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Integration of Structural Resilience, Loading Conditions, and Cost-Effectiveness in Optimizing pile-supported Quay Design

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Abstract: The article presents a comprehensive investigation into the design intricacies of quays in coastal regions, with a specific focus on open-type and closed-type quay structures. The study acknowledges the strategic importance of ports in such areas and their vulnerability to seismic and hydrodynamic forces. By synthesizing insights from diverse research endeavors related to the seismic behavior of wharves, the article elucidates the methodologies employed to assess stability and performance. The research is centered around Chamkhaleh Port and underscores the significance of innovative design strategies, especially in light of the vulnerabilities observed at the nearby Bandar Anzali port. The article meticulously analyzes design considerations, load distribution mechanisms, and cost-efficiency aspects, particularly in relation to pile diameters and lengths. The findings highlight the necessity of tailored design approaches to ensure the structural robustness of quays and to mitigate risks arising from various forces. The research not only offers valuable insights to engineers and stakeholders engaged in port infrastructure development but also advocates for safety, sustainability, and cost-effectiveness in the realm of port design and construction.

Keywords: component; Pile supported quay; Numerical analysis; Numerical analysis; Optimization.

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1. INTRODUCTION

Coastal areas frequently host significant and strategic infrastructures, such as ports and facilities for industrial or tourist activities. Meanwhile, a considerable number of ports around the world are situated in regions susceptible to seismic and tsunami events, compounding the risk due to two intertwined factors: the pivotal societal function served by these ports and their vulnerability to natural hazards. Effective structural design plays a pivotal role in minimizing vulnerability and, by extension, reducing risk.

Numerous studies have been dedicated to examining the seismic behavior of wharves. For instance, Dodds et al. (2004)(Dodds et al., 2004) utilized elastic-perfectly plastic models to assess the seismic stability of the Kings Wharf in Suva, Fiji, incorporating site soil materials and piles. Similarly, Smith et al. (2004)(Smith et al., 2004) adopted a comparable modeling approach to evaluate a novel design for a wharf at the Port of Vancouver in British Columbia. Another illustrative instance involves the work of Roth et al. (2003)(Roth et al., 2003), who modeled several wharves along the West Coast of the United States. Their model integrated elastic perfectly plastic soil models and elastoplastic beam elements that could develop plastic hinges at predetermined locations. Similarly, Na et al. (2009)(Na et al., 2009) followed a similar modeling procedure to formulate fragility curves, characterizing the response of a typical pile-supported marginal wharf structure to ground motions generated under the SAC Project (FEMA 2000)(FEMA, 2000), which was a collaborative effort involving the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the Consortium of Universities for Research in Earthquake Engineering (CUREE). Lastly, Donahue et al. (2005)(Donahue et al., 2005) investigated the seismic performance of the wharf structure at Berth 24/25 of the Port of Oakland during the 1989 Loma Prieta earthquake. Shafieezadeh et al.(Shafieezadeh et al., 2012) investigated the modal properties and vulnerability of such structures by using advanced structural and soil modeling procedures to perform two-dimensional nonlinear plane-strain seismic analyses using time histories of ground displacement and excess pore water pressures within the underlying soil embankment.

Quays establish a logical and coherent connection between the maritime and terrestrial sectors, selected and designed based on their utilization type, whether it's for cargo, passengers, or other various parameters. Apart from the quay's placement within the port, quay types can be divided into two categories, vertical face and open. (PIANC, 2001)

In open-type quays, the quay deck surface extends over the water with a forward slope. Water flows beneath it, and the deck surface transfers the loads from the upper superstructure elements to the load-bearing ground sections located in the depth. Generally, the quay's front edge should maintain a sufficient distance from the ground level to ensure adequate depth for vessel berthing. As a result, the decks are extended to the appropriate depth, or the quay's foundation is lowered to achieve the required depth. Since these quays advance further into the water, facing challenges from dryness and stable or sometimes unstable slopes, necessary measures should be considered to stabilize the shoreline slope, especially when sedimentation and periodic dredging are concerns during the quay's operation. (PIANC, 2001)

Another aspect of designing open-type quays is ensuring their structural integrity against various loads. According to valid maritime regulations, the structural elements of the quay must withstand loading scenarios such as dead loads, live loads, seismic loads, equipment and machinery loads, as well as forces generated by vessel berthing and mooring, including forces from fenders and bollards. The operational surface of the quay should not be jeopardized. Particularly significant for open-type quays is their lateral stiffness against horizontal forces resulting from fenders, bollards, and earthquakes, as lateral loads are generally resisted by bending frames or diagonal structural elements. Therefore, structural modeling and analysis of the quay must accurately assess the lateral load-bearing capacity of deep foundations (piles) from the perspective of soil as well. In some cases, due to inadequate soil-bearing capacity, the construction of such quays might not be justified.

