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Actions on berthing structures caused by large-tonnage ships

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Abstract – **Maritime transport plays a crucial role in the global economy, facilitating international trade in goods and services. With the increasing volume of transported goods, large-tonnage ships have grown significantly in size, imposing substantial demands on berthing structures. This article examines the impacts of large-tonnage ships on quays and other berthing structures, highlighting the challenges and available solutions. Berthing structures are classified and analyzed based on the materials used and the type of structure, including gravity quays, sheet pile quays, and jetties.**

Large-tonnage ships are classified based on their carrying capacity and technical specifications, with each type of vessel having distinct operational requirements. The stresses on berthing structures include static pressure, impact during berthing, and bollard pull. The scour phenomenon, caused by the water jet generated by ship propellers, is a major concern as it can lead to the instability and degradation of quays.

Traditional protection methods, such as the use of riprap and reinforced concrete, are complemented by modern solutions, including composite materials and advanced technologies like 3D printing. These innovations provide durable and adaptable solutions for quay protection.

In conclusion, the design and implementation of effective protection measures are essential to ensure the durability of port infrastructure. Recommendations include the use of a combination of traditional and modern methods, continuous monitoring, and the adoption of sustainability policies. This enables ports to effectively address the challenges posed by large-tonnage ships while maintaining long-term safety and functionality.

Keywords – berthing structures, large-tonnage ships, maritime transport, protection methods, scour.

1. THE GLOBAL CONTEXT OF MARITIME TRANSPORT

Maritime transport plays a crucial role in the global economy, facilitating the international exchange of goods and services. According to the United Nations Conference on Trade and Development (UNCTAD), approximately 80% of global trade by volume is conducted via maritime transport. Global economic development and the increasing volume of transported goods have led to the construction of increasingly larger ships, equipped with powerful propulsion systems capable of providing the necessary maneuverability. This evolution has imposed significant demands on berthing structures, stresses that, while difficult to observe or anticipate, can cause considerable damage.

2. THE IMPORTANCE OF PORT INFRASTRUCTURE

Port infrastructure is essential for the efficiency of maritime transport. Modern ports must be capable of accommodating large-tonnage ships, handling high volumes of cargo, and ensuring constant operability under various climatic conditions. Investments in port infrastructure are necessary to meet the current and future demands of maritime trade while ensuring the durability and safety of port operations.

3. BERTHING STRUCTURES

Berthing structures are port engineering works designed to enable the docking and mooring of ships for the execution of cargo handling operations, ship outfitting, or passenger traffic. These structures are constructed to facilitate the connection between the ship and the shore, providing support for the land behind them. Depending on how the land behind is supported, berthing structures can be classified into two types: those with retaining walls (gravity or anchored) and those without retaining walls.

The quay represents the continuous line of structures where ships dock, while the berthing front is the vertical section of the quay where the ship makes contact. A discontinuous berthing front is called an "apron," and in passenger traffic, the berthing front is referred to as a "pier." When a ship needs to be fixed within the port waters, isolated independent structures known as "dolphins" can be used. These are often positioned in front of berthing fronts to protect against the impact of ships during docking or, when connected by walkways, can themselves serve as berthing fronts. In international specialized literature, these structures are also referred to as "dolphins" and are commonly found in tanker berthing systems. In river ports, floating quays are also found, connected to the shore by walkways and secured with mooring piles.

In terms of layout, quays can be constructed either parallel to the shore, perpendicular to it, or at an angle, forming a mole or pier, depending on the structure's width. In cross-section, quays can be built as vertical, sloped, semi-sloped, or semi-vertical structures.

