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Comparison of fender dimensions, PIANC WG211 and PIANC WG33

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PIANC WG211 was tasked with updating the guidelines for design of marine fender systems. One of the changes to the new guideline is the change in approach to the design. Whilst the load and resistance factor design approach is widely adopted in the design of marine structures, the PIANC WG33 (2002) design guideline utilises a global safety factor, referred to as the factor for 'abnormal' impact. Based on statistical data from recorded berthing velocities, fender manufacturers' data, and adjustment factors for uncertainties in berthing energy calculation, PIANC WG211 has established partial factors of safety for fender selection. To gain clarity on what the effects the updated design approach is, this paper compares the outcomes of the old PIANC WG33 and the new PIANC WG211 guideline. Data from actual project fender design specifications have been considered. Given similar input variables the new design method generally results in marginally smaller fender dimensions. WG211, however, recommends, on the basis of PIANC WG145 (2019), higher berthing velocities for large seagoing vessels compared to Brolsma's berthing velocity curves in PIANC WG33, which can result in quite large fenders in the absence of site-specific information. During this study, however, the higher berthing velocities recommended by PIANC WG211 were confirmed based on new berthing records collected in a port in the northeast part of Europe. In general, when site-specific information is used to evaluate the navigation conditions and the associated berthing velocity, the design method of PIANC WG211 will result in reasonable fender dimensions. In addition, it was found that the fender dimensions can, in some cases, largely be optimised based on a parametric analysis of the fender pitch. Consequently, the conclusion is that the new design approach results in reasonable fender dimensions for majority of the ports and terminals around the world. Nevertheless, it is crucial to examine the influence of the local navigation conditions, such as wind, wave, currents and berthing manoeuvres, on the berthing velocity and that the asset owner, e.g. port or terminal authority, specifies the required safety level of the fender system specific to the berth.

Keywords: Port engineering, PIANC WG211, Fender systems, Berthing velocity, Berthing energy.

Introduction

Typically, a marine structure is equipped with a fender system to absorb the kinetic energy of a berthing vessel (Fig. 1). The design recommendations of PIANC WG33 (WG33) are widely adopted by the maritime industry and as such, many fender systems have been designed using the current WG33 guidelines. PIANC started a new working group in 2019, PIANC WG211 (WG211), which was tasked with updating the work of WG33. However, WG211 became a complete re-write. This paper compares the outcome of the WG33 and WG211 design approaches based on selected number of actual project design specifications.

The aim of this study is to: (i) compare the WG33 and WG211 design approaches; (ii) verify and validate the WG211 proposed design approach; (iii) understand and/or avoid the background to possible trend breaks. Unlike previous studies related to this topic, the effects of the differences in failure consequences, navigation conditions and of multiple fenders in contact with the vessel hull on the dimensions of the fender systems were studied, which provided a better understanding of the influence of these important design considerations. New berthing velocity records were gathered from one of the reference projects and have confirmed the higher berthing velocities of large vessels recommended by PIANC WG145 (WG145).

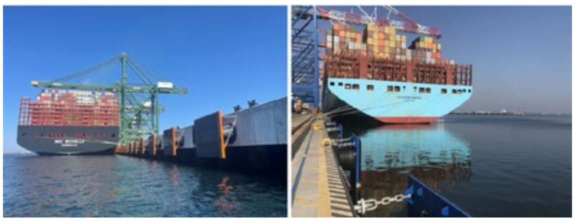

Figure 1 Quay walls equipped with cone fenders (Photo left Shibata Fender Team; Photo right Trelleborg Marine Systems)

WG33 Design Approach

The design approach of WG33 aligns with the global-safety-factor method (Eq. 1).

$$E_f \geq E_{ab} = E_d C_{ab} \qquad (1)$$

$$E_d = \frac{1}{2} M V_B^2 C_e C_m C_s C_c \qquad (2)$$

where E_f = Energy absorption capacity of the fender system [kNm]; E_{ab} = Abnormal kinetic energy exerted by the berthing vessel [kNm]; E_d = Design energy (under normal conditions) to be absorbed by the fender system [kNm]; C_{ab} = Factor for abnormal (berthing) impact; M = Mass equivalent to water displacement of the approaching vessel [tonnes]; V_B = Berthing velocity perpendicular to the berthing line [m/s]; C_m = Virtual mass factor; C_e = Eccentricity factor; C_s = Softness factor; C_c = Berth configuration factor.

Assessment of the berthing velocity is needed when calculating the berthing energy under normal conditions. Although the Brosma's velocity curves (Brolsma at al., 1977) are widely known, WG33 suggests that in the absence of more accurate figures to use the berthing velocities recommended in Spanish ROM Standard 0.2-90 (WG33 Table 4.2.1) which are commonly embedded in the national design codes in Spain and Germany should be used. Figure 2 shows that the Brolsma curves recommend much lower velocities compared to the Spanish ROM for large sea going vessels. It therefore is reasonable to underline that WG33 does NOT provide clear recommendations for berthing velocities.

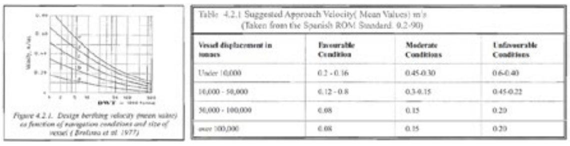

Table 4.2.1 Suggested Approach Velocity(Mean Values) m/s
(Taken from the Spanish ROM Standard. 0.2-90)

Vessel displacement in tonnes	Favourable Condition	Moderate Conditions	Unfavourable Conditions
Under 10,000	0.2 - 0.16	0.45-0.30	0.6-0.40
10,000 - 50,000	0.12 - 0.8	0.3-0.15	0.45-0.22
50,000 - 100,000	0.08	0.15	0.20
over 100,000	0.08	0.15	0.20

Figure 2 Recommendations for berthing velocity in PIANC WG33 (2002).

