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Evaluation of Mooring Forces on Berths Bollards

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Abstract: In this study, mooring analysis was conducted for different vessel displacements in various locations in Egypt. The analysis focused on simulating extreme weather conditions to assess the suitability of existing codes and standards in limiting maximum forces on bollards. Locations included Damietta harbor, Suez Canal, Safaga port, and Safaga Abu Tartour, with meticulous consideration of environmental criteria. The analysis incorporated factors such as wind, wave, and current under Lowest Astronomical Tide (LAT) and loaded conditions, utilizing the OPTIMOOR software. Mooring arrangements adhered to Oil Companies International Marine Forum (OCIMF, 2008) guidelines. Results, primarily obtained from OPTIMOOR simulations, allowed for a comparative assessment of bollard forces across different cases and standards. Recommendations include a 10%-20% increase in design bollard forces for vessels with displacements under 50,000 tons, with variations for sheltered areas. Notably, a correlation between maximum bollard force and vessel displacement was observed, aligning with international port and harbor standards. Additionally, this study demonstrated the compatibility between measured mooring forces and OPTIMOOR predictions. OPTIMOOR serves as the basis for developing bollard force guidelines across various berth conditions, including Mediterranean harbors, the Suez Canal, and Red Sea berths. This research contributes valuable insights into the design and safety considerations for mooring systems in diverse maritime environments.

Keywords: Mooring analysis, wave, wind, current, tide, bollard

1. 1. INTRODUCTION

Since the beginning of the 21st century, with the continuous advancement of economic globalization, trade between countries has become more frequent, and shipping has become the main mode of transportation. However, when the ship is parked or encounters severe sea conditions, it will inevitably be affected by wind, wave and flow loads, resulting in complex multi-degree of freedom coupling movements. Therefore, in order to ensure the safe operation of the ship, its mooring system is essential and mooring bollards are the important facility in ports which are used to fasten the ship to the initial position at the berth. Based on that, an overview and comparison of recommended mooring forces on berths bollards according to different international standards and codes had been performed. Then, evaluation of standards, codes and recommendations was done by using OPTIMOOR software (OPTIMOOR Mooring Analysis Computer Program USERS GUIDE, 2012). Furthermore, selected types of berths, vessels and environmental conditions, were examined to determine the allowable mooring forces on bollards. An experimental verification has been performed by OPTIMOOR simulator based on the literature before performing analysis of the following study cases:

Case 1 - Berth in harbor protected by breakwaters.
Case 2 - Berth in open sea in natural significantly sheltered area in Safaga
Case 3 - Berth in open sea in natural partially sheltered area in Safaga
Case 4 - Berth along navigation channel in Port Said

Based on the comparison between the different standards, codes, in addition to the outputs of the simulated runs compared with different international standards and codes recommendations, applicable limitation of different international standards and codes was determined.

1.1 Loads

A ship moored at berth is subjected to three sources of environmental loads namely the wind wave and current. Wind loads are location specific. Maximum wind speed and the direction are to be assessed for design of mooring lines. Maximum wave height with direction specifics is needed as well as current loads. For mooring analysis, combination of all the three loads in each direction around the berth is usually studied. However, selection of berths was based on site environmental conditions, type, size of vessels and operation conditions. According to (OCIMF, 2008), the mooring arrangement should be as symmetrical as possible and the spring line angle should be less than 10° with respect to horizontal line and the breast line angle should be within 15°, with respect to vertical line. The vertical angles of the mooring line with respect to horizontal should be within 25°. The symmetry conditions are restricted due to practical constraints in determining the fairleads for mooring. In some cases, the mooring line angles are slightly above the allowable limit. The vertical angles for all the mooring lines are less than 25°.

2.Materials and Methods

2.1 OPTIMOOR simulator:

OPTIMOOR is primarily a 2D software rapidly computes mooring forces for specific vessels and berths, accounting for environmental factors like wind, waves, and currents, as well as draft, trim, and tide changes. It facilitates quick exploration of different mooring setups, environmental conditions, and vessel characteristics. By specifying vessel dimensions, fairlead positions, mooring line details, and materials, OPTIMOOR determines breaking strength and force extension. Berth details, including vessel, bollard, and fender characteristics, are also defined. Environmental data, such as wind, current, and waves, are input, stored, and used for analysis. OPTIMOOR calculates forces on mooring lines, fenders, and bollards based on input data and environmental conditions. All equations are illustrated in Appendix C of (OPTIMOOR Mooring Analysis Computer Program USERS GUIDE, 2012)

2.2 Overview of standards and codes

Port, harbor international standards and codes recommend that design mooring force for different vessels sizes should be based on its displacement or gross tonnage weight. Table 1 includes the different international standards and codes, that are used as a reference for the paper scope.

