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International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Analyzing Berthing Platform Structural Design for Modern Oil Terminals under Operational Loads

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DOI: https://doi.org/10.55248/gengpi.4.923.52587

ABSTRACT

The evolution of maritime transport has spurred the development of specialized berthing facilities tailored to diverse cargo types. In this context, the study focuses on berthing dolphins at the newly established oil terminals in Bandar Anzali, Iran. As vessels and facilities have grown in complexity, the need for enhanced operational efficiency and safety has led to updated guidelines for facility design and ship piloting. This investigation delves into the performance evaluation of berthing platforms, considering loading conditions and structural behavior. The study employs numerical modeling to assess the stability and integrity of the dolphins under operational and ultimate limit loads. The results indicate that the stress ratios of piles are within acceptable bounds, and the maximum displacements of the structure are significantly below permissible limits. Design criteria for bending moments are presented, further contributing to the understanding of berthing platform behavior and ensuring operational safety. This research offers insights into the secure and efficient berthing of vessels for oil product transfer, aligning with evolving maritime standards.

Keywords: Mooring Forces; Numerical Analysis; Oil Terminals; Berthing Platform; Coastal Structure

Introduction

Throughout maritime history, vessels tasked with transporting cargo and passengers have necessitated the presence of berthing, loading, and unloading facilities. As vessels have grown in size and complexity, dedicated infrastructure and specialized terminals have emerged to cater to distinct cargo types, including liquid bulk, dry bulk, and containers. Over time, the imperative to enhance operational efficiency and bolster safety standards has driven the development of updated guidelines for facility design and ship piloting. Consequently, operational protocols and innovative technologies have been devised to ensure increasingly tailored and secure berthing maneuvers (1–6).

In the context of liquid bulk terminals, jetties serve as the conventional mooring apparatus. Typically, vessels are secured to specific berthing dolphins, which can adopt flexible or rigid, single, or multi-pile configurations. Rigid dolphins commonly incorporate rubber fenders to augment their functionality. In the realm of dolphin, fender, and mooring platform design, the presence of a suitable method to elucidate the mooring maneuver of sizable tankers at a jetty is paramount. Such a method should anticipate maximal deflection and load within the mooring system. The structural stiffness of the mooring system, particularly its horizontal aspects, is intricately linked to factors like the elasticity properties, geometric intricacies, and attachments of the structure. Moreover, the maximum pile deflection is contingent upon parameters such as the lateral speed and displacement of the approaching vessel.

The existing practice of structural design for berth structures is rooted in internationally recognized standards, such as the "Guidelines for the Design of Fender Systems" (7) and the "Technical Standards and Commentaries for Port and Harbour Facilities in Japan" (8). These standards prescribe the computation of mooring forces through simplified methods, often relying on linear static analysis that decouples vessel movements and lacks consideration of relative stiffness or nonlinearity in mooring elements. Dynamic response is typically approximated via dynamic amplification coefficients. Despite their limitations, these methods are convenient for design and analysis, as evident in works by Carbonari et al. (2019), Jafarzadeh et al. (2021 and 2023), Joushideh et al. (2023), Das et al. (2015), Shakouri Mahmoudabadi (2020), Comin and De Souza (2017), Mehraeen et al. (2022), and Gaythwaite (2014) (9–18), among others. Nonetheless, it's acknowledged that mooring stiffness exhibits nonlinearities, both physical (e.g., elastomeric fender softening) and geometrical (e.g., occasional fender-ship detachment), raising questions about the adequacy of linear analyses.

The design of mooring platforms in oil terminals assumes critical importance as it directly shapes the secure and efficient berthing of vessels for oil product transfer. These platforms, often equipped with breasting dolphins, necessitate meticulous engineering to absorb and dissipate the significant energy generated during vessel approach, preventing harm to both vessels and infrastructure. The configuration and structural robustness of berthing dolphins and related fender systems play a pivotal role in curbing vessel movement induced by external factors such as wind, currents, and tides. This study focuses on evaluating the performance of berthing platforms at the newly established oil terminals in Bandar Anzali. After scrutinizing the existing loading conditions, the structure was meticulously replicated using SAP 2000 software. Structural analysis, encompassing existing loads and diverse combinations, underscored the structure's stability across scenarios. Lateral deformations and pile stress distribution ratios remained within acceptable bounds. This inquiry enhances the comprehension of berthing platform behavior, ensuring structural integrity and operational safety within the oil terminals.