Based on the method of supporting the soil mass of the shore and mobilizing the backfill pressure they sustain, berthing structures can be categorized as follows:

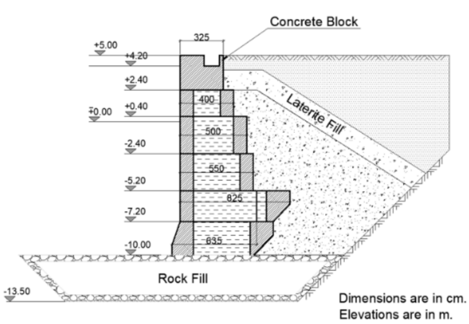
- Retaining berthing structures, whose function is to absorb the lateral pressure acting along the entire height of the structure, which is the predominant stress. Stability against overturning or sliding is ensured by the structure's own weight. This type of berthing structure includes gravity quays constructed from blocks, floating caissons, open caissons, corner structures, cofferdams, large diameter reinforced concrete cylinders, and others. By leveraging the self-weight effect through embedding or anchoring with tie rods, less massive berthing structures can be built, such as anchored or unanchored sheet pile walls, or slab foundations on piles with sheet piles placed either behind or in front of the structure.
- Non-retaining berthing structures, known as jetties, are constructed by preserving the shore terrain in a sloped and protected form and building a superstructure supported on piles or columns. This category also includes quay walls with infrastructure made from

heavy, massive piles. The primary forces acting on this type of structure are generated by ships and transshipment equipment. These forces are absorbed by the entire structure and transferred to the foundation soil.

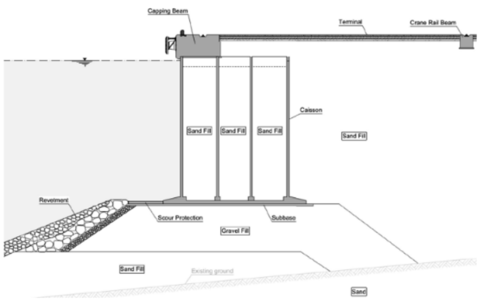
The selection process between one type of berthing structure or the other largely depends on the characteristics of the foundation soil. For instance, gravity quay walls are constructed in conditions where the soil exhibits superior geotechnical properties (pconv > 100 kPa, φ > 30°) and is located relatively close to the basin's bottom. In cases where these conditions are not met, it is recommended to explore indirect foundation methods rather than soil improvement solutions.

Based on the construction materials used, quays can be built from wood (timber pile foundations, cofferdams, sheet piles), stone (dry stone masonry walls), metal (metal sheet piles and infrastructure supported by metal piles), or concrete, whether plain, conventionally reinforced, pre-tensioned, or post-tensioned.

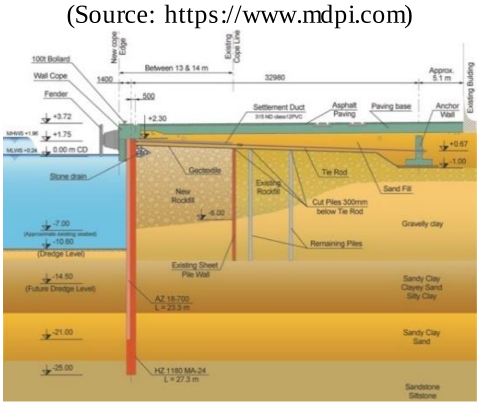
The choice of a solution for quay construction must be grounded in a multicriteria analysis, considering the foundation soil and backfill characteristics, water currents and movement in front of the quay, the magnitude of stress, operational technological schemes, traffic volumes, available resources for construction, water properties, and other factors. The total height of the berthing structure must equal the sum of the depth required for the design ship, the maximum variation in water level, and the safety clearance above the maximum water level.