WG211 Design Approach

WG211 recommends a different design approach, which better aligns with the modern load and resistance factor design approach, and considers a fender system to be reliable when the design value of the energy absorption capacity of the fender system ($E_{f,d}$) is greater than the design value of the kinetic energy exerted by the berthing vessel ($E_{k,d}$), both measured in kNm:

$$E_{f,d} \geq E_{k,d} \qquad (3)$$

The calculation of the energy absorption capacity of a fender system and the kinetic energy exerted by the berthing vessel, encompass a number of uncertainties. To account for these uncertainties, WG211 has introduced partial resistance factors (for the calculation of the fender energy absorption capacity) and partial energy factors (for the calculation of the vessel berthing energy). These partial factors are applied to the characteristic energy absorption capacity of the fender system ($E_{f,c}$) and the characteristic berthing energy to be absorbed by the fenders in contact (and the supporting structure where applicable) during the impact ($E_{k,c}$) in kNm to determine the associated design values of $E_{f,d}$ and $E_{k,d}$.

$$E_{k,d} = \gamma_E \; E_{k,c} \qquad (4)$$

$$E_{f,d} = \frac{E_{f,c}}{\gamma_m} \qquad (5)$$

Where $E_{k,c}$ = Characteristic energy to be absorbed by the fenders in contact (and the supporting structure where applicable) during the impact [kNm]; $E_{f,c}$ = Characteristic energy absorption capacity of the fender system [kNm]; γ_E = Partial energy factor; γ_m = Partial resistance factor related to the materials utilised in the fender system.

In addition to the vessel geometry, the berthing angle and the berthing velocity are two critical design variables. WG211 updated the recommendations for these design variables to align with the new generation of more modern seagoing vessels. Furthermore, WG211 takes account of the following new design aspects:

- Refined description of navigation conditions.
- Effects of using berthing aid systems or berthing speed limits.
- Effects of the number of berthings per year.
- Failure consequence classes and associated reliability levels.
- Effects of variation in water displacement of berthing vessels.
- Effects of multiple fenders in contact with vessel hull.

The above aspects influence the partial energy factor and hence the design value of the energy of the berthing vessel. Consequently, it is crucial to accurately assess these aspects to select an appropriate fender system. Fender system design requires the Base Energy absorption (E_{base}) and Base Reaction force (R_{base}) obtained from manufacturers' catalogue to be adjusted by correction factors (as below) to account for deviation from test conditions that are specific to the berth where the fender will be installed. In this paper energy based of constant velocity is used to determine E_{base} and not the energy based of rated performance data.

$$E_f = E_{base} \, C_{ang} \, C_t \, C_v \, C_{mult} \qquad (6)$$

$$C_{mult} = \frac{E_{f,system}}{E_{base}} = \frac{E_{f_1}+E_{f_2}+\dots+E_{f_n}}{E_{base}} = \frac{\sum_{i=1}^{n_f} E_{f_i}}{E_{base}} \quad (7)$$

where E_{base} = Base energy absorption capacity of the fender system established using standard compression velocities between 0.33 & 1.33 mm/s, a standard ambient air temperature of 23 ℃ and a standard berthing / flare angle of 0° [kNm]; C_{ang} = Angular factor; C_t = Temperature factor; C_v = Velocity factor; C_{mult} = Multiple fender contact factor; $E_{f,system}$ = Energy absorbed by fender systems in contact with the vessel [kNm]; $E_{f,i}$ = Berthing energy absorbed by the i^{th} compressed fender [kNm]; n_f = number of fenders in contact.

For most alongside berthing manoeuvres, the longitudinal berthing velocity and rotational velocity are small and hence the vessel berthing energy can be simplified in calculation to consider only the berthing velocity perpendicular to the berthing line (V_B). When the first point of contact is eccentric to the centre of mass of the vessel some of its berthing energy get transformed into kinetic rotational energy and this is accounted for in the calculated energy using an eccentricity factor (C_e). In this paper, the method of Vasco Costa is used to calculate C_e and the 'WG33 method is used to estimate C_m. A change from WG33 to WG211 is that both softness factor and berth configuration factor have been removed because for many design cases a factor of 1.0 has been used in the industry. The kinetic berthing energy is estimated using the following simplified equation (Eq. 8).

$$E_k = \frac{1}{2} M V_B^2 C_e C_m \quad (8)$$

where E_k = Kinetic energy to be absorbed by fender and structure during the vessel impact [kNm]; M = Displacement of the berthing vessel, including cargo [tonnes]; V_B = Berthing velocity of vessel at the time of impact, perpendicular to the berthing line [m/s].

The WG211 design method distinguishes four time-dependent design variables, i.e the berthing velocity, berthing angle, displacement, and ambient air temperature. The uncertainty in the berthing velocity significantly influences the uncertainty in the calculated kinetic energy and therefore, berthing velocity is the "dominant" design variable (Ueda et al., 2010). The other three important, but less dominant variables are the displacement (M), the berthing angle (α) and ambient air temperature (T). When the largest displacement, highest berthing velocity and extreme berthing angle are simultaneously considered in a fender selection process, this may lead to a significant overdesign of the fender system. WG211 recommends the following combination of characteristic values of the four design variables when calculating the characteristic berthing energy (Eq. 8) and capacity of the fender system (Table 1). Variations and other uncertainties in energy calculation can be accounted for by using a partial energy factor.

Table 1 Definition characteristic values

Design variable	Characteristic value
Berthing velocity ($V_{B,c}$)	0.02% of probability being exceeded per berthing manoeuvre.
Displacement (M_c)	Largest operational displacement of the design vessel resulting in the highest characteristic berthing energy.
Berthing angle (α_c)	5% probability of exceedance per berthing manoeuvre.
Temperature ($T_{c,high}$)	The average monthly mean ambient air temperature of the hottest month of the year.
Temperature ($T_{c,low}$)	The average daily mean ambient air temperature of the coldest day of the year with a return period of five years.

$$E_{k,c} = \frac{1}{2} M_c V_{B,c}^2 C_m C_e \quad (9)$$

where $E_{k,c}$ = Characteristic energy to be absorbed by the fenders in contact (and the supporting structure where applicable) during the impact [kNm]]; M_c = Characteristic displacement of the berthing vessel [tonnes]; $V_{B,c}$ = Characteristic berthing velocity perpendicular to the berthing line [m/s].

