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Corrosion-Induced Degradation of Marine Reinforced Concrete Structures: Case Studies from Polish Ports and Implemented Repair Methods

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ABSTRACT: Most marine hydraulic structures, such as breakwaters, quay walls, and piers, operate both above and below the water surface throughout their service life. Maintaining, modernising, or reinforcing these concrete and reinforced concrete structures, which are in constant contact with seawater, poses a significant engineering challenge. Ensuring structural performance and operational continuity during repair work is particularly demanding. This study identifies the main types of environmental impact and the associated mechanisms of concrete degradation in marine infrastructure, including chemical, physical, and mechanical interactions that accelerate deterioration. Documented examples of corrosion damage observed in harbour breakwaters, quay walls, and pier structures are presented, along with proposed repair strategies and their practical implementation. Photographic documentation illustrates the extent of damage, repair processes, and the final condition of the renovated elements.

The paper focuses on selected case studies of repair and strengthening works carried out on marine reinforced concrete structures exposed to the aggressive conditions of the Baltic Sea. The analysed facilities are located in Polish ports along the Gulf of Gdańsk, with the exact location of each provided in the respective case description. Each case study includes a detailed account of the applied repair technologies, ranging from surface reprofiling and polymer-cement coatings to low-pressure crack injection, prefabricated GRC elements, and CFRP strengthening systems. The findings demonstrate that accurate diagnosis of deterioration processes, combined with repair strategies tailored to the specific structural type and extent of damage, can effectively mitigate corrosion, restore structural and operational capacity, and significantly extend the service life of port infrastructure.

1 INTRODUCTION

The durability of reinforced concrete structures operating in marine environments is a critical concern in hydraulic engineering. These structures are continuously exposed to a variety of aggressive factors, including chloride and sulfate ions, fluctuating humidity, temperature changes, and cyclic mechanical and hydrodynamic loads caused by waves, tides, and currents. Over time, these influences intensify corrosion processes in both concrete and reinforcement steel, leading to the progressive deterioration of structural integrity, reduced load-bearing capacity, and impaired watertightness. As a result, targeted repair and strengthening interventions are essential to maintain functionality and extend service life. Further discussion on the causes and mechanisms of concrete degradation in marine conditions can be found in the following publications: [1], [2], [3], [4], [5], [6].

Most maritime hydraulic structures, such as breakwaters, quay walls, and piers, function for decades under simultaneous exposure to underwater and atmospheric conditions. Their location in dynamic marine zones subjects them to constant degradation, often requiring interventions ranging from routine maintenance to extensive reconstruction [7]. The most significant technical challenge in such works lies in ensuring the structural stability and safety of the facility during ongoing operations. This is especially true for commercial port infrastructure, where downtime may lead to severe economic and logistical consequences. Because of the diverse and site-specific nature of environmental impacts and damage mechanisms, standardized repair protocols are rarely applicable. Each project demands an individual approach that considers environmental exposure, loading conditions, material characteristics of the original construction, and the type and extent of damage observed in structural components. A detailed overview of the degradation mechanisms affecting concrete in marine environments (including the influence of chlorides, sulfates, cyclic wetting and drying, and carbonation) can be found in several comprehensive publications [1], [3], [8]. Additional insights specific to port infrastructure and technical aspects of repair strategies in Polish marine conditions are discussed by [9], [10], [11] and in relevant national standards, especially PN-EN 1504 [12], [13], [14], [15], [16], [17], [18], [19], [20] which is described in detail in [21].

This study presents selected examples of repair and strengthening works conducted on marine hydraulic structures. The described cases demonstrate a range of engineering solutions tailored to different types of degradation and environmental constraints. They highlight the practical challenges involved in repair execution under marine conditions and evaluate the long-term effectiveness of the applied techniques in restoring both functionality and durability.

2 EFFECTS OF SEAWATER ENVIRONMENT ON THE DURABILITY OF CONCRETE AND REINFORCED CONCRETE

Marine hydraulic structures are essential components of port and coastal infrastructure. They facilitate maritime transportation, protect coastlines, and enable various economic activities related to shipping, logistics, and fisheries. Their design and operation require special consideration of both mechanical loads and the severe conditions typical of marine environments such as wave action, tidal fluctuations, chemical and biological corrosion, and dynamic hydrodynamic forces [22], [23], [24]. The primary types of such structures include breakwaters, quay walls, piers, jetties, and platforms. Breakwaters serve a protective role by shielding harbour basins from direct wave impact and coastal erosion. Quay walls are massive shoreline structures that allow ships to berth and cargo or passengers to be loaded and unloaded, they are often integrated with the port's logistics and storage facilities. Piers and jetties, which extend into the water, enable berthing along both sides and increase handling efficiency. Platforms usually lighter in design are often used in marinas and small fishing ports for temporary docking or pedestrian access [24].

Failures and damage to hydraulic structures (particularly those located in marine environments) are most often the result of progressive degradation of key structural components, especially concrete and reinforcing steel. The primary mechanism of deterioration is the development of corrosion processes in marine concrete, often accompanied by reinforcement corrosion, whose onset and progression are highly dependent on environmental exposure conditions as well as material properties and structural design quality [5], [6].