Overview of study case

Bandar Anzali is situated in the northwest of Iran within the Gilan province. Positioned approximately 40 kilometers northwest of the city of Rasht, it resides in the central sector of Anzali county, nestled between the Caspian Sea's shores and the Anzali Wetland. The development plan for Bandar Anzali has intricately factored in the classification of goods exchanged within the port, predicting their future expansion phases and envisaged volumes. As per the findings presented in the study by Joushideh et al., the Bandar Anzali port has been identified as significantly vulnerable to settlement and potential collapse. The research underscores the pressing necessity for the implementation of inventive design strategies aimed at tackling this critical challenge (19). In alignment with these considerations, quays have been designed for the berthing of various types of vessels, including container ships, general cargo carriers, and oil tankers. For accommodating oil tankers, three dolphin-type quay posts have been strategically positioned. These structures, characterized by their dolphin configuration, comprise access bridges, discharge, loading platforms, and mooring and berthing dolphins.

Each berthing dolphin structure encompasses six vertical piles, and its platform spans dimensions of 9.3 by 5.4 meters with a thickness of 1.25 meters. The elevation of the top surface of the berthing dolphins stands at +3.2 meters, while the elevation of the pile tips is -28.0 meters, and the seabed level is at -11.0 meters relative to the Anzali port's zero reference level. The employed fendering system for these dolphins is of the SCN1000/E 1.6 variant. Details of a berthing dolphin are represented in Figure 2.