Examples and Navigation Conditions

This section introduces five fender design examples considered in this study. These examples are based on typical berthing configurations from selected berths around the world. Predominantly, berths facilitating large seagoing vessels are considered, since the recommendations for berthing velocity and factors of safety can largely differ for different navigation conditions. For each project the design specification of the fenders have been provided. Table 2 lists the local navigation conditions in accordance with WG211 and the design vessel characteristics that were used in the original fender design and the same is used in this study.

Table 2 Navigations conditions and design vessel characteristics

Variable	1. Africa	2. Mediterranean	3. N. Europe	4. L. America	5. Australia
Nav. conditions	Favourable	Favourable	Moderate	Moderate	Unfavourable
Vessel type	Gas Carrier	ULCV*	ULCV*	VLCC**	Ore carrier
L_{OA} (m)	345.3	399.87	395.5	326	310
L_{BP} (m)	332	384	379.4	313	305
B (m)	53.8	59	59	56.6	57
D (m)	12	16.4	15	28.6	10.4***
U_c (m)	2.31	3.10	0.92	Unknown	9***
DWT (tonnes)	126,000	197,725	199,273	318,000	230,000
M_c (tonnes)	178,579	257,075	258,360	325,000	142,000***

*) Ultra Large Container Vessel; **) Very Large Crude Carrier; ***) Vessels do not arrive fully laden

Comparison of Results

This section presents the outcomes of the comparison of the five project examples selected in this study. The main input and output variables of the calculations are listed in the respective tables. Comparisons consider and reports type, grade and size of a cone fender in all examples based on a single manufacturer's catalogue data (Trelleborg, 2017). This, however, does not mean that other catalogues cannot be used in fender design. In this study, grades smaller than 1.8 are not considered, since higher grades result in lowest cost for the fender system. Furthermore, information about berthing frequency was not provided, and hence the default of 100 berthing events per year was taken into account in all examples. Variation in calculated berthing energies have been compared against a reference calculation carried out for the scenario where site-specific information is available. However, recorded information on berthing velocities and berthing angles of the design vessels were not available for any of the projects except where specifically stated. Furthermore, in the WG33 calculations the same temperatures as in the project specification have been used. For dolphin berths the angular compression angle was assumed to be equal to the berthing angle, whereas for continuous quays the positive effects of angular comparison is not considered, since most of the compression angles are below 10 degrees.

Example 1: Africa Single Fender Contact

The first example is the design of the fenders installed on an LNG jetty and dolphin berth located in the eastern part of Africa. If no site-specific information were available, WG211 users would classify this berth as 'moderate' navigation conditions, and WG33 users would consider 'easy navigation conditions, exposed'. However, the local project team has provided additional information regarding environmental conditions. It was observed that although this jetty was located offshore, the wave and wind climate seem to be surprisingly calm and currents appear to be rather low. Consequently, the authors consider the navigation conditions to be 'favourable' in accordance with WG211 (base calculation for comparison) and "difficult berthing conditions, sheltered" as per WG33. In the original project fender design specifications, a berthing velocity of 0.10 m/s was prescribed and a shore based docking system was proposed to be installed displaying a berthing speed limit. Furthermore, all vessels will be assisted by tugs when berthing. For large tankers WG33 recommends applying an abnormal impact factor (C_{ab}) of 1.25, whereas the project design specification prescribes an abnormal impact factor of 1.3. Since this is quite an important jetty for the region, the consequences of failure are considered to be moderate (Class B), and hence WG211 recommends a partial energy factor (γ_E) of 1.55 assuming that variations in displacement (CoV_M) are fairly low and that the berthing speed is 'monitored'. However, in the absence of site-specific information WG211 recommends a partial energy factor of 1.8. It has been also noted that the British Standard BS 6349-4:2014, recommends a safety factor of 2.0 for gas carriers berthing at LNG facilities considering a high-risk situation.

Table 3 shows the berthing energy calculations of several scenarios: two calculations based on WG211 assuming that local information is provided (i) and is not provided (ii). In addition, the berthing energy listed in the original project fender design specification (iii) calculated in accordance with WG33 and an energy calculation showing the influence of the higher safety factor recommended by BS 6349-4 (iv). The last three calculations are in accordance with WG33 distinguishing different berthing velocities, i.e. the prescribed berthing velocity of 0.10 m/s (v) velocity derived from Brolsma berthing velocity curve b giving a velocity of 0.076 m/s (vi) and curve c where a 0.115 m/s velocity is considered (vii).

Table 3 Berthing energy calculations Example 1: Africa single fender contact.

Variable	SI	PIANC WG211		Project	BS6349	PIANC WG33		
Local information		Yes (i)	No (ii)	Yes (iii)	No (iv)	Yes (v)	No (vi)	No (vii)
Design method		WG211	WG211	WG33	BS6349	WG33	WG33	WG33
Nav. conditions		Monitored	Moderate	-	Curve c	-	Curve b	Curve c
Impact point	% L_{BP}	33%	33%	33%	33%	33%	33%	33%
Conc. class		B	B	-	-	-	-	-
$V_{b,c}$	m/s	0.100	0.150	0.100	0.100	0.100	0.076	0.115
α_c	deg	4	4	6	6	6	6	6
M_e	tonnes	178,579	178,579	178,579	178,579	178,579	178,579	178,579
C_e		0.75	0.75	0.76	0.74	0,74	0.74	0.74
C_m		1.73	1.73	1.73	1.45*	1.73	1.73	1.73
E_d	kNm	-	-	1,167	963	1,150	664	1,520
$E_{k,c}$	kNm	1151	2590	-	-	-	-	-
C_{ab}		-	-	1.30	2.00	1.25	1.25	1.25
E_{ab}	kNm	-	-	1,518	1926	1,437	830	1,901
γ_E		1.55	1,80	-	-	-	-	-
$E_{k,d}$	kNm	1783	4659	-	-	-	-	-
		Ref	+161%	-15%	+8%	-19%	-53%	+7%

*In BS6349 the Vasco Costa method was used to determine C_m

When no site-specific information is available, WG211 recommends a berthing velocity of 0.15 m/s, which results in a 161% higher berthing energy (ii) in comparison to the reference calculation (i). In comparison the original project specification results in a 15% lower design berthing energy (iii), whereas the WG33 calculation assuming 0.076 m/s returns a 53% lower berthing energy (vi). In contrast, the British Standard results in an 8% higher design berthing energy for LNG jetties given a velocity of 0.10 m/s (iv). Table 3 shows that the berthing velocity and the safety factor largely influence the outcome of the berthing energy calculation. Based on all berthing energy calculations, the fender type, grade and size were determined as presented in Table 4.