The durability of marine concrete is affected by a complex interplay of multiple loads and external factors. Structural degradation typically results from the simultaneous influence of mechanical loads, including self-weight and operational loads (e.g. from vehicles, cranes, or superstructures), as well as environmental loads, which are highly variable and often synergistic. These actions may interact and accumulate over time, accelerating the degradation rate and adversely affecting the structure's stability, serviceability, and durability [25], [26].

Key environmental loads affecting marine hydraulic structures polish Baltic sea coast include [27]:

- Sea level fluctuations, typically ranging from several tens of centimeters to over 150 cm during extreme events such as storm surges, backwater effects, or high tides. These fluctuations result in varying wetting-drying cycles, which facilitate chloride ingress and carbonation.
- Wind actions, predominantly from the west but also from periodic northeasterly directions, influencing wave generation and flow patterns.
- Wave and current-induced effects, including the transformation of wave parameters (height, length, period, direction) as they approach the shore. Near-bottom currents often transport sediments and contribute to abrasion and erosion of concrete surfaces [4].
- Ice conditions, particularly in winter months. While southern Baltic ports do not regularly freeze, floating or pressure ice may exert dynamic and mechanical forces on structural elements causing increased surface wear (ice sheet abrasion).
- High temperature amplitudes, especially daily or seasonal freeze-thaw cycles near 0°C, which cause cracking and surface spalling due to internal expansion of water in concrete pores.
- Hydrostatic pressure and moisture cycles, which promote the movement and crystallization of chloride salts within concrete, exacerbating microstructural degradation [5].
- Physicochemical effects of seawater, including the presence of aggressive ions such as Cl^-, Mg^{2+}, SO_4^{2-}, and CO_2, which lead to decalcification of the cement matrix, secondary ettringite formation, and leaching of calcium hydroxide [6].
- Biological impacts, particularly in coastal zones with freshwater inflows, where nutrient rich waters (e.g., containing nitrogen and phosphorus) support the growth of microorganisms that can accelerate biodegradation of surface concrete and coatings.

These environmental factors are random in nature, characterized by continuous variability, often irregular, sudden, and difficult to predict, and exhibit both quantitative and qualitative changes over time [7].

A synthesized classification of such loadings, including design implications, can be found in reference [8].

Due to the complexity of these effects, the design, operation, and repair of marine hydraulic structures require a multidisciplinary and durability-oriented approach, taking into account not only material strength but also resistance to long-term environmental degradation mechanisms.

3 CORROSION MECHANISMS IN CONCRETE AND REINFORCED CONCRETE UNDER MARINE ENVIRONMENTAL EXPOSURE

Like other construction materials, concrete undergoes progressive degradation processes known as corrosion. This phenomenon encompasses both chemical and physicochemical mechanisms, as well as physical processes that contribute to the deterioration of the material's structure and properties. Technical literature distinguishes six primary types of concrete corrosion: leaching, sulfate, chloride, carbonation, acid, and magnesium corrosion [9] comprehensively discussed in sources such as [6-8] [28]. In marine environments, chloride and sulfate corrosion are of particular concern due to the high concentrations of Cl^- and SO_4^{2-} ions in seawater [28], [29]. It is important to emphasize that the chemical composition of port waters is both complex and dynamic. In addition to naturally occurring salts, these waters may contain anthropogenic pollutants such as petroleum hydrocarbons, heavy metals (e.g., Cu, Zn, Pb), detergents, and biocides. Therefore, when assessing corrosion risks, the potential occurrence of all known corrosion mechanisms must be considered.

Concrete exposed to marine environments is vulnerable to a range of degradation mechanisms, each of which affects its structure and performance in different ways. One of the most insidious forms is leaching corrosion, which typically occurs when concrete is subjected to prolonged contact with soft water that contains a low concentration of dissolved salts. In such conditions, the calcium hydroxide [$Ca(OH)_2$] present in the cement matrix becomes increasingly soluble and is gradually washed out [30]. This leaching process results in higher porosity and a progressive weakening of the concrete's internal structure, a phenomenon often referred to as the "white death" of concrete due to the characteristic whitening of affected areas [31].

Carbonation corrosion is another widespread form of degradation, driven primarily by the presence of carbon dioxide (CO_2) in both air and water [32]. CO_2 penetrates the porous structure of concrete and reacts chemically with calcium hydroxide to form calcium carbonate ($CaCO_3$). Although $CaCO_3$ is relatively stable, the reaction reduces the alkalinity of the concrete, lowering its pH and thereby compromising the passive layer that protects embedded steel reinforcement. Once this protective layer is breached, the steel becomes susceptible to corrosion. This process is especially aggressive when the relative humidity ranges between 40% and 80%, creating ideal conditions for carbonation [33].

Chloride-induced corrosion poses a particularly severe threat in coastal or submerged structures, as chloride ions (Cl^-) present in seawater are able to infiltrate concrete via diffusion or capillary action. Once these ions reach the reinforcement, they disrupt the passive film on the steel surface, initiating localized pitting corrosion. This type of degradation is often accompanied by visible symptoms such as a glossy or glass, like appearance on the surface and spalling or detachment of the concrete cover, especially around the corroding steel [28], [29].