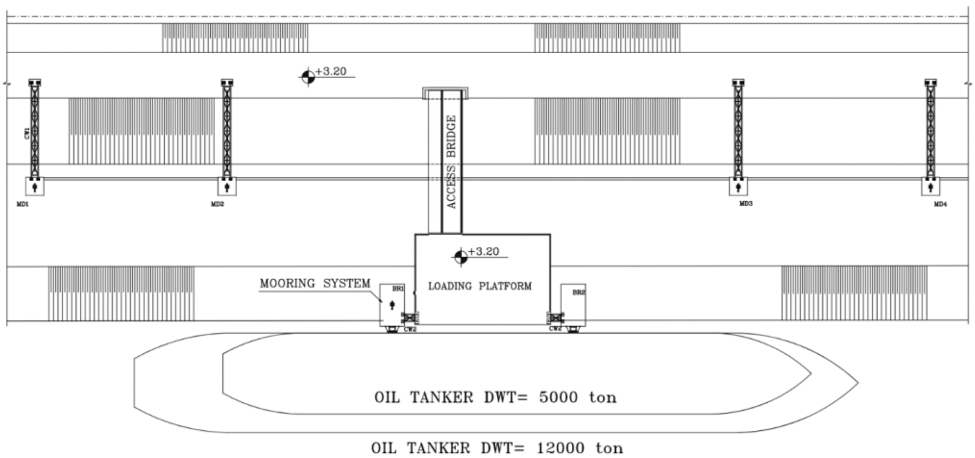

Figure 1 Oil Terminal Jetty Plan, Position, and Number of Berthing Dolphins

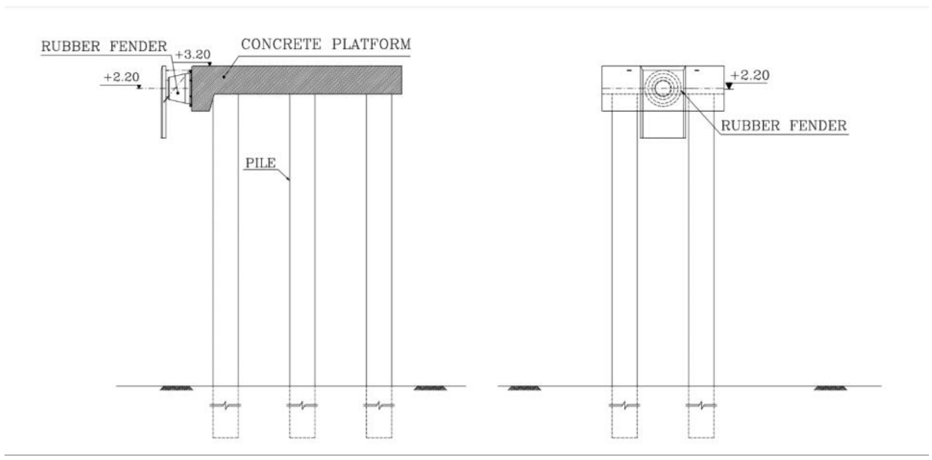

Figure 2 Details of oil terminal berthing dolphin

Loading

The forces acting upon berthing dolphins encompass impact forces arising from vessel berthing and mooring forces associated with vessel mooring arrangements. The impact force resulting from vessel berthing, considering the chosen SCN 1000/1.6 fender system, is estimated at 2.84 tons. This force acts vertically onto the corresponding structure (berthing dolphin). Additionally, a friction force equivalent to 30% of the berthing force is applied in both vertical and horizontal directions (non-simultaneously). Based on the Joushideh et al. study the Gross Tonnage (GT) of vessel for this port is equal to 8300 tons. To determine the mooring force, Table 1 has been referenced. As evident from the mentioned table, the mooring force for a mooring post, corresponding to a vessel with a GT of 8300 tons, is 70 tons. Accordingly, the mooring force for berthing dolphins is established at 50 tons. Given the mooring arrangements of the vessel and the restrictions on Q.R.H types produced in the factories, a single-arm Q.R.H with a capacity of 75 tons is utilized for mooring dolphins, and a single-arm Q.R.H with a capacity of 60 tons is used for berthing dolphins. Other loads considered in the berthing dolphin design encompass dead loads stemming from weight and live loads equivalent to 200 kilograms per square meter.

Table 1 Standard Values of Tractive Force by Ships (8).

GT of the ship (ton)	Tractive force acting on a bollard (kN)	Tractive force acting on a mooring post (kN)
200<GT<500	150	150
500<GT<1000	250	250
1000<GT<2000	250	350
2000<GT<3000	350	350
3000<GT<5000	350	500
5000<GT<10000	500	700
10000<GT<20000	700	1000
20000<GT<50000	1000	1500

To comprehensively account for all conceivable scenarios concerning the loads applied to the berthing dolphins, these loads have been categorized in accordance with Table 2.

Table 2 Load Types and Descriptions for Berthing Dolphin Analysis.

Load type	Description
Dead	Dead load resulting from the structural elements' weight
L_{unif}	Uniform live load equivalent to 200 kilograms per square meter, arising from the weight of installed equipment and personnel
Berth-V	Berthing force of 2.84 tons along with 30% frictional force in the vertical direction
Berth-H	Berthing force of 2.84 tons along with 30% frictional force in the horizontal direction
Moor-X	Mooring force of 50 tons in the horizontal plane parallel to the berthing line
Moor-Y	Mooring force of 50 tons in the horizontal plane perpendicular to the berthing line
Moor-XY	Mooring force of 50 tons in the horizontal plane at a 45-degree angle relative to the berthing line
Moor-XZ	Mooring force of 50 tons at a 25-degree angle relative to the horizontal plane in a parallel configuration to the berthing line
Moor-YZ	Mooring force of 50 tons at a 25-degree angle relative to the horizontal plane in a perpendicular configuration to the berthing line
Moor-XYZ	Mooring force of 50 tons at a 25-degree angle relative to the horizontal plane and a 45-degree angle relative to the berthing line in the plane

Table 3 and Table 4 provide the loading combinations utilized in the berthing dolphin modeling, presented for both serviceability-level loads and ultimate-limit loads, respectively. These selected combinations of loading have been specifically tailored to suit the characteristics of the analyzed structure. Notably, less impactful loading scenarios that exhibit negligible effects, even without explicit modeling, have been excluded. For example, due to the relatively modest weight of the dolphins, the seismic force is not a determining factor when compared to the more significant berthing forces (84.2 tons) and vessel mooring forces (50 tons). Consequently, it can be safely disregarded due to its non-simultaneous occurrence. Additionally, considering the platform's compact dimensions, the influence of thermal forces is of minimal consequence. Thus, loading combinations encompassing such forces have been omitted. Given the dolphins' limited windage surface area, the wind force directly affecting them is significantly minor in comparison to other lateral forces, thus it has been omitted from the loading combinations. It is important to mention that the mooring force resulting from the wind force acting on the vessel has been conservatively accounted for in the dolphin analysis. In scenarios where the mooring force is diminished in its effect on vertical forces due to the 25-degree angle with the horizontal surface, loading combinations incorporating uniform live loads exhibit reduced criticality when compared to those without live loads. As a result, these combinations have been excluded from consideration.