Table 1 Different international standards, codes

No	Standard or code	Editor	Edition years
1	Recommendations of the Committee for Waterfront Structures, Harbours and Waterways, Ernst & Sohn	Committee for Waterfront Structures of the German Port Technology Association and the German Geotechnical Society (EAU)	1975, 1990, 1996, 2004 & 2012
2	Technical Standards, Commentaries for Port and Harbour Facilities in Japan	The Overseas Coastal Area Development Institute of Japan (OCDI)	1980, 1991, 2002 & 2009
3	Guidelines for the design of maritime structures	Australian Standard (AS) 4997	2005
4	Code of practice for design of fendering and mooring system	British standard (BS) 6349-4:2014	2014
5	Port Designer's Handbook, Third edition	Institution of Civil Engineers (ICE)	2014
6	Code of practice for assessment of actions	British standard (BS) 6349-1-2:2016	2016
7	Design of Marine facilities, Third edition	American Society of Civil Engineers (ASCE)	2016

2.3 Mooring definition

Mooring is the process of safely securing a ship to a berth. It must withstand extreme environmental conditions such as wind, currents, waves, and passing vessel surges. Mooring facilities should accommodate various ship sizes, and ships arriving should cooperate with port authorities for mooring arrangements. Forces on the structure include tension in bollards, horizontal pressure from wind and currents, and vertical forces from ship movements. The mooring system must handle these forces while preserving operational capabilities and ensuring safety.

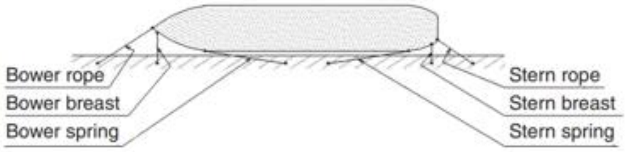


Fig 1 General mooring arrangement for a ship to a berth by way of bollards *(ICE, 2014)*

Key principles for mooring forces:
For safe and efficient berthing operations, use breast lines for forces perpendicular to the berth front and spring lines for forces along it. Breast lines reduce sway and yaw, while spring lines minimize surge motion. Consider wind, waves, and currents in your approach. Head and stern lines can complement spring and breast lines, and ensure your fender systems are robust. Follow port engineering standards to specify minimum bollard loadings for different ship sizes, guaranteeing structural integrity during berthing. In summary, a well-planned combination of lines and adherence to standards is essential for safe berthing.

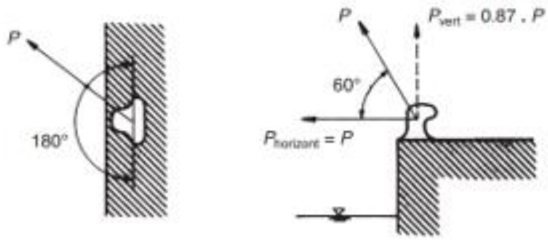


Fig 2 Bollard load direction and value (ICE, 2014)

Various mooring recommendations and conditions include designing bollard anchorage for 1.5 times the expected load (EAU, 2012) considering mooring forces from vessel maneuvering (Australian Standards, 2005), using storm bollards (>250 t) and accounting for non-horizontal mooring lines (BS 6349, 2014), designing for minimum loading to protect berth structures (ICE, 2014), calculating probable maximum mooring loads for larger vessels (BS 6349, 2016), and increasing values by 25% in exceptional conditions (ASCE, 2016). Table 2 illustrates the Mooring bollards forces for the latest editions of different standards and codes. In addition, comparison of different editions for EAU, OCDI is illustrated in **Error! Reference source not found.** and
Table 4, respectively.

Table 2 Mooring bollards forces for the latest editions of different standards and codes

Displacement (t)	Bollard pull force (t)					
	EAU 2012	**AS, 2005**	**BS 6349-4:2014**	**ICE 2014**	**BS 6349-1-2:2016**	**AS CE, 2016**
Up to 50	-	5	-	-	-	-
Up to 200	-	10	-	-	-	-
Up to 1000	-	20	-	-	-	-
Up to 2000	-	-	-	10	10	10
Up to 5000	-	-	-	20	-	-
Up to 10 000	30	30	-	30	30	30
Up to 20 000	60	50	-	50	60	60
Up to 30 000		-	-	60	-	-
Up to 50 000	80	80	80	80	-	80
Up to 100 000	100	100	100	100	-	100
Up to 200 000	200	150	150	150	-	150
> 200 000	-	200	≥ 200	200	-	200
Up to 250 000	250	-	-	-	-	-
> 250 000	> 250	-	-	-	-	-

