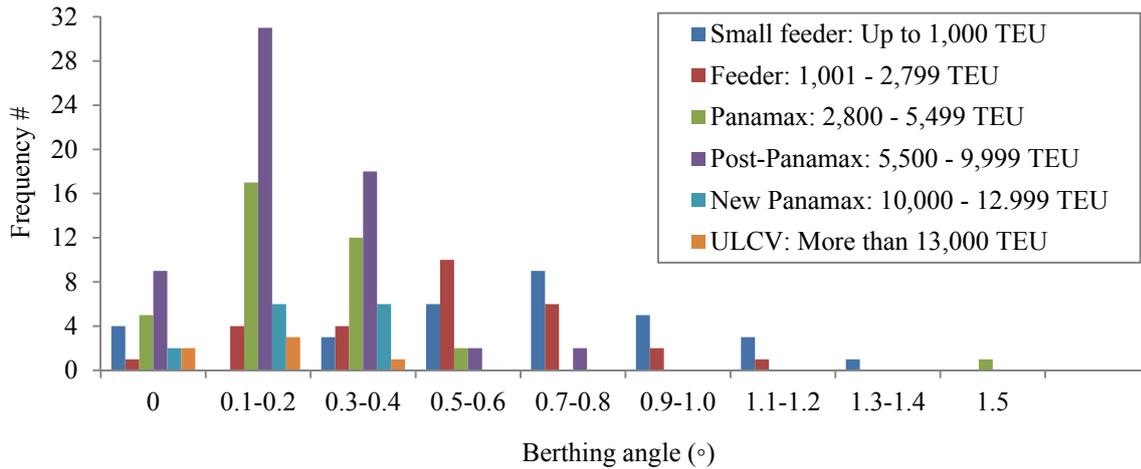
Figure 12: Correlation between tug assistance and dimensions of container vessels for mean berthing velocities and DWT

#### 1.4.4 Type of landing

Small feeders and feeders (DWT < 38,500 tonnes) appeared to have higher berthing velocities, as assumed in most of the design codes. Studying these particular berthing records showed that the smaller vessels were not able to accomplish a parallel landing operation. The approach angle was much higher and fewer tugs were used. The berthing angle at the moment of impact mostly remained between 0° and 1.5° (Figure 13) and sometimes the 2<sup>nd</sup> berthing impact was governing. Large container vessels always used tug assistance and were equipped with bow and stern thrusters, which allowed them to berth almost parallel to the fender line. Container vessels with large water displacement (DWT > 38,500 tonnes) were stopped 20–30 m from the berth in parallel position. The approach angle during the landing procedure remained small. Initial approach velocities measured at some distance from the berthing line were generally in the order of approximately 10–40 cm/s (Table 3). The track records showed that captains still seemed to have an influence on the landing procedure during the final metres. Berthing velocity at the moment of impact for various container vessel types generally remained between 0 and 10 cm/s. All records of berthing operations of container vessels showed berthing angles, typically of 1.5° or less (Figure 13).

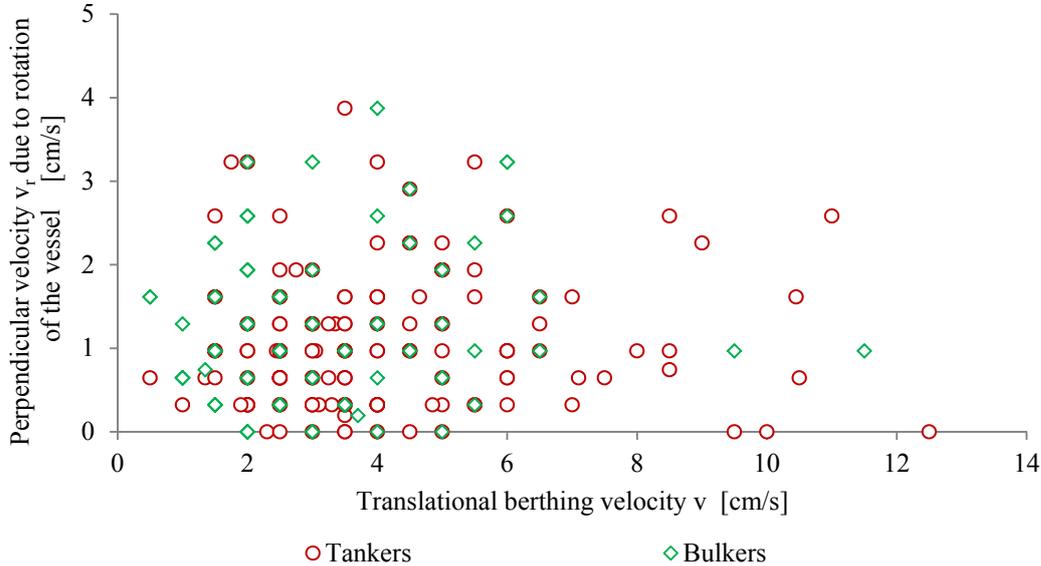
Table 3: Approach velocity during berthing manoeuvre of container vessels, Maasvlakte Rotterdam