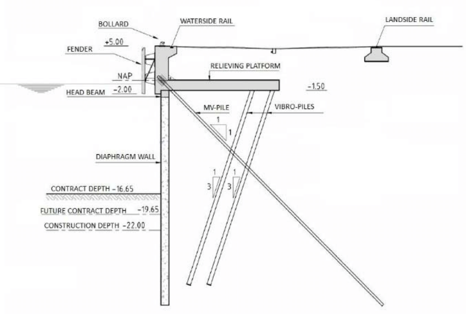
Quay wall made of hollow blocks
(Source: https://www.mdpi.com)



Quay wall made of floating caissons
(Source: springer.com)

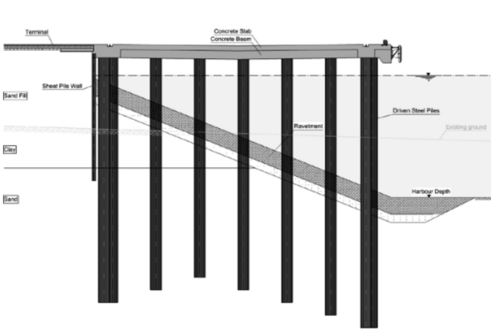


Quay wall made of steel sheet piles
(Source: https://sheetpiling.arcelormittal.com)



Quay made of diaphragm walls
(Source: researchgate.net)

Fig. 1 Types of Retaining Berthing Structures



Jetty-type quay (Source: springer.com)

Image beneath the jetty of the Galați Mineral Port (Source: own)

Fig. 2 Types of Non-Retaining Berthing Structures

4. LARGE-TONNAGE SHIPS

4.1. Classification of large-tonnage ships

Large-tonnage ships are classified based on their carrying capacity and type of cargo. For example, tankers are categorized by their deadweight tonnage (DWT), while container ships are classified by their capacity in TEUs (Twenty-foot Equivalent Units). The main categories of ships include tankers, container ships, and bulk carriers, each with distinct technical specifications and operational requirements.

4.2. Technical specifications and operational requirements

Each type of ship has unique technical specifications and operational requirements. VLCCs (Very Large Crude Carriers) have capacities of up to 320,000 DWT and require specially designed quays to withstand the significant stresses generated by these vessels. Large container ships can carry over 12,000 TEUs and demand appropriate infrastructure for the fast and efficient handling of containers. Capesize bulk carriers, with capacities exceeding 80,000 DWT, are used for transporting raw materials in bulk and require quays capable of handling heavy loads and dynamic stresses.

Tankers

Ultra Large Crude Carrier (Source: https://www.wartsila.com)

Container Ships

Post-Suezmax Container Ship (Source: https://maritimeoptima.com)

Bulk Carriers

Capesize Bulk Carrier (Source: https://drycargomag.com)

Fig. 3 Types of Large-Tonnage Ships

Table 1 Types of large-tonnage ships

Tankers	Container Ships	Bulk Carriers
Handysize: 10,000 - 50,000 DWT; Panamax: 50,000 - 80,000 DWT; Aframax: 80,000 - 120,000 DWT; Suezmax: 120,000 - 200,000 DWT; VLCC: 200,000 - 320,000 DWT; ULCC: over 320,000 DWT	Small Feeders: până la 1,000TEU; Feeders: 1,000 - 2,000 TEU; Panamax: 2,500 - 5,000 TEU; Post-Panamax: 5,000 - 10,000TEU; Suezmax: 10,000 - 12,000EU; Post-Suezmax: over 12,000 TEU	Handysize: 10,000 - 35,000 DWT; Handymax: 35,000 şi 59,000 DWT; Panamax: 60,000 şi 80,000 DWT; Capesize: over 80,000 DWT

5. DEMANDS OF SHIPS ON BERTHING STRUCTURES

During docking and mooring maneuvers at the quay, the actions of large-tonnage ships on the berthing structures can manifest through static pressure, impact during berthing, bollard pull, and the scour phenomenon caused by the ships' propellers during maneuvers. Ships up to 20,000 DWT can dock at the quay using their own propulsion system, while large-tonnage vessels are brought close to the quays with the help of tugboats, with berthing occurring at extremely low speeds. For this reason, impact during berthing will not be addressed in this article, as this type of demand is not specific to large-tonnage ships.

