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PARTIAL SAFETY FACTORS FOR BERTHING VELOCITY AND LOADS ON MARINE STRUCTURES

by

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Key words: partial safety factor, berthing velocity, berthing energy, berthing impact, berthing load, marine structures

1.1 Abstract

Design methods for marine structures have evolved into load and resistance factor design, however existing partial safety factors related to berthing velocity and loads have not been verified and validated by measurement campaigns. In this study, field observations of modern seagoing vessels berthing in Bremerhaven, Rotterdam and Wilhelmshaven were used to evaluate partial safety factors for berthing energy and berthing impact loads. Various types of vessels and navigation conditions were statistically examined. The results show that characteristic values of berthing velocity with a return period of 50 years are in line with design recommendations in literature. Design values of berthing velocity are sensitive to the number of berthing operations during the lifetime of a marine structure. Typical partial safety factors for sheltered and exposed navigation conditions were derived by extrapolating distribution fits and applying extreme value theory. Differences in structural response due to soil stiffness and the type of berthing system installed influence partial safety factors for berthing impact loads. The probability of an uncontrolled berthing event was higher for exposed navigation conditions (strong tidal currents). In these circumstances, higher partial safety factors for berthing velocity should be considered in the design of marine structures. When berthing aid systems are used, the probability of extreme berthing velocities is lower, resulting in lower partial safety factors. The key findings of this study could be beneficial for the structural design of new and lifetime extension of existing marine structures.

1.2 Introduction

Numerous marine structures, such as quay walls, jetties and flexible dolphins, have been realised all over the world to accommodate ships' berthing, mooring and loading operations. During the service life of a marine structure, functional requirements may change. These changes often result in uncertainty regarding actual berthing energy and structural integrity, especially if size of design increases at existing berthing facilities. Existing design guidance for assessing berthing energy, such as PIANC [17], British Standards [4], EAU [6] and Spanish ROM [13], suggest applying an overall safety margin. These guidelines do not include partial factor analyses of individual parameters and their individual contributions to the uncertainty in berthing energy. It is often not clear how resultant fender forces derived from such analyses should be applied in accordance with the safety philosophy of Eurocode standards [10], which predominantly recommend applying a partial safety factor to characteristic values of loads and resistance.

Metzger et al. [9] stated that load demands on berthing structures are not well understood due to a lack of information about berthing parameters. Therefore, there is a strong need to determine design values of berthing parameters and partial safety factors by using field observations. Although design guidelines recommend collecting sophisticated berthing records, data are mostly not available. Ueda et al. [19] showed that berthing velocity is the most important design parameter in defining berthing energy. The port authorities of Bremerhaven [7] and Rotterdam [14] therefore decided to start a measurement campaign on berthing velocity in order to evaluate and validate the performance of existing berthing facilities and the design guidance of EAU and PIANC. They wanted to know whether

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the berthing velocity curves of EAU and PIANC, presented in Figure 1, are still representative of and safe for modern vessels.

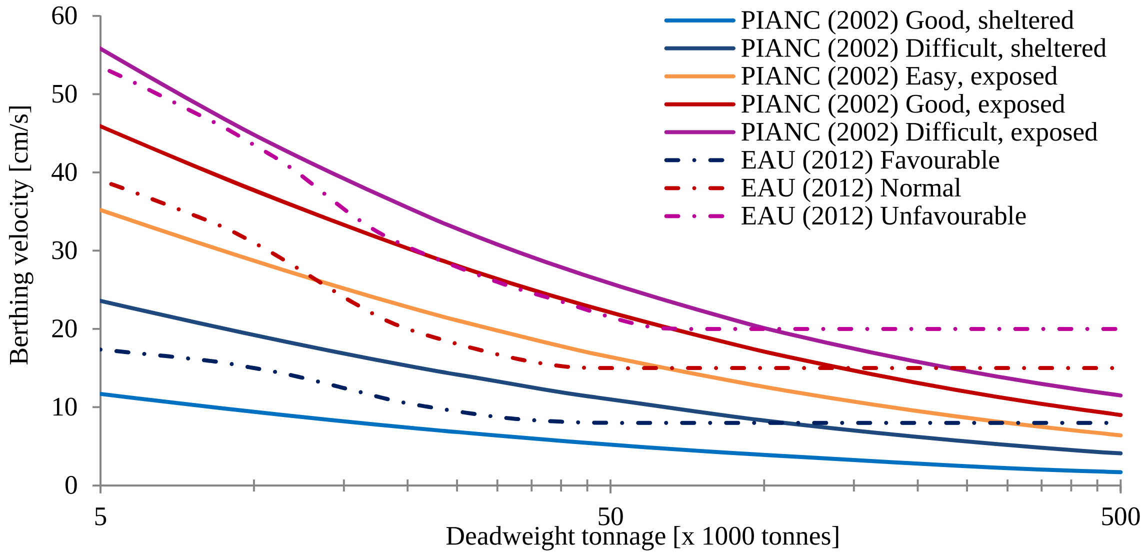

Figure 1: Berthing velocity curves of PIANC 2002 (Brolsma curves [2]) and EAU 2012 as a function of navigation conditions and vessel size [14]

The statistical meaning of berthing velocity curves is often unknown to or misinterpreted by designers and code writers of marine structures [1]. Where berthing records are available, existing design guidelines do not provide explicit recommendations with regard to the statistical examination of berthing velocities. It is therefore mostly not clear how to use field observations.

This study aims to provide guidance to code developers and engineers on the use of field observations and derivation of partial safety factors for berthing velocity and loads on marine structures. The main focus is on deriving characteristic values and associated partial safety factors for berthing velocity, because this is the dominant parameter in assessing berthing impact [19]. It should be noted that ship collision impact is not taken into consideration in this study [18]. During the study, recently recorded field observations of berthing velocity in the ports of Bremerhaven, Rotterdam and Wilhelmshaven were used to determine theoretical design berthing velocities and corresponding partial safety factors in accordance with the Eurocode standard [10]. The main focus was on comparing characteristic and design berthing velocities based on field measurements with previous design practice. Following modern design principles, partial safety factors were derived by using large datasets for sheltered and exposed navigation conditions.

It was expected that collecting and analysing field observations would contribute to the assessment of berthing facilities and the evaluation of design recommendations. The results of this study show that research could introduce new (business) opportunities by, for example, allowing larger vessels to berth at existing marine structures and/or extending the service life of marine structures.

1.3 Literature survey

1.3.1 General principles of berthing energy and impact

The objective of this section is to elucidate the general principles of and methods to account for berthing energy and the resulting berthing impact loads in structural design. Berthing energy is generally calculated on the basis of a large number of parameters in line with the following equation:

$$E_{kin} = {}^{1}\!/_{2}\, Mv^2\, C_m C_s C_c C_E \qquad (1)$$

in which:

E_{kin} Kinetic energy [kNm]

M Mass of vessel/water displacement [tonnes]

v Total translation velocity of centre of mass at time of first contact (includes component parallel and perpendicular to berthing line) [m/s]

C_m Virtual mass factor [-]

C_s Ship flexibility factor [-]

C_c	Waterfront structure attenuation factor [-]
C_E	Eccentricity factor [-]

Equation (1) is embedded in most design guidelines, or they refer to PIANC 2002 [17]. PIANC berthing velocity curves are widely used by the industry to determine the 'normal' berthing energy. Given a normal berthing energy, an abnormal berthing impact factor C_{ab} is applied to derive an abnormal berthing energy. In fact, C_{ab} is an overall safety margin, but since the introduction of Eurocodes this has been used as a partial safety factor for variable berthing impact loads together with design values of resistance parameters.

$$E_{abnormal} = C_{ab} \mathrm{E}_{normal} \tag{2}$$

in which:

$E_{abnormal}$	Abnormal berthing energy [kNm]
C_{ab}	Abnormal berthing factor [-]
E_{normal}	Normal berthing energy [kNm]

The berthing impact load F to which a marine structure is subjected is a function of the kinetic energy absorbed by the berthing system and of its deformation characteristics δ. Given a certain berthing velocity, the resulting berthing impact load largely depends on the stiffness of the marine structure and the soil conditions [13].

$$E_{kin} = \int_0^{\delta_{max}} F(\delta) d\delta \tag{3}$$

The deformation characteristics of a berthing system can be linear or non-linear. Equation (7) shows that a berthing impact load in a linear system (e.g. flexible dolphins without fenders) is proportional to berthing velocity. The effect of linear and non-linear behaviour is further discussed in section 1.6.1. In the case of linear-elastic behaviour, a berthing impact load can generally be derived by applying the following equations:

$$E_{kin} = \frac{1}{2} F\delta \tag{4}$$

$$\delta = \frac{F}{k} \tag{5}$$

$$F = \sqrt{2E_{kin}k} \tag{6}$$

$$F = v\sqrt{M\, C_m\, C_s\, C_c\, C_e k} \tag{7}$$

in which:

F	Berthing impact load [kN]
δ	Deflection of berthing structure [m]
k	Stiffness of berthing structure and soil [kN/m]

Eurocode standards [10] do not recommend using an overall safety margin, but advise applying partial safety factors to characteristic design parameters. Partial safety factors are predominantly related to both loads and resistance. Within the framework of this study, the load component was of interest and partial load factors define the ratio between the design value for load S_d and its characteristic value S_k.

$$S_d = \gamma_Q S_k \tag{8}$$

in which:

S_d	Design value variable load [kN]
S_k	Characteristic value variable load [kN]
γ_Q	Partial safety factor variable load [-]

It should be noted that the partial factor for variable loads γ_Q already takes account of the possibility of unfavourable deviations as well as uncertainties in modelling the effects of loads.

1.3.2 Return periods of berthing velocity curves

The berthing velocity curves presented in Figure 1 are frequently used to determine berthing impact loads in the design of marine structures. In this section, return periods of berthing velocity curves in literature are summarised in order to provide insight into the reliability of berthing impact loads used in practice.

The German recommendations for waterfront structures EAU 2012 [6] do not include information on the reliability of velocity curves, but refer to ROM 0.2-90 [12]. The berthing velocity tables of the Spanish ROM appear to be based on a return period of 50 years. The general recommendation of the Japanese OCDI [15] and Eurocode EN 1990 [10] do not cover this topic. Brolsma's original curves were reproduced and slightly modified over time, and published in PIANC 2002 [17] and BS 6349-4 [4]. The authors noted that Brolsma's berthing velocity curves are often not applied correctly. Mainly, the term 'mean design', included in PIANC 2002, was misinterpreted. This value is not equal to the mean berthing velocity of a vessel. Scrutiny of the original Brolsma paper revealed that the measurements were extrapolated. The associated berthing velocity curves were derived for a berthing frequency of 3000 vessels during a reference period of 30 years. This is equal to 100 berthings per year, assuming two very large crude carrier (VLCC) vessels per week.