Equally destructive is sulfate corrosion, which occurs when sulfate ions (SO_4^{2-}), also present in marine and polluted waters, react with the calcium aluminate phases of hydrated cement. These reactions produce ettringite and gypsum, both of which are expansive products. Their formation within the concrete matrix leads to the development of internal stresses that ultimately cause cracking, delamination, and structural disintegration [34].

When concrete is exposed to acidic environments ($pH < 6$), it is prone to general acid corrosion. In this case, acidic solutions dissolve calcium compounds from the cement matrix, resulting in the formation of highly soluble salts. The outcome is increase d porosity, loss of mechanical integrity, and a reduction in overall durability [27].

Table 2. Types of Concrete Corrosion - Causes and Reactions; own source based on: [23], [24], [27], [35], [36], [37], [38]

Types of Concrete	Detailed Causes	Chemical Reactions
Leeaching	Long-term contact of concrete with soft water (low mineral content); ionic imbalance leads to dissolution and leaching of $Ca(OH)_2$	$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$ (leaching of calcium hydroxide)
Carbonation	Presence of CO_2 in air or water under moderate humidity; CO_2 penetrates pores and reacts with $Ca(OH)_2$.	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ (lowering pH of concrete)
Chloride-induced	High concentration of Cl^- ions in seawater; migration into concrete and depassivation of steel reinforcement.	$Fe \rightarrow Fe^{2+} + 2e^-$; Cl^- accelerates localized corrosion of reinforcing steel
Sulfate-induced	Contact with sulfate-containing solutions (SO_4^{2-}), sulfuric acid, or gypsum; formation of ettringite and gypsum causes expansion.	$3CaO \cdot Al_2O_3 + 3(CaSO_4 \cdot 2H_2O) + 26H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ (ettringite formation)
General Acid	Exposure to acidic solutions (e.g., H_2SO_4, HCl, humic acids); acids dissolve calcium compounds forming soluble salts.	$Ca(OH)_2 + 2H^+ \rightarrow Ca^{2+} + 2H_2O$; Ca^{2+} + acid anions $\rightarrow$ soluble salts
Magnesium-induced	Ion exchange between Ca^{2+} and Mg^{2+} from seawater or deicing agents; formation of loose $Mg(OH)_2$ (brucite) and breakdown of C-S-H.	$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2$ (brucite, structurally weak product)

Finally, magnesium corrosion is a process that typically results from long-term exposure to seawater rich in dissolved magnesium salts or from the use of deicing agents. It involves the replacement of calcium ions (Ca^{2+}) in the cement paste with magnesium ions

(Mg^{2+}), leading to the precipitation of brucite ($Mg(OH)_2$). Unlike calcium-based hydrates, brucite has no binding properties and forms a weak, porous layer that further undermines the structural integrity of the concrete. In the case of quay structures, this phenomenon is particularly evident in the mooring path area [27].

4 CORROSION PREVENTION AND THE IMPORTANCE OF ENVIRONMENTAL DIAGNOSTICS

In marine environments, various repair techniques are commonly used to restore and extend the service life of deteriorated reinforced concrete structures. Among these, polymer-cement mortars and coatings (PCC) are widely applied to protect surfaces against environmental factors such as chlorides and carbon dioxide. These materials adhere well to existing concrete, allow water vapor transmission (enabling the structure to "breathe"), and, depending on the accessibility of the repaired surfaces, are suitable for both hand and spray application. Their use is most effective when the substrate is properly prepared, although the limited thickness of the applied layers may restrict their applicability in deeper repairs [39].

Another frequently applied method is shotcreting, which involves pneumatically spraying concrete or mortar onto damaged surfaces [40]. This technique is less time-consuming for repairing large surface areas and is also effective in zones such as splash regions or submerged surfaces. It provides excellent compaction and adhesion but requires specialized equipment and experienced operators. It may also be less suitable for small-scale or precision repairs.

For cases involving severe structural degradation, prefabricated reinforced concrete elements are often used. These premanufactured components provide high-quality control, accelerated installation, and high mechanical strength. However, they typically entail higher transport and installation costs and require precise anchoring or integration with the existing structure.

CFRP (carbon fiber reinforced polymer) systems, in the form of adhesive-applied strips or mats, are increasingly used to strengthen elements subjected to tension or with existing cracking. These composites exhibit extremely high tensile strength, excellent chemical resistance, and minimal weight, allowing for effective strengthening without adding significant mass. Nevertheless, their application can be limited in highly humid conditions without adequate surface preparation [41].

Lastly, low-pressure injection is a repair strategy focused on sealing and bonding cracks as well as stabilizing the microstructure of deteriorated concrete. Using materials such as epoxy resins, polyurethane gels, or silicate suspensions, these systems are ideal for preventing water ingress and inhibiting further salt migration. However, they do not provide significant structural reinforcement and are best suited for addressing minor cracks and sealing purposes [41].