Table 3 Mooring bollards forces based on different editions of EAU

Displacement (t)	Bollard pull force (t)				
	1975	**1990**	**1996**	**2004**	**2012**
Up to 2000	10	10	10	10	-
Up to 10 000	30	30	30	30	30
Up to 20 000	60	60	60	60	60
Up to 50 000	80	80	80	80	80
Up to 100 000	100	100	100	100	100
Up to 200 000	150	150	150	150	200

> 200 000	200	200	200	200	-
Up to 250 000	-	-	-	-	250
> 250 000	-	-	-	-	> 250

Table 4 Mooring bollard forces based on different editions of OCDI

Gross tonnage of ship (t)	Bollard pull force (t)			
	1980	**1991**	**2002**	**2009**
200 - 500	15	15	15	15
500 – 1 000	25	25	25	25
1 000 – 2 000	35	35	25	25
2 000 – 3 000	35	35	35	35
3 000 – 5 000	50	50	35	35
5 000 – 10 000	70	70	50	50
10 000 – 15 000	100	100	-	-
10 000 – 20 000	100	100	70	70
20 000 – 50 000	150	150	100	100
50 000 – 100 000	200	200	100	100

2.4 Previous experimental studies:

(Santos et al., 2010) simulated the Lexioes oil terminal under challenging environmental conditions, finding that increasing breast line tension reduces vessel movement during mooring. However, the model lacked accuracy in estimating factors like wave overtopping and agitation, warranting further investigation. (Das et al., 2015) used numerical simulations for a 200,000 DWT moored oil tanker, concluding that quasi-static methods predict acceptable ship motions and mooring forces noting a maximum bollard pull of 199 tons, close to the 200-ton standard for this displacement. (van der Molen et al., 2016) studied Geraldton Harbor, recommending pneumatic fenders and constant tension winches to reduce vessel motions and mooring line forces. (Dev Raju et al., 2017) conducted mooring analysis for a Liquified Gas Tanker (LNG) vessel, concluding the proposed arrangement was suitable for specific conditions, with Quick Release Hooks providing enhanced safety. (Esferra et al., 2018) improved mooring at Ponta da Madeira Port Terminal, suggesting a combination of board and shore ropes for safe operation. Finally, (Sáenz et al., 2023) highlighted that Ultra Large Container Vessels (ULCVs) generate significantly higher mooring forces than conventional vessels, emphasizing the importance of bollard design and placement in port infrastructure.

3.Study Cases

The study areas that will be taken into consideration are Damietta harbor, Suez Canal, Safaga port and Safaga Abu Tartour. The first, is LNG berth located in Damietta harbor and has 276.0 meters length and 12.0 m water depth protected by breakwaters as shown in Fig 3. The second is container berth along Suez Canal, Port Said area, Egypt as shown in Fig 4 and has 345.0 m length and 13.6 m water depth. The third is the aluminum berth at Safaga port, Red Sea, Egypt which is located at the southern part of the port and has 221.5 meters length and 11.0 meters water depth as shown in Fig 5. The last one located at Safaga Abu Tartour, Red Sea, Egypt as shown in Fig 5 with 56.0 length and 11.5 water depth. Table 5 is illustrating the vessel main characteristics and site conditions for different study cases. Different environmental cases along with the available conditions (shown in Table 6) at the site in order to simulate maximum potential extreme weather conditions, to evaluate the validity of codes and standard limits of maximum forces on bollards to be considered in basic design. Detailed design should imply much more elaborated analysis such as OPTIMOOR or equivalent. The mooring analysis is carried out by considering the effect of wind, wave and current for the LAT and loaded condition. Moreover, OPTIMOOR has been used to carry out dynamic mooring analysis (including the passing vessel effect) for study case 2. The analysis using this software has been done to study the combined effect of both the passing vessel and environmental loads on the line tension of the mooring lines. The dynamic analysis allows the use of Seelig-Wang method for passing vessel effects (SHEN, 1975) (Seelig, 2001). The main parameters were; Passing vessel speed is 8 knot, clear gap between vessels is 60 m and draft to depth ratio is 1.15.