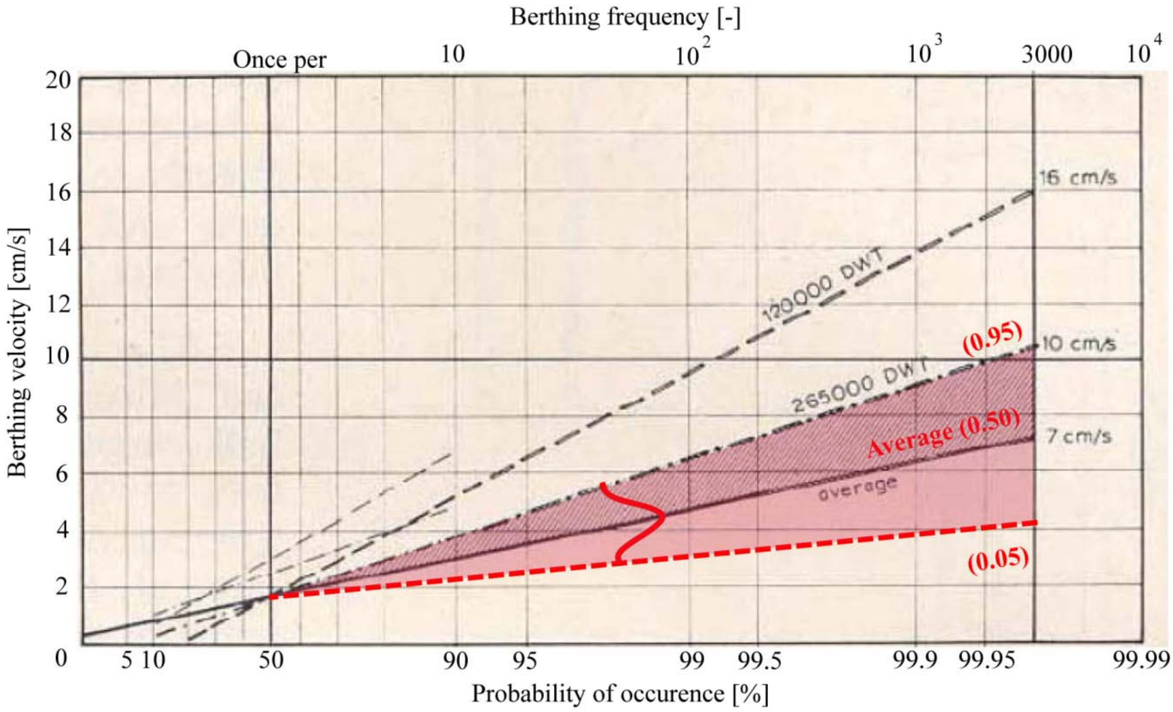

Figure 2: Extrapolation of 150 measurements derived by Brolsma et al. in 1977 [2]

Figure 2 is included in the original paper of Brolsma et al. [2] and shows an extrapolation of berthing velocities up to 3000 berthings. Brolsma showed that the average value (solid line representing the 0.50 quantile in Figure 2) of a VLCC tanker (265,000 DWT) in a reference period of 30 years was approximately 7 cm/s. The berthing velocities with a 5% probability of exceedance in a reference period of 30 years (dashed lines representing the 0.95 quantile in Figure 2) were approximately 10 cm/s and 16 cm/s for VLCC tankers and Aframax tankers (120,000 DWT), respectively. A reference period close to 30 years is in line with industry practice values for the design lifetime of a marine structure in the 1970s. An overview of return periods of berthing velocity curves in relevant literature is given in Table 1.

Table 1: Overview of return periods of berthing velocity curves in literature

	SI	PIANC (2002)	BS 6349-4 (2014)	EAU (2012)	ROM (1990)	OCDI (2009)	EN 1990 (2011)
T_R	year	30[1]	30[1]	50[2]	50	-	-

[1]) Based on berthing frequency published by Brolsma et al. [2]

[2]) Based on ROM 0.2-90 [13]

1.3.3 Abnormal berthing and load factors

When the backgrounds of the berthing velocity curves are known, the abnormal berthing factors C_{ab} and partial safety factors γ_Q are compared in order to gain an insight into the actual reliability level of relevant literature. Given a general cargo vessel, BS 6394-4 [4] recommends using an abnormal berthing factor equal to C_{ab}=1.5. For LNG, LPG and ferries, C_{ab}=2.0 is recommended. EAU 2012 [6] recommends applying a safety factor to characteristic berthing energy to account for exceptional berthing manoeuvres. These safety factors correspond to the abnormal berthing factors of PIANC 2002 [17]. An overview of abnormal berthing factors in literature is given in Table 2.

Table 2: Abnormal berthing factor C_{ab} [-] in literature.

Ship type	Size	PIANC (2002)	EAU (2012)	BS 6349-4 (2014)	ROM (1990)	OCDI (2009)	EN 1990 (2011)
Tankers	Largest-Smallest	1.25-2.00	1.25-2.00[1]	-	2.00	-	-
Bulkers	Largest-Smallest	1.25-2.00	1.25-2.00[1]	-	2.00	-	-
Container	Largest-Smallest	1.50-2.00	1.50-2.00[1]	-	2.00	-	-
General Cargo	-	1.75	1.75[1]	1.50[2]	2.00	-	-
RoRo, ferries	-	≥ 2.00	≥ 2.00[1]	-	2.00	-	-
Tugs, workboats	-	2.00	2.00[1]	-	2.00	-	-
LNG, LPG	-	-	-	2.00	2.00	-	-
Island berth	-	-	-	2.00	2.00	-	-

[1]) Based on PIANC 2002 [17]

[2]) Continuous quay handling conventional cargo vessels

As indicated, berthing energy is absorbed by the deflection of a marine structure and the hull of a vessel resulting in a berthing impact load on a marine structure. BS 6349-4 [4] therefore recommends also applying additional partial safety factors to a resulting berthing impact load. The partial safety factors for normal and abnormal berthing impact loads are γ_Q=1.35 (persistent situation) and γ_Q=1.2 (transient situation), respectively.

BS 6394-1-2 [3] considers an uncontrolled berthing procedure an accidental design situation, and the consequences of failure of a fender system being overloaded (e.g. direct and indirect future losses) must be taken into consideration. According to the British Standards, typical return periods of extreme environmental events for permanent structures are 50–100 years for persistent and 500–1000 years for accidental design situations. The recommended design lifetime for marine structures and fender systems is 50 and 15 years, respectively. Replacement of fenders during the lifetime of the structure is thus considered normal practice.

The German EAU 2012 distinguishes permanent, transient and accidental design situations and is consistent with Eurocode EN 1990 [10]. The partial safety factors γ_Q of loading classes 1, 2 and 3 for unfavourable variable loads are 1.0, 1.3 and 1.5, respectively. No exceptional/accidental berthing impacts (collisions/loss of control) need to be taken into consideration. The partial safety factors for loads related to berthing manoeuvres in the design of quay walls are in line with these values, but the partial safety factor in the design of flexible dolphins are all set at 1.0 in accordance with table R218-1 of EAU 2012 [6].

The Spanish ROM 0.2-90 [13] determines berthing loads as variable dynamic impact loads and also accounts for accidental berthing impacts (e.g. mechanical failures of tugs or vessels, mooring line breakage, sudden environmental condition changes, human error, etc.). Typical return periods of accidental impact loads are 1000 years and they are classified as ‘abnormal’ impacts. In this case, it is recommended to apply a safety factor to berthing energy of C_{ab}=2.0. The recommended partial safety factor to apply to a berthing impact load is γ_Q=1.5, which needs to be combined with other permanent and variable loads on marine structures [12].

The Japanese design code OCDI for marine structures considers serviceability, restorability and safety [16]. The design philosophy emphasises minimum port performance requirements and does not prescribe reliability. The general recommendation is to use a return period of 50 years for the derivation of characteristic variable loads. The OCDI suggests that a variable action with an annual exceedance probability of at least 1% should be the basic performance requirement. In fact, this probability is a threshold and represents a minimum return period of 100 years. The OCDI recommends using the threshold carefully, as it is only a guide for situations in which a design working life is in accordance with design standards.

Eurocode EN 1990 [10] does not provide specific recommendations for the design of marine structures. In the case of environmental loads, a characteristic value with a return period of 50 years is recommended. The partial safety factors γ_Q of reliability classes RC1, RC2 and RC3 are 1.35, 1.5 and 1.65 for unfavourable variable loads, respectively. An overview of return periods T_R and partial safety factors γ_Q in literature is given in Table 3:

Table 3: Return periods and partial factors of variable and berthing impact loads in literature

	SI	PIANC (2002)	BS 6394-1-2 (2015)	EAU (2012)	ROM (1990)	OCDI (2009)	EN 1990 (2011)
Variable loads (in general) [1]							
T_R SLS	Year	-	50-100	50	50	50	50
T_R ALS	Year	-	500-1000	-	1000	-	-[2]
γ_Q ULS	-	-	1.35-1.50	1.3-1.5	1.50	-	1.35/1.5/1.65
Berthing impact							
γ_Q (persistent)	-	-	1.35	1.00[3]	-	-	-
γ_Q (transient)	-	-	1.20	1.00[3]	-	-	-

[1]) Design codes do not uniformly describe SLS, ULS and ALS and are not completely consistent.
[2]) In the case of earthquakes, characteristic values with return periods in the range of 475-2475 years are recommended [11].
[2]) In the case of flexible dolphins.

1.4 Materials & methods

1.4.1 Data collection

Approximately 1393 and 555 records of berthing operations were collected in Germany and the Netherlands, respectively. The field observations regarding these berthing operations are further described by Hein [7] and Roubos et al. [14]. Various types of vessels, berths and navigation conditions were represented in the datasets. All berthing records were collected in well-organised port environments, namely Bremerhaven (1235), Rotterdam (555) and Wilhelmshaven (158). An overview of the collected data is given in Table 4. The berths in Bremerhaven were classified as exposed and berthing operations seemed to be influenced by strong tidal currents; the tidal range is typically about 3.8 m with tidal currents of 2.5–3.5 knots. All other berths were classified as sheltered.

Table 4: Overview of field observations of berthing velocity

Ship type [-]		n [-]	v_μ [cm/s]	v_{max} [cm/s]	Berth type [-]	Berthing aids [-]	Wind [-]	Waves [-]	Current [-]
Container	□	177	4.0	10	Closed quay	None	High	Sheltered	Low
Tankers	○	329	4.3	12	Jetty / dolphin	PPU/ docking system	High	Sheltered	Low
Bulkers	◊	144	4.4	13	Closed quay	Portable pilot units	High	Sheltered	Low
Container	□	1235	6.6	26	Closed quay	None	High	Exposed	High

The vessels were differentiated by ship type into container vessels, tankers and bulkers. They were then further differentiated into specific vessel classes in order to illustrate their differences or similarities. The classification was largely based on the international Lloyds database of vessels. All container vessels berthed at closed quay walls equipped with either hard buckling or soft cylindrical fender systems. Bulkers berthed at closed quay walls equipped with rigid timber beams. The tanker berths were equipped with flexible breasting dolphins provided with buckling fender systems. Studies by Yamase et al. [20] and Roubos et al. [14] have shown that berthing velocities are not influenced by type of marine structure or type of fendering.