5.1. Static load

Static load on ships refers to the phenomenon caused by the action of wind and currents. Thus, a wind speed of 20-24 m/s is considered normal, while storm winds range from 34-40 m/s, considering that the effect of the wind and currents is transmitted to the berthing front only over the length corresponding to the straight section of the ship (l1), which is related as follows:

$$l_1 = \beta L \tag{1}$$

where:

L - the total length of the ship,

β is chosen from the table below.

Table 2 Coefficients for determining the length of the straight section and the sail area of ships

Ship Type	a	b
Solid cargo	0,1	0,30
Passengers Ships	0,12	0,25
Tankers	0,1	0,35
Fishing Vessels	0,11	0,30

In the case of mooring to a duc d'albi, the reactions are considered concentrated, with their sum equal to the total forces of wind and currents.

The wind's effect is directly proportional to the velocity, v (m/s) with a 2% safety margin, and to the sail area of the ship.
The transverse and longitudinal forces acting on the ship are calculated using the following relationships:

$$P_x = 7{,}5 \cdot 10^{-5} \cdot F_x \cdot v_x^2 \cdot k \quad (2)$$

$$P_y = 5{,}0 \cdot 10^{-5} \cdot F_y \cdot v_y^2 \cdot k \quad (3)$$

where:

F_x and F_y represent the transverse and longitudinal sail areas of the ship (m²),
v_x and v_y are the transverse and longitudinal components of the wind velocity,
k accounts for the wind's non-uniformity across the ship's body, as determined from the table below:

Table 3 Coefficient of wind non-uniformity on ships

Ship Lenght, m	< 25	25-30	50-100	> 100
Coefficient k	1	0,8	0,63	0,5

The longitudinal sail area will be calculated using the following formula:

$$F_x = \alpha \cdot L^2 \quad (4)$$

where α is chosen from Table 2.

The transverse or longitudinal force generated by the current is calculated using the following formula:

$$P_c = 0{,}06 \cdot F_s \cdot u^2 \quad (5)$$

where:

F_s is the transverse or longitudinal area of the submerged part of the ship, measured in m²,
u is the transverse or longitudinal component of the water current with a 2% safety margin during the navigation period, measured in m/s.

The force transmitted by the ship per unit length of the quay, due to the transverse action of the wind and the current, is calculated using the following formula:

$$\frac{P_c}{p} = 1{,}1 \cdot L_c \quad (6)$$

where:

L_c is equal to the length of the straight section of the ship, and if the length of the berthing front is smaller than the length of the straight section of the ship, they will be considered equal.

The coefficient value of 1.1 accounts for the eccentricity of the wind or current.

5.2. Bollard traction

This type of demand largely depends on the geometric dimensions of the ship, the wind speed, the exposure of the ship, the degree of shielding, and the number of bollards used for mooring the ship.

Table 4 Number of bollards and the distance between them based on the ship's length

Maximum Ship Length (m)	<50	150	250	>300
Maximum Distance Between Bollards (m)	2	4	6	8
Number of Bollards to Which the Ship is Moored (units)	20	25	30	35

The bollard traction load value is selected from the table below, based on the ship's displacement.

Table 5 Bollard pull load based on ship displacement

No.	Ship Displacement (kN)	Bollard Traction (kN)
1	< 5.000	50
2	– 15.000	100
3	> 15.000 – 25.000	150
4	> 25.000 – 50.000	200
5	> 50.000	250
1	< 20.000	100
2	> 20.000 – 100.000	350
3	> 100.000 – 200.000	600
4	> 200.000 – 500.000	800
5	> 500.000 – 1.000.000	1000
6	> 1.000.000 – 2.000.000	1500
7	> 2.000.000	2000

5.3. Scour phenomenon

The main cause of the scour phenomenon is the water jet generated by the ship's propellers. Thus, the initial velocity of the water jet can be calculated using the following formula:

$$V_o = 1{,}6nD_0\sqrt{K_t} \tag{7}$$

where:

n represents the number of propeller rotations per second; D0 represents the propeller diameter.