Another aspect related to these quays is their construction method. If open-type quays are initiated from the seaward side, employing barges, cranes, and pile drivers, the construction costs will significantly increase. Starting from the land side, the construction method is different. Seaward progress depends on installing piles, constructing the slab and beams, and ensuring that cranes and pile drivers can move forward onto the initially built deck. Therefore, the decision to construct such quays is generally made by considering all factors and their mutual impacts on the execution of the work. (PIANC, 2001)

2. STUDY AREA

This research centers on the Chamkhaleh Port, located in the southwestern quadrant of the Caspian Sea at coordinates 37.2155 degrees latitude and 50.2769 degrees longitude. Notably, the port features two rubble mound breakwaters, strategically positioned at the outlets of the Shalmanrood and Langaroud rivers, measuring approximately 530 meters and 430 meters in length, respectively. Since the construction of these breakwaters, significant sedimentation has occurred in the northern and southern parts, resulting in a considerable reduction of available water space to 190 meters and 130 meters for the northern and southern breakwaters, respectively. The sedimentation margin spans about 2 to 3 kilometers with a maximum width of 420 meters and a minimum of 80 meters.

Considering the planned capacity of one million tons and the current efficiency of the existing quays in Chamkhaleh, in this phase, the design and initial estimation have been conducted for one multipurpose service quay post and one developmental service quay post. Additionally, plans been outlined for another service quay post for fuel, a recreational quay post, and another multipurpose quay post.

in a recent study, Joushideh et al. (Joushideh, Majidi, et al., 2023) highlighted that the Bandar Anzali port is at risk of sinking and collapsing. They stress the need for new and creative designs to address this serious problem. Considering the close proximity of Bandar Anzali to Chamkhale, it's important to note that a similar situation could apply to Chamkhale as well. Therefore, when designing, it's crucial to take this into account.

3. QUAY LENGTH

The length of the quay is contingent upon vessel size, potential variations in the specifications of berthing vessels over the operational life of the quay, and the composition of berthing vessels (within port complexes). The designed vessel for Chamkhaleh Port is 140 meters in length, and 17 meters in width, with a required draft of 6.4 meters, accommodating a maximum of 15% annual inbound traffic. Subsequent vessel sizes, considering 85% of annual inbound traffic, are equal to or smaller than 120 meters.

As the allowable distance for berthing vessels is influenced by vessel size, in PIANC for larger vessels, the quay length corresponds to the length of the largest vessel plus an additional 30 to 40 meters to accommodate mooring, thus a 150-meter quay has been designated as suitable for a 120-meter vessel (Pianc, 2002).

The length of the mooring structure in contact with the vessel is contingent upon cargo type and loading/unloading methods. Depending on the cargo type (such as iron and timber, currently being unloaded in Anzali), the unloading and loading equipment needs access to all cargo holds of the vessel. Therefore, the mooring structure's length in this study is equal to the vessel's length.

The proposed 510-meter quay length for the three 150-meter quay posts (for 120-meter vessels) is appropriate. Additionally, considering other combinations of the 140-meter designed vessel and smaller-sized vessels, as shown in Table 1, is viable.

Table 1- Possible Scenarios for Mooring Vessels Considering the Type and Length of the Vessel.

Quantity	Vessel Length	Quay Length	Final Summation
3	140	170	510
3	120	150	450
2 1	140 120	170 120	460

According to PIANC, the clear distance from the ship's stern to the quay edge for vessels with the maximum draft in calm conditions is generally taken as 5.0 meters downwards. However, additional values for bed leveling error, leaning, and wave-induced movement must also be added (Pianc, 2002). In Chamkhaleh, the same sea bed level of 5.5 meters has been considered for the quay fronts.

In the design of ports, operational considerations must be incorporated within the framework of a larger transportation network, of which the port is a component. Practical aspects of the port's operations, such as ship capacity, equipment and machinery capabilities for material handling, dimensions and extent of the relevant storage depots, and the type of land transportation network, collectively determine the optimal economic scenario for the designated complex.