1.4.2 Partial safety factors

A probabilistic study by Ueda et al. [19] showed that the contribution of berthing velocity to the uncertainty in kinetic berthing energy was approximately 85%, indicating that safety factors should be applied predominantly to berthing velocity. When defining kinetic berthing energy berthing velocity is assumed to be the only stochastic variable in equation (1). The partial safety factors derived in the present research were therefore applied to a characteristic value of berthing velocity. The partial safety factor γ_v was defined as the ratio between a design berthing velocity v_d and a characteristic berthing velocity v_k. The following equation was used to determine partial safety factors for berthing velocity:

$$\gamma_v = \frac{v_d}{v_k} \tag{9}$$

in which:

- γ_v Partial safety factor for berthing velocity [-]
- v_d Design value of berthing velocity [cm/s]
- v_k Characteristic value of berthing velocity [cm/s]

Characteristic and design berthing velocities were considered to be extreme events and were derived by extrapolating distribution fits and applying extreme value theory. In the present study, characteristic berthing velocities had a return period of 50 years representing a time-variant berthing velocity with a 2% probability of being exceeded during a reference period of one year. It should be noted that this is not equal to a 2% probability that a single berthing operation will exceed the characteristic berthing velocity. This insight is important, because a marine structure facilitates multiple vessels per year. It is further emphasised that a return period is not the same as a reference period. The probability that an event will occur with a return period of 50 years in a reference period of one year is 2% and in a reference period of 50 years 63.5%.

A design value for berthing velocity is typically selected such that a marine structure has sufficient reliability (or a sufficiently low probability of failure). Assuming a normal distribution, this is written as follows:

$$P_\mathrm{f} = \Phi(-\beta_d) \text{ or } \beta_d = \Phi^{-1}(P_\mathrm{f}) \qquad (10)$$

in which:

P_f	Probability of failure of an event [-]
β_d	Target reliability index [-]
Φ^{-1}	Inverse of standard normal distribution function [-]

Target reliability indices β_d are generally prescribed in design codes, such as Eurocode standards [10]. The derivation of design berthing velocities with a probability of exceeding a certain threshold is further explained in section 1.4.4 in accordance with the following principle:

$$\mathrm{P}(v > v_d) = \Phi(-\alpha_S \beta_d) \qquad (11)$$

in which:

v	Berthing velocity [cm/s]
v_d	Design value berthing velocity [cm/s]
α_S	Sensitivity factor for dominating load/solicitation [-]

When establishing extreme berthing velocities from field observations, the size of the datasets was of significant importance, especially as the objective was to derive a set of generalised partial safety factors. Partial safety factors are preferably derived using large datasets, because extreme berthing velocities are influenced by the fit of the low probability tail of an extreme value distribution to field observations. In the present study, three large datasets were developed, namely 'All tankers', 'All sheltered' and 'All exposed'. The dataset of all tankers is a subset of the dataset all sheltered and represents the use of berthing aid systems, such as portable pilot units (PPU) and fixed shore-based laser docking systems. The use of berthing aid systems could reduce the probability of extreme/ uncontrolled berthing events. Further, the available data were subdivided into sheltered and exposed navigation conditions. An overview of the datasets is given in Table 5.

Table 5: Large datasets

Large datasets [-]	n [-]	v_μ [cm/s]	v_{max} [cm/s]	Berth type [-]	Berthing aids [-]	Wind [-]	Waves [-]	Current [-]
All tankers ○[1]	392	4.6	12	Open	PPU/docking system	High	Sheltered	Low
All sheltered ∆	713	4.4	13	Mixture	Mixture	High	Sheltered	Low
All exposed □	1235	7.1	26	Closed	None	High	Exposed	High
All data	1948	6.6	26	Mixture	Mixture	High	Mixture	Mixture

[1]) Dataset is a subset of all sheltered

1.4.3 Data analysis

This section concerns the methods used for deriving berthing velocities with low probabilities of exceedance in order to determine partial safety factors. OCDI [15] and Roubos et al. [14] statistically examined field observations of single berthing velocities. Both studies showed that a distribution fit of the low-probability tail was closer to a Weibull distribution $F(x;\lambda,k)$ than to a normal or lognormal distribution. In the present study, the collected berthing velocities were therefore described using a Weibull distribution fit on the basis of maximum likelihood estimation. Typical distribution fits for all sheltered and exposed data are illustrated in Figure 3 and Figure 4.

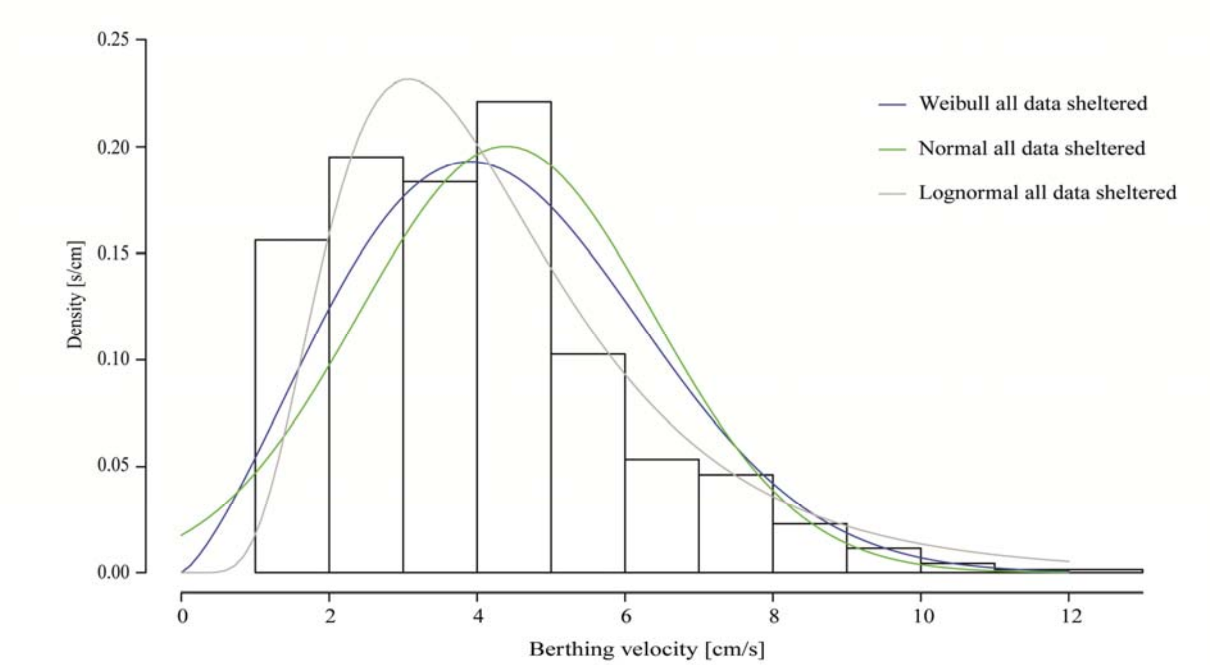

Figure 3: Histogram and probability density functions of all sheltered berthing records (n=713)

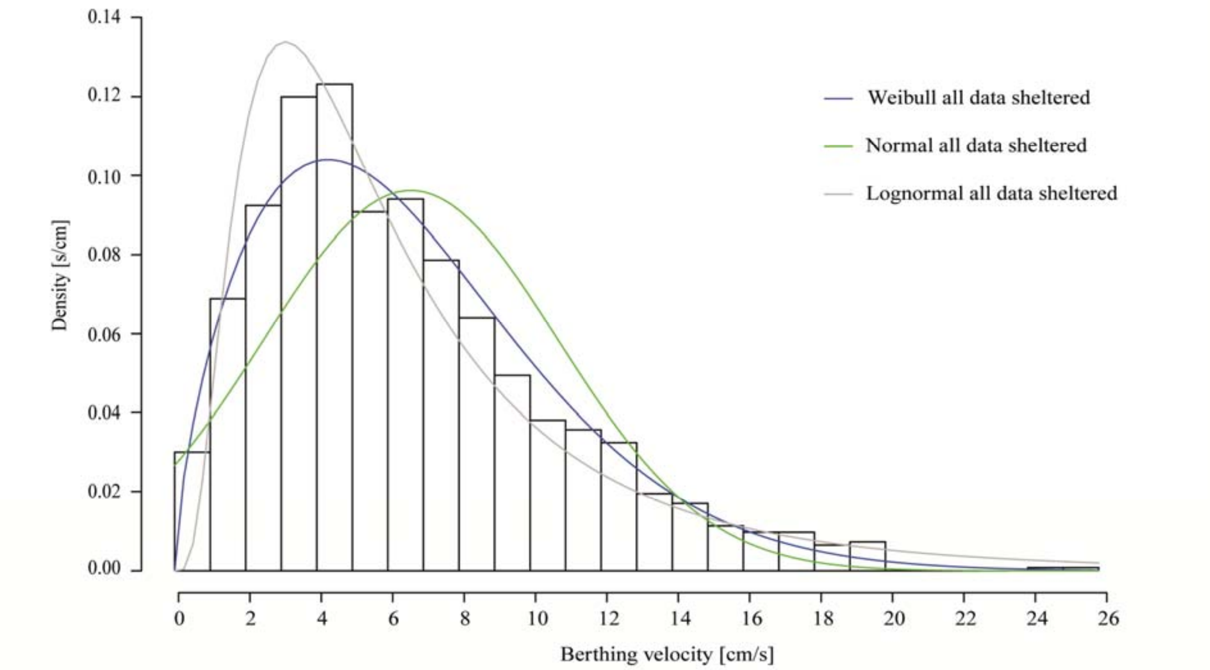

Figure 4: Histogram and density functions of all exposed berthing records (n=1235)

Characteristic and design berthing velocities were derived on the basis of extreme value theory by using the following methods:

- A direct assessment was performed by extrapolating the Weibull distribution fit to the original dataset.
- An indirect assessment based on the use of normal distributions only, in line with the method often used for load extrapolations as per Eurocode by applying a two-step extreme value analysis of annual and lifetime maxima.