Table 3. Comparison of Repair Methods for Reinforced Concrete Structures - Marine Environment

Repair Method	Application	Advantages	Limitations
Polymer-Cement Mortars and Coatings (PCC)	Surface protection of concrete against environmental factors; patch repairs	Good adhesion; resistance to chlorides; water vapor permeability	Requires properly prepared substrate; limited layer thicknes
Shotcreting	Covering large surfaces in hard-to-reach areas (e.g., splash zone)	High efficiency; good adhesion; fast application	Requires specialized equipment and skilled operator; less effective for small repairs
Prefabricated Reinforced Concrete Elements	Replacement of severely degraded structural elements	Controlled quality; fast installation; high strength	High transport and installation costs; need for accurate anchoring
CFRP Strengthening (Strips/Mats)	Strengthening cracked or weakened elements (beams, columns, slabs)	Very high tensile strength; chemical resistance; low weight	Unsuitable for high humidity conditions without surface preparation
Low-Pressure Injection	Sealing and bonding of cracks; stabilization of concrete microstructure	Precise application possible; limits water and salt migration	Does not strengthen the cross-section structurally; limited to minor cracks

The following sections of this study discuss selected methods for the repair and strengthening of corroded structural elements of breakwaters and quays, with an emphasis on the application of modern material and technological solutions. The techniques presented include the use of polymer-cement mortars and coatings (PCC), shotcreting, prefabricated reinforced concrete elements, and strengthening systems based on carbon fiber composite strips.

An integral part of the study is the photographic documentation, which illustrates typical damage, repair interventions, and strengthening measures applied to seaward-facing concrete walls. This documentation offers readers a unique opportunity to gain insight into the performance and deterioration of hydraulic structures operating in harsh marine environments, particularly from the seaward side, which is typically inaccessible from within the port area.

To complement the analysis and provide a clearer understanding of the technical solutions applied, the study also includes selected design schematics that illustrate the adopted repair systems and execution technologies in a structured and visual format.

5 CASE STUDIES AND THEIR IMPORTANCE

Case studies play a key role in advancing sustainable construction, offering insight into the real-world performance of environmentally friendly materials. They highlight both successes and practical challenges, such as sourcing, compatibility with existing systems, or variability in material quality [42]. Take, for example, the rehabilitation of a reinforced concrete beam forming part of a mass-handling pier structure. The pioneering at that time use of carbon fiber strips and mats in marine repair work became a reference point for the development of current design guidelines.

Publishing case studies in scientific journals, industry reports, and at conferences broadens knowledge across the sector and builds confidence in innovative technologies. Well-documented examples help shape future standards and encourage wider adoption of sustainable practices. The following six cases illustrate the long-term performance of reinforced concrete structures in aggressive marine environments, their degradation patterns, and the applied repair and strengthening techniques.

All the cases analysed in this paper are located in Polish ports on the Gulf of Gdańsk, and their exact locations are indicated for each case study discussed.

5.1 *Case Study 1: North Breakwater, Port Gdynia*

A coastal breakwater constructed in the 1920s to shield harbour basins from open sea exposure was originally designed as a hybrid structure-featuring a timber palisade section (approx. 155 meters) and a caisson-type head segment (approx. 57 meters), totalling 212 meters in length. Over time, it underwent several modernization phases, including reconstructions in the 1950s and subsequent reinforcements along the sheltered side in the late 20th century, mostly targeting the superstructure.

Underwater inspections carried out in the early 2010s revealed significant deterioration, especially on the seaward side. The timber palisade, topped with a reinforced concrete cap beam, showed advanced decay. Its porous configuration, combined with local material losses, led to migration of the stone backfill, decreased stability, and wave transmission into protected basins. Seepage through joints was also observed, causing water to emerge on the crest, (Fig. 1).

Figure 1. Case study 1, Corroded lower edge of the reinforced concrete superstructure of the palisade breakwater (on the seaward side), showing significant concrete losses and exposed, corroded reinforcement bars in the zone affected by fluctuating sea levels and wave action, source: own

Corrosion was particularly severe along the tidal fluctuation zone, where the lower section of the cap beam exhibited spalling, deep losses, and exposed timber pile heads-signs of compromised structural integrity. Experts concluded that due to the extent of the degradation, partial demolition and comprehensive repair were necessary.

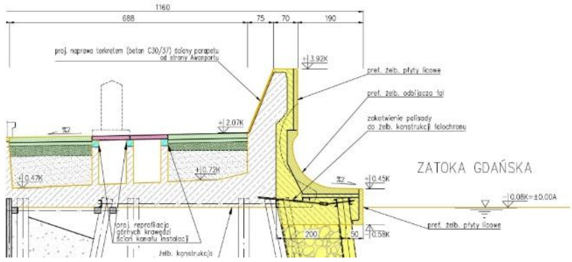

Figure 2. Case study 1, Cross-section of the North-Eastern Breakwater - scope of the proposed modernization works [43]

As a result, a full-scale rehabilitation of the seaward face of the head section was undertaken in 2012. The repair involved breaking down the damaged concrete parapet between +2.20 m and +0.70 m to a depth of 30 cm, followed by the installation of prefabricated reinforced concrete facing panels and the construction of a new parapet within this protective shell. The new parapet was cast from C30/37 concrete and reinforced with BSt500S ribbed steel bars (ø12 mm and ø16 mm), with a specified concrete cover of 70 mm. The seaward wall was formed using prefabricated panels, while the port-facing side was coated with shotcrete made of C30/37 concrete, (Fig. 2, Fig. 3).

