Structural Performance of Breasting Dolphin Under Berthing Load Variations

Oryza Lhara Sari[1*], Basyaruddin[2], Alvin[3], Lorddy Zefanya Nugroho[4]
(Received: 9 June 2026 / Revised: 12 June 2026 / Accepted: 27 June 2026 / Available Online: 1 September 2026)

***Abstract*—** Breasting dolphins are critical marine structures that transfer vessel impact loads to the jetty system during berthing operations. In several existing terminals, increasing operational demands may necessitate the accommodation of vessels larger than the original design vessel, provided that water depth and terminal functionality permit such operation. However, operational feasibility cannot be evaluated solely based on navigational clearance, as berthing velocity, fender reaction, pile stiffness, and soil–pile interaction may significantly influence structural demand. The objective of this study is to evaluate whether an existing breasting dolphin originally designed for a 6,000 DWT vessel can safely accommodate larger vessels up to 10,000 DWT under varying berthing velocity conditions. Four vessel capacities, namely 7,000, 8,000, 9,000, and 10,000 DWT, and five berthing velocity conditions were assessed using a three-dimensional structural model. Additional permanent loads, fender and bollard loads, and soil support modeled using spring element were included. Structural acceptability was assessed based on the occurrence of plastic member behavior and axial force–biaxial bending interaction criteria. The results indicate that only two scenarios remained fully elastic: 7,000 DWT at 0.108 m/s and 8,000 DWT at 0.103 m/s. All other applicable scenarios exhibited plastic member behavior, with critical interaction utilization under difficult sheltered berthing ranging from 3.392 to 3.706. These findings highlight that operational approval for larger vessels should be controlled by berthing velocity and verified structural capacity, rather than by water depth alone.

Keywords—berthing load; breasting dolphin; existing structure; pile-supported jetty; structural capacity; vessel velocity

**Corresponding Author: oryza@lecturer.itk.ac.id*

I. INTRODUCTION

Breasting dolphins serve as the primary interface between an approaching vessel and a jetty or terminal structure. Their main function is to absorb berthing impact energy through the fender system and transfer the resulting forces to the piles, pile caps, and surrounding soil. In marine terminals, particularly oil and gas shore-base facilities, the structural reliability of breathing dolphins is critically important because localized structural damage may disrupt berthing operations and reduce the operational capacity of the terminal. Previous studies have demonstrated that berthing velocity and berthing load are highly uncertain operational parameters, and that design assumptions based on historical vessel data may not adequately represent current berthing conditions [1], [2]. Consequently, the assessment of existing berthing structures requires a comprehensive evaluation that explicitly relates vessel characteristics, approach velocity, fender reaction, and structural response [3], [4].

The structural performance of an existing breasting dolphin becomes increasingly critical when operational demands exceed the original design assumptions. Although a port facility may still have sufficient water depth to accommodate a larger vessel, this does not necessarily imply that the breasting dolphin has adequate structural capacity to safely resist the associated berthing loads. Berthing energy and impact force increase with vessel mass and, more significantly, with the square of the vessel approach velocity [1], [5]. Consequently, even a relatively small increase in berthing velocity may produce a substantial increase in structural demand. This issue is particularly important in terminals where environmental and operational factors, such as currents, tugboat maneuverability, human factors, and equipment limitations, influence the actual berthing velocity during operation [6], [7]. Therefore, the engineering assessment of existing berthing structures should not be bassed solely on vessel deadweight tonnage (DWT), but should also incorporate variations in berthing velocity and their corresponding effects on structural response and member performance.

Previous studies have extensively investigated the factors influencing berthing energy and structural response in marine facilities. Roubos et al. [1], [2] demonstrated that berthing velocity is one of the most uncertain and influential parameters governing berthing loads, highlighting the importance of considering actual operational conditions rather than relying solely on design assumptions. Design guidelines such as PIANC [8] and OCDI [9] similarly recognize vessel approach velocity as a key factor affecting berthing energy and fender performance.