The propulsion force coefficient is calculated using the following formula:

$$K_t = \frac{T}{\rho n^2 D_0^4} \tag{8}$$

where:

T is the propulsion force of the propeller and r is the density of water.

Based on experiments, a value of 0.42 can be adopted for K_t. Thus, the velocity V_0 can be estimated with a 20% margin of error using the following formula:

$$V_0 = 0{,}95 n D_p \tag{9}$$

In the case of a free jet propeller,

$$D_0 = D_p\sqrt{2} \text{ and } D_0 = D_p \tag{10}$$

if the propeller is placed in a tunnel.

If the propulsion value Pd is known, the following formula can be used:

$$V_0 \cong C\frac{P_d}{D^2} \tag{11}$$

where:

C = 1.17 for a propeller placed in a tunnel and 1.48 for a free propeller.

The maximum velocity at the bottom of the basin can be estimated using diagrams.

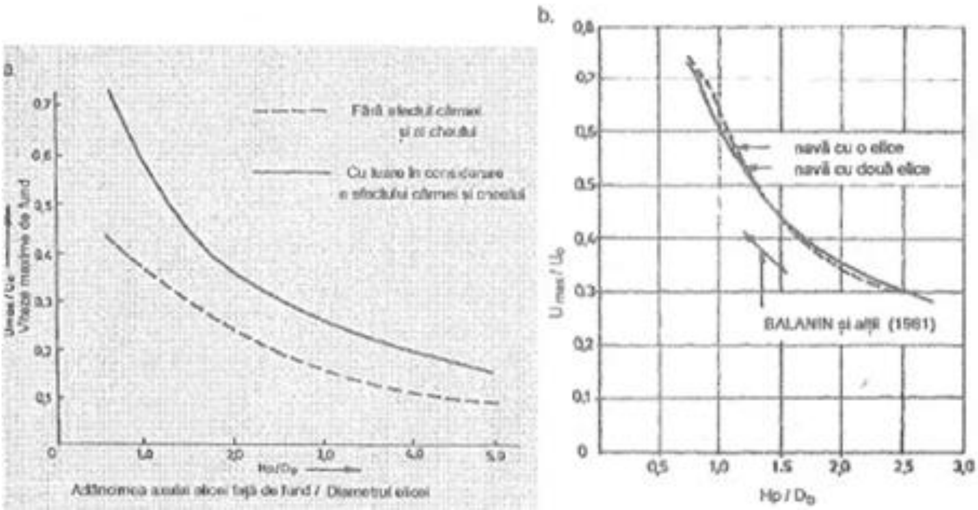


Fig. 4 Diagrams for determining the velocity at the bottom of the basin in unlimited spaces (a); maximum velocity for ships with one or two propellers (b).

For a jet propagating laterally in unlimited spaces, at a distance of (5÷10)Z_b behind the propeller, this velocity can be estimated using the following formula:

$$V_b = aV_0\frac{D_0}{Z_b} \tag{12}$$

where:

a = 0.71 for vessels with the rudder located on the axis,
a = 0.42 for ships without a rudder,
a = 0.25 for ships with a propeller in a tunnel.

The velocity of the water jet is influenced by the rudder, its number and position, the presence of the quay that limits the propagation space, etc.

The calculation diagram for the protection zones at the bottom is shown in the figure below, indicating the points X_p and X_s where the limit and the axis of the jet meet the bottom of the basin.

Based on experimental data, for ships without a rudder, the angle of divergence of the water jet towards the bottom of the basin is 25° and, respectively, 22°–23° towards the quay and 16° towards the free water surface. It was also determined that the axis of the current towards the bottom is tilted at 15°, while towards the quay, it is at 11°.