Distance to fender line [m]	Approach velocity [cm/s]
20–50	10–30
5–20	10–20
0–5	5–15
0	0–10



**Figure 13: Distributions of berthing angle of container vessels at Maasvlakte**

For tankers and bulkers only the velocities at the moment of impact were available. Landing operations of large seagoing tankers and bulkers showed similarities with landings of small container vessels. For the datasets of tankers and bulkers the angular velocity was calculated. The perpendicular component of the angular velocity  $v_r = \omega k$  was plotted against the translational velocity perpendicular to berthing line (Figure 14). This component is not completely the same as the rotational component of the actual berthing velocity due to the fact that the distance of the point of impact to the centre of mass is not necessarily the same as the radius of gyration. The translational component parallel to the berthing line was not recorded. The latter value has an effect on the velocity angle  $\phi$  and thus on the  $C_E$  factor. It is noted that, on average, an angular velocity term of 2–3 cm/s was added. The dependency on the translational velocity was weak. For the bulk carriers, measurements of the berthing angle were available (Figure 15). A slight effect of higher angular velocities at small berthing angles was observed.



**Figure 14: Measured rotational and translational velocities for tankers and bulkers**

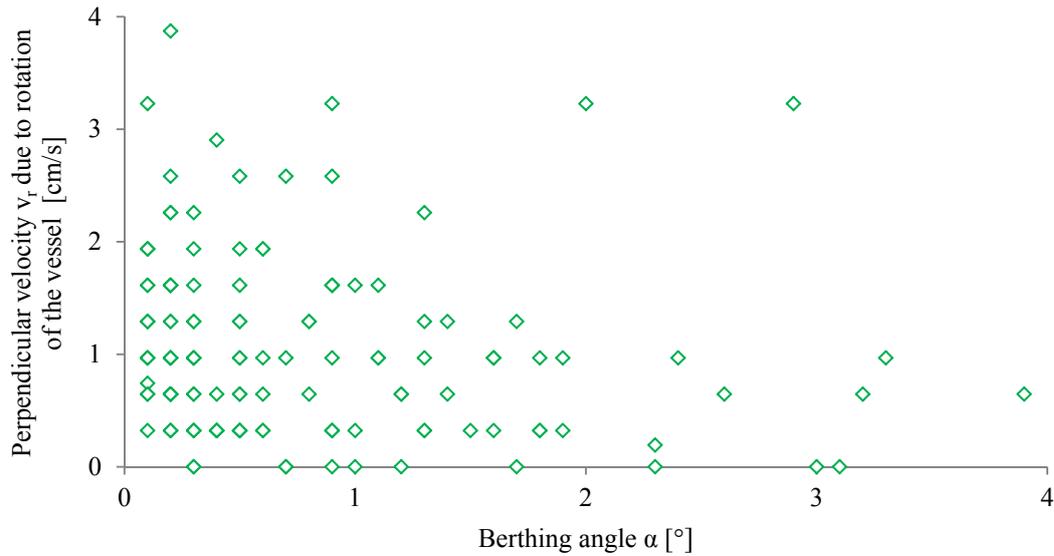


Figure 15: Measured rotational velocity for bulk carriers against berthing angle

#### 1.4.5 Distribution of berthing velocities

An adequate fit of the low-probability tail of the distribution to the dataset was made in order to estimate extreme berthing velocities. The accuracy of the fit of the tail was investigated for normal, lognormal and Weibull distributions (Figure 16). In addition, a Weibull fit for the data points with a Peak-Over-Threshold (POT) of 95% was conducted. The parameters for the best fit with normal, lognormal and Weibull and Weibull POT 95% probability distributions functions are listed in Table 4 per vessel class respectively.