Research has also focused on the interaction between breasting dolphins and fender systems. Carbonari et al. [3] proposed a performance-based approach for coupled

Oryza Lhara Sari Department of Civil Engineering, Kalimantan Institute of Technology, Balikpapan, East Kalimantan 76127, Indonesia. E-mail: oryza@lecturer.itk.ac.id

Basyaruddin Department of Civil Engineering, Kalimantan Institute of Technology, Balikpapan, East Kalimantan 76127, Indonesia. E-mail: basyaruddin@lecturer.itk.ac.id

Alvin Department of Civil Engineering, Kalimantan Institute of Technology, Balikpapan, East Kalimantan 76127, Indonesia.. E-mail: oryza@lecturer.itk.ac.id

Lorddy Zefanya Nugroho Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei 10607, Taiwan. Universidad Politécnica Taiwán Paraguay (UPTP), Asunción Paraguay. E-mail: lorddynugroho@mail.ntust.edu.tw

dolphin-fender systems, while Magda [4] demonstrated that explicit consideration of elastic fender-dolphin interaction can significantly influence force distribution and structural demand. These studies improved the understanding of load transfer mechanisms and contributed to more efficient marine structure design.

In addition, numerous studies have examined ship impact behavior, pile-supported marine structures, and soil-structure interaction effects [10]-[12]. Fan and Yuan [11] and Wang and Morgenthal [12] demonstrated that the response of pile-supported marine structures subjected to ship impact is strongly influenced by structural configuration, foundation stability, and soil-structure interaction. More recently, Zeng et al. [5] optimized ship berthing methods for high-pile wharves using surrogate models, whereas Lee et al. [6] developed a machine-learning-based framework to predict unsafe berthing velocity and improve operational safety. Although these studies provide valuable insights into berthing mechanics, structural response, and operational management, they primarily focus on design optimization, impact analysis, or operational safety assessment rather than evaluating the structural acceptability of existing breasting dolphins under increased operational demands.

Although previous studies have investigated berthing energy, fender-dolphin interaction, ship impact, and soil-structure interaction, limited attention has been given to evaluate existing breasting dolphins when operational demands exceed the original design vessel capacity [3]-[17]. In practice, larger vessels may be permitted based on available water depth, while the structural adequacy of the breasting dolphin remains uncertain. The novelty of this study lies in integrating vessel size, berthing velocity, structural response, plastic member occurrence, and axial force-biaxial bending interaction into a single assessment framework. The proposed approach provides practical guidance for determining the operational acceptability of existing marine structures.

This study addresses this gap by evaluating the structural performance of an existing breasting dolphin at an oil and gas shore-base jetty under varying berthing load conditions. The original design vessel capacity of the structure was 6,000 DWT, whereas current operational requirements necessitate assessment for vessels up to 10,000 DWT. The objective of this study is to identify acceptable berthing scenarios based on structural response, occurrence of plastic members, and axial force-biaxial bending interaction criteria. In contrast to the companion risk-oriented investigation, the present study focuses solely on structural capacity and operational acceptability. The findings are intended to provide a rational basis for determining whether larger vessels can be accommodated safely under specific berthing velocity conditions and to support operational decision-making for existing marine terminal facilities.

II. Method

A. Case Structure and Data Input

The object of this study is an existing breasting dolphin located at a jetty serving oil and gas shore-base operations. The structural model was developed based on the as-built configuration of the breasting dolphin and consists of a pile-supported platform with fender and bollard systems. The analysis incorporated the self-weight of the structure, superimposed dead loads, fender loads, bollard loads, and vessel berthing loads.

Soil resistance along the embedded pile length was represented using spring supports, as the lateral behavior of piles is strongly influenced by soil stiffness, pile embedment depth, and nonlinear soil-pile interaction effects [18]-[22]. This simplified modeling approach is commonly used in practical structural assessment when detailed continuum-based soil modelling is unavailable, while pile-soil flexibility still needs to be adequately represented in the structural response analysis. In addition, offshore geotechnical design guidelines emphasize that foundation flexibility should be considered in the evaluation of pile-supported marine structures [19].