A pivotal indicator in port design is the area of the operational space behind the quays, measured in square meters per meter of quay length. In past years, due to smaller vessel sizes and lower cargo discharge and loading tonnages, the area per meter of quay length for supporting facilities, including deck space, storage areas, and rail/road lines, has been approximately 50 square meters. In this context, to ensure access to the maximum berthing length of the quays, they have been constructed in a long and narrow manner, as depicted in Figure 1.

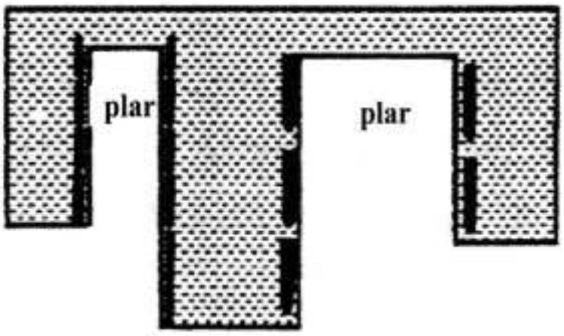

Figure 1. Modern quay designs emphasize a vertical alignment.

As ships grew larger and their cargo handling capacities and rates increased, the need for fewer berths and larger operational areas became more apparent. Consequently, the aforementioned indicator gradually increased from 100 square meters to 340 square meters per unit length of each quay. This shift was driven by the realization that a new fleet of ships twice the length could carry eight times the cargo capacity of an older vessel. As a result, in recent years, with the elimination of basins, all quays have been constructed in a linear arrangement, Figure 2. This configuration offers excellent operational efficiency and performance.

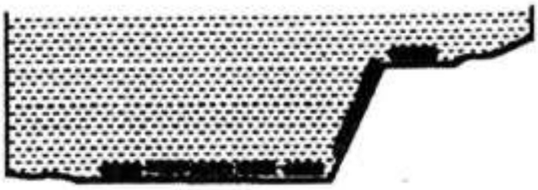

Figure 2. Quay layouts are designed to maximize operational areas.

4. HYDRODYNAMICAL CONDITION

In coastal regions, wind passing over the water surface generates shear stress due to air-water friction, leading to inclined water surfaces and elevated water levels near coastlines. Storm surges, including wind-induced run-up and wave generation, can cause significant damage. Understanding these hydrodynamic conditions is vital for coastal engineering projects.

To study the hydrodynamics of the Caspian Sea, Joushideh et al. (Joushideh, Shomal Zadeh, et al., 2023)adopted a comprehensive approach. They utilized hydrographic maps to create a bathymetric file with irregular triangular mesh representation, refining the grid for accuracy. Wind data was extrapolated across the sea to model wind-induced flows, and a calibrated hydrodynamic model was employed. The computational grid was designed to capture fine-scale flow characteristics. Time step stability and calibration coefficients were carefully chosen. By simulating wind-induced flows over 12 years, the researchers gained insights into water level fluctuations across the sea, focusing on specific coordinates. Maximum water level changes were found to be approximately 30 centimeters. Illustrated in Figure 3.

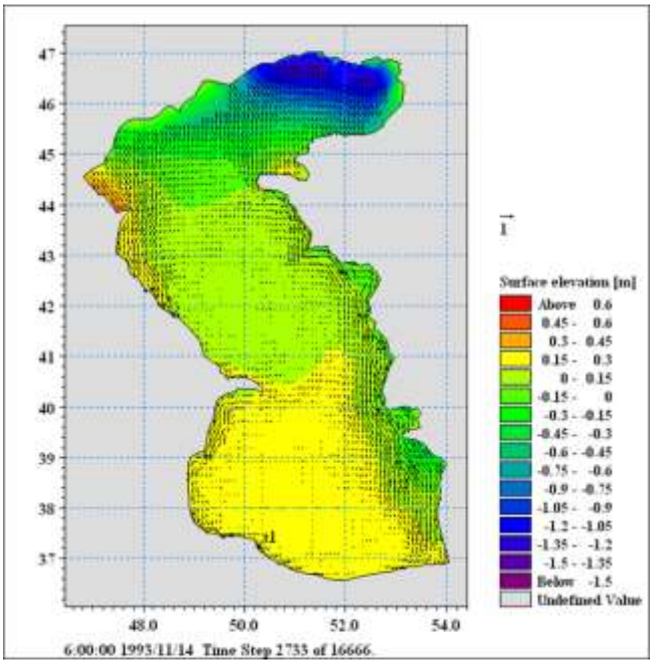

Figure 3. Water Level Fluctuations Across the Caspian Sea at a Specific Time.