Table 3 Berthing Dolphin Loads Combinations All Possible Scenarios

Load Combination	Load Cases									
	Dead	L_{unif}	Berth-V	Berth-H	Moor-X	Moor-Y	Moor-XY	Moor-XZ	Moor-YZ	Moor-XYZ
STL-01	1	1								
STL-02	1	1	1							
STL-03	1	1		1						
STL-04	1		1							

STL-05	1			1						
STL-06	1	1			1					
STL-07	1	1				1				
STL-08	1	1					1			
STL-09	1							1		
STL-10	1								1	
STL-11	1									1

Table 4 Berthing Dolphin Loads Combinations All Possible Scenarios

Load Combination	**Load Cases**									
	Dead	**Lunif**	**Berth-V**	**Berth-H**	**Moor-X**	**Moor-Y**	**Moor-XY**	**Moor-XZ**	**Moor-YZ**	**Moor-XYZ**
CON-01	1.4	1.7								
CON-02	1.4	1.7	1.7							
CON-03	1.4	1.7		1.7						
CON-04	0.9		1.7							
CON-05	0.9			1.7						
CON-06	1.4	1.7			1.7					
CON-07	1.4	1.7				1.7				
CON-08	1.4	1.7					1.7			
CON-09	0.9							1.7		
CON-10	0.9								1.7	
CON-11	0.9									1.7

Numerical modelling

The berthing structure is composed of six vertical piles, interconnected by a unified concrete deck that is cast in place. Figure 3 illustrates the three-dimensional model of the berthing dolphin. The foundation level at the location of the berthing dolphins is established at an elevation of -11.0 meters. The permissible depth of pile penetration is determined through equation (1):

$$z_f = 1.8T \, , T = \sqrt[5]{\frac{EI}{n_h}}$$

Where E and I represent the modulus of elasticity and the moment of inertia of the pile, respectively, and n_h is the coefficient of soil stiffness increase. Considering empirical relationships and the local soil properties, a value of 1400 kN/m^3 is assumed for this parameter. Accordingly, the calculated effective depth of the steel piles, having a diameter of 44 inches and a thickness of 18.26 millimeters, as employed in the berthing structure, amounts to 7.6 meters. The pile embedment depth with respect to the platform level is taken from the reference point at 11.0 meters below sea level. As a result, the base elevation of the piles is situated at 18.6 meters below sea level. Taking into account the elevated position of the deck (3.2 meters above sea level) and the thickness of the deck (1.25 meters), the upper level of the piles is determined at 2.575 meters above sea level.

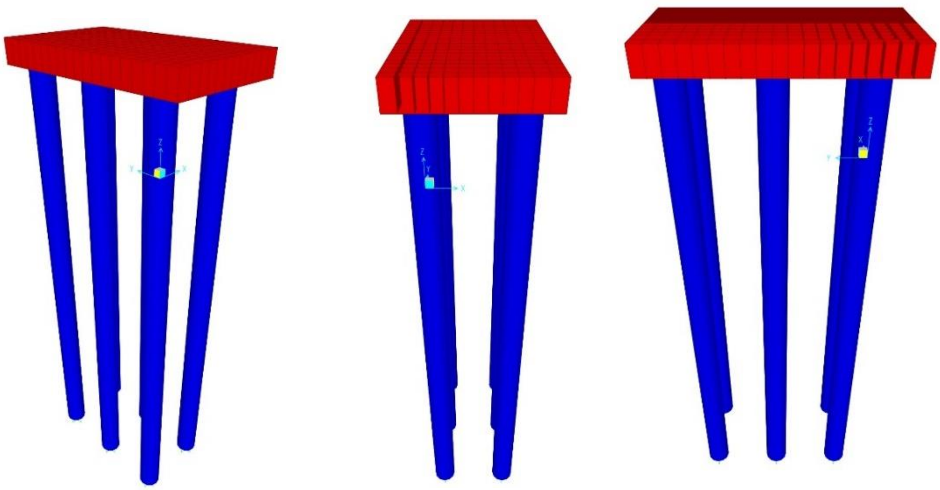

Figure 3 Three-Dimensional Model of Berthing Dolphin

The piles of the berthing structure are constructed using steel pipes with an outer diameter of 44 inches (1117.6 millimeters) and a thickness of 18.26 millimeters. In the pile modeling process, considering corrosion in different areas, three scenarios have been considered. In the splash zone (from sea level to 2.575+ meters), a corrosion allowance of 6 millimeters is accounted for, resulting in an outer diameter of 1105.6 millimeters and a thickness of 12.27 millimeters for the piles. In the submerged zone (from sea level to the seabed at 11.0 meters), a corrosion allowance of 3 millimeters is considered, leading to an outer diameter of 1111.6 millimeters and a thickness of 15.27 millimeters for the piles. No corrosion is taken into account in the buried zone within the soil.