The modelling procedure consisted of four stages: (1) defining the structural geometry and support conditions; (2) applying permanent and operational loads; (3) calculating berthing load scenarios based on vessel size and approach velocity; and (4) evaluating the structural response for each load condition. An ultimate limit state (ULS) approach was adopted to identify member demand under the governing load combinations.

Structural demand was evaluated in terms of axial force and biaxial bending moment acting on the critical piles above and near the seabed level. These locations were identified as critical because lateral berthing loads generate significant combined axial-bending actions that may induce plastic behavior in pile members. This response mechanism is consistent with findings reported in previous studies on laterally loaded and impact-loaded pile-supported marine structures [11], [12], [18], [20], [23].

TABLE 1.
ADDITIONAL LOADS APPLIED TO THE STRUCTURAL MODEL

Load component	Load type	Value	Unit
Additional dead load (SIDL)	Area load	501.93	kg/m²
Bollard	Joint load	212	kg
Fender	Joint load	1,343	kg

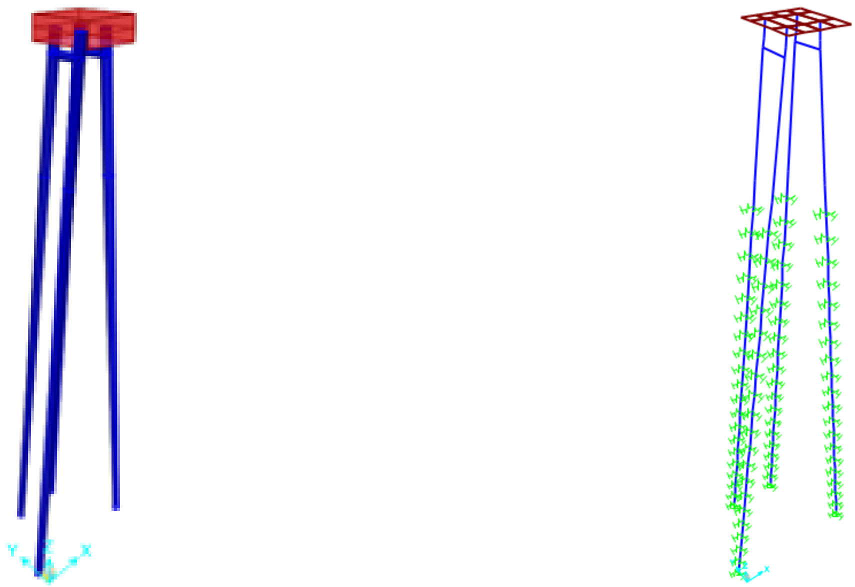

Figure. 1. Breasting dolphin structural model: extruded view and standard view.

B. Berthing Load Scenarios

The berthing load scenarios were developed based on four vessel capacities and five vessel approach velocity conditions. The vessel capacities considered in this study were 7,000, 8,000, 9,000 and 10,000 DWT. The approach velocity conditions were classified as good sheltered, difficult sheltered, easy exposed, good exposed, and difficult exposed conditions. These classifications follow established fender-system and port-design guidelines, in which environmental exposure, operational control, and berthing conditions influence the design berthing velocity [1], [2], [22], [23]. Recent studies have further emphasized that measured or predicted berthing velocity is a critical safety parameter in terminal operations and should therefore be verified against the original design assumptions [5], [6], [24]. For each scenario, the calculated berthing load was applied individually to the structural model. Scenarios tdeemed inapplicable due to geometric limitations or operational constraints were excluded from the analysis. The berthing load was modeled as a lateral impact action transferred through the fender contact point. This approach is consistent with common marine structural assessment practice, in which berthing energy is first converted into fender reaction force or an equivalent lateral berthing load prior to evaluating the structural performance of the supporting members [3], [4], [22], [25]. Table 2 presents the berthing load scenarios considered in the present study.