Subsections Joushideh et al, also examined wind-induced flow rates, revealing predominant flow directions and low velocities. Using the Extreme Value Analysis method, the researchers estimated design water levels induced by wind for different return periods. They considered wave setup, wind setup, and long-term water level changes, presenting a comprehensive assessment of the total design level for coastal protection shown in Table 2.(Joushideh, Shomal Zadeh, et al., 2023)

Table 2 Design Water Level Values for Various Return Periods in Chamkhaleh Area (Joushideh et al)(Joushideh, Shomal Zadeh, et al., 2023)

Returnperiod [yr]	2	5	25	50	100
MaximumWave Setup [m]	0.29	0.29	032	0.32	0.32
MaximumWind Setup [m]	0.71	0.22	0.26	0.29	0.32
MaximumLong-term Level [m]	0.52	0.52	0.52	0.52	0.52
MaximumTotal Level [m]	0.98	1.03	1.1	1.13	1.16

5. LOADING

The loading of the quay, like other structures, consists of the following components:
Dead Load: Incorporates construction materials and fixed loads.

Live Load: Arising from vehicle-related loads, equipment associated with unloading/loading, as well as a uniform load for unloading/loading cargo onto/from the vessel. Considering the port's utilization in Chamkhaleh, a uniform live load of 5 tons per square meter has been considered.

Earthquake Load: As per the methodology outlined in the Japanese code, the earthquake coefficient is a product of the regional coefficient, soil bed condition coefficient, and importance factor. For the Chamkhaleh port, the values of 1.4, 1, and 2.1 have been considered for the regional coefficient, soil bed condition coefficient, and importance factor, respectively. Thus, the earthquake coefficient is 1.7 (Kh), which is calculated for the operational-level earthquake. The force resulting from the vessel impact (reaction from fenders) is calculated based on berthing configuration, fender type, spacing, angle of impact, and other factors.(OCDI, 2020)

Considering that this force is compressive, it does not create critical conditions for closed-type quays but does affect the dimensions and alignment of beams and piles in open-pile and slab-type quays. Therefore, the initial assumption for design is 70 to 90 tons for the Fender reaction, which will be refined after the Fender design, and the final value will be used in calculations.

Mooring Force: According to PIANC, mooring lines are installed at intervals of 15 to 30 meters, which is set as 15 meters in this study. Mooring line capacity for berthing and loading, in accordance with PIANC for vessels ranging from 2,000 tons to 10,000 tons, must consider a 30-ton capacity for each mooring line (Pianc, 2002). In other codes such as Japan, for vessels between 3000 to 5000 tons, this force is specified as 35 tons. Accordingly, a mooring force of 35 tons is considered for this study (OCDI, 2020).

Lateral Loads from Soil and Water Pressure:For closed-type quays, lateral pressures from the soil should be considered under normal and earthquake conditions. Due to the presence of water on two sides and varying velocities on both sides, precise conditions must be controlled and calculated.

6. QUAY DESIGN AND ANALYSIS

In this section, we present a preliminary design for a 50-meter quay, outlining its essential specifications. The design encompasses both the piles and the deck, with a concrete deck and concrete piles featuring a diameter of 120 centimeters. The spacing between the piles is set at 6 meters along the width and 5 meters along the length of the quay.

Upon establishing the model and subjecting it to various loads, including live, earthquake, fender, and bollard loads, initial findings regarding the forces exerted on the piles have been obtained. Notably, the results reveal a compressive force (P) of 370 tons and a tensile force (P) of 53 tons.

To ensure structural integrity, it's imperative to consider a safety factor of approximately 2 to 2.5 for the piles. This entails that the vertical loads on the piles must withstand compressive resistance ranging from 740 to 925 tons during vertical pile load tests. However, taking into account soil conditions and practical constraints, the execution of 30-meter piles is deemed unfeasible. Consequently, accounting for 3 * 33 units of 30-meter piles, a total of approximately 1000 meters of piles are indispensable for a 50-meter quay.