The first method was based on the extrapolation of a distribution fit to the original data. Assuming that the number of berthings per year and the required target reliability during a certain reference period are known, characteristic v_k and design berthing velocities v_d were established by extrapolating the Weibull distribution fit. The probability that a berthing velocity X was higher than a particular berthing velocity x was calculated by generating corresponding berthing velocities directly from the Weibull distribution function $P(X > x)=1-F(x)$:

$$F(x;\lambda,k) = 1 - \exp\left(-\left(\frac{x}{\lambda}\right)^k\right) \quad (12)$$

$$\left(\frac{x}{\lambda}\right)^k = -ln\big(1 - F_x(x)\big) = -ln\big(P(X > x)\big) = \ln\left(\frac{1}{P(X > x)}\right) \quad (13)$$

$$\left(\frac{x}{\lambda}\right) = \left(\ln\left(\frac{1}{P(X > x)}\right)\right)^{\frac{1}{k}} \quad (14)$$

$$x = \lambda\left(\ln\left(\frac{1}{P(X > x)}\right)\right)^{\frac{1}{k}} \quad (15)$$

in which:

$F(..)$	Probability distribution function [-]
x	Berthing velocity [cm/s]
μ	Mean value [cm/s]
σ	Standard deviation [cm/s]
λ	Scale parameter Weibull distribution [cm/s]
k	Shape parameter Weibull distribution [-]

Given the number of berthings within a year n berthing velocities, with a certain probability of exceedance during a reference period expressed by a return period T_R, were calculated with the following equation:

$$v(T_R, n) = \lambda\left(\ln\left(\frac{1}{P(X > x)}\right)\right)^{\frac{1}{k}} = \lambda(\ln(T_R n))^{\frac{1}{k}} \quad (16)$$

in which:

T_R	Return period [years]
n	Number of berthings per year [-]

The second method is based on extreme value theory and is suggested in the Implementation of Eurocodes handbook [5]. In the case of time-dependent loads, distributions of annual and lifetime maxima were used to account for alternative reference periods or target reliability indices in order to determine and generalise partial safety factors. In this study, the probability that all berthing operations during a certain reference period were lower than or equal to a particular berthing velocity were calculated by examining distributions of extreme berthing velocities. In analogy with the Eurocodes, the extreme value distributions were called distributions of annual and lifetime maxima. The following general mathematical principles of extreme value theory were applied:

$$F_{x_n^n} = P(x_1 \le x \cap x_2 \le x \cap..\cap x_n \le x) = P(x_1 \le x)P(x_2 \le x)..P(x_n \le x) \quad (17)$$

$$F_{x_n^n} = \left(F_{x(x)}\right)^n \quad (18)$$

The parameters $x1,...x2$, represent field measurements of berthing velocities $v1,...v2$, and were assumed to be independent Weibull distributed random variables:

$$F(x;\lambda,k) = 1 - \exp\left(-\left(\frac{x}{\lambda}\right)^k\right) \quad (19)$$

From the typical Weibull distribution fit, random berthing velocities corresponding to a certain reference period were generated. The maximum berthing velocities during this reference period were selected and stored.

$$P(X > x) = P(\max(v_{1,} v_2 \ldots\ldots, v_n) > x) \quad (20)$$

This process was repeated at least 200 times to ensure an appropriate population of maximum berthing velocities. In this way a new distribution of maxima was formed that appeared to be a normal distribution (Figure 5). The fit to the tail of this distribution was of significant importance when deriving berthing velocities with low probabilities of occurrence. The dark blue dashed line in Figure 5 is the distribution of annual maxima and represents the distribution of maximum berthing velocities during a reference period of one year. The red dashed line is the lifetime maxima and represents the maximum berthing velocity during a reference period of 50 years.

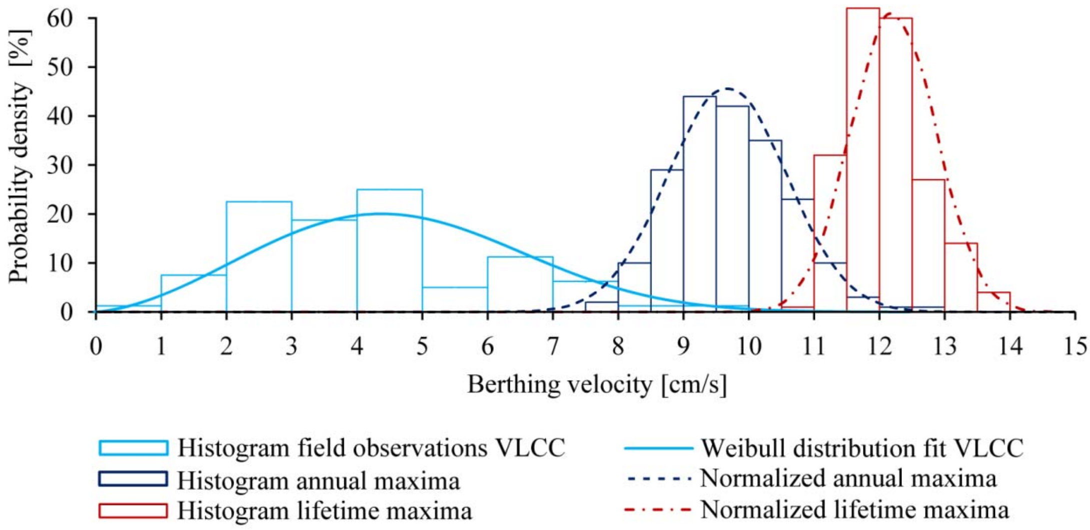

Figure 5: Distribution of annual and lifetime maxima (t_{ref}=50 years) VLCC vessels Rotterdam

It should be noted that the second method was also influenced by the number of berthings during a certain reference period. An increase in berthings resulted in an increase in the mean value and a decrease in the coefficient of variation. This insight is essential to interpret the results of extreme value theory and the influence of berthing frequency.

1.4.4 Characteristic and design berthing velocities

The magnitude of extreme berthing velocities largely depends on the number of berthings during a certain reference period. Some design codes explicitly provide recommendations on target reliability β_d index and other codes on return period T_R. Given a target reliability index for a certain reference period, the corresponding return period was calculated with the following equations:

$$P_d = 1 - \left(1 - \frac{1}{T_R}\right)^{t_{ref}} \quad (21)$$

$$T_R = \frac{1}{1-(1-P_d)^{\frac{1}{t_{ref}}}} = \frac{1}{1-\left(1-\Phi(-\alpha_S\beta_d)\right)^{\frac{1}{t_{ref}}}} \quad (22)$$

in which:

P_d	Lifetime probability of failure of an event [-]
T_R	Return period of variable load [years]
t_{ref}	Reference period [years]
α_S	Sensitivity factor for dominating load/solicitation [-]
β_d	Prescribed target reliability index [-]

In this study, the principles of ISO 2394 [8] were applied in order to comply with existing design codes and standards. The safety philosophies of Eurocodes [10] and OCDI [15] are both based on the principles of ISO 2394, and British Standards, EAU and ROM are consistent with Eurocodes. ISO 2394 recommends applying sensitivity factors to dominant and non-dominant loads. In this study, both load and strength were assumed to be important and only dominant loads were taken into consideration. Non-dominating loads were not taken into account because in the case of load combinations, modern design codes generally recommend applying a set of combination factors to transform dominating loads into non-dominating loads. The importance of berthing velocity was expressed by applying a sensitivity factor α_S=-0.7 to dominating variable loads. It should be noted that α_S has a negative value and could be verified by a probabilistic assessment. Consequently, the probability of a dominating variable berthing velocity exceeding a design berthing velocity was evaluated by equation (11).

Eurocode standard EN 1990 defines target reliability indices β_d for reliability classes RC1, RC2 and RC3. Other design guidelines incorporate recommendations for return periods T_R (see section 1.3.2). The theoretical return periods of the target reliability indices of EN 1990 for dominant loads (α_S=-0.7) for a reference period of 50 years were determined by applying equation (22) and are listed in Table 6.

Table 6: Theoretical return periods for variable loads during a reference period of 50 years according to EN 1990

	SI	RC1	RC2	RC3
β_d	-	3.3	3.8	4.3
α_s	-	-0.7	-0.7	-0.7
P_d	%	1.05	0.40	0.13
T_R	year	4750	12,500	38,250

In the present study, extreme berthing velocities for different return periods were derived in order to compare field observations with existing design guidelines. Design berthing velocities corresponding to return periods of 100, 475, 1000, 4750, 12,500 and 38,250 years were derived. It should be noted that the codes are intended not to cover the incidence of such very rare events, but to create a low probability that structures will fail under the conditions of a reasonably rare incident during the service lifetime, also taking into account all sources of errors and adverse conditions not explicitly covered by the partial factors. Characteristic berthing velocities represented a return period of 50 years. For comparison, the number of berthings was set at approximately 100 berthings of a design vessel per year. This is similar to the underlying assumption of the berthing velocity curves derived by Brolsma et al. [2].

Characteristic berthing velocities were derived by directly extrapolating the Weibull distribution fit (method 1) and by examining distributions of annual maxima (method 2). The distribution of annual maxima appeared to be a normalised distribution with a mean value and standard deviation (μ_{v_k} , σ_{v_k}) (see Figure 7). Given n=100 berthings per year, the reliability of T_R =50 years corresponds to once per 5000 berthings (T_R*n). The inverse of T_R =50 years is a probability of 2% being exceeded in a reference period of one year, and the corresponding annual reliability index therefore equals $\beta_{2\%}$=2.054. In this study, the following equations were used to determine berthing velocities with a return period of 50 years:

$$v_k = \lambda(\ln(T_R n))^{\frac{1}{k}} = \lambda(\ln(5000))^{\frac{1}{k}} \text{ (method 1)} \tag{23}$$

$$v_k = \mu_{v_k} + \beta_{2\%} \times \sigma_v = \mu_{v_k}\left(1 + 2.054 \times V_{v_k}\right) \text{ (method 2)} \tag{24}$$

The design berthing velocities for different return periods or the probability of exceedance were derived using the same methods. Design berthing velocities according to method 1 were derived by using equation (25). In the case of normalised distributions of lifetime maxima (method 2), the corresponding design berthing velocities were found by applying equation (26).

$$v_d = \lambda\left(\ln\left(\frac{n}{1-\left(1-\Phi\left(-\alpha_S\beta_d\right)\right)^{\frac{1}{t_{ref}}}}\right)\right)^{\frac{1}{k}} \text{ (method 1)} \tag{25}$$

$$v_d = \mu_{v;d} - \alpha_S\beta_d\, \sigma_{v;d} = \mu_{v;d}(1 - \alpha_S\beta_d\, V_{S;d}) \text{ (method 2)} \tag{26}$$

in which:

$\mu_{v;d}$	Mean value of lifetime maxima [cm/s]
$\sigma_{v;d}$	Standard deviation of lifetime maxima [cm/s]
α_S	Sensitivity factor for dominating berthing velocity [-]
$V_{S;d}$	Covariation of lifetime maxima [-]

1.5 Results

1.5.1 Extreme berthing velocities

As an example, the population of VLCCs with a deadweight tonnage of 260,000–319,000 was statistically examined by using direct extrapolation of the Weibull distribution fit (method 1) and extreme value distributions (method 2).

An extrapolation of the Weibull distribution fit based on 80 field measurements of VLCC tankers was used to determine extreme berthing events (Figure 6). Assuming 100 berthings of a design vessel per year, the characteristic berthing velocity v_k was approximately 11.9 cm/s. The design berthing event corresponding to a target reliability equal to β_d=3.8 and a sensitivity factor equal to α_S=-0.7 had a probability of exceedance equal to $P(v \leq v_d)$≈0.4%. In fact, this means a 0.4% chance of being exceeded during a period of 50 years, which corresponds to a theoretical return period of 12,500 years and a probability of exceedance of 1/1,250,000. A design berthing velocity v_d of approximately 14.4 cm/s was found (Figure 6).