TABLE 2.
BERTHING VELOCITY AND LOAD SCENARIOS

Vessel capacity	Condition (a)	Condition (b)	Condition (c)	Condition (d)	Condition (e)
7,000 DWT	0.108 m/s; 55.25 ton	0.218 m/s; 226.77 ton	0.326 m/s; 505.27 ton	0.426 m/s; 863.60 ton	0.514 m/s; 1,256.07 ton
8,000 DWT	0.103 m/s; 57.36 ton	0.210 m/s; 236.61 ton	0.313 m/s; 527.65 ton	0.410 m/s; 904.48 ton	0.492 m/s; 1,303.73 ton
9,000 DWT	–	0.201 m/s; 243.42 ton	0.300 m/s; 543.35 ton	0.393 m/s; 934.34 ton	0.470 m/s; 1,333.62 ton
10,000 DWT	–	0.192 m/s; 246.62 ton	0.287 m/s; 551.06 ton	0.377 m/s; 950.86 ton	0.448 m/s; 1,342.73 ton

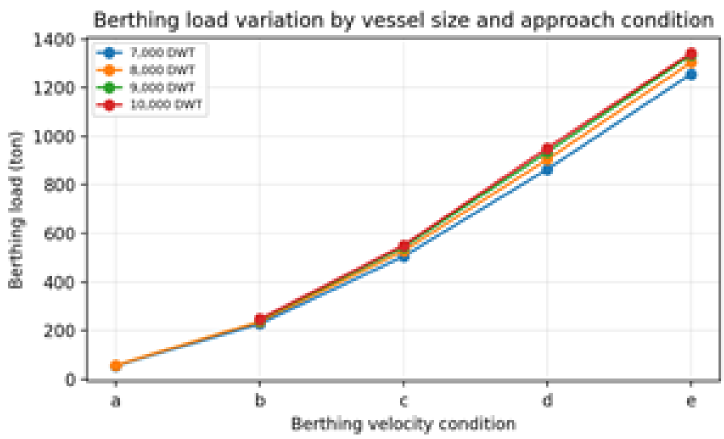

Figure. 2. Berthing load variation for each vessel size and velocity condition

C. *Structural Performance Criteria*

The structural response was evaluated based on two performance criteria. The first criterion was the occurrence of plastic behavior in the structural members obtained from the analysis results. A berthing scenario was considered operationally acceptable only when all structural member remained within the elastic range and no plastic member behavior was observed. The second criterion was the axial force-biaxial bending interaction of the critical pile members. This interaction assessment is important because breasting dolphin piles are subjected not only to bending moments, but also to combined axial force, major-axis bending, and minor-axis bending resulting from eccentric berthing loads and overall frame action [10], [11], [14], [20]. The interaction equation used in this study is presented in Eq. (1).

$$1 - \cos[(\pi/2)(P/P_n)] + \sqrt{(M_y^2 + M_z^2)}/M_n \le 1.0 \quad (1)$$

where P is the axial force, M_y and M_z are bending moments about the local axes, P_n is nominal axial capacity, and M_n is nominal bending capacity. The locations of the critical structural members are illustrated in Figure 3. This interaction framework has been widely used in structural capacity assessment, as it enables the simultaneous consideration of axial and flexural demands, rather than treating them independently [14], [20], [23], [26].

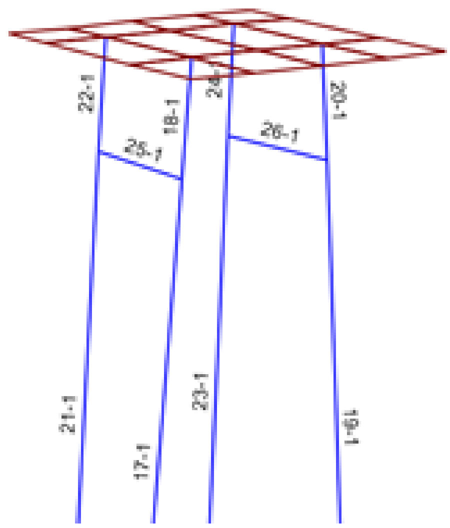

Figure. 3. Critical pile members evaluated using axial force-biaxial bending interaction.