Fig 3 Location of study case 1 – Damietta harbor - Liquified Gas Tanker (LNG) berth

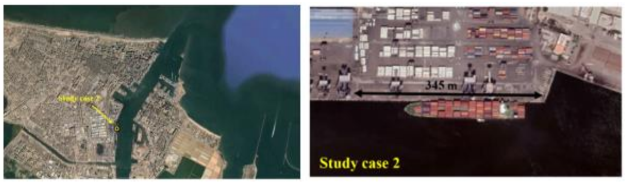


Fig 4: Location of study case 2 – Suez Canal - The container berth

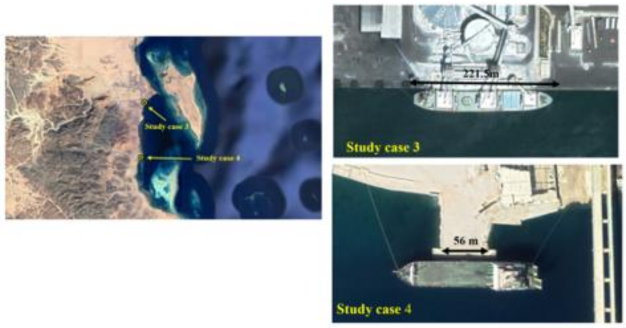


Fig 5: Locations of study case 3 - Safaga port - Aluminum berth and case 4 - Cement berth - Safaga Abu Tartour

Table 5 Vessel main characteristics and site conditions for different study cases

Study case		1	2	3	4
		Gas tanker berth in harbor protected by breakwaters	Container berth along navigation channel	Aluminum berth in open sea in significantly sheltered area	Cement berth in open sea in partially sheltered area
Location		Damietta harbor	Suez Canal	Safaga port	Safaga Abu Tartour
Water depth (m)		12.0	13.6	11.0	11.5
Design vessel	Type	Liquid Natural Gas Tanker	Container	Bulk Carrier	Bulk Carrier
	Displacement (t)	75,000	53,900	40,000	25,000
	LOA (m)	255.0	230.0	192.0	157.0
	LBP (m)	245.0	217.0	181.0	148.0
	Beam (m)	38.0	30.2	27.3	23.0
	Loaded draft (m)	10.5	11.8	10.6	9.2
	Molded depth (m)	23.0	17.0	15.6	14.0

Table 6 Environmental conditions

Environmental conditions	Wind		Wave			Current	
	Wind speed (knot)	Direction (degree)	Sign. Wave height (m)	Wave period (s)	Direction (degree)	Current speed (knot)	Direction (degree)
1	60.0	-90.0	-	-	-	-	-
2	60.0	0.0	1.0	7.0	45.0	1.0	0.0
3	60.0	-45.0	1.0	7.0	45.0	1.0	0.0
4	-	-	-	-	-	-	-
5	30.0	45.0	1.0	7.0	45.0	-	-
6	40.0	45.0	1.0	7.0	45.0	-	-

Table 7 Environmental conditions (wind in red color, wave in blue color and current for green color

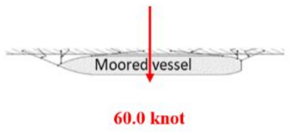
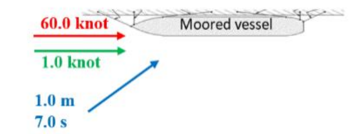
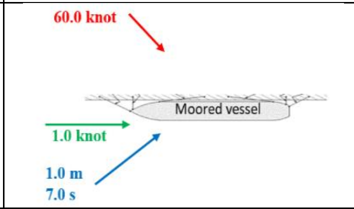
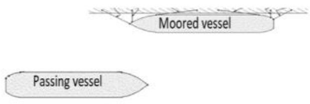
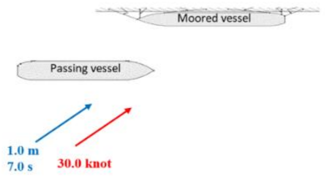
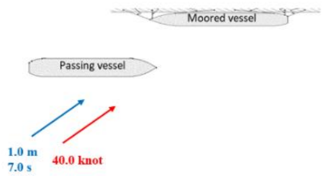
Load case	1	2	3
Environmental conditions			
Load case	4	5	6
Environmental conditions			

Table 8 OPTIMOOR outputs of study cases for selected berths in Egypt

Study case		1	2	3	4
		Gas tanker berth in harbor protected by breakwaters	Multipurpose berth along navigation channel	Aluminum berth in open sea in significantly sheltered area	Cement berth in open sea in partially sheltered area
Bollard force according to codes and standards (t)		80.0 x 125% = 100.0	80.0 x 125% = 100.0	70.0 x 110% = 77.0	60.0 x 120% = 72.0
Max. bollard force from OPTIMOOR	Case 1	44.6	46.1	27.5	40.9
	Case 2	62.7	52.1	41.1	59.5
	Case 3	35.9	72.3	56.0	60.0
	Case 4	-	37.5	-	-
	Case 5	-	62.1	-	-
	Case 6	-	76.8	-	-