Figure 3. Case study 1, Left: reconstruction works on the seaward wall of the North-Eastern Breakwater. Right: view of the seaward wall of the North-Eastern Breakwater approximately 12 years after reconstruction. The structure remains in good technical condition, despite visible signs of exposure to wave action, fluctuating water levels, and biological source: own

5.2 *Case Study 2: Caisson type North Breakwater, Port Gdańsk*

Constructed between 1972 and 1978, this caisson-type breakwater, extending approximately 1,625 meters was designed not only to shield the harbour basins from direct wave action, but also to dissipate part of the incoming energy through an innovative reinforced concrete superstructure. The crest featured a two-part design: on the seaward side, an expansion chamber facilitated partial wave energy dispersion, while the port-facing section incorporated a high, curved parapet designed to reflect overtopping waves and provide access for maintenance.

After more than forty years of continuous service, a condition survey conducted in 2015 identified significant deterioration, despite earlier localized repairs. The most critical issues included the poor state of the expansion chamber surface, exposed and corroded reinforcement in the parapet crest, cracked and unsealed joints between caisson units, structural gaps, and visible damage to the prefabricated deflectors mounted in the expansion zone. Out of the thirty such elements, many showed signs of advanced corrosion despite having undergone previous maintenance interventions, (Fig. 4-6).

Figure 4. Case study 2, View of the expansion chamber from the bay side: visible surface damage to the wave deflectors and exposed reinforcement of the breakwater parapet, source: own

Figure 5. Case study 2, View of the expansion chamber from the bay side: visible damage to the superstructure (exposed reinforcement) and wave deflectors, as well as rust stains caused by reinforcement corrosion and concrete loss in the area of the structural expansion joints, source: own

Figure 6. Case study 2, View from the expansion chamber; visible surface damage to the breakwater parapet following previously conducted repairs, source: own

Although the core function of the breakwater protecting the harbour remained intact, a comprehensive repair program was deemed necessary to preserve its operational performance. The remedial strategy involved the installation of prefabricated glass fiber reinforced concrete (GRC) components to shield the parapet crown, combined with polymer-modified shotcrete reinforced with alkali-resistant fibers to restore the surfaces. In areas adjacent to port infrastructure, the parapet was elevated to +4.90 meters above sea level, with new reinforced ribs introduced at regular intervals to support the additional height. The expansion chamber surface was rebuilt using an 8 cm thick overlay of polymer-modified concrete, also reinforced with fiberglass and treated with a hydrophobic sealant to enhance durability. Furthermore, both the seaward and port-facing cap beams were reinforced with cast-in-place concrete jackets, protected by precast facing panels (Fig. 7).

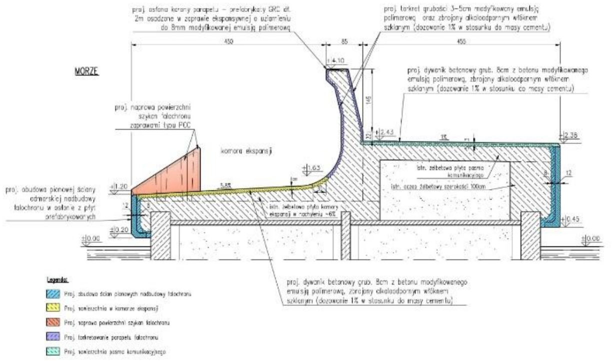

Figure 7. Case study 2, Typical cross-section of the Northern Island Breakwater within the scope of repair works [44]

Together, these interventions not only addressed the structural and material deficiencies but also extended the overall service life of the breakwater, ensuring continued protection of the port against marine forces.

Figure 8. Case study 2, Left: Repair works on the seaward wall of the Northern Island Breakwater.
Right: View of the repaired parapet of the Northern Island Breakwater from the inner side visible shotcrete coating on the parapet and surface sealing with spray applied polymer-cement coatings, source: own

The photograph (Fig. 8 left) shows the removal of the reinforced concrete parapet and the surface layer of the expansion chamber down to sound concrete, as well as the application of polymer-cement mortar. In contrast to the previously described repair works on another (Case 1) breakwater structure, this case allows for the evaluation of the superstructure repair only, as the intervention was completed just a few months ago (Figs. 8 right). Despite the short time since completion, initial signs of biological growth are already visible at the tidal fluctuation zone, indicating the beginning of natural environmental interaction with the renovated surface.

5.3 *Case Study 3: Caisson quay structure, Port Gdańsk*

The quay, constructed in the 1970s, is based on prefabricated reinforced concrete caissons topped with a trapezoidal coping beam forming the superstructure. After over fifty years of service in harsh marine conditions, significant deterioration of the concrete surface was observed, particularly in the tidal zone. In several locations, reinforcement was exposed due to delamination of the concrete cover, leading to localized corrosion and structural concerns.