III. Results and Discussion

A. *Berthing Load Response*

The berthing load exhibited a nonlinear increase with respect to the approach velocity. For the 7,000 DWT vessel, the berthing load increased from 55.25 ton in condition (a) to 1,256.07 ton in condition (e). For the 8,000 DWT vessel, the corresponding increased ranged from 57.36 ton to 1,303.73 ton. For the 9,000 and 10,000 DWT vessels, the applicable load values under conditions (b) to (e) ranged from 243.42 ton to 1,333.62 ton and from 246.62 ton to 1,342.73 ton, respectively. This trend confirms that berthing velocity is the dominant factor governing the escalation of berthing demand, as berthing energy is strongly velocity-dependent [1], [2], [8].

The sharp increase from condition (b) to conditions (c), (d) and (e) highlights the critical importance of controlling berthing velocity during vessel approach. This result is consistent with established design literature, which identifies berthing velocity as one of the most sensitive parameters governing berthing energy and the resulting structural demand [1], [2]. It also aligns with recent operational studies that employ measured berthing velocities, predictive models, and optimization techniques to improve berthing safety [5], [6], [24]. Accordingly, operational control measures such as tug assistance, berthing aid systems, continuous velocity monitoring, and regulated approach procedures are directly relevant to ensuring the structural safety of existing breasting dolphins [1], [6], [27].

The findings also demonstrate that berthing velocity has a greater influence on structural demand than vessel size alone. While vessel deadweight tonnage contributes to the berthing energy, the velocity-squared relationship causes relatively small increases in approach velocity to generate disproportionately larger impact loads. This explains why structural acceptability is highly sensitive to operational berthing conditions and highlights the importance of velocity control as an effective risk mitigation measure for existing marine facilities.

B. Plastic Member Occurrence

Table 3 summarizes the structural performance results for all analyzed scenarios. Only two scenarios remained fully elastic: 7,000 DWT vessel under velocity condition (a) and the 8,000 DWT vessel under velocity condition (a). These conditions correspond to berthing velocities of 0.108 m/s and 0.103 m/s, respectively. Under these scenarios, the corresponding berthing loads of 55.25 ton and 57.36 ton did not induce plastic member behavior in the structural model.

This result indicates that the existing breasting dolphin retains limited reserve capacity for operational expansion, provided that vessel approach occurs under good sheltered conditions and that berthing velocity is adequately controlled.

All other analyzed scenarios exhibited plastic behavior in one or more structural members. The initiation of plasticity was already observed under condition (b) for all vessel sizes ranging from 7,000 to 10,000 DWT. Conditions (c), (d) and (e) resulted in progressively more extensive plastic behavior due to the significantly higher associated berthing loads.

The concentration of critical response in the lower pile region is consistent with the expected behavior of laterally loaded pile systems, where maximum bending moments typically develop near or below the seabed, depending on pile stiffness, soil support conditions, and load eccentricity [11], [12], [18], [21]. These findings confirm that the structural limit state is governed by member-level response and soil-pile interaction effects, rather than by vessel size alone.

A notable finding of this study is that plastic member behavior was initiated under the difficult sheltered condition for all analyzed vessel sizes. This suggests that the structural capacity threshold of the existing dolphin is reached at relatively moderate increases in berthing demand. From an operational perspective, the results indicate that the reserve capacity of the structure is limited and that future increases in vessel traffic should be accompanied by detailed structural verification.

TABLE 3
PLASTIC MEMBER OCCURRENCE FOR DIFFERENT VESSEL CAPACITIES AND BERTHING CONDITIONS

Vessel capacity	Condition (a)	Condition (b)	Condition (c)	Condition (d)	Condition (e)
7,000 DWT	No plastic member	Plastic members occur	Plastic members occur	Plastic members occur	Plastic members occur
8,000 DWT	No plastic member	Plastic members occur	Plastic members occur	Plastic members occur	Plastic members occur
9,000 DWT	Not analyzed	Plastic members occur	Plastic members occur	Plastic members occur	Plastic members occur
10,000 DWT	Not analyzed	Plastic members occur	Plastic members occur	Plastic members occur	Plastic members occur

C. Critical Member Interaction

The interaction evaluation further supports the plastic member-based interpretation. For the difficult sheltered condition, the maximum interaction utilization index ranged from 3.392 for 7,000 DWT vessel to 3.706 for 10,000 DWT vessel. As all values exceed unity, the interaction check indicates that the critical pile members are not acceptable under condition (b) without either structural strengthening or operational restrictions. The use of axial force-biaxial bending interaction provides a more rigorous engineering assessment than relying solely on plasticity indicators, as it quantifies the combined demand acting on critical members [10], [14], [20], [23].