Table 4 Fender selection Example 1: Africa single fender contact.

Variable	SI	PIANC WG211		Project	BS6349	PIANC WG33		
Local information		Yes (i)	No (ii)	Yes (iii)	No (iv)	Yes (v)	No (vi)	No (vii)
p_f	m	30	30	30	30	30	30	30
E_{base}	kNm	1,826	4,736	1,589	2,056	1,518	869	2,003
R_{base}	kN	2,445	5,577	2,091	2,270	1,959	1,280	2,203
$C_{manufacturer}$		-	-	0.90	0.90	0.90	0.90	0.90
$T_{c high}$	°C	27,9	27,9	34	34	34	34	34
$T_{c low}$	°C	12,2	12,2	18	18	18	18	18
$C_{v,c}$		1.06	1.07	1.05	1.05	1.06	1.05	1.05
$C_{t,c}$		0.985	0.985	0.966	0.966	0.966	0.966	0.966
$C_{ang,c}$		1.03	1.03	1.05	1.05	1.05	1.05	1.05
C_{mult}		1.00	1.00	1.00	1.00	1.00	1.00	1.00
$E_{f,c}$	kNm	1,963	5,139	-	-	-	-	-
γ_m		1.10	1.10	-	-	-	-	-
$E_{f,d}$	kNm	1,784	4,762	1,522	1,970	1,461	833	1.937
Type		**cone**	**Cone**	**cone**	**cone**	**cone**	**cone**	**cone**
Grade		**3.1**	**2.9**	**2.8**	**2.2**	**2.6**	**2.2**	**2.1**
Size	**mm**	**1400**	**2000**	**1400**	**1600**	**1400**	**1200**	**1600**

Both reference calculation (i) and the fender selected using the project design specification (iii) resulted with similar fender (type and size). When no site-specific information is available the WG211 calculation resulted with a much larger fender size (ii), whereas using Brolsma berthing velocity curve b of WG33 returns a 1200 cone fender (vi). The authors of this paper consider the reference calculation in accordance with WG211 to be realistic and felt that a safety factor equal to or lower than 1.3 for fenders installed on an LNG facility is rather optimistic compared to typical safety factors applied to variable loads. A partial energy factor of 1.55 and a berthing velocity of 0.10 m/s seem reasonable since a berthing aid docking system is installed. Without site-specific information WG211 recommends a much larger fender (ii), which is the result of the measurements collected by WG145. These measurements show berthing velocities up to 0.18 m/s for large LNG tankers.

Example 2: Africa Single Fender Contact

This example is from a container terminal project located in the Mediterranean. The project consists of upgrading the existing continuous solid quay in order to facilitate larger container vessels. The navigation conditions are such that the berth can be exposed to moderate winds and currents since no breakwater is installed and there is an open access to the berth. Hence WG211 classifies the navigation conditions as 'moderate', which aligns with 'easy navigation conditions, exposed' in WG33.

The project design specifications prescribe a berthing velocity of 0.10 m/s for container vessels and mentions that this velocity is confirmed by local pilots. Without this local information WG211 would recommend a berthing velocity of 0.15 m/s and WG33 a velocity of 0.095 m/s given the navigation conditions. WG33 recommends, in the case that there is no accurate data for a continuous berth, the impact point of the vessel to be at 25% of the length from the bow, and hence C_e = 0.5. However, a more detailed analysis of the fender system geometry and vessel dimensions, such as the bow radius and parallel body length at fender elevation level, show that the berthing impact point is close to 'third' point berthing. WG211 and the project specification therefore recommend a higher eccentricity factor.

Since the terminal is equipped with three continuous berths facilitating big and large container vessels, the consequences of failure align with WG211 Class A and the variations in displacement (CoV_M) are high. Due to the low berthing angle multiple fenders absorb the berthing energy of the vessel. Consequently, a safety factor of 1.2 is recommended. WG33 recommends a safety factor of 1.5. Table 5 shows several berthing energy scenarios. The reference calculation based on WG211 (i), an additional calculation to show the effect of a higher berthing velocity (ii), the outcome of the original design specification (iii), and two further calculations in accordance with WG33 having a berthing velocity of 0.10 m/s (iv) and a velocity of 0.095 m/s (v) were considered.

Table 5 Berthing energy calculations Example 2: Mediterranean multiple fender contact.

Variable	SI	PIANC WG211		Project	PIANC WG33	
Local information		**Yes (i)**	**No (ii)**	**Yes (iii)**	**Yes (iv)**	**No (v)**
Design method		WG211	WG211	WG33	WG33	WG33
Navigation conditions		Moderate	Moderate	-	-	Curve c
Impact point	% L_{BP}	33%	33%	33%	25%	25%
Consequence class		A	A	-	-	-
$V_{B,c}$	m/s	0.10	0.15	0.10	0.10	0.095
α_c	deg	2	2	2	6	6
M_c	tonnes	257,075	257,075	257,075	257,075	257,075
C_e		0.70	0.70	0.69	0.53	0.50
C_m		1.73	1.73	1.56*	1.73	1.73
C_c		-	-	0.90	0.90	0.90
E_n	kNm	-	-	1,245	1,187	1,005
$E_{k,c}$	kNm	1,548	3,482	-	-	-
C_{ab}		-	-	1.50	1.50	1.50
E_{ab}	kNm	-	-	1,867	1,780	1,508
γ_E		1.20	1.20	-	-	-
$E_{k,d}$	kNm	1,856	4,176	-	-	-
		Ref	**+125%**	**+1%**	**-4%**	**-19%**

*In the original design specification the Vasco Costa method was used to determine C_m.