To address these issues, a targeted repair program was implemented, focusing exclusively on the concrete elements of the superstructure (Fig. 9). The damaged concrete was carefully removed, reinforcement was cleaned and coated with a corrosion inhibiting primer, and reprofiling was performed using polymer-modified PCC mortars classified as R4 according to EN 1504. To protect the lower edge of the coping beam from ice abrasion, L-shaped GRC prefabricated elements were installed along the quay wall-20×20 cm in standard areas and 20×80 cm at the low quay section recesses where access ladders were located. The selected materials ensured resistance to chlorides, seawater, frost cycles, and mechanical impact. Final surface finishing included sealing with flexible polymer-cement coatings and injecting PCC mortar between the GRC panels and the original concrete to create a durable, cohesive repair system suitable for long-term exposure in a marine environment (Fig. 10, 11).

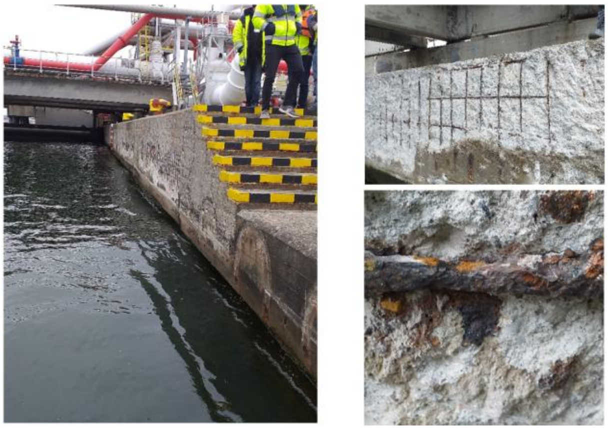

Figure 9. Case study 3, Condition of the quay and capping beam before the 2018 renovation, with close up views of the damaged elements shown on the right, source: own

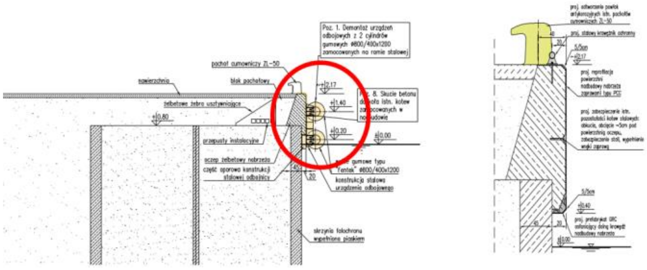

Figure 10. Case study 3, Fender line replacement project: close up view shows the designed surface reprofiling using PCC mortars and the proposed GRC prefabricated element protecting the lower edge of the quay superstructure. Platform modernization project: coloured elements indicate components designated for repair; a detailed view is shown on the right [45]

Figure 11. Case study 3, View of the modernized structure after reconstruction, source: own

5.4 *Case Study 4: Access platform, Port Gdańsk*

Case 4 concerns the renovation of a reinforced concrete access platform and approach walkway leading to a port berth, originally constructed in the 1980s. The structures, consisting of precast prestressed beams supported by reinforced concrete pile caps on prefabricated piles, had been in continuous use for over thirty years under severe marine conditions. Prolonged exposure to saltwater, temperature changes, and heavy use led to advanced degradation of concrete, reinforcement corrosion, and damage to the steel bearings supporting the spans (Fig. 12).

Based on a prior technical assessment, a comprehensive repair project was developed. The scope of work included reprofiling and waterproofing of the top and side surfaces of the pile caps, patching and sealing cracks and defects in the precast beams, replacement of corroded steel bearings with elastomeric types, application of anticorrosion coatings to steel components, and the installation of protective surface systems on areas vulnerable to moisture and environmental exposure. The project employed a variety of advanced materials, including PCC repair mortars, dry spray shotcrete, epoxy-based compounds, low-shrinkage and expansive grouts, and flexible protective coatings. Waterproof PVC membrane expansion joints were also installed to ensure tightness and structural durability (Fig. 13).

Work was conducted in phases using suspended scaffolding and temporary supports, allowing parts of the installation to remain in service during the renovation. The adopted technologies and material solutions restored the structural integrity and serviceability of the platform, extending its operational life for decades to come (Fig. 14).