Although the condition (b) berthing loads differ only moderately across vessel sizes, the utilization index increases with increasing vessel capacity. This trend suggests that structural sensitivity is controlled by both load magnitude and load distribution within the structural system. This observation is consistent with previous studies on ship impact and berthing behavior, which have shown that pile-supported marine structures are governed by the coupled interaction of vessel impact, fender response, structural flexibility, and soil-structure interaction [3], [4], [11], [12], [25]. For existing terminals, this implies that increases in vessel size require a full structural reassessment rather than a simple comparison between vessel DWT and available water depth.

From a structural management perspective, the interaction results indicate that difficult sheltered berthing condition should not be accepted for the evaluated structure without implementing additional engineering measures. Potential mitigation strategies include limiting allowable berthing velocity, improving tugboat assistance, applying berthing aid systems, increasing fender energy absorption, strengthening critical piles, or conducting more detailed nonlinear analysis. These approaches are consistent with established marine facility design and assessment practice, where operational control and structural upgrading are jointly applied to ensure acceptable performance [1], [3], [4], [8], [27].

TABLE 4.
CRITICAL INTERACTION UTILIZATION FOR CONDITION B

Scenario	Minimum U	Maximum U	Interpretation
7,000 DWT-b	3.298	3.392	Exceeds limit
8,000 DWT-b	3.450	3.547	Exceeds limit
9,000 DWT-b	3.319	3.655	Exceeds limit
10,000 DWT-b	3.365	3.706	Exceeds limit

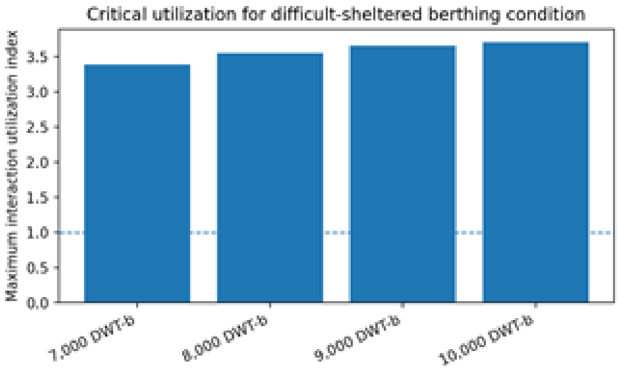

Figure. 4. Maximum interaction utilization index for difficult sheltered berthing condition.

D. Operational Implications

The main practical implication of this study is that the existing breasting dolphin can only be considered structurally acceptable for the two elastic scenarios identified, namely the 7,000 DWT vessel at 0.108 m/s and the 8,000 DWT vessel at 0.103 m/s. The 9,000 and 10,000 DWT scenarios did not satisfy the elastic performance criterion under the applicable velocity conditions. This does not imply that larger vessels cannot be accommodated under any circumstance; rather, it indicates that the current structural configuration is not suitable for such operations without imposing operational restrictions, implementing structural strengthening, or conducting further detailed verification. These findings are consistent with the broader understanding that life extension or operational modification of existing marine structures must be supported by updated load assessment and structural capacity assessment [1], [13], [15], [16].

The results are significant because port accessibility based on water depth alone does not guarantee structural adequacy. Operational approval must therefore be based on a combined assessment of vessel size, berthing velocity, fender system performance, and structural member capacity. In the present case, the most immediate and practical control measure is to limit the approach velocity to the identified elastic scenarios. If operations beyond these limits are required, more advanced nonlinear modelling analysis, site-specific soil parameter calibration, fender performance verification, and condition assessment of existing members should be conducted [3], [11], [18], [22], [27].