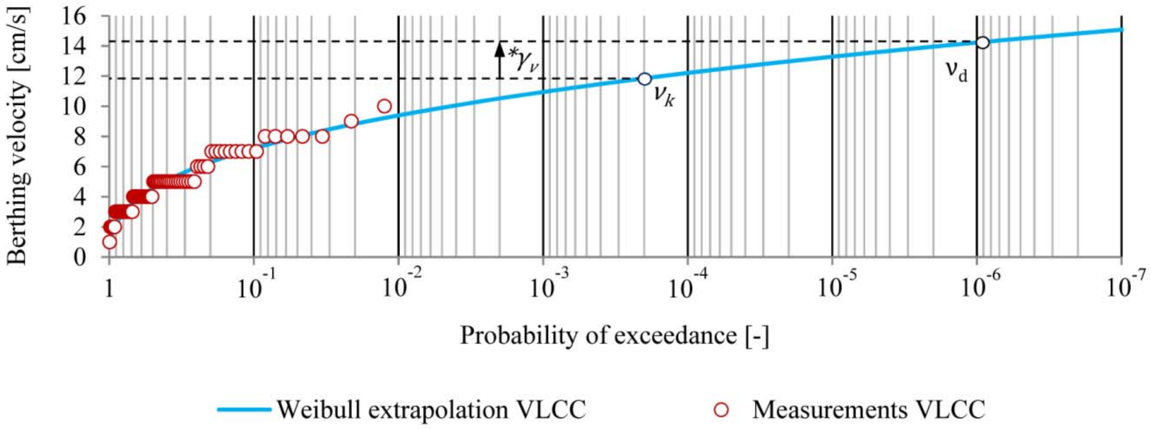

Figure 6: Extrapolation of Weibull distribution fit to VLCC tankers (method 1)

The Implementation of Eurocodes handbook [5] uses extreme value theory to determine appropriate partial safety factors. The same principles were applied in this study. They are illustrated in Figure 7. The solid blue line represents the probability density function of a Weibull distribution fit to the original dataset. The dashed blue and red lines are the normalised extreme value distributions of annual maxima and lifetime maxima, respectively. The mean value of lifetime maxima was higher and the probability density function was steeper than the density function of annual maxima.

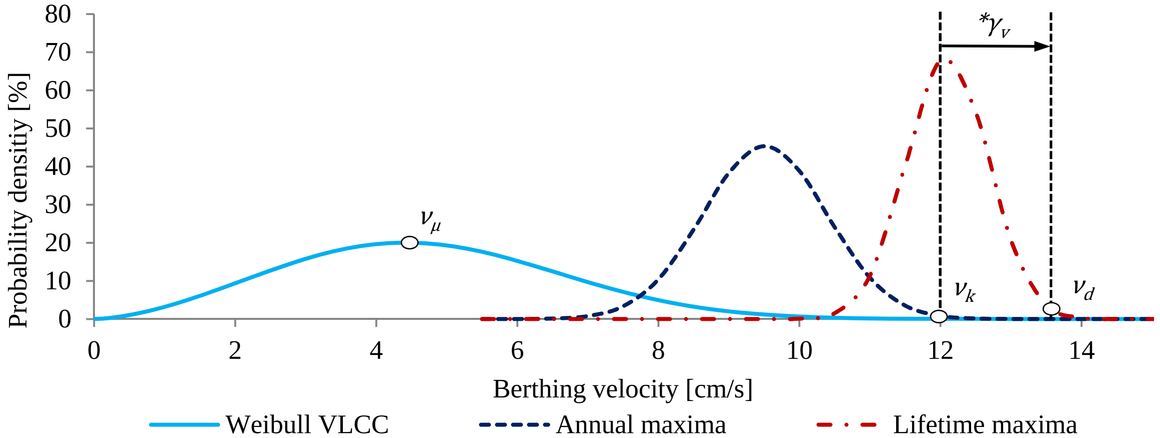

Figure 7: Extreme value distributions of annual maxima and lifetime maxima (t_{ref}=50 years) for VLCC tankers (method 2)

On the basis of 80 VLCC berthing operations, a single berthing had a mean berthing velocity v_μ of approximately 4.5 cm/s. The characteristic berthing velocity v_k with a theoretical return period of 50 years was equal to approximately 12 cm/s. Assuming 5000 VLCC berthings and a 0.4% chance of being exceeded during a reference period of 50 years, a design berthing velocity v_d of approximately 13.6 cm/s was found (Figure 7).

This example showed that similar design berthing velocities v_d were found by applying direct extrapolation (method 1) and indirect extreme value distributions (method 2). The small differences were mainly caused by inadequate modelling of the low-probability tail of both normalised annual and lifetime maxima distributions. The typical shape and scale parameters of the Weibull distribution fits and distributions for annual and lifetime maxima are given in Appendix A. An overview of calculation results of both methods is given in Table 7. It should be noted that the derived berthing velocities were based on a berthing frequency of 100 berthings per year, a sensitivity factor α_S=-0.7 and a reference period of 50 years.

Table 7: Extreme berthing velocities individual vessel classes [cm/s]

	kDWT	*n*[1]	*max*[2]	Extrapolation of Weibull distribution fit							Extreme value distributions			
$P(v \leq v_d)$ [%]				63.50	39.50	10.00	4.88	1.05	0.40	0.13	63.50	10.00	0.40	0.13
T_R [Years]				50	100	475	1000	4750	12,500	38,250	50	4750	12,500	*38,250*
Tankers ○														
Panamax	60-85	23	9	12.6	12.9	13.6	13.9	14.5	14.8	15.2	12.6	14.1	14.3	14.5
Aframax[3]	85-105	175	12	11.1	11.4	12.1	12.4	13.0	13.4	13.8	10.8	12.8	13.0	13.3
Suezmax	115-165	95	11	11.5	11.9	12.6	12.9	13.5	13.9	14.2	11.2	13.0	13.2	13.4
VLCC	260-319	80	10	11.9	12.3	13.0	13.3	14.0	14.4	14.8	12.0	13.4	13.6	13.8
Fix. Laser	260-319	19	7	8.9	9.1	9.7	9.9	10.4	10.6	10.9	8.6	9.9	10.1	10.2
Bulkers ◊														
Capesize[4]	150-205	107	13	15.3	16.0	17.4	18.0	19.2	19.9	20.8	14.9	18.4	18.8	19.2
VLBC[4]	205-365	37	10	12.8	13.3	14.3	14.7	15.6	16.1	16.7	12.5	15.4	15.7	16.0
Containers □														
Coasters	7 - 15	37	10	12.7	13.0	13.5	13.8	14.3	14.6	14.9	12.6	13.9	14.1	14.3
Feeders	15 -42	31	9	12.2	12.6	13.3	13.7	14.3	14.7	15.2	12.0	14.1	14.4	14.6
Panamax	42-70	31	8	10.8	11.1	12.0	12.3	13.1	13.5	14.0	10.1	12.9	13.1	13.4
Post Panamax	70-118	60	7	10.3	10.7	11.6	12.1	12.9	13.4	13.9	10.1	12.3	12.5	12.8
New Panamax[3]	118-171	18	3	3.8	3.9	4.1	4.1	4.3	4.4	4.5	3.7	4.2	4.3	4.3
Containers □														
Coasters	7 - 15	177	20	29.8	31.4	34.8	36.4	39.6	41.5	43.7	27.7	38.1	39.1	40.1
Feeders	15 -42	250	20	29.4	30.9	34.2	35.7	38.7	40.6	42.6	28.4	37.3	38.2	39.2
Panamax	42-70	104	19	26.9	28.0	30.5	31.6	33.8	35.2	36.6	26.1	31.8	32.5	33.1
Post Panamax	70-118	288	25	28.7	30.1	33.0	34.3	37.0	38.6	40.4	27.7	35.1	35.9	36.7
New Panamax	118-171	150	20	26.9	28.1	30.7	31.8	34.2	35.6	37.1	25.7	32.8	33.5	34.3
ULCV	171-195	266	26	26.7	28.2	31.4	32.8	35.8	37.6	39.6	22.9	33.6	34.4	35.2
Large datasets														
All tankers ○	60-319	932	12	11.5	11.8	12.6	12.9	13.5	13.9	14.3	11.1	13.0	13.2	13.4
All sheltered Δ	7-365	713	13	12.6	13.1	14.0	14.4	15.2	15.7	16.3	12.1	15.0	15.3	15.6
All exposed □	7-195	1235	26	26.4	27.7	30.4	31.6	34.1	35.6	37.2	25.2	32.6	33.4	34.2
All data	60-319	1948	26	25.0	26.3	29.1	30.4	32.9	34.4	36.2	22.7	31.8	32.6	33.5

[1]) Number of field observations
[2]) Maximum measured berthing velocity
[3]) Dataset is most likely too optimistic [14]
[4]) Dataset is most likely too conservative [14]

1.5.2 Characteristic berthing velocities

In Figure 8 the berthing velocities of individual vessel classes representing a return period of 50 years are compared with those of EAU 2012 [6] and PIANC 2002 [17]. It should be noted that the berthing velocity curves of EAU 2012 represent berthing velocities with a return period of 50 years, while those of PIANC 2002 represent berthing velocities with a return period of 30 years. The characteristic values of berthing velocity v_k of individual vessel classes were determined by using existing design practice and by interpreting the results derived in section 1.5.1.