The reference berthing energy calculation using WG211 (i) leads to a fairly similar design berthing energy compared to the original specification (iii). Compared to WG33 (iv and v) the design method of WG211 results in a higher berthing energy. The main reason being the difference in the eccentricity factor Ce. The authors, however, agree that berthing impact point of 25% of L_{BP} is unrealistic for a 2 degree angle of approach. In the absence of site-specific berthing records, WG211 recommends a higher characteristic berthing velocity of 0.15 m/s, which results in a 125% higher value of the calculated energy (ii). Table 6 presents fender selection of the considered scenarios.

Table 6 Fender selection Example 2: Mediterranean multiple fender contact.

Variable	SI	PIANC WG211		Project	PIANC WG33	
Local information		Yes (i)	No (ii)	Yes (iii)	Yes (iv)	No (v)
p_f	m	24.80	24.80	24.80	24.80	24.80
E_{base}	kNm	1,660	3,077	1,826	1,950	1,826
R_{base}	kN	2,223	3,047	2,445	2,136	2,445
$C_{manufacturer}$		-	-	0.90	0.90	0.90
$T_{e,high}$	°C	28.5	28.5	37.32	37.32	37.32
$T_{e,low}$	°C	1.2	1.2	4.2	4.2	4.2
$C_{v,e}$		1.05	1.06	1.05	1.06	1.05
$C_{t,e}$		0.990	0.990	0.955	0.955	0.955
$C_{ang,e}$		1.00	1.00	1.00	1.00	1.00
C_{mult}		1.19	1.43	1.20	1.00	1.00
$E_{f,c}$	kNm	2,065	4,624	-	-	-
γ_m		1.10	1.10	-	-	-
$E_{f,d}$	kNm	1,877	4,204	1,996	1,777	1,648
Type		cone	cone	cone	cone	cone
Grade		3.0	2.4	3.1	2.0	3.1
Size	mm	1400	1800	1400	1600	1400

The fender size found using the WG211 design method (i) is again of similar size to the original project (iii). PIANC WG33 also results (v), in similar size fenders. A berthing angle of 6 degrees gives single fender contact for a fender pitch of 24.8m. However, based on the measurements provided by WG145 a berthing angle of 6 degrees seems unrealistic, as it is quite likely that a vessel approaching with a 6 degree angle will crash on and cause damage to the container cranes.

Using a more realistic berthing angle of 2 degrees a smaller fender can be selected due to the effect of multiple fenders in contact. Although a fender pitch of 24.80 m is prescribed in the original fender design specification, this distance is quite large compared to similar container terminals throughout the world and might not be the optimal distance resulting in fairly large fender dimensions. When the spacing for instance is reduced to 12.56m (same fender pitch as in Example 3), the fender size found would have been 1150 grade 2.8 cone. This indicates that the size of individual fenders can be largely influenced by the fender pitch (p_f) and that the fender selection process can be optimised based on economic optimisation.

Example 3: Northern Europe Multiple Contact
This example discusses a fender system installed on a solid quay of a container terminal located in the northern part of Europe. The container berth is situated behind a breakwater and hence currents and wave impact seem to be quite low. The orientation of the berth in relation to the wind climate is not favourable, and it is likely that berthing manoeuvres are frequently exposed to moderate winds. WG211 classifies the navigation conditions as 'moderate', which aligns with WG33 as 'easy navigation conditions, exposed'.

In 2015, the project design specifications reported a berthing velocity of 0.10 m/s for large container vessels. In the absence of site-specific information WG211 and WG33 (Brolsma curves) recommend a berthing velocity of 0.15 m/s and of 0.095 m/s respectively. Damage of the fender system has been reported and the quality of the existing fenders is also in question. Furthermore, recent berthing velocity measurements indicate much higher velocities than 0.10 m/s, such as 0.14 m/s and 0.15 m/s. In addition, the berthing records show that multiple fenders get fully compressed during conventional berthing, since the actual berthing angles were smaller than 1 degree. In contrast, the previous design specification includes a berthing angle of 6 degrees and the revised specification consider a 2 degree berthing angle with a berthing velocity of 0.15 m/s. Similar to Example 2, following the recommendations of WG33 the eccentricity factor C_e = 0.5 was selected, e.g. 'quarter' point berthing. However, a more detailed analysis of the fender system geometry and vessel dimensions of these large container vessels shows that the berthing impact point is close to 'third' point. WG211 and the project specification therefore recommend a higher eccentricity factor compared to WG33. The consequences of failure align with WG211 consequence class A since failure of a single fender is not likely to impose operating limits at the berth. Furthermore, the variations in displacement (CoV_M) are high due to the berth facilitating both small and large vessels. Table 7 shows scenarios of berthing energy calculations for this example: reference calculation in accordance with WG211 assuming moderate navigation conditions (i), a calculation that aligns with the project specifications, e.g. a berthing velocity of 0.10 m/s (ii). Further three comparisons following WG33 given the berthing velocity records and the same eccentricity factor (iii), a calculation for a berthing velocity of 0.15 m/s as per the project (iv) and berthing velocity selected on the basis of berthing Brolsma velocity curve c 'good navigation conditions at an exposed location' to assess the scenario when no site-specific information is available, i.e. 0.095 m/s (v).

Table 7 shows that the berthing energy of the project design specification is 42% lower (ii) than the recommended berthing energy by WG211 (i). In the upcoming project, however, a higher berthing velocity of 0.15 m/s will be prescribed on the basis of the berthing velocity records. Given the higher berthing velocity WG33 (iv) and WG211 (i) will result in almost the same berthing energy. It should however be noted that the authors consider 'quarter' point berthing is not correct in combination with a small berthing angle and the geometry of the large container vessels. When the same eccentricity factor and berthing velocity are considered the WG33 approach results in an approximately 24% higher energy (iii) compared to WG211, which is mainly caused by the lower partial energy factor γ_E. Assuming 'quarter' point berthing and a berthing velocity of 0.10 m/s WG33 result in a 60% lower berthing energy (v). Table 8 presents the resulting fender type, grade and size for the four calculations.