Table 4: Cumulative distribution functions for various vessel classes

				Normal			Lognormal		Weibull		Weibull POT 95%	
kDWT	n	max		$\mu_s$	$\sigma_s$	$V_s$	$Ln(\mu_s)$	$Ln(\sigma_s)$	$\lambda$	k	$\lambda$	k
<b>Tankers</b>												
Panamax	60–85	23	0.09	0.055	0.018	0.33	-2.96	0.339	0.063	3.09	0.059	2.82
Aframax*	85–105	175	0.12	0.044	0.018	0.40	-3.21	0.469	0.050	2.68	0.031	1.26
Suezmax	115–165	95	0.11	0.047	0.018	0.39	-3.13	0.395	0.053	2.75	0.057	2.49
VLCC	260–319	80	0.10	0.047	0.019	0.40	-3.15	0.422	0.053	2.65	0.044	1.91
Fixed laser	260–319	19	0.07	0.035	0.013	0.36	-3.40	0.348	0.041	2.77	0.019	0.92
<b>Bulkers</b>												
Capesize	150–205	107	0.13	0.045	0.022	0.50	-3.22	0.449	0.050	1.91	0.046	1.51
VLBC	205–365	37	0.10	0.042	0.019	0.44	-3.25	0.405	0.048	2.18	0.048	1.85
<b>Containers</b>												
Coasters	7–15	37	0.10	0.063	0.019	0.31	-2.83	0.360	0.071	3.68	0.063	2.74
Feeders	15–42	31	0.09	0.047	0.019	0.41	-3.17	0.496	0.054	2.63	0.058	2.99
Panamax	42–70	31	0.08	0.036	0.016	0.46	-3.46	0.510	0.041	2.22	0.034	1.51
Post Panamax	70–118	60	0.07	0.030	0.015	0.52	-3.66	0.540	0.034	1.93	0.036	2.27
New Panamax	118–171	18	0.03	0.018	0.006	0.33	-4.06	0.361	0.021	3.60	0.010	0.92
Rotterdam data	7–365	555	0.13	0.043	0.021	0.59	-3.29	0.594	0.046	2.28	0.044	1.72
All data	7–365	713	0.13	0.044	0.020	0.45	-3.24	0.498	0.049	2.28	0.043	1.75

\*) The fit of the Weibull distribution to the measured data resulted in an underestimation of the highest actual measured berthing velocities with the PPU. Although the reliability of the maximum values measured with the PPU was carefully analysed, these values are probably unsafe to use for determining the design berthing velocity.

Generally, the fit of the Weibull distribution of the berthing velocity of a single berthing operation provided the most appropriate description of the tail, compared to a normal and lognormal distribution. This is illustrated by the theoretical density functions and the Q-Q probability plot (Figure 16).