Contrastingly, when considering a quay with contiguous concrete piles having a diameter of 120 centimeters, the calculation for executing 42 piles across a 50-meter length and a depth of 18 meters yields a total length of 756 meters. This length encompasses piles with a diameter of 120, which are required to be executed to a depth of 18 meters. The distinction between the two scenarios becomes more evident when factoring in cost differences arising from the varying depths of 18 meters and 30 meters, along with additional expenses related to the drilling and casting of concrete piles. Furthermore, ancillary factors like formwork for beams and the deck must also be accounted for in estimating costs for an open-type quay. Consequently, it is evident that for an open quay with concrete piles of 100 centimeters in diameter, taking into consideration loading conditions, soil type, and execution method, the cost is expected to surpass that of a closed quay with 120-diameter concrete piles.

Alternatively, if the design involves steel piles with a diameter of 100 centimeters and a thickness of 18 millimeters instead of concrete piles, the associated costs showcase a substantial disparity between this scenario (open quay) and a closed quay featuring bonded 120-diameter concrete piles. The 3D model of pile supported quay is shown in Figure 4.

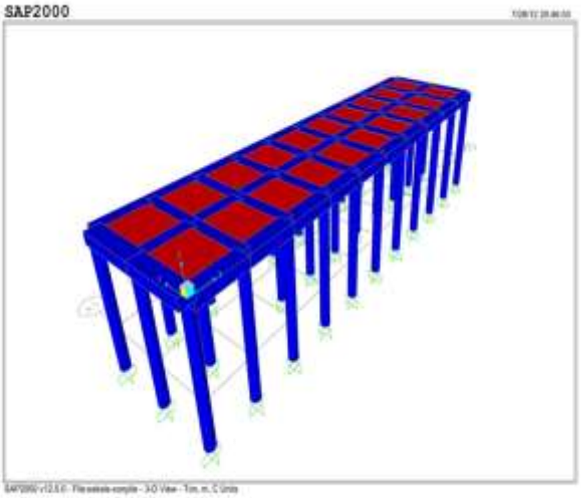

Figure 4. Three-Dimensional View of the Designed Model

This analysis underscores the intricate interplay of design, material selection, and practical considerations in determining the optimal construction approach for quays, ensuring both structural reliability and cost-effectiveness. The obtained results for vertical forces, bending moments at anchor points, and deformations caused by the fender force are presented in Figures 5 to 7, respectively.

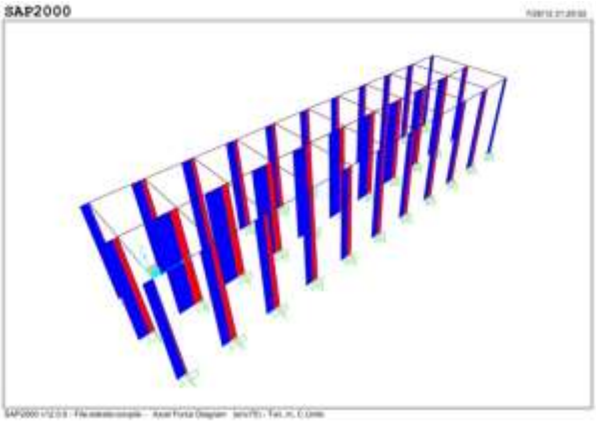

Figure 5. The vertical force distribution obtained from the analysis results.

Figure 6. The bending moment forces obtained from the analysis results.

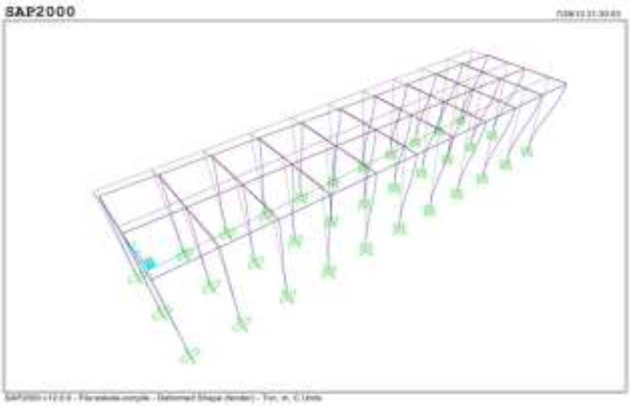

Figure 7. The displacements resulting from the fender force.