Figure 12. Case study 4, Condition of the platform before renovation Visible severe damage to both fixed and unidirectional sliding bearings. Extensive corrosion is observed on both steel and elastomeric components. Bearing pedestals are heavily degraded, with numerous cracks, material losses, and spalling, source: own

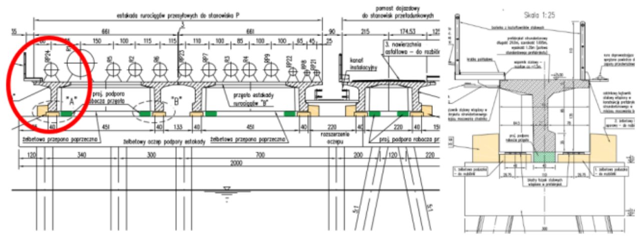

Figure 13. Case study 4, Platform modernization project, with the elements designated for renovation marked in colour; a structural detail is visible on the right side [46]

Figure 14. Case study 4, Condition of the platform after renovation, source: own

5.5 *Case Study 5: Port Authority Quay, Port Gdańsk*

The project concerned the renovation of a section of a berthing quay constructed in 1974, used primarily for tug operations. The objective was to replace the obsolete fender line and refurbish the mooring walkway to meet current operational requirements. The jetty type structure, supported on three rows of prefabricated reinforced concrete piles, included a rear steel sheet pile wall anchored with rock fill (Fig. 15). The scope of works included dismantling of existing fender units and walkway components, construction of a new reinforced concrete coping wall, and installation of point type fender systems using rubber beams with steel stiffeners. The outer edge of the walkway was protected with L-shaped GRC prefabricated elements, and the paved surface was designed in compliance with maritime construction regulations. Mooring bollard blocks were replaced, and coping wall extensions were added at fender locations. The work was divided into three stages to maintain berthing capacity for four tugs throughout the rehabilitation (Fig. 16, 17).

Figure 15. Case study 5, Quay ccondition before renovation, showing significant concrete losses and exposed, corroded reinforcement wall, source: own

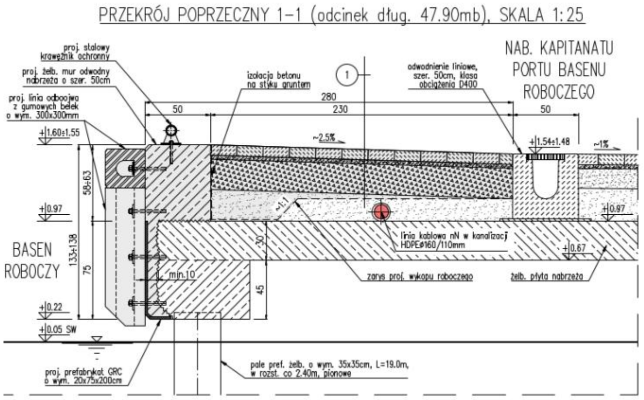

Figure 16. Case study 5, Project for the renovation of the mooring and fender line, including the proposed GRC prefabricated element [47]

Figure 17. Case study 5, View of the mooring and fender line after reconstruction, with the GRC prefabricated element visible on the quay wall, source: own

5.6 *Case Study 6: Reinforced Pier, Port Gdańsk*

After more than 30 years of service in a harsh marine environment, one of the reinforced concrete pier structures supporting mass loading equipment showed serious signs of structural fatigue. Cracking near supports, delamination of reinforcement cover, and general material degradation led to an urgent decision to carry out repairs and structural strengthening (Fig. 18).

The chosen solution involved reprofiling the damaged concrete beams and applying external carbon fiber reinforcement. Carbon fiber mats and strips were bonded with epoxy resins to restore load bearing capacity. This method, widely used in structural engineering, offers high tensile strength, corrosion resistance, and allows work to be conducted without heavy equipment. Repairs were performed using suspended scaffolding, with the affected section temporarily closed during works. Other areas of the terminal remained operational. The method proved technologically efficient and economically viable. Thanks to the durability of carbon fiber composites, the reinforced structure is expected to continue functioning reliably for many years (Fig. 19-23).

Figure 18. Case study 6, Bottom layer of the beam - visible delamination of the reinforcement cover, exposed reinforcing bars, source: own

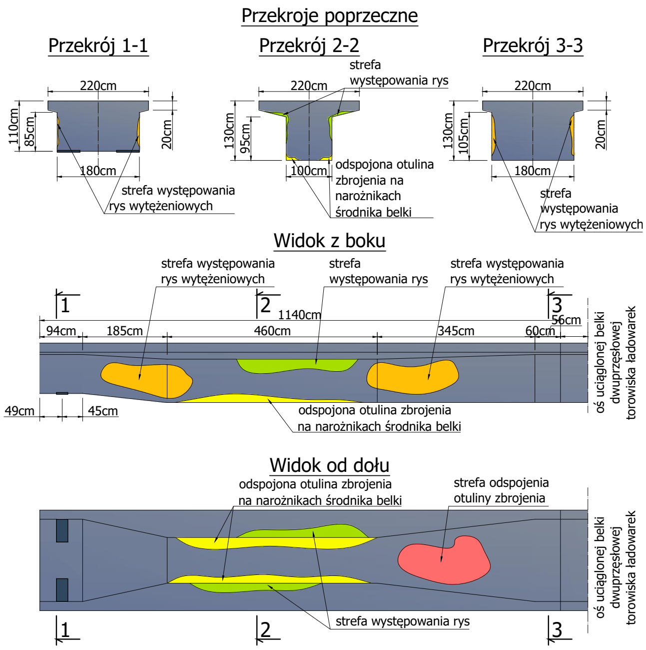

Figure 19. Case study 6, Locations of damage according to preliminary design tests, [48], [49]