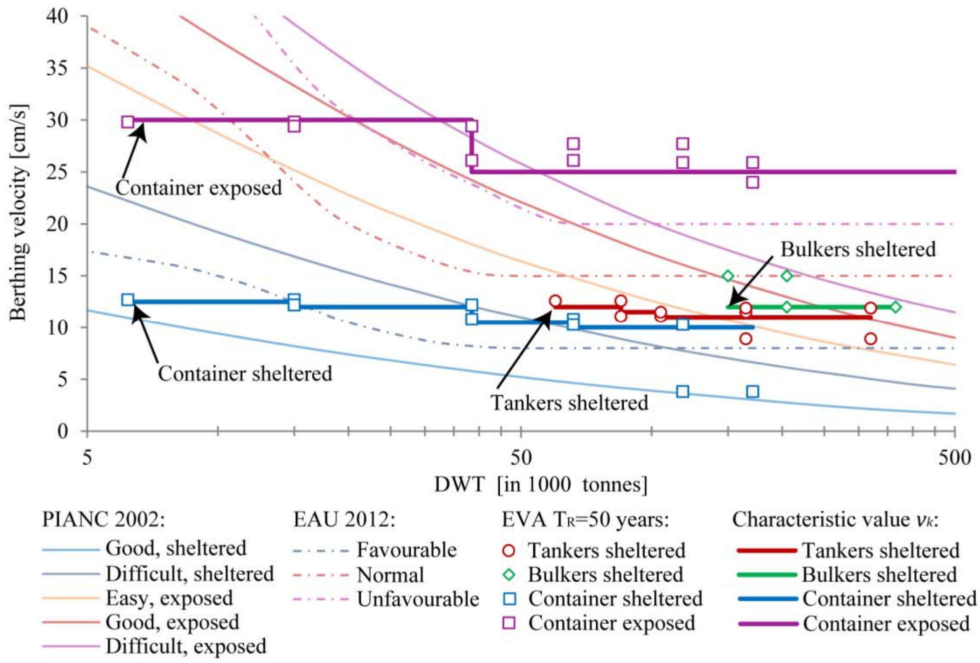

Figure 8: Characteristic berthing velocities compared with PIANC 2002 and EAU 2012

According to the statistical examination of extreme berthing velocities, no real correlation between berthing velocity and mass of the vessel was found for tankers in sheltered conditions. The goodness of fit of the Weibull distribution function to the individual dataset of Aframax tankers was low and should be used with care [14]. In practice, characteristic values of berthing velocity are generally higher than 10 cm/s. If a shore-based docking system has been installed, characteristic berthing velocities of 8 cm/s are more common. Similar values were found in section 1.5.1. It should be noted that individual datasets of bulk carriers most likely contain overestimated berthing velocities at the moment of impact [14]. For large seagoing bulkers, no real correlations were found. Characteristic berthing velocities of 12 cm/s for large bulkers in sheltered conditions were typically used in practice. A small correlation between vessel size and berthing velocity was found for container vessels in sheltered conditions. The berthing velocities were influenced by type of manoeuvre/landing procedure and berthing policy [14]. Berthing velocities of large seagoing container vessels in exposed navigation conditions showed no real correlation with vessel size [7]. The berthing velocities were higher compared to EAU velocity curves, but due to very low berthing angles (always between 0° and 1°) deflection of the fenders showed that the actual berthing energy was still less than the design energy [7]. It should be noted that for most individual vessel classes, there were insufficient data to determine partial safety factors per vessels class and therefore large datasets were developed.

1.5.3 Partial safety factors for berthing velocity γ_v

In this study, partial safety factors were defined as the ratio between a design value and a characteristic value of berthing velocity, and they were derived by direct interpolation of a Weibull distribution fit (method 1) to large datasets. The results are given in Table 8. It is important to realise that partial safety factors for time-dependent design berthing velocities are theoretically not constant. Partial safety factors are influenced by the uncertainly and importance of a berthing velocity as well as the target probability of failure during a certain reference period.

***Table 8: Partial safety factors for berthing velocity γ_v* by applying method 1, extrapolation of Weibull distribution fit**

		Reliability class of *EN 1990*		
γ_v	SI	RC1	RC2	RC3
All tankers ○	-	1.17	1.20	1.24
All sheltered Δ	-	1.21	1.25	1.29
All exposed □	-	1.29	1.34	1.41
All data	-	1.31	1.38	1.44

Figure 9 shows that the Weibull distribution fits to the datasets of 'All tankers' and 'All sheltered' navigation conditions slightly underestimate low probability berthing velocities. This was considered acceptable, because the highest measured berthing velocities were caused by too conservative measurements, for example small seagoing tankers and large seagoing bulkers [14]. The dataset 'All exposed' contains numerous berthing velocities just below 20 cm/s, as well as two higher berthing velocities of 25 and 26 cm/s (see Figure 9). The Q–Q probability plot of Figure 10 shows that theoretical and empirical quantiles of the two extreme berthing velocities measured in Bremerhaven were almost identical.

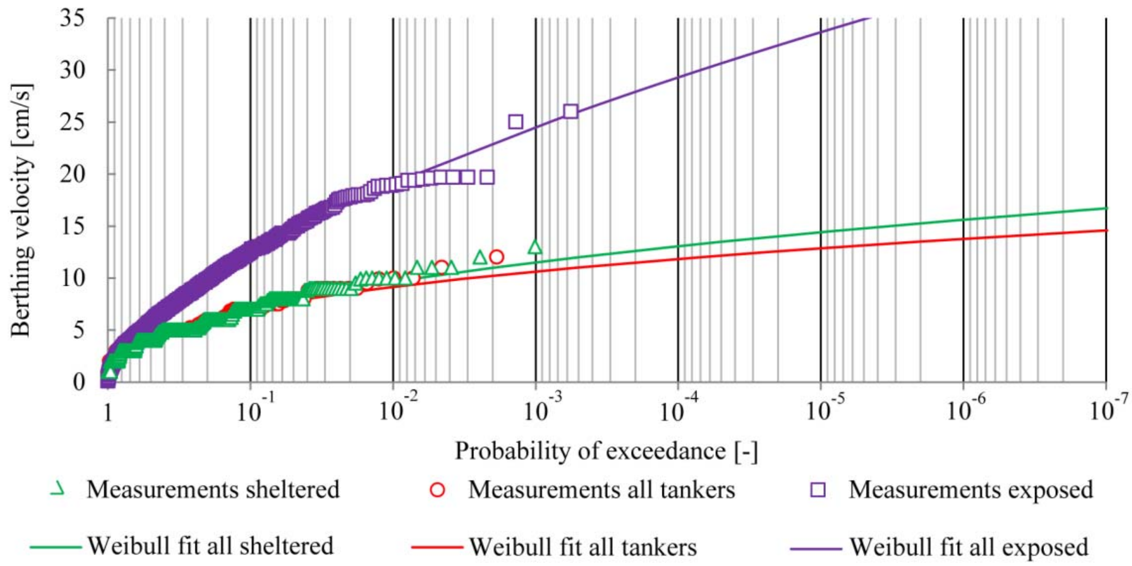

Figure 9: Probability of exceedance plot large datasets

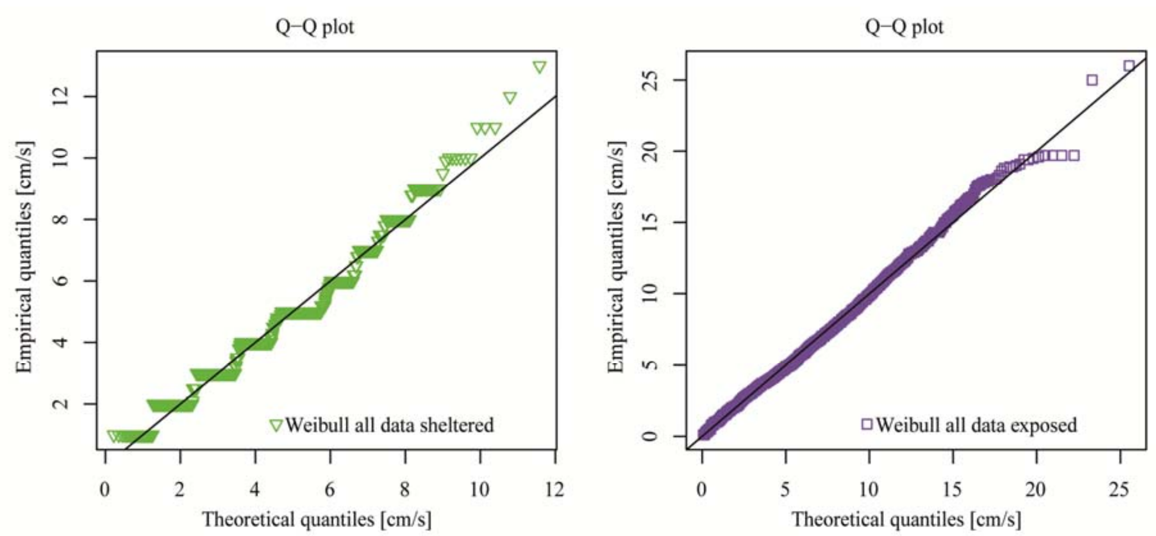

Figure 10: Probability distribution plot all sheltered and exposed data

1.6 Discussion

1.6.1 How to use berthing velocity records and partial safety factors in the design

This section discusses how to implement field observations of berthing velocity and partial safety factors in structural assessments of berthing impact loads on marine structures. As explained in section 1.3.1, the berthing impact load to which a marine structure is subjected largely depends on the type of berthing structure, that is, its linear or non-linear deformation characteristics. The effect of linear and non-linear behaviour on berthing impact load F is further explained by the following simplified equation to illustrate the effect of difference in performance:

$$F = k\delta^N \quad (27)$$

in which:

F	Berthing impact load [kN]
δ	Deflection of fender + berthing structure [m]
k	Stiffness of berthing structure and soil [kN/m]
N	Coefficient for linearity [-]

Examples of berthing structures showing linear and non-linear structural behaviour are given in Table 9. When, for instance, a pneumatic or cylindrical fender system is installed on a rigid quay wall, the berthing energy is absorbed by fender deflection showing non-linear hardening (N>1). Flexible dolphins equipped with timber fendering absorb berthing energy by deflection showing an approximately linear-elastic behaviour ($N=1$). When a buckling type fender system is installed on a flexible dolphin, structural behaviour often shows softening (N<1), but when the capacity of a fender system is exceeded, the response of a berthing structure will be similar to a situation without fendering (N=1), for example during the full compression of a fender equipped with a fender stop. If buckling-type fender systems are installed on rigid quay walls, the amount of energy absorbed by the marine structure itself is negligible. In this case, the fender system absorbs most of the berthing energy by deflection and the resulting berthing impact load is mainly influenced by fender characteristics showing typically ideal plastic behaviour (N≈0).

Table 9: Examples linear and non-linear behaviour of marine structures

Range	Behaviour	Examples
$N > 1$	Non-linear hardening	Rigid marine structure (quay wall) + cylindrical/pneumatic type fender system Flexible dolphin + cylindrical/pneumatic type fender system
$N = 1$	Linear elastic	Flexible dolphin without energy absorbing fender system (timber fendering)
$N < 1$	Non-linear softening	Flexible dolphin + buckling type fender system
$N \approx 0$	Ideal plastic	Rigid marine structure (quay wall) + buckling type fender system

The process to derive a design berthing impact load by applying simultaneously the two design approaches described in section 1.3.1 is illustrated in Figure 11. The principal difference is the application of a partial safety factor either to characteristic berthing velocity γ_v or to characteristic berthing impact load γ_Q. The flowchart starts with the determination of a characteristic berthing velocity v_k by using field observations. Typical characteristic berthing velocities measured at well-organised ports are presented in Figure 8. It should be noted that the berthing frequency influences the characteristic berthing velocity. This is further discussed in section 1.6.3. The derivation of partial safety factor γ_v was based on a statistical examination of sophisticated datasets of representative field observations. The partial safety factor γ_v does not take uncertainty in modelling the effects of loads into account, while partial safety factor γ_Q complies with design codes and standards, such as EN 1990 [10], and already includes model uncertainty. In analogy with the Eurocode standard, equation 6.2 of EN1990, an additional partial safety factor γ_{Sd} for berthing impact load F_v needs to be applied. It should be noted that the governing berthing impact load F_d depends on the type of berthing structure and the values of partial safety factors γ_v, γ_{Sd} and γ_Q.