The results are significant because port accessibility based on water depth alone does not guarantee structural adequacy. Operational approval must therefore be based on a combined assessment of vessel size, berthing velocity, fender system performance, and structural member capacity. In the present case, the most immediate and practical control measure is to limit the approach velocity to the identified elastic scenarios. If operations beyond these limits are required, more advanced nonlinear modelling analysis, site-specific soil parameter calibration, fender performance verification, and condition assessment of existing members should be conducted [3], [11], [18], [22], [27].

IV. CONCLUSION

This study investigated the structural performance of an existing breasting dolphin subjected to varying vessel berthing load conditions. Four vessel sizes ranging from 7,000 to 10,000 DWT and five berthing velocity conditions were analyzed using a structural model incorporating permanent loads, fender and bollard loads, berthing loads, and spring-based soil support.

The results indicate that only two berthing scenarios remained fully elastic: the 7,000 DWT vessel at 0.108 m/s and the 8,000 DWT vessel at 0.103 m/s. These scenarios may be considered structurally acceptable for the evaluated dolphin under the modeling assumptions used in this study. Therefore, the objective of identifying acceptable berthing scenarios based on structural response, plastic member occurrence, and axial force-biaxial bending interaction criteria was successfully achieved.

All other scenarios exhibited plastic member behavior, including all applicable vessel sizes under the difficult sheltered condition. For condition (b), the axial force-biaxial bending interaction utilization exceeded unity for all vessel sizes, ranging from 3.392 to 3.706. The results demonstrate that berthing velocity is more critical parameter than vessel deadweight tonnage in determining the structural acceptability of the existing dolphin. This finding confirms that operational decisions should be based not only on vessel size and water depth, but also on the structural response associated with actual berthing conditions.

It is therefore recommended that terminal operations be limited to the identified elastic scenarios unless structural strengthening, improved fender performance, or more detailed nonlinear verification is conducted. Future work should integrate site-specific geotechnical investigation, measured berthing velocity data, experimental or calibrated fender performance models, and probabilistic approaches to support long-term operational decision-making for existing marine infrastructure.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the project stakeholders who provided technical information for the breasting dolphin case study.

REFERENCES

[1] A. Roubos, D. J. Peters, L. Groenewegen, and R. Steenbergen, "Partial safety factors for berthing velocity and loads on marine structures," Marine Structures, vol. 58, pp. 73-91, 2018, doi: 10.1016/j.marstruc.2018.01.001.

[2] A. Roubos, L. Groenewegen, and D. J. Peters, "Berthing velocity of large seagoing vessels in the Port of Rotterdam," Marine Structures, vol. 51, pp. 202-219, 2017, doi: 10.1016/j.marstruc.2016.10.011.

[3] S. Carbonari, G. Antolloni, F. Gara, C. Lorenzoni, and A. Mancinelli, "A performance-based approach for the design of coupled dolphin-fender berthing structures," Marine Structures, vol. 64, pp. 78-99, 2019, doi: 10.1016/j.marstruc.2018.10.013.

[4] W. Magda, "Elastic fender-dolphin interaction for economic design of berthing dolphins," Journal of Waterway, Port, Coastal, and Ocean Engineering, vol. 145, no. 5, 2019, doi: 10.1061/(ASCE)WW.1943-5460.0000511.

[5] H. Zeng, R. Zhu, Q. Wang, J. Zheng, and J. Zou, "Framework and application of ship berthing methods optimization in high-pile wharf based on surrogate models," Ocean Engineering, vol. 300, p. 117420, 2024, doi: 10.1016/j.oceaneng.2024.117420.

[6] H. T. Lee, S. W. Lee, and H. J. Park, "Development of machine learning strategy for predicting the risk range of ship's berthing velocity," Journal of Marine Science and Engineering, vol. 8, no. 5, p. 376, 2020, doi: 10.3390/jmse8050376.

[7] M. H. A. Altun and S. Kum, "Safety indications of navigation audit for tankers to develop a bridge inspection method," Journal of ETA Maritime Science, vol. 7, no. 1, pp. 1-13, 2019.