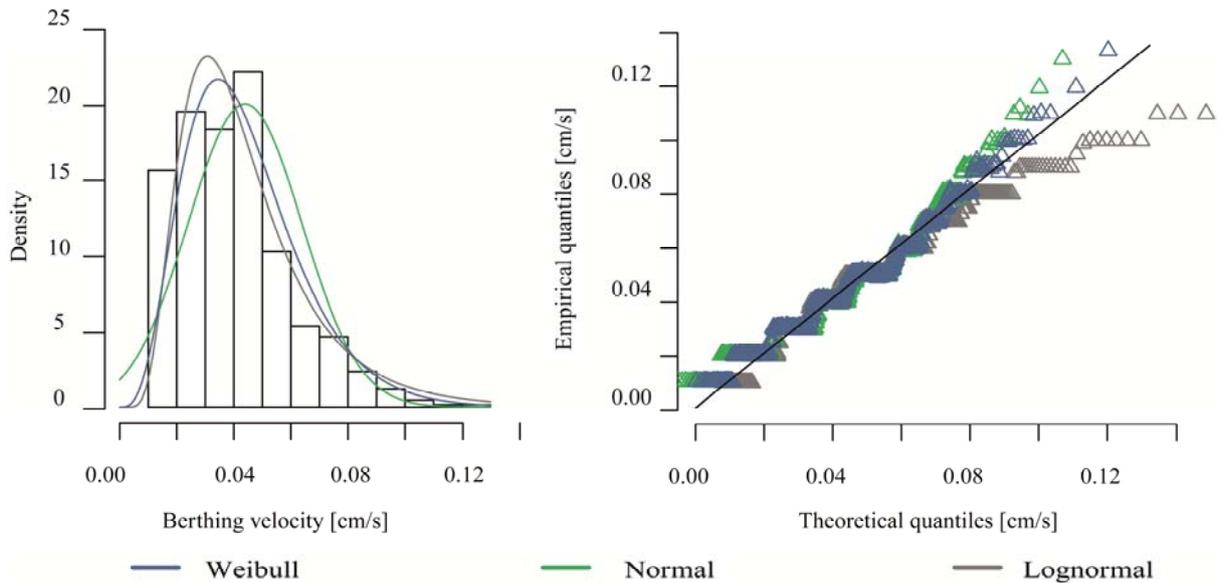


Figure 16: Histogram and theoretical density functions (left) and Q-Q probability plot (right) of all 713 observations

Only the Aframax tankers had a coefficient of correlation less than  $R^2 < 0.85$  and should be used carefully. The lognormal distribution was not convincing as a realistic estimation of the low-probability tail and overestimated the extreme berthing velocities with a small probability of exceedance (Figure 17). Conversely, the normal distribution regularly resulted in an underestimation of the maximum measured berthing velocity. The shape of the POT distribution fits is useful, but not reliable for small populations.

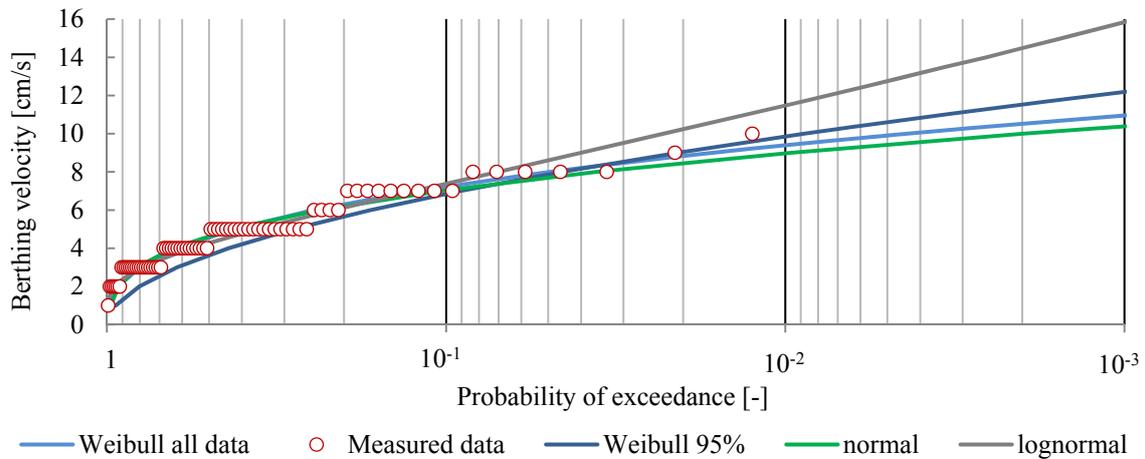


Figure 17: Probability distribution functions for 80 observations of VLCC tankers (260 - 319 kDWT) measured in Germany and Rotterdam

The number of berthings during the service life may differ by berth. Design berthing velocities are in fact time dependent. It should be noted that extreme berthing conditions were therefore most likely not included in small data populations. The probability of exceedance in Figure 17 is related to a single berthing operation and not to the return period of a certain berthing velocity during the design lifetime. The number of arrivals during the lifetime will influence the relevant design berthing velocities for a marine structure. For example, the berthing velocity with a probability of exceedance of approximately 1% ( $P = 0.01$ ) of a single berthing is approximately 9.4 cm/s according to a Weibull distribution. This corresponds to a return interval of once per 100 arrivals. Note that the maximum observed velocity in a population of 80 observations of VLCC was 10.0 cm/s. If 1000 arrivals are to be expected during the lifetime, the berthing velocity with a return interval of once per 1000 berthings is approximately 11.0 cm/s ( $P = 0.001$ ). This indicates the importance of the distribution of the extreme values and the frequency of arrivals during a certain reference period.