Figure 12 shows that a partial safety factor for berthing velocity γ_v is only proportional to a partial safety factor for berthing impact load γ_Q for linear-elastic behaviour (N=1). If we assume that $\gamma_v = \gamma_Q$ then in the case of non-linear softening (N<1) the partial safety factor for berthing impact load γ_Q will result in the governing berthing impact load F_d. Conversely, in the case of non-linear hardening (N>1), a partial safety factor for berthing velocity γ_v will result in the governing berthing impact load F_d. The effect of uncertainty in modelling the load effect is illustrated by applying γ_{Sd} to F_v.

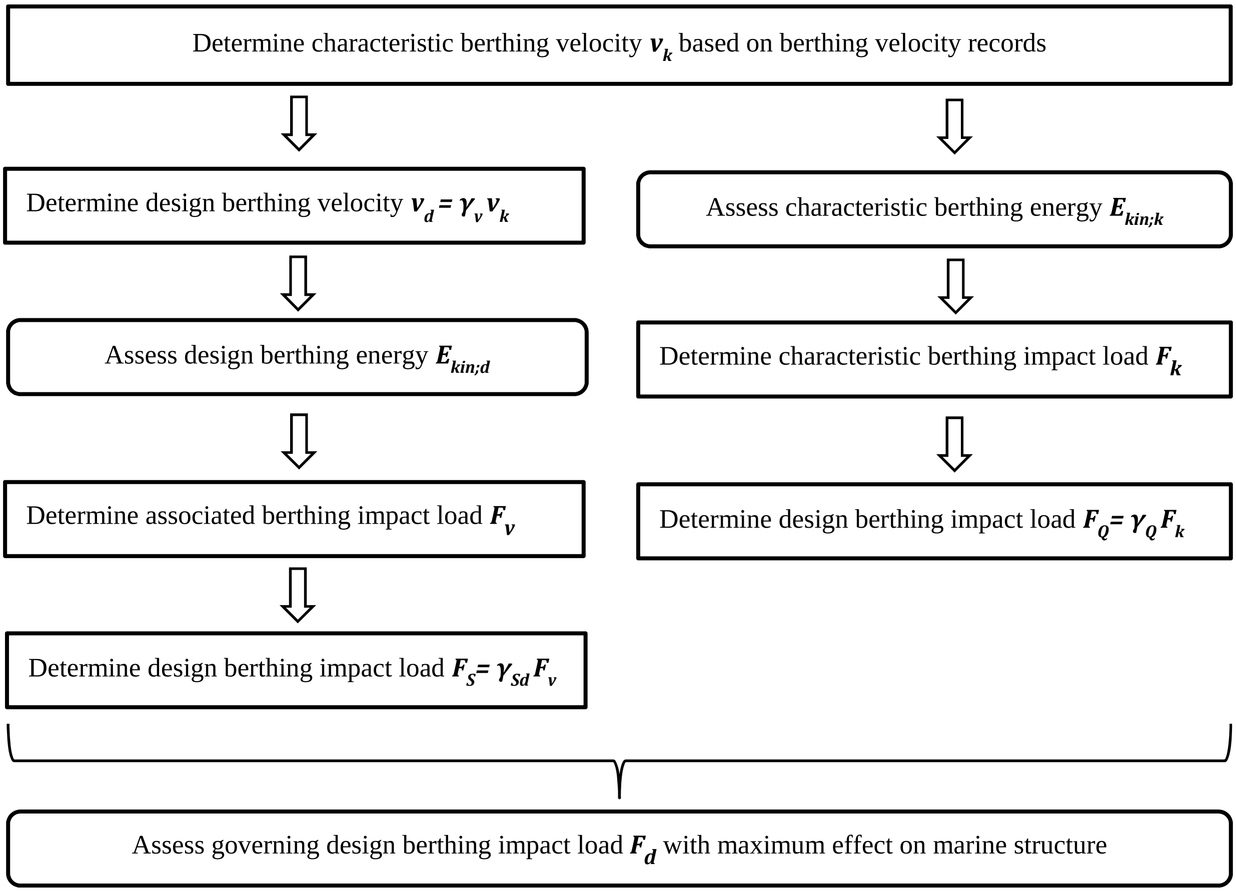

Figure 11: Global flowchart assessing berthing impact on a marine structure

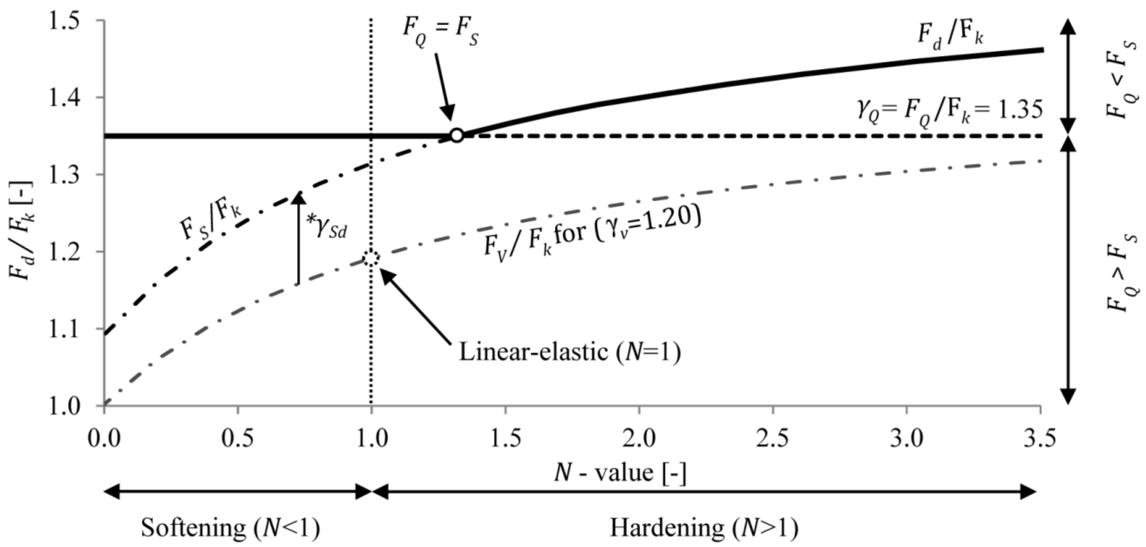

Figure 12: Influence of linear and non-linear behaviour on design berthing impact load

If large datasets are available for a statistical approach it is recommended to determine partial safety factors by evaluating extreme berthing velocities. Table 10 presents generalised partial safety factors for berthing velocities γ_v as concluded in this study. It should be noted that γ_v is proportional to $\sqrt{C_{ab}}$. For the dataset of sheltered navigation conditions, lower partial safety factors were found compared to the dataset of exposed navigation conditions (strong tidal currents). The use of berthing aid systems resulted in even lower design velocities and lower partial safety factors.

Table 10: Partial safety factor γ_v for berthing velocity (v_k) and abnormal berthing factor C_{ab} for berthing energy (E_k) given well-organised navigation conditions

Navigation conditions	Pilot assistance	Symbol	Reliability class EN 1990		
			RC1	RC2	RC3
Sheltered and monitored[1]	*Yes*	γ_v	1.15	1.20	1.25
		C_{ab}	1.35	1.45	1.55
Sheltered	*Yes*	γ_v	1.20	1.25	1.30
		C_{ab}	1.45	1.55	1.70
Exposed[2]	*Yes*	γ_v	1.30	1.35	1.40
		C_{ab}	1.70	1.80	2.00

[1]) Pilots are aware of the allowable berthing velocity and use berthing aid systems, such as portable pilot units.
[2]) Strong tidal currents.

When significant softening (*N<1*) occurs between a characteristic berthing impact load (service limit state) and a design berthing impact load (ultimate limit state), a reduction of the partial safety factor γ_Q could be considered. The effect of softening on energy absorption due to linear and non-linear behaviour is illustrated in Figure 13. When the hatched areas below the linear (left) and non-linear (right) load-deflection curve are equal, the design berthing impact load F_Q is lower in the case of softening.

$$E_{kin;linear} = E_{kin;non-linear} = \int_0^{\delta_{max}} F\,(\delta)d\delta \quad (28)$$

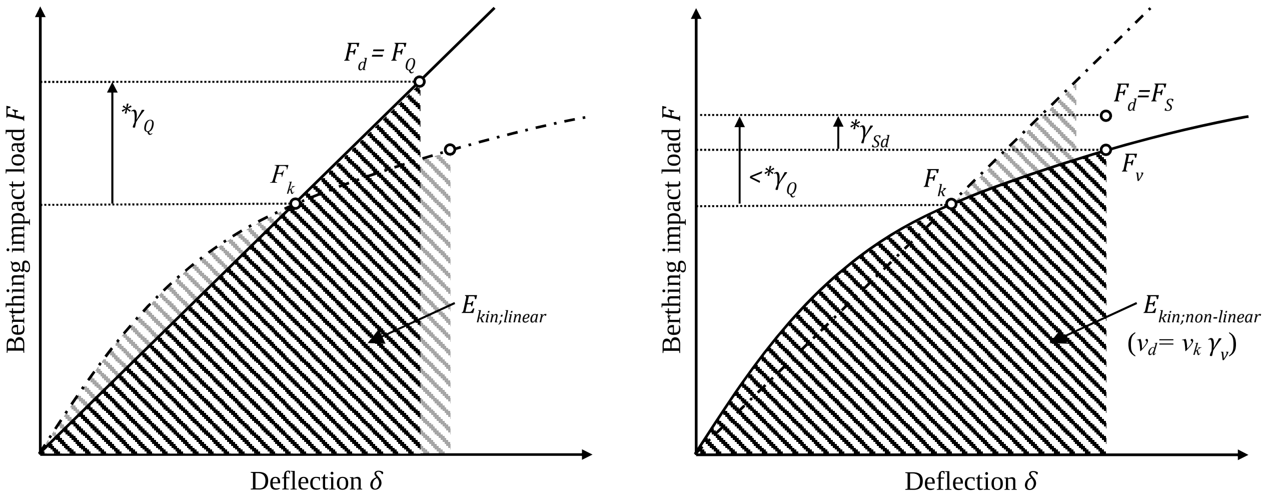

Figure 13: Linear system (left) and non-linear system with significant softening (right)

In case of non-linear softening the partial safety factor is smaller than γ_Q. The berthing impact load should be derived by using a partial safety factor γ_v on berthing velocity and was based on the assumption that an ultimate limit state is a theoretical situation/event, which has a very low probability of occurrence during the service life. In the case of repetitive loading above a service limit state situation, the effect of softening should not be applied or should be used carefully. The partial safety factor γ_{Sd}, applied to berthing impact load F_v, was suggested in order to comply with the safety philosophy of the Eurocode standard [10]. It should be noted that all partial safety factors of the Eurcode standard were derived by accounting for uncertainties in modelling the effect of loads and γ_{Sd} was generally assumed equal to approximately 1.1. Applying γ_{Sd} to resulting berthing impact loads acting on marine structures should be done with great care, because in the determination of berthing energy as well as in the design of fender systems already additional safety factors are considered. It is recommended to further study the application of γ_{Sd} in case of berthings with and without pilot assistance.