Table 7 Berthing energy calculations Example 3: Northern Europe multiple fender contact

Variable	SI	PIANC WG211	Project	PIANC WG33		
Local information		Yes (i)	No (ii)	Yes (iii)	No (iv)	No (v)
Design method		WG211	WG33	WG33	WG33	WG33
Nav. conditions		Moderate	-	-	Table 4.2.1 (moderate)	Curve c
Impact point	% L_{BP}	29%	25%	29%	25%	25%
Consequences class		A	-	-	-	
V_B	m/s	0.15	0.10	0.15	0.15	0.095
α_c	deg.	2	6	2	6	6
$M_{D,c}$	tonnes	258,360	258,360	258,360	258,360	258,360
C_e		0.63	0.50	0.62	0.50	0.50
C_m		1.80	1.80	1.80	1.80	1.80
E_n	kNm	-	1,169	3,256	2,616	1,049
$E_{k,c}$	kNm	3,290	-	-	-	-
C_{ab}		-	1.50	1.50	1.50	1.50
E_{ab}	kNm	-	1,744	4,884	3,924	1,574
γ_E		1.20	-	-	-	-
$E_{k,d}$	kNm	3,945	-	-	-	-
		Ref	-42%	+24%	0%	-60%

Table 8 Fender selection Example 3: Northern Europe multiple fender contact

Variable	SI	PIANC WG211	Project	PIANC WG33		
Local information		Yes (i)	No (ii)	Yes (iii)	No (iv)	No (v)
p_f	m	12.56	12.56	12.56	12.56	12.56
E_{base}	kNm	1,826	1,130	2,728	2,728	1,188
R_{base}	kN	2,445	1,542	3,191	3,191	1,631
$C_{manufacturer}$		-	0.90		-	0.90
$T_{c,high}$	°C	17.4	35	35	35	35
$T_{c,low}$	°C	-8.4	-20	-20	-20	-20
$C_{v,c}$		1.08	1.06	1.07	1.07	1.06
$C_{t,c}$		1,01	0.963	0.963	0.963	0.963
$C_{ang,c}$		1.00	0.86	1.00	1.00	1.00
C_{mult}		2.33	1.00	2.00	1.57	1.45
$E_{f,c}$	kNm	4,655	-	-	-	-
γ_m		1.10	-	-	-	-
$E_{f,d}$	kNm	4,232	1,820	5,057	3,962	1,585
Type		cone	cone	cone	cone	cone
Grade		3.1	2.3	3.1	3.1	2.5
Size	mm	1400	1300	1600	1600	1300

The reference calculation of PIANC WG211 results in the selection of a 1400 grade 3.1 cone fender for this project (i). Due to the low berthing angle and therefore the effect of multiple fender in contact results in a higher value for C_{mult}. In the project design specification (ii), the effect of multiple fenders in contact has not been taken into consideration. However, when the effect of multiple fenders in contact is neglected in the WG33 calculations, this would result in unrealistically large fenders e.g. cone fenders of size 2000, which have not yet been installed in practice. Based on the Brolsma berthing velocity curves in WG33 (v) a smaller fender can be selected. However, a berthing velocity of 0.095 m/s seems too optimistic given the wind climate of the project site. When the same berthing velocity, berthing angle and eccentricity factor are considered, WG211 results in slightly smaller fenders compared to WG33 (iii). The main reason for this is the lower partial energy factor, the higher value for C_{mult}, and lower value for the high characteristic ambient air temperature. Given the field measurements from project site, the berthing velocity seems to be largely underestimated by berthing velocity curve c of WG33. The authors consider a berthing velocity of 0.15 m/s as a realistic estimate, which aligns with WG33 Table 4.2.1 (Fig. 2) and WG211.

Example 4: Latin America Single Fender Contact

This example discusses the fender selection of a Very Large Crude Carrier (VLCC) berth equipped with buckling fenders. The fenders are installed on raked dolphins, which are situated directly behind a closed breakwater and hence the berth is well protected against waves and currents. Without further information, such as wind data, WG211 will classify this berth as 'moderate' navigation conditions. The project design specification show that the berthing velocity of 0.10 m/s was directly selected from Brolsma berthing velocity curve d in WG33. It is unclear whether site-specific information is used to verify this berthing velocity. In the absence of site-specific information, WG211 recommends a characteristic berthing velocity of 0.15 m/s for VLCCs berthing in 'moderate' navigation conditions. When discussing the local navigation conditions, the authors agree that the orientation of this berth is quite favourable compared to the governing wind direction, and hence a berthing velocity of 0.10 m/s seems reasonable. For VLCC tankers WG33 recommends to apply an abnormal impact factor C_{ab} of 1.25. Since there are three VLCC berths giving some functional redundancy, WG211 recommends a partial energy factor γ_E of 1.6 assuming that the variations in displacement (CoV_M) are fairly low for moderate conditions and 1.5 for favourable conditions.

Table 9 presents four berthing energy calculations: A calculation assuming that local information underlines the assumption that VLCC berthings have insignificant influence from wind and that the berthing velocity of 0.10 m/s is reasonable (i); A calculation in accordance with WG211 assuming "moderate" navigation conditions and that local information about the navigation conditions is not provided, and hence a berthing velocity of 0.15 m/s and berthing angle of 3 degrees have been taken into consideration (ii); The results on the basis of the original project design specification (iii); A calculation in accordance with WG33 assuming Brolsma's berthing velocity curve d "Good navigation conditions, exposed" (iv).