## 1.5 Discussion

### 1.5.1 Performance of berthing facilities and fender systems

In order to correctly interpret the collected data, the performance of marine structures during the service life was briefly discussed with nautical experts, pilots and asset managers from the port of Rotterdam. The asset managers explained that some berthing facilities are approaching the end of the design lifetime. Most of the marine structures still appears to be in good condition. Berthing facilities equipped with soft cylindrical fenders require significantly less maintenance than berths with hard buckling fenders. The reported damage to fender systems was often related to chains, stairs and panels. Damage of this type is usually not directly caused by excessively high berthing velocities. The asset managers also noted that berths which are suitable for both seagoing vessels and inland barges showed much more local damage to fender systems. Local damage to fender panels was caused mainly by irregularities of the ship's hull or by inappropriate use of mooring lines. The timber structure installed on bulk berths appeared to be frequently subjected to uncontrolled manoeuvring of inland barges (pusher/towboats). The latter concept does not absorb energy and results in high hull pressures. Assuming that an enhancement of hull pressure was undesirable, berthing velocity was expected to be lower. The measurements of bulkers showed slightly lower mean values (Table 4), but the coefficient of variance and maximum/extreme berthing velocities appeared to be higher for bulkers. This could be explained by the overestimation of berthing velocity from the PPU track records. Generally, no significant differences were found between the berthing velocities of various fender systems at container terminals. The pilots confirmed that they do not consider the type of fender system in their berthing policy.

### 1.5.2 Navigation aids and target berthing velocity

In recent decades, there has been an increase in the use of navigation aids such as portable pilot units and fixed shore-based docking systems. In Rotterdam, pilots and boatmen are all well trained and have ample experience. It is their job to moor and unmoor in a safe and efficient manner. The pilots and boatmen confirmed that modern tools, which introduced real-time monitoring of vessel movements, increased their control and confidence during the berthing process. According to nautical experts, uncontrolled berthings of large seagoing vessels are not likely to happen in well-organised ports. In most situations the pilots and captains are not aware of the design berthing velocity. Generally their objective is to land with a berthing velocity of approximately 3 to 4 cm/s. A berthing velocity of 8 cm/s was mentioned as unlikely to happen in the case of pilot and tug assistance. Five jetties for liquid bulk carriers are equipped with shore-based docking aid systems to assist in reducing the berthing velocities. Generally, the determination of such a target resulted in increased confidence concerning the condition of the marine structure. On the one hand, a pilot may observe a berthing facility that is in a relatively poor condition. In this case, most likely a lower approach velocity could be expected. On the other hand, during the first months of berthing onto a brand new berthing facility, there is often less experience, but the condition of the berth is in relatively good condition. In this case, pilots may consider a higher berthing velocity. Typical target berthing velocities of onshore docking systems are illustrated in Table 5.

**Table 5: Target berthing velocities of onshore docking systems at tanker berths in the port of Rotterdam**

Target berthing velocity [cm/s]			Traffic light	Explanation
Terminal 1*	Terminal 2**	Terminal 3		
0–7	0–4	0–6	Green zone	Safe
7–11	4–6	6–10	Orange zone	Too high
> 11	> 6	> 10	Red zone	Unsafe/Damage

\*) Vessels with a DWT > 150,000 tonnes have to berth in the green zone. The landing of vessels with a DWT < 150,000 may incidentally exceed the green zone.

\*\* ) If the velocity is higher than 8 cm/s an alarm signal will be given.

In cases where approach velocities exceeded the limit, a red sign was visible. If the manoeuvre was continued, the captain of the vessel would be held responsible for any damage. At some berths vessels with less water displacement were allowed to berth in the orange zone. Note that the measurements were almost perfectly in line with these target berthing velocities. The pilots explained that they try to reach the upper limit of the green light instead of aiming for 3 to 4 cm/s. Establishing a target berthing velocity may prevent extreme berthing velocities, but could result in higher mean values.

The 'human factor', expressed in experience of captains and knowledge of local environmental as well as navigation conditions is an important parameter regarding berthing velocity. For large seagoing vessels human influence will most likely result in fewer extreme events. If the pilots intuitively classify an approach velocity as too high, adequate measures will be taken or the berthing operation will be aborted immediately. Conversely, the opposite could be the case regarding smaller seagoing vessels and inland barges, due to less experience or responsibility of captains. The human factor could result in an increase of extreme events or higher values of uncontrolled berthing velocities. Small seagoing vessels and inland barges berthing without tug assistance and pilot assistance should therefore have a greater margin of safety.