The thickness of the platform slab is established at 125 centimeters. To model the concrete platform, square shell elements with dimensions of 5.0 meters have been employed.

Results

According to maritime standards references, displacements of foundation piles and the platform up to 30 centimeters are permissible. The analysis results indicate that the maximum displacement of the deck center in the vertical and parallel directions to the mooring line is 7.3 and 4.6 centimeters, respectively, both of which significantly exceed the allowable limits. Displacement calculations have been performed based on operational loading combinations. Figure 4 illustrates the deformed plan of the platform under the STL-04 and STL-06 loading combinations.

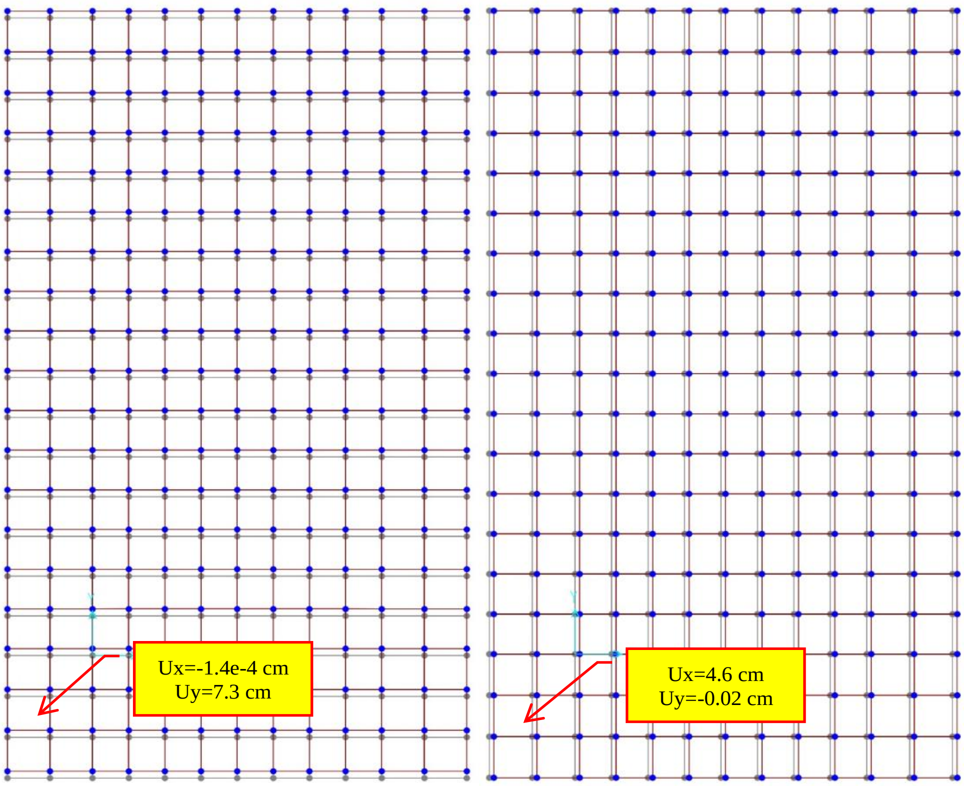

Figure 4 Modified Shape of Berthing Dolphin under Load Combination STL06 (Right) and STL04 (Left)

The results obtained from the structural analysis for the piles include bending moments, shear forces, and axial forces in the operational condition as presented in Table 5, and in the ultimate condition as shown in Table 6. The numbering scheme for the piles is illustrated in Figure 5. These results are determined based on the load combinations specified in accordance with Table 3 and Table 4.

Table 5 The maximum values of bending moments, shear forces, and axial forces in the piles under operational loads.

P(Ton)	**V2(Ton)**	**V3(Ton)**	**M2(Ton.m)**	**M3(Ton.m)**
60.95	8.35	15.37	177.15	99.47
-109.26	-0.08	-8.48	-148.25	-77.4

Table 6 The maximum values of bending moments, shear forces, and axial forces in the piles under ultimate loads.