Table 9 Berthing energy calculations Example 4: Latin America single fender contact

Variable	SI	PIANC WG211		Project	PIANC WG33
Local information		Yes (i)	No (ii)	No (iii)	No (iv)
Design method		WG211	WG211	WG33	WG33
Navigation conditions		Favourable	Moderate	-	Curve d
Consequences class		A	A	-	-
Impact point	% L_{BP}	33%	33%	unknown	35%
V_B	m/s	0.10	0.15	0.10	0.10
α_c	deg	3	3	Unknown	6
$M_{D,c}$	tonnes	325,000	325,000	325,000	325,000
C_e		0.70	0.70	0.882	0.70
C_m		1.80	1.80	1.80	1.80
E_n	kNm	-	-	2,580	2,048
$E_{k,c}$	kNm	2,035	4,578	-	-
C_{ab}		-	-	1.25	1.25
E_{ab}	kNm	-	-	3,225	2,559
γ_E		1.50	1.60	-	-
$E_{k,d}$	kNm	3,050	7,319	-	-
		Ref	+140%	+6%	-16%

WG33 (iv) results in a 16% lower berthing energy compared to the reference calculation of WG211 (i). This difference is predominantly caused by the difference in safety factor. It should be noted that an abnormal safety factor of 1.25 is very low for such large tankers handling hazardous cargo, since there is no justification that lower factors of safety can be used for large tankers. In the absence of local information, WG211 recommends a berthing velocity of 0.15 m/s, which results in a 140% higher berthing energy (ii).

Table 10 Fender selection Example 4: Latin America single fender contact

Variable	SI	PIANC WG211		Project	PIANC WG33
Local information		Yes (i)	No (iii)		Yes/No (iv)
p_f	m	25	25	25	25
E_{base}	kNm	3,228	7,604	3,904	2728
R_{base}	kN	3,241	5,503	3,430	3191
$C_{manufacturer}$		-	-	Unknown	0.90
$T_{c;high}$	°C	28.4	28.4	Unknown	35.0
$T_{c;low}$	°C	11.2	11.2	Unknown	10.0
$C_{v;c}$		1.04	1.05	Unknown	1.05
$C_{t;c}$		0.983	0.983	Unknown	0.963
$C_{ang;c}$		1.04	1.04	Unknown	1.05
C_{mult}		1.00	1.00	1.00	1.00
$E_{f;c}$	kNm	3,539	8,155	-	-
γ_m		1.10	1.10	-	-
$E_{f;d}$	kNm	3,117	7,413	3,571	2,572
Type		**cone**	**cone**	**cell**	**cone**
Grade		**2.6**	**2.6**	**2.1**	**3.1**
Size	**mm**	**1800**	**2500**	**2000**	**1600**

Table 10 presents the outcome of the fender selection for the four berthing energy calculations. WG211 reference case resulted in a larger fender compared to WG33. In the project, a slightly bigger fender has been selected (iii). Table 10 also shows that a berthing velocity of 0.15 m/s, results in bigger fenders (ii). It is therefore recommended to verify the berthing velocity based of local information. Given the orientation of this berth a velocity of 0.10 m/s in combination with a lower berthing angle of 3 degrees seems reasonable for this project.

Example 5: Exposed Jetty Single Fender Contact

This example involves a jetty situated in exposed navigation conditions in Australia, which aligns with WG211 'unfavourable' navigation conditions and WG33 'difficult navigation conditions, exposed'.

When no local information is available, WG211 recommends, based on the work of WG145, to consider a characteristic berthing velocity of 0.25 m/s, whereas Brolsma's berthing velocity curve e in WG33 recommend 0.15 m/s for a fully laden large ore carrier (230,000 DWT). However, it must be noted that the ore carriers do not arrive fully laden. The project design specification prescribes a normal berthing velocity of 0.16 m/s given that operational limits for berthing are applied. For instance, for this project it is not allowed to berth when windspeeds are higher than 30 knots (10 min average) and berthing during peak lateral currents to be avoided. Berthing within the operational window generally aligns with 'moderate' navigation conditions.

It should be noted that the port authorities prescribed a very high energy of 10,000 kNm ($\approx$ 6 times the calculated normal berthing energy of fenders) that needs to be absorbed by deformation of the semi-flexible dolphin and fenders. Given this extreme event the fenders are fully compressed and plastic deformation of the flexible berthing dolphins is allowed. However, for the purpose of this study the energy absorbed by the flexible dolphins have been assumed to be the same for all scenarios and has been discarded. Given the large number of berthing dolphins and the geometry of the ore carrier WG211 approach results in 'quarter' point berthing, whereas WG33 recommends an eccentricity factor of 0.7 for dolphin berths.

The port area consists of multiple berths and hence it is fair to assume that there is some functional redundancy. Furthermore, the project specification describes that temporary measures will be taken in case of fender damage, for instance by installing floating fenders. Consequently, the failure consequences corresponding to WG211 is class A. The variations in displacement (CoV_M) are fairly low. WG211 recommends a partial energy factor of 1.6 for moderate conditions and 1.8 for unfavourable conditions, whereas the project specification prescribe a safety factor of 2.0 and WG33 recommends an abnormal impact factor of 1.25.

Table 11 presents four scenarios: Two calculations in accordance with WG211 assuming that local information is provided, and hence the berthing velocity limit of 0.16 m/s taking into account operational restrictions (i) and (ii); A calculation conform WG211 while assuming a berthing velocity of 0.25 m/s assuming that no site-specific information is provided (iii); The original project design specification prescribing a berthing velocity of 0.16 m/s and a safety factor of 2.0 (iv), and a calculation in accordance with WG33 approach with a berthing velocity taken from curve e (0.15 m/s) and a safety factor of 1.25 for large bulkers (v).

Table 11 Berthing energy calculations Example 5: Exposed jetty in Australia single fender contact

Variable	SI	PIANC WG211			Project	PIANC WG33
Local information		Yes (i)	Yes (ii)	No (iii)	Yes (iv)	No (v)
Design method		WG211	WG211	WG211	BS 6349	WG33
Navigation conditions		Unfavourable*	Moderate*	Unfavourable	-	Curve e
Consequences class		A	A	A	-	-
Impact point	% L_{BP}	25%	25%	25%	25%	35%
V_B	m/s	0.16	0.16	0.25	0.16	0.15
α_c	deg	3	3	3	10	6
M_c	tonnes	142,000	142,000	142,000	142,000	142,000
C_e		0.56	0.56	0.56	unknown	0.70
C_m		1.50	1.50	1.50	unknown	1.50
E_n	kNm	-	-	-	1,680	1,677
E_{kc}	kNm	1,530	1,530	3,736	-	-
C_{ab}		-	-	-	2.00	1.25
E_{ab}	kNm	-	-	-	3,360	2,097
γ_E		1.80	1.60	1.80	-	-
E_{kd}	kNm	2,754	2,447	6,720	-	-
		Ref	**-11%**	**+144%**	**+22%**	**-25%**

*) There is an operational window. Berthing in very unfavourable conditions is not allowed.