### 1.5.3 Vessel characteristics and water cushion effect

For tankers and bulkers with relatively large water displacement, with a DWT > 100,000 tonnes, the correlation between ship mass and velocity seems insignificant. This is more or less in line with the recommendations provided by the EAU and ROM. Although there was a weak correlation between the dimensions of a container vessel (DWT) and berthing velocity, the collected data did not confirm the historical assumption that berthing velocities are strongly correlated to ship dimensions (Figure 7). The mean berthing velocities of large seagoing vessels were between 3 and 4 cm/s (Table 4), which is in accordance with the objective of the pilots. It should be noted that the maximum values were still below the design velocities (for 'abnormal' berthing operations). The maximum berthing velocities were generally caused by smaller vessels than the design vessel (Figure 18). The abnormal berthing velocities were established by multiplying the normal berthing velocities by  $\sqrt{C_{ab}}$ ,  $C_{ab}$  being the abnormal berthing impact factor as concluded from design recommendations [11]. It should also be noted that a value of 10 cm/s was implemented as a lower limit for 'normal' berthing velocities.

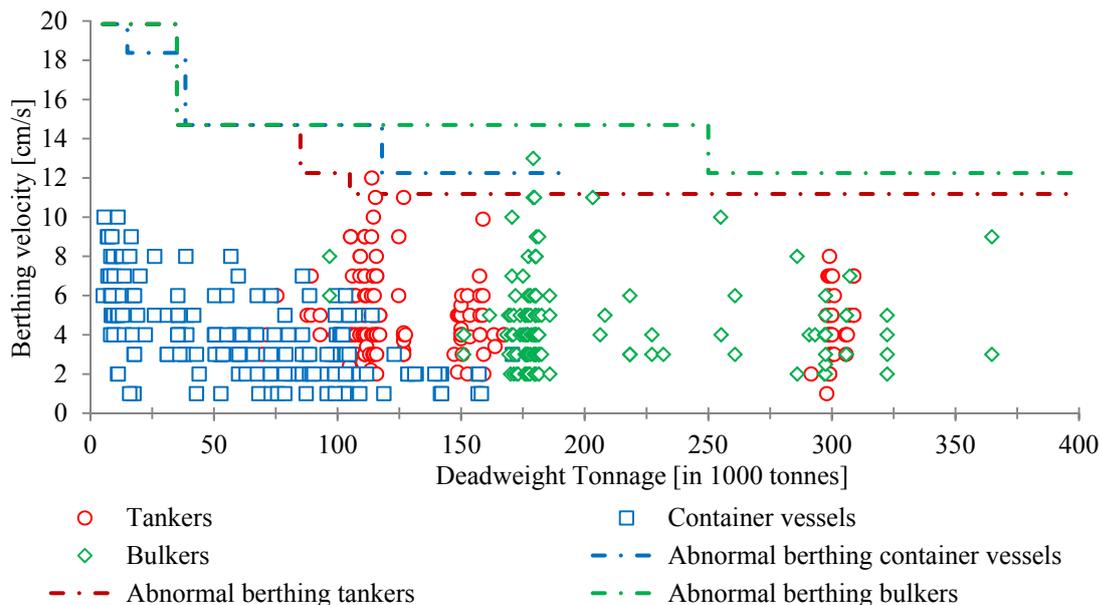
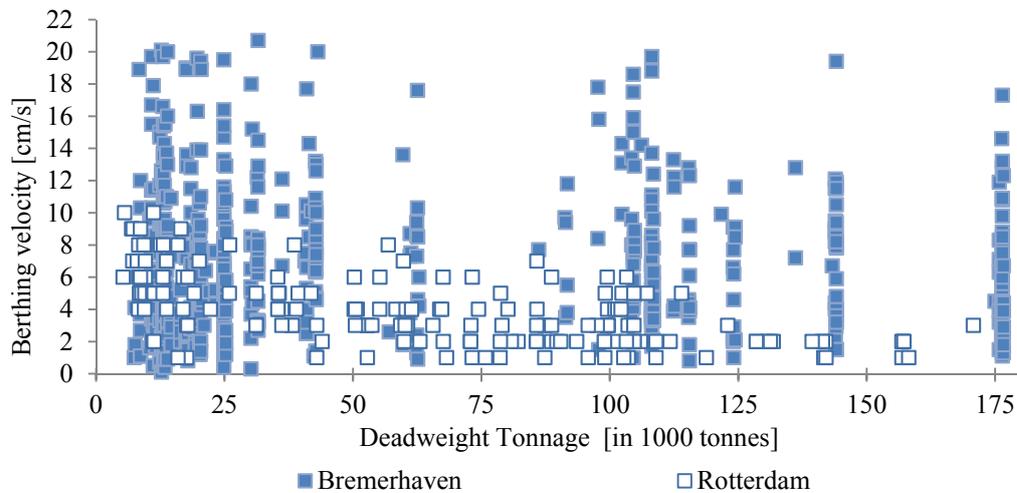