Table 9 Vessel displacements regarding bollard force

Displacement (t)	50	200	1 000	10 000	20 000	50 000	100 000	200 000	250 000
Bollard force (t)	5	10	20	30	60	80	100	150-200	> 250

3.1 Environmental conditions:

The mooring arrangement should be effective to cope with the environmental loads from any direction. Fenders, mooring lines and bollards should be able to withstand the loads from the wind, wave and current. The environmental conditions for 1, 2 and 3 are based on the following criteria; 60.0 knots wind speed from any direction simultaneously with (1.0 m significant wave height at 45º and 1.0 knots current at 0º). Regarding 4, 5 and 6, where the passing ship effect is considered, the environmental conditions are as follow: 40.0 and 30.0 knots wind speed at 45º to reach the maximum force on bollard (1.0 m significant wave height at 45º) and the current in Suez Canal is usually smaller than 0.4 knot which is minimal and to be neglected in these conditions (Suez Canal Research Center, 1976). The mooring analysis is carried out for loaded condition in low tide incorporating the six combinations of environmental conditions. The cases considered are given in Table 6 that gives the environmental conditions for which the analysis has been carried out. Furthermore, two cases are be investigated considering sea water levels to examine the effect of such variation (Low and high water tide).

4.Results and Discussion

The results of moored ship bollard forces from the OPTIMOOR simulations are provided in this section. The focus in this paper is on the comparison between bollard forces for different study cases, codes and standards. The results are discussed first in this section to evaluate different recommendations. Subsequently, the improvements by increasing the bollard capacity is discussed. Basically, the allowable bollard force depends on the vessel displacement. Moreover, according to codes and standards, the bollard pull forces should be increased by 25 % for vessels of 50,000 t or greater displacement (EAU, 2012)which is applicable for study cases 1 and 2. For study cases 3 and 4 (less than 50,000 displacement), caution should be taken because codes have not mentioned safety factor for such displacements. However, below the recommended safety factor in red color based on the numerical simulations.

The tidal variation is considered for study case 3 (i.e., Aluminum berth in open sea in significantly sheltered area). Sea water surface fluctuations are mainly due to astronomical tide, partially due to wind set up and wave set up. The semi-diurnal tidal component is dominant. Long term analysis for sea water surface levels results in the following pattern relative to Admiralty Chart Datum (A.C.D.). This datum properties are +1.20 meter for High high-water level (H.H.W.L.), +0.9 meter for Mean high water level (M.H.W.L.), + 0.60 meter for Mean water level (M.W.L.), +0.30 meter for Mean low water level (M.L.W.L.) and ± 0.00 meter for Low low water level (L.L.W.L.) according to (Suez Canal Research Center, 1976). For study case 3; the maximum bollard forces, measured in tons, vary with tide conditions as follows: In load case 1, the maximum bollard force is 27.5 tons at low tide and 28.5 tons at high tide. In load case 2, it measures 41.1 tons during low tide and 40.6 tons during high tide. load case 3 experiences the highest bollard forces, with 56.0 tons at low tide and 52.7 tons at high tide. Accordingly, it can be seen that there is no significant difference between two cases which the difference is not more than 6%. Therefore, a low tide case shall be considered in the four study cases discussed above. Moreover, mooring forces still remain the same for all tidal conditions. As shown in Table 8, the maximum force of the bollard is found to be within allowable limits in **Error! Reference source not found.** and

Table 4 which is not exceeded in all cases. All different cases are covered in the study including various effects such as environmental forces (wind, wave and current) as well as forces generated from ship moving beside the harbor in addition to tidal variation conditions (high and low levels) in loaded conditions. Moreover, an overview of port, harbor international standards and codes illustrate that maximum force on berth bollard is related to vessel displacement according to Table 9**Error! Reference source not found.** .

5.Conclusions

It can be concluded that 10%-20% increase for design bollard force for vessels that have displacement less than 50,000 tons. Furthermore, it is recommended for vessels less than 50,000 to increase their design bollard force by 20% for significantly sheltered area and 10% for partially sheltered area. Most standards and codes include a percentage of increase related to special environment, berth conditions, etc. Furthermore, published physical models, prototype measured mooring forces on bollards are compared with the analysis outputs of OPTIMOOR illustrating satisfactory correlation between measured and OPTIMOOR predicted mooring forces on bollards. OPTIMOOR is used to develop guidance for bollards forces for the following berths conditions; vessel moored on berth inside Mediterranean harbor protected by breakwaters, vessel moored on berth along Suez Canal subject to forces from passing vessels and vessel moored on open sea significantly or partially sheltered berth in Red Sea.

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