1.6.2 Evaluation of partial safety factors

Although existing design guidelines do not differentiate between sheltered and exposed navigation conditions, the partial safety factors listed in Table 10 are in the range of the recommended values in literature (see Table 2). BS 6394-4 [4] recommends using C_{ab}=1.5 for situations with a low risk profile and C_{ab}=2.0 for situations with a high risk profile. Given the absence of field observations, an abnormal berthing factor equal to C_{ab}=1.5 in the case of general cargo vessels must be used. This is quite similar to the results found in section 1.5.1 for sheltered berthings in RC2. For LNG, LPG and ferries, C_{ab}=2.0

is recommended, which is close to the abnormal berthing factor for exposed conditions in RC3. The reason for this increase is not explicitly given in BS 6394-4. For an LNG or LPG berth, a higher consequence class with a higher reliability index could be considered. An explanation for C_{ab}=2.0 for ferry berths could be a higher berthing frequency, captains of ferries do not make use of pilot or tug assistance, and numerous passengers are on board.

PIANC [17] and EAU 2012 [6] recommend applying lower abnormal berthing factors, approximately C_{ab}=*1.25,* for large seagoing tankers and bulkers. In this study, higher abnormal berthing factors were found. The higher abnormal berthing factors could be caused by a higher target reliability index of the Eurocodes or the use of shore-based docking systems. PIANC is aware of the influence of the low reliability level and recommends using a higher confidence level for normal berthing (section 4.2.8.4 of PIANC 2002 [17]) for berths with very low approach velocities. PIANC 2002 and EAU 2012 suggest that there is a correlation between vessel size and abnormal safety factor C_{ab}. Although berthing policy (e.g. use of berthing aid systems, pilot and tug assistance) was to some extent related to vessel size, in this study no correlation between type and size of vessel and partial safety factor γ_v was found.

BS 6349-4 also recommends applying an additional partial safety factor to the resulting berthing impact load. The partial safety factors representing normal (characteristic) and design situations given in the code are 1.35 for persistent and 1.2 for transient situations. The values found were quite similar to the partial safety factor of exposed and sheltered navigation conditions. Although without accounting for non-linear softening, a design following BS 6349-4 could result in a conservative design.

1.6.3 Influence of berthing frequency

As explained, partial safety factors γ_v were based on a berthing frequency of 100 design vessels per year. The Spanish ROM [13] already addresses the importance of berthing frequency. Logically, if fewer arrivals are expected during a reference period the design berthing velocity will decrease, because theoretically each berthing operation has a probability of exceeding the design berthing velocity. There are two ways to deal with this effect: apply either an alternative characteristic berthing velocity v_k or a correction factor to partial safety factor γ_v. If applied correctly, both methods should result in the same design berthing velocity. The influence of berthing frequency on partial safety factor γ_v was calculated by applying a correction factor $C_{berthing}$:

$$C_{berthing} = \frac{\gamma_a}{\gamma_v} = \frac{v_a}{v_d} \qquad (29)$$

in which:

$C_{berthing}$	Correction factor for γ_v [-]
γ_a	Alternative partial safety factor [-]
v_a	Alternative berthing velocity [cm/s]

The alternative berthing velocity v_a was derived by using equation (25). The correction factors for the datasets all tankers, all sheltered and all exposed are given in Table 11 and illustrated in Figure 14.

Table 11: Correction factor $C_{berhting}$ for partial safety factor γ_v given an alternative berthing frequency n

n	1	2	5	10	25	50	100	200	1000
All tankers ○	0.863	0.886	0.915	0.936	0.962	0.981	1.000	1.018	1.058
All sheltered Δ	0.840	0.866	0.900	0.924	0.955	0.978	1.000	1.021	1.069
All exposed □	0.782	0.817	0.862	0.895	0.938	0.969	1.000	1.030	1.099
All data	0.776	0.812	0.858	0.892	0.936	0.968	1.000	1.031	1.102

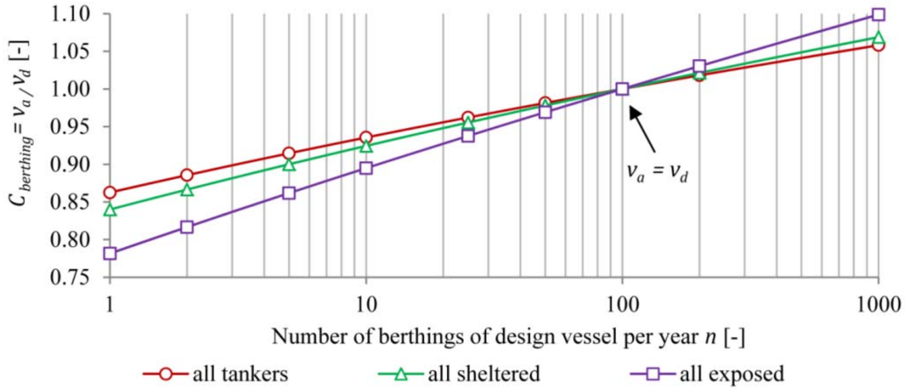

Figure 14: Influence of alternative numbers of berthings on partial safety factor γ_v given a reference period of 50 years

1.7 Conclusions

This paper provided guidance on the use of field observations and partial factors for berthing velocity and loads on marine structures. The results of the research were used to evaluate existing design guidance. The most important conclusions are:

- Characteristic values of berthing velocities found in this research were generally in the range of recommendations in literature. Only the derived characteristic berthing velocity of large seagoing vessels in exposed navigation conditions (strong tidal currents) was higher, but these berthings appeared to have very low berthing angles at the moment of impact, resulting in less fender compression.
- A characteristic value of berthing velocity with a return period of 50 years based on a berthing frequency of 100 berthings per year shows a close correlation with existing recommendations for the design of new marine structures. When assessing existing structures, actual berthing frequency needs to be taken into consideration.
- A partial safety factor for berthing velocity is not a fixed value, as it is influenced by the prescribed probability of failure during a reference period and variation of the berthing velocity.
- The partial safety factors found in this research did not show a correlation with vessel size. Higher partial safety factors were found for exposed navigation conditions (strong tidal currents) and lower partial safety factors when berthing aids were applied.
- The existing design guidelines were considered to be safe for most situations. Applying the British Standards [4] could result in a conservative design. When using the recommendations of PIANC [17] and EAU [6], applying an abnormal berthing factor C_{ab} lower than 1.5 should be done with great care.

If site-specific data are not available, partial safety factors for berthing velocity γ_v as derived in this study could be used instead of applying an overall safety margin. It is recommended to further study the risk of high berthing velocities found for navigation conditions with strong tidal currents. In particular, the effect of a second berthing impact could reduce the amount of energy transferred if berthing angles are low. Sophisticated datasets and partial safety factors for berthing velocity of inland barges and smaller seagoing coasters are still lacking. It is recommended to collect field observations of smaller vessels in order to better account for the human influence, which is believed to be stronger when berthings are not assisted by well-trained pilots. The presented methods for deriving characteristic and design values for berthing velocity are easy to apply and could be beneficial for assessing existing marine structures. Given the distribution characteristics listed in appendix 1, the effect of lower target reliabilities, alternative reference periods and berthing frequency could be accounted for by using equation (25). This will generally result in lower design berthing velocities.

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Appendix A:

Table 12: Typical distribution parameters Weibull fit, annual and lifetime maxima distributions

Ship type	Size	n[1]	Max[2]	Weibull fit		Annual maxima			Lifetime maxima		
				λ	k	$\mu_{v;1}$	$\sigma_{v;1}$	$V_{S;1}$	$\mu_{v;50}$	$\sigma_{v;50}$	$V_{S;50}$
[-]	[kDW]	[-]	[cm/s]	[cm/s]	[-]	[cm/s]	[cm/s]	[-]	[cm/s]	[cm/s]	[-]
Tankers ○											
Panamax	60-85	23	9	6.3	3.09	10.61	0.90	0.085	12.83	0.56	0.044
Aframax[3]	85-105	175	12	5.0	2.68	9.24	0.74	0.080	11.42	0.61	0.053
Suezmax	115-165	95	11	5.3	2.75	9.58	0.81	0.085	11.75	0.54	0.046
VLCC	260-319	80	10	5.3	2.65	9.51	0.88	0.093	12.10	0.58	0.048
Fix. laser	260-319	19	7	4.1	2.77	7.26	0.64	0.088	8.95	0.43	0.048
Bulkers ◊											
Capesize[4]	150-205	107	13	5.0	1.91	11.44	1.20	0.105	15.73	1.14	0.073
VLBC[4]	205-365	37	10	4.8	2.18	10.10	0.95	0.094	13.31	0.90	0.067
Containers □											
Coasters	7 - 15	37	10	7.1	3.68	11.05	0.80	0.072	12.86	0.47	0.037
Feeders	15 -42	31	9	5.4	2.63	10.37	1.10	0.106	12.56	0.68	0.054
Panamax	42-70	31	8	4.1	2.22	8.45	0.78	0.092	11.15	0.74	0.066
Post Panamax	70-118	60	7	3.4	1.93	7.83	1.00	0.128	10.56	0.74	0.070
New Panamax[3]	118-171	18	3	2.1	3.60	3.36	0.25	0.074	3.86	0.16	0.041
Containers □											
Coasters	7 - 15	177	20	7.2	1.50	21.10	3.23	0.153	31.40	2.90	0.092
Feeders	15 -42	250	20	7.4	1.55	21.29	3.46	0.162	30.84	2.78	0.090
Panamax	42-70	104	19	8.5	1.86	20.62	2.67	0.130	27.73	1.78	0.064
Post Panamax	70-118	288	25	8.0	1.68	21.24	3.15	0.148	29.86	2.28	0.076
New Panamax	118-171	150	20	8.1	1.79	20.10	2.71	0.135	27.82	2.14	0.077
ULCV	171-195	266	26	6.2	1.47	18.76	3.13	0.167	28.04	2.39	0.085
Large datasets											
All tankers ○	60-319	392	12	5.2	2.69	9.40	8.4	0.089	11.67	0.58	0.049
All sheltered Δ	7-365	713	13	4.9	2.28	10.05	9.9	0.098	13.00	0.85	0.065
All exposed □	7-195	1235	26	7.4	1.61	20.44	29.1	0.142	29.04	2.44	0.084
All data	60-319	1948	26	6.4	1.57	17.83	23.5	0.132	26.19	2.41	0.092

[1]) Number of field observations
[2]) Maximum measured berthing velocity
[3]) Dataset is most likely too optimistic [14]
[4]) Dataset is most likely too conservative [14]