The maximum velocity along the axis of the propeller for ships with a rudder angle of zero can be determined using the following formula:

$$V = V_0 \cdot 1{,}515\sqrt{X - 0{,}5D} \tag{13}$$

By inserting the values of X_p and X_s into this formula, the velocity values at the center or at the limit of the water jet can be obtained.

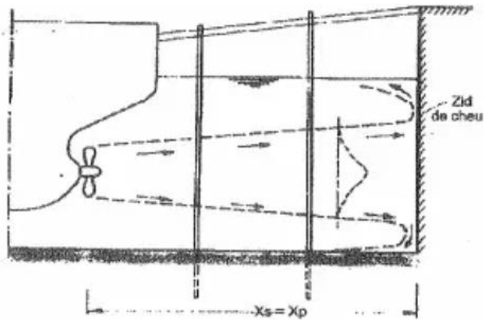


Fig. 5 Return Current at the bottom of the basin for RO-RO ships with linkspan stations

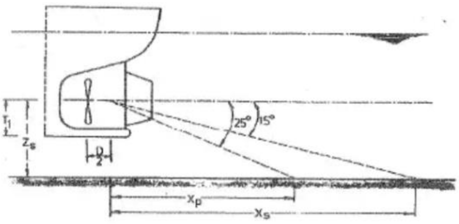


Fig. 6 Calculation elements for the jet contact zone with the bottom of the basin

It can be considered that the most exposed scour area has a width of 1 to 1.5 ship widths and a length between X_p and X_s, or more prudently, twice this distance.

For this reason, the practical solution will be to maintain a safe berm in front of the quay with a width approximately equal to the quay height. When analyzing the areas to be protected, the influence of ships with transverse propulsion will also be taken into account, by increasing the protection of the surface exposed to scour.

6. PROTECTION METHODS AND INNOVATIONS

6.1. Traditional and modern methods

Traditional protection methods against scour include the use of riprap and reinforced concrete. These methods are well-documented and widely used due to their durability and efficiency. Riprap protects the quay's base by reducing the speed of the water jet, while reinforced concrete provides robust protection against mechanical and hydraulic damage.

Modern methods involve the use of composite materials and advanced technologies, such as 3D printing. Composite materials, such as geotextiles and reinforced plastic materials, offer significant advantages in terms of durability and adaptability to various environmental conditions. 3D printing allows for the creation of complex structures tailored exactly to the specific needs of each port, optimizing material usage and reducing costs. Additionally, this process enables the creation of customized structures, such as protective barriers and fastening elements, which can be designed to perfectly adapt to the quay's configuration and local hydrodynamic conditions. This technology also allows for rapid repairs and maintenance of berthing structures, ensuring long-term durability and functionality. The composite materials used in these processes offer increased resistance to wear and corrosion, making them ideal for use in harsh marine environments.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Summary of key findings

The study highlights the importance of rigorous design and the implementation of effective protection measures for berthing structures. The demands generated by large-tonnage ships require continuous adaptation of port infrastructure. The use of traditional methods, combined with modern innovations, can ensure efficient and durable quay protection. Scour, a major phenomenon caused by the water jet of the propeller, requires well-designed protection solutions to prevent structural damage and ensure long-term stability.

7.2. Recommendations for design and implementation

It is recommended to use protection methods tailored to the specific characteristics of each port, including both traditional solutions and technological innovations. The design must consider the geotechnical characteristics and local climatic conditions. Implementing composite materials and advanced technologies, such as 3D printing, can significantly enhance the durability and efficiency of port infrastructure.

Additionally, continuous monitoring of the condition of berthing structures and periodic maintenance and repair work is essential. The adoption of sustainability policies and material recycling can help reduce environmental impact and increase economic efficiency. Ports must develop comprehensive strategies that include risk assessment, intervention planning, and the use of innovative technologies to efficiently address the challenges posed by large-tonnage ships, maintaining safety and functionality in the long term.

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