P(Ton)	**V2(Ton)**	**V3(Ton)**	**M2(Ton.m)**	**M3(Ton.m)**
122.28	14.19	26.13	301.3	169.08
-177.32	-0.16	-14.41	-252.02	-131.5

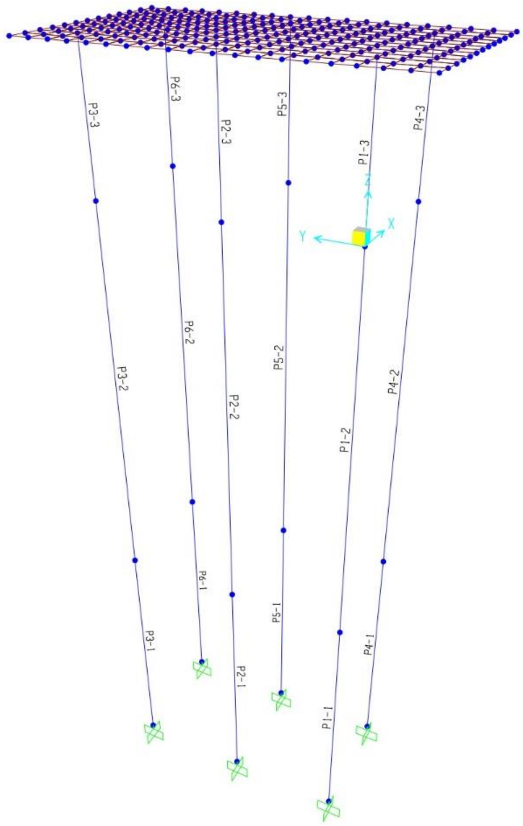

Figure 5 The numbering scheme for the piles.

The moment distribution of the slab resulting from the load combination in the ultimate limit state is provided in Table 7. As an example, the condition of the bending moment in the X-direction (M11) under the load combination CON-06 is illustrated in Figure 6, and the condition of the bending moment in the Y-direction (M22) under the load combination CON-07 is depicted in Figure 7.

Table 7 The values of bending moments in the slab under the load combinations in the ultimate limit state.

Load Combination	**M11+ (t.m/m)**	**M11- (t.m/m)**	**M22+ (t.m/m)**	**M22- (t.m/m)**
CON-01	4	4	4	5
CON-02	54	59	109	102
CON-03	62	71	103	112
CON-04	55	58	110	102
CON-05	65	70	104	112
CON-06	61	62	35	42
CON-07	30	37	61	63
CON-08	47	44	47	51
CON-09	55	56	31	40
CON-10	29	32	55	56
CON-11	42	42	42	44