[8] PIANC, Guidelines for the Design of Fender Systems: 2002. Brussels, Belgium: International Navigation Association, 2002.

[9] Overseas Coastal Area Development Institute of Japan (OCDI), Technical Standards and Commentaries for Port and Harbour Facilities in Japan, Tokyo, Japan: Overseas Coastal Area Development Institute of Japan, 2009.

[10] H. Shao and J. Lee, "Optimal pile design of dolphin structure considering axial compressive pressure-bending moment ratio under offshore load conditions," Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, vol. 233, no. 4, pp. 1100-1112, 2019.

[11] W. Fan and W. C. Yuan, "Numerical simulation and analytical modeling of pile-supported structures subjected to ship collisions including soil-structure interaction," Ocean Engineering, vol. 91, pp. 11-27, 2014, doi: 10.1016/j.oceaneng.2014.08.011.

[12] W. Wang and G. Morgenthal, "Parametric studies of pile-supported protective structures subjected to barge impact using simplified models," Marine Structures, vol. 63, pp. 138-152, 2019.

[13] F. Guede, "Risk-based structural integrity management for offshore jacket platforms," Marine Structures, vol. 63, pp. 444-461, 2019.

[14] W. Lopes, M. Moura, C. Viegas, and M. Real, "Analysis of a dolphin by analogy of grid, finite element method with plate element and equivalent frame method," Research on Engineering Structures and Materials, vol. 5, no. 4, pp. 427-436, 2019.

[15] J. R. Tawekal and R. L. Tawekal, "Risk reliability-based underwater inspection method for jacket platforms in Indonesia," International Journal of Structural Integrity, vol. 9, no. 5, pp. 603-615, 2018.

[16] N. M. Parra, A. Nagi, and W. Kersten, "Risk assessment methods in seaports: A literature review," Transportation Research Procedia, vol. 30, pp. 223-232, 2018.

[17] A. Bouzaher, L. Bahmed, F. Masao, and M. Fedila, "Designing a risk assessment matrix for Algerian port operations," Journal of Failure Analysis and Prevention, vol. 15, no. 6, pp. 860-867, 2015.

[18] L. C. Reese, W. M. Isenhower, and S. T. Wang, Analysis and Design of Shallow and Deep Foundations. Hoboken, NJ, USA: John Wiley & Sons, 2006.

[19] M. F. Randolph and S. Gourvenec, Offshore Geotechnical Engineering. Boca Raton, FL, USA: CRC Press, 2011.

[20] J. Propika, L. L. Lestari, and A. D. Puspasari, "Lateral bearing capacity analysis of pile foundation using a spring modelling system," IOP Conference Series: Materials Science and Engineering, vol. 1010, p. 012034, 2021.

[21] O. Taheri, R. Z. Moayed, and M. Nozari, "Lateral soil-pile stiffness subjected to vertical and lateral loading," Journal of Geotechnical and Transportation Engineering, vol. 1, no. 2, pp. 30-37, 2015.

[22] L. C. Reese and W. F. Van Impe, Single Piles and Pile Groups Under Lateral Loading, 2nd ed. Leiden, Netherlands: CRC Press/Balkema, 2011.

[23] API, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design, API Recommended Practice 2A-WSD, 22nd ed. Washington, DC, USA: American Petroleum Institute, 2014.

[24] H. Lee, S. Lee, and Y. Park, "Analysis of feature importance of ship's berthing velocity using classification models," Journal of the Korean Society of Marine Environment & Safety, vol. 26, no. 2, pp. 139-148, 2020.

[25] DNV, Environmental Conditions and Environmental Loads, Recommended Practice DNV-RP-C205. Oslo, Norway: Det Norske Veritas, 2019.

[26] AISC, Specification for Structural Steel Buildings, ANSI/AISC 360-16. Chicago, IL, USA: American Institute of Steel Construction, 2016.

[27] G. Gaythwaite, Design of Marine Facilities for the Berthing, Mooring, and Repair of Vessels, 3rd ed. Reston, VA, USA: ASCE Press, 2016.