The reference calculation using WG211(i) results in slightly higher energy than that calculated using WG33 (v). When no site-specific information of berthing velocity is available WG211 results in a 144% higher berthing energy due to the much higher berthing velocity of 0.25 m/s (iii). The project specification also includes a higher berthing energy, which is largely caused by the safety factor of 2.0 (iv). Table 12 presents the outcome of the fender selection of all scenarios.

Fenders are mounted on semi-flexible dolphins and therefore the total energy exerted by the vessel is absorbed partly by elastic deformation of the dolphin structures and partly by the fenders. In case of an accidental berthing situation, cone fenders will compress fully and the remaining energy will be absorbed by deflection of the flexible dolphins. In extreme events, some damage is also accepted. This project design specification shows that much higher values for berthing energy are taken into account in the design of the marine structure compared to energy estimated using the berthing velocity curves of WG33 in exposed navigation conditions. Nevertheless, a characteristic berthing velocity of 0.25 m/s might be too conservative when operation limits are imposed on the berthing operation. When no site-specific information is available, WG211 will result in much bigger fenders when all the energy needs to be absorbed by the fender system (iii). The calculation using WG211 assuming moderate navigation conditions (ii) results in similar fender dimensions compared to WG33 (v) for this project.

Table 12 Fender selection Example 5: Exposed jetty in Australia single fender contact

Variable	SI	PIANC WG211			Project	PIANC WG33
Local information		Yes (i)	Yes (ii)	No (iii)	Yes (iv)	No (v)
p_f	m	54	54	54	54	54
E_{base}	kNm	2,850	2,427	6,819	3,883	2,215
R_{base}	kN	2,792	2,815	5,748	4,045	2,471
$C_{manufacturer}$		-	-	-	0.90	0.90
$C_{v,c}$		1.07	1.08	1.08	1.08	1.08
$T_{c,high}$	°C	32.9	32.9	32.9	45	45
$T_{c,low}$	°C	4.5	4.5	4.5	4.5	4.5
$C_{t,c}$		0.97	0.97	0.97	0.93	0.93
$C_{ang,c}$		1.04	1.04	1.04	1.00	1.05
C_{mult}		1.00	1.00	1.00	1.00	1.00
$E_{f,c}$	kNm	3,073	2,699	7,501	-	-
γ_m		1.10	1.10	1.10	-	-
$E_{f,d}$	kNm	2,794	2,454	6,819	3,510	2,106
Fender type, grade		**cone**	**cone**	**cone**	**cone**	**cone**
Grade		**2.1**	**2.9**	**3.0**	**3.1**	**2.5**
and size	mm	**1800**	**1600**	**2250**	**1800**	**1600**

Conclusions

The results of this study are intended to provide a better understanding of the differences between WG211 and WG33. Its most notable findings are:

- PIANC WG211 strongly advocates the use of site-specific information and experience, such as berthing records, past service performance, or insights from pilots and harbour masters, when determining the characteristic berthing velocity. When site-specific information about the navigation conditions is used, WG211 will mostly result in slightly smaller fenders compared to WG33.
- In cases where site-specific information is unavailable, PIANC WG211 recommends employing higher berthing velocities compared to Brolsma's velocity curves (particularly for large seagoing vessels berthing in unfavourable navigation conditions). It is noted that these berthing velocities may be conservative for unfavourable navigation conditions, especially when berthing velocity is monitored or operational limits are in place. Under such circumstances, determining a project-specific berthing velocity is preferable in order to prevent overdesigning the fender system.
- This study confirms that Brolsma's berthing velocities can be too optimistic for large container vessels berthing in windy conditions. Berthing velocities close to 0.15 m/s were measured, whereas the Brolsma's velocity curves recommend significant lower berthing

velocities. The findings in this study align with the work of WG145.

- Selecting the berthing velocity is critical since this value can largely influence the size of the fender system. Although measurements in exposed navigation conditions are not available, the recommended characteristic berthing velocities by WG211 (and based on the results of WG145) seem reasonable. Examining the influence of the local navigation conditions, such as wind, wave, currents in relation to the orientation of the berth and type of berthing manoeuvre, on the berthing velocity is extremely important and need to be carried out by the asset owner, e.g. port or terminal authority.
- Given the same berthing velocity and berthing angle the partial safety factors recommended by WG211 for consequence classes A and B generally result in slightly smaller fenders compared to WG33. Since WG33 recommends a fairly low abnormal impact factor, e.g. 1.25 for large seagoing tankers, WG211 may result in a slightly higher design berthing energy compared to WG33. WG211 considers a factor of safety of 1.25 for vessels handling hazardous cargos factor to be too low, which is a reasonable consideration since there is no evidence that partial factors of safety are lower in these circumstances.
- The partial factors of safety largely depend on the navigation conditions and the failure consequences of the fender system. WG211 recommends that these important design aspects be determined by the asset owner, e.g. the port or terminal authority.
- The recommended berthing angles by WG211 are slightly lower compared to WG33 and hence the favourable effects of multiple fenders in contact with the vessel hull can be taken into account to optimise the geometry of the fender system, such as fender size, grade and geometry.
- Compared to WG33, the WG211 design guideline will include a method to take into account the berthing frequency and discusses the influence of the fender pitch in selecting a fender. Both design aspects can largely influence the size of the fender system. Usually, the fender pitch is prescribed in the client specification. However, it is highly recommended that the fender pitch be varied during the early stages of a project to study the effect of the cost of the fenders system and the supporting structure.

One of the biggest challenges faced when using the new WG211 design guideline for this study was the absence of detailed information regarding the environmental and navigation conditions in the original design specification. Since these conditions can significantly influence the fender dimensions, it is highly recommended that these conditions be included in new client design specification for fendering. Interpreting these conditions must be carried out using detailed knowledge about the local conditions and is an important factor when selecting a reasonable fender dimensions.

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