7. CONCLUSION

In conclusion, the outcomes of this comprehensive study shed light on the pivotal considerations in the design of quays, particularly in relation to the type of quay structure, loading conditions, and the behavior of piles under different forces. The distinction between open-type and closed-type quays has been elucidated, emphasizing the varying significance of vertical loads coupled with bending forces on the main load-bearing piles in open-type quays, and the prevalence of bending forces in closed-type quays. This distinction underscores the need for tailored design approaches that align with the specific structural characteristics and loading conditions of each quay type.

Furthermore, the study underscores the cost-effectiveness of using piles with larger diameters. The cost savings derived from employing larger diameter piles are not only attributed to the reduction in casing installation, removal, and internal drilling costs, but also to the streamlined labor and material expenses associated with shorter pile lengths. However, it is important to acknowledge that the extent of diameter increase must be judiciously determined based on the capabilities of local contractors, availability of suitable machinery, and rigorous project supervision to ensure optimal results.

In the broader context, these findings contribute to the ongoing discourse surrounding the efficient and resilient design of quay structures. By highlighting the nuanced interplay between structural behavior, loading conditions, and cost considerations, this study provides valuable insights for engineers and stakeholders involved in port and harbor infrastructure development. Future research endeavors could further delve into the practical implications of implementing these findings within the context of real-world projects, ultimately advancing the field of coastal and marine engineering towards enhanced safety, sustainability, and cost-efficiency in port design and construction. As the demand for reliable and resilient port infrastructure continues to grow, embracing innovative and cost-effective design approaches becomes increasingly crucial in safeguarding both maritime operations and coastal communities.

8. REFERENCES

[1] Dodds, A. M., Martin, G. R., Arulmoli, K., Bauleka, W., & Toan, D. Van. (2004). Lifeline Upgrade for a Wharf in Soft Ground. Geotechnical Engineering for Transportation Projects, 1739–1746. https://doi.org/10.1061/40744(154)167

[2] Donahue, M. J., Dickenson, S. E., Miller, T. H., & Yim, S. C. (2005). Implications of the Observed Seismic Performance of a Pile-Supported Wharf for Numerical Modeling. Earthquake Spectra, 21(3), 617–634. https://doi.org/10.1193/1.1978887

[3] FEMA. (2000). Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings. www.seaoc.org

[4] Joushideh, N., Majidi, A., Tabrizi, H., & Shomal Zadeh, S. (2023). Characterization of Scour-Induced Subsurface Deformations in Port Structures with Contiguous Pile Walls using Ground-Penetrating Radar (GPR). CRPASE: Transactions of Civil and Environmental Engineering, 9(2). https://doi.org/10.52547/crpase.9.2.2847

[5] Joushideh, N., Shomal Zadeh, S., Bahrami, B., & Shakouri Mahmoudabadi, N. (2023). Pseudo-static slope stability analysis and numerical settlement assessment of rubble mound breakwater under hydrodynamic conditions. World Journal of Advanced Research and Reviews, 19(2), 273–287. https://doi.org/10.30574/wjarr.2023.19.2.1542

[6] Na, U. J., Chaudhuri, S. R., & Shinozuka, M. (2009). Performance Evaluation of Pile-Supported Wharf under Seismic Loading. TCLEE 2009, 1–10. https://doi.org/10.1061/41050(357)98

[7] OCDI. (2020). Technical Standards and Commentaries for Port and Harbour Facilities in Japan.

[8] PIANC. (2001). Seismic design guidelines for port structures (1st ed.). A.A. Balkema Publishers.

[9] Pianc. (2002). Guidelines for the design of fender systems. In Report of Working Group 33 of the Maritime Navigation Commission. Pianc Brussels, Belgium.

[10] Roth, W. H., Dawson, E. M., Mehrain, M., & Sayegh, A. (2003). Analyzing the Seismic Performance of Wharves, Part 1: Structural-Engineering Approach. Advancing Mitigation Technologies and Disaster Response for Lifeline Systems, 385–394. https://doi.org/10.1061/40687(2003)40

[11] Shafieezadeh, A., DesRoches, R., Rix, G. J., & Werner, S. D. (2012). Seismic Performance of Pile-Supported Wharf Structures considering Soil-Structure Interaction in Liquefied Soil. Earthquake Spectra, 28(2), 729–757. https://doi.org/10.1193/1.4000008

[12] Smith, D., Naesgaard, E., & Kullmann, H. (2004). Seismic Design of a New Pile and Deck Structure Adjacent to Existing Caissons Founded on Potentially Liquefiable Ground in Vancouver, BC. 13th World Conference on Earthquake Engineering.