Figure 18: Field observations against currently recommended abnormal berthing velocities

The pilots suggested that, due to the low approach velocities, the advanced propulsion systems, parallel landing procedure and their ability to stop a container vessel even at one metre in front of the berth, the influence of the cushion effect did not have a dominant effect on the berthing velocity of container vessel arrivals. To underline their experience, the pilots mentioned that they are actually able to 'feel' the water cushion at specific bulker berths. The water cushion was only felt during the final metre of the landing procedure of vessels with low UKC at closed quay walls. The UKC effect was most likely excluded due to the overestimation from the PPU track records. The influence of the water cushion effect most likely existed only in the case of very low under keel clearance [2].

The maximum berthing velocities measured were slightly higher than the maximum of 8 cm/s mentioned by the pilots. It should be emphasized that the extreme berthing velocities of tankers and bulkers measured with PPUs are likely to be slightly conservative. The higher extreme velocities were mostly caused by a 2<sup>nd</sup> berthing impact due to yaw motion and angular velocity of vessels (see Section

1.5.5). This was also found in other ports in Germany [6] and Japan [15]. The observations of approximately 1500 large container vessels arrivals in Bremerhaven were compared with the measurements in Rotterdam (Figure 19).



**Figure 19: Measurements of container vessels in Bremerhaven and Rotterdam against PIANC 2002.**

The berthing velocities measured in Bremerhaven deviate significantly from the same individual container vessel classes measured in Rotterdam. After consulting with the German and Dutch pilots, a reasonable explanation was that this was most likely caused by angular velocity due to different environmental conditions (strong tidal currents) and type of landing procedure.

#### 1.5.4 Environmental conditions and type of landing

All berths at the Maasvlakte have high degrees of shelter to waves and currents. In the port of Rotterdam, manoeuvring of container vessels is mainly influenced by wind. Therefore berthing operations of container vessels were explicitly recorded during the windy season. Examination of the data showed that wind did not directly or indirectly influence berthing velocity. Similar conclusions were drawn from filed observations of onshore container berths in Japan and Asia [15]. A plausible explanation for the fact that wind is not of major influence may be found in the implemented berthing policy. Harbour masters and pilots adjusted their berthing policy depending on environmental conditions.

The measurements conducted in the port of Bremerhaven enhanced the understanding of the effects of currents, since this port has relatively exposed navigation conditions. The German pilots implemented the tidal current of the River Weser in their type of landing. In particular, the approach angle during the berthing procedure was high, but at the final moment of impact the berthing angle was always less than 1 degree. Figure 19 shows that effects of strong currents can double or even triple berthing velocities (sum of transverse and angular velocity component) compared to the parallel landing procedure applied in Rotterdam. With the use of tug assistance and early attachment of mooring lines during the final landing, container vessels practically always berth parallel to the quay wall in Rotterdam [8].

The berthing angles at the moment of impact in Rotterdam and Bremerhaven were significantly smaller compared to the literature (

Table 6). It should be noted that the angle of approach was higher in Bremerhaven, but the berthing angle at the moment of impact was small. For large seagoing container vessels, the maximum measured berthing angle out of a population of 1500 berthings was 0.82°. The average berthing angle was approximately 0.24°[6].

**Table 6: Comparison of measured berthing angles of container vessels with guidelines**

Design codes	Ship dimensions	Berthing angle without tugs	Berthing angle with tugs
PIANC (2002)	> 50,000 DWT	-	Smaller than 5–6°
	Coasters	8°–10°	-
	Barges	15°	-
EAU (2012)	All	10°–15°	Smaller than 6°
ROM 0.2–90 (1990)	All	5°–15°	7°–10°
Measurements (2011)	> 50,000 DWT	-	0°–1°
	Coasters	0°–1.5°	-

The current design guidelines tend to prescribe rather conservative values for berthing angles. For some vessels and quay types these high angles are very unlikely and do not correspond with observed practice. In many cases the vessel would hit the quay wall or cranes before it touches the fender system. If the berthing angle is relatively small, the vessel might touch more than one fender, which is of course favourable for energy absorption. For parallel berthing against flexible dolphins at dedicated positions, this will often not be the case. Generally, engineers will assess the most onerous condition where all the berthing energy will be absorbed by a single fender with a minimum berthing angle. More fenders will be activated simultaneously only at very low berthing angles. This needs to be reconsidered for closed quay walls in the case of container berths. An improved understanding of actual berthing angles is relevant for assessments of fender spacing and offset relative to marine structures to avoid collisions between ships and quays. Further analysis on this aspect is recommended in order to optimise design values.