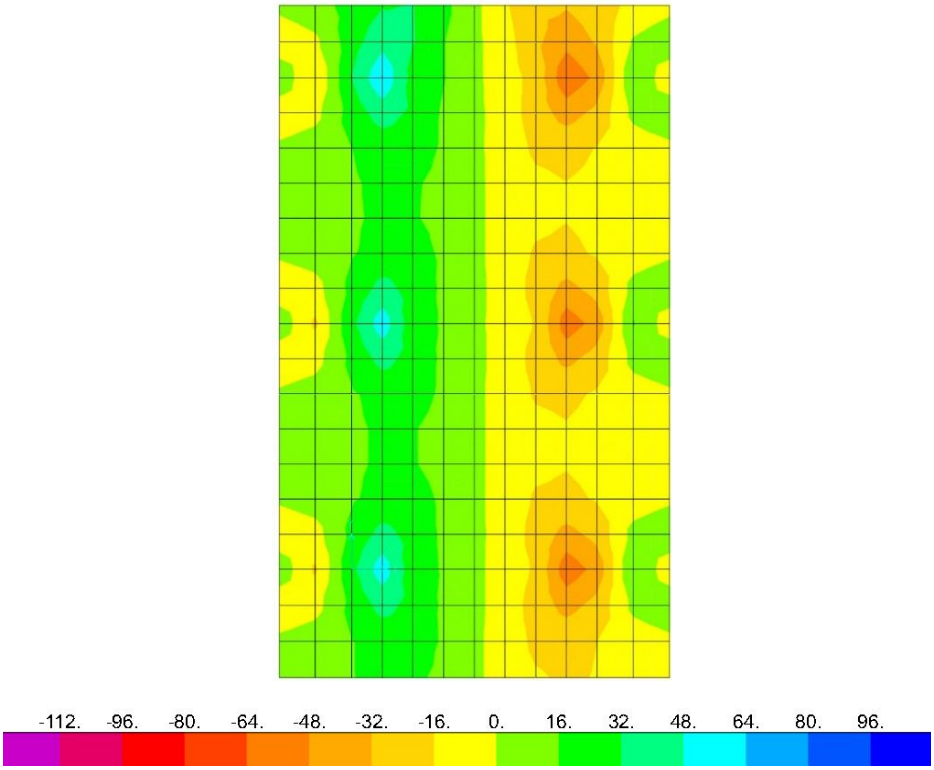

Figure 6 bending moment contour in the X-direction (M11) under load combination CON-06 ($ton.m/m$).

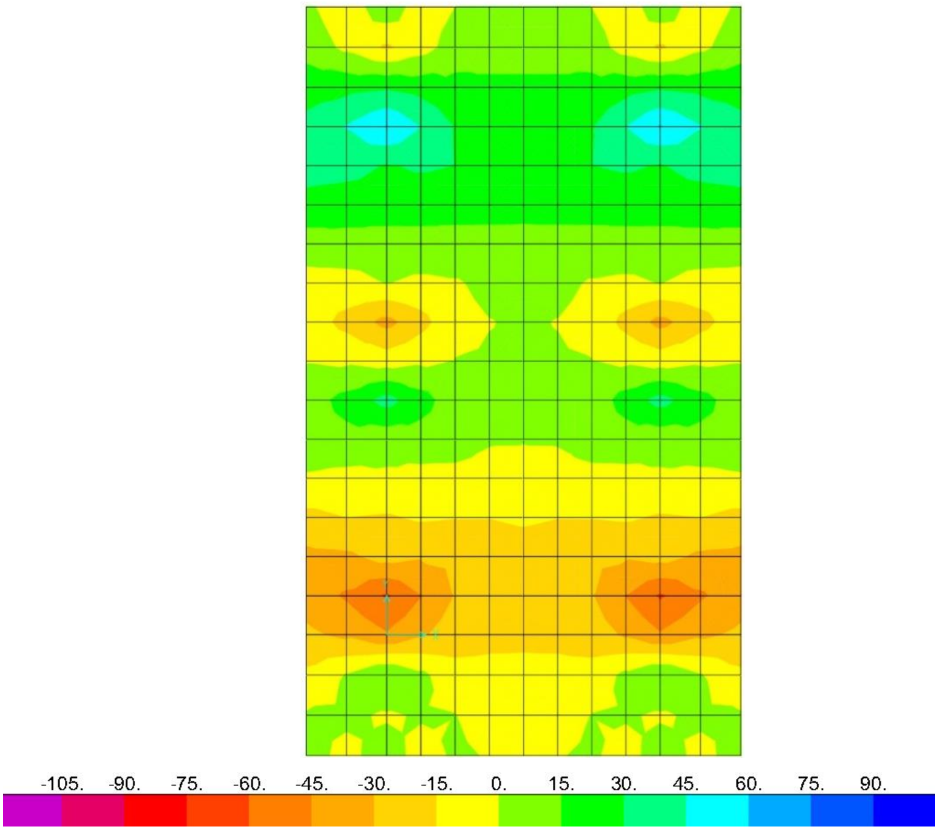

Figure 7 bending moment contour in the Y-direction (M22) under load combination CON-07 ($ton.m/m$).

Conclusion

Considering the results obtained from the analysis of the new oil terminal dolphins in Bandar Anzali, the stress ratios of all piles remain within the allowable range. The maximum structural displacement after loading is 6.4 centimeters along the X-axis and 3.7 centimeters along the Y-axis, both of which are significantly below the permissible limits. Given the limited number of piles, the required penetration depth of the piles should be determined to withstand the maximum tensile and compressive forces obtained under different loading conditions.

The results from the analysis under ultimate limit state load combinations in Table 7 are presented for the concrete beam's Mx and My directions. According to these findings, the maximum positive and negative bending moments in the X and Y directions are 71 and 112 ton-meters per meter, respectively, which serve as the design criteria.

Compliance with ethical standards

Acknowledgment

The authors would like to acknowledge the support and resources provided during the research and writing of this article. We are grateful for the contributions of all individuals who have helped and supported us throughout this project.

Disclosure of conflict of interest

The authors declare no conflicts of interest.

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