### 1.5.5 Differences between tankers and container vessels

Seagoing tankers showed 20–30% higher berthing velocities compared to large seagoing container vessels with similar dimensions (water displacement), while the same pilots, boatmen and environmental conditions were involved. A plausible explanation could be that most tankers were berthing at berths with shore-based docking aid systems. Captains and pilots were therefore aware of allowable/target berthing velocities. Most tankers arrived with PPU assistance as well. The pilots therefore had an enhanced confidence level and aimed for target berthing velocities. Generally, there was no cushion effect at tanker berths while all container vessels berthed onto closed quay walls. Also the added mass of tankers could be larger and the greater approach angle of tankers resulted in the fact that the water between a sloped revetment and a jetty was squeezed out. Additional rotational velocity was therefore excluded. Tankers are not equipped with bow thrusters. The availability of these thrusters gave captains of container vessels more control during berthing operations, and the thrusters were used to reduce approach angles. Berthing angles adjacent to container berths were often restricted due to interfaces between the bow flare angles of vessels and container cranes or occupancy of berths. The allowable hull pressure of tankers is probably higher due to safety requirements in vessel design guidance (this needs further investigation). The total duration of general berthing procedures for tankers appeared to be 2 to 3 times longer. (Aframax is 1 hour; VLCC 1 hour; containers 20–30 minutes). Due to greater inertia, tankers have to stay in motion to guarantee manoeuvrability, while container vessels were therefore stopped in a parallel position a few metres in front of the fender line. Note that stopping a tanker will result in an extra 15–20 minutes compared to stopping a container vessel. Tankers had a smaller free board and windage area. Within the port of Rotterdam, the berthing policy regarding container vessels strongly depends on weather conditions. The governing wind conditions probably occurred during sailing through main channels, and an extra tug was probably available to assist during the final landing.

## 1.6 Conclusion

Since the development of the Brolsma curves in the 1970s, new measurements of berthing velocities have been provided by the port of Rotterdam. The data analyses resulted in a better understanding of various factors influencing berthing velocity. The most important conclusions are:

- The measured berthing velocities were lower compared to current recommendations on design values. Typically, the mean values of individual vessel classes varied between 3 and 5 cm/s. The maximum observed berthing velocity of 555 berthings was 13cm/s.
- The collected data do not confirm the historical assumption that berthing velocities are strongly related to ship dimensions of large seagoing vessels. No evidence was found to suggest that berthing velocities of a fully laden vessel were lower compared to empty vessels, or partly ballasted vessels.
- No evidence was found to suggest that berthing velocity is influenced by the type of marine structure or type of fender system.
- No correlation between wind speed (environmental factors) and berthing velocity was found in the sheltered (no waves and currents) port basins of Rotterdam.
- Berthing velocities strongly depend on berthing policy (type of landing, experienced and well-trained pilots, tug assistance, berthing aid systems, etc.)
- Establishing a target berthing velocity results in a decrease of extreme berthing events, but not necessarily in a decrease of berthing velocity during regular/normal berthing operations.
- The theoretical distribution of the low-probability tail of the measurements is closer to a Weibull distribution than to a normal or lognormal distribution.

Berthing velocity seemed to be the dominating design parameter for fender systems. Nominal values for the mass of a vessel and the accompanying water displacement could be considered for structural assessments of marine structures. The measured berthing angles were much lower at the moment of impact compared to design guidance used in practice. Further investigation on these aspects is recommended. It is recommended that a rotational velocity component should be considered if no parallel landing operation is guaranteed. Strong (tidal) currents in particular may result in far higher berthing velocities. The factors affecting berthing velocity may change during the life of hydraulic structures. These factors include experience of captains and pilots and the condition of the berthing facility. Further research on extreme berthing events and reliability-based design is recommended. Most design guidance embedded a load and resistance factor design approach, while adequate partial safety factors of berthing velocity or berthing energy are still lacking.

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