Figure 20. Case study 6, Left: after removal of loose or poorly bonded concrete fragments; all reinforcement bars of the bottom layer are visible. Right: the same element during repair - application and anchoring of carbon fiber tapes, source: own

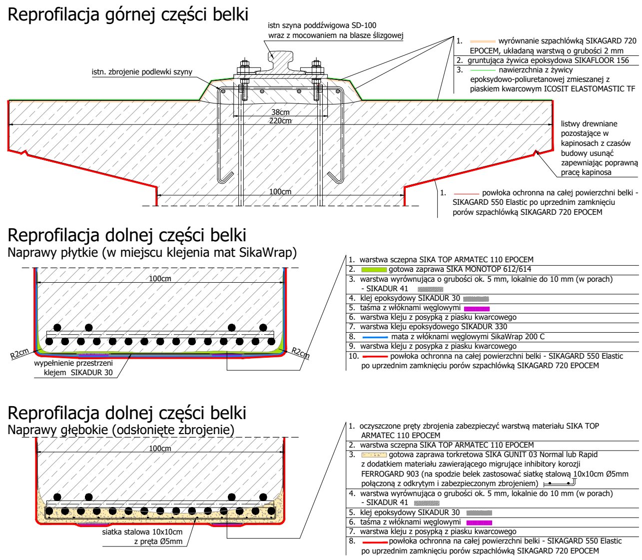

Figure 21. Case study 6, Designed reprofiling and strengthening of crane support beams [49]

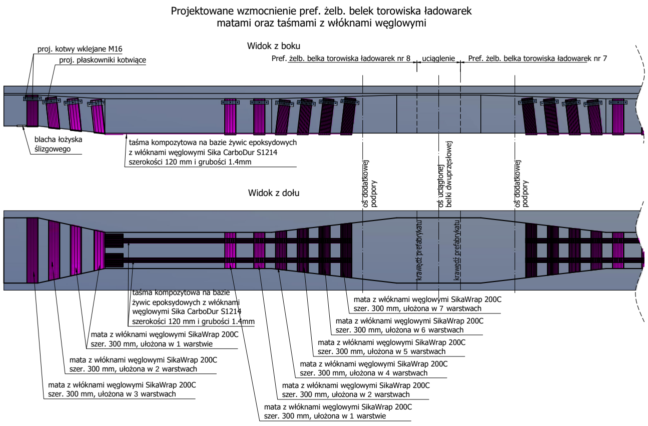

Figure 22. Case study 6, Placing carbon mats and tapes with one prefabricated crane beam [48], [49]

Figure 23. Case study 6, Application and anchoring of carbon fiber mats, source: own

6 DISCUSSION OF CASE STUDIES FURTHER RECOMMENDATIONS

The case studies presented illustrate the diverse nature of concrete and reinforced concrete degradation in marine environments, as well as the wide range of remedial approaches used to address such damage. A key commonality among all the analyzed structures is their long-term service under harsh conditions including water level fluctuations, salinity and humidity, and cyclic loads induced by vessel traffic and wave action. These aggressive factors contributed to gradual deterioration in each case, necessitating timely intervention. In older structures (for example, early 20th century breakwaters), degradation was mostly confined to the concrete superstructures, parapets, and the outer concrete cover protecting the rebar. Repairs in these instances typically involved surface reprofiling and sealing of relatively shallow defects to restore the protective cover. In contrast, more complex or heavily loaded structures such as reinforced concrete crane beam slabs or access platforms experienced damage not only to the outer concrete layers but also to the primary load-bearing elements. These severe cases required more advanced repair technologies to restore structural capacity. Notably, one rehabilitation project involving the external strengthening of crane rail beams with CFRP (carbon fiber reinforced polymer) strips and mats stood out as an innovative solution, and it has since become a reference point for similar works. Other cases employed glass fiber reinforced concrete (GRC) prefabricated elements to protect exposed edges, specialized anticorrosion treatments and low-shrinkage grout for bearing supports, as well as multistage repair works carried out under ongoing port operations to minimize downtime. This breadth of techniques demonstrates the importance of choosing repair strategies tailored to the specific failure mechanisms and operational constraints of each structure. As summarized in the comparative analysis table (see Table 4), the effectiveness of a given rehabilitation approach depended not only on the material properties of the repair products but also on practical aspects of execution, for instance, staging of works to ensure continued quay availability, the accessibility of damaged zones, and underlying foundation at the site. Notably, in most cases the applied repair solutions enabled the facilities to remain in long-term use with no further deterioration observed in the rehabilitated areas. This confirms that the chosen interventions were generally successful in arresting damage and prolonging the service life of the structures.

The presented cases illustrate a wide range of degradation mechanisms and repair strategies for marine concrete structures. As demonstrated in the comparative table (see above), the chosen techniques were specifically adapted to the structure type, extent of damage, and operational constraints. Older structures (Cases 1-3) were primarily affected by surface level concrete deterioration and rebar corrosion, particularly in splash zones or at the interfaces of prefabricated elements. Their rehabilitation focused on reprofiling, the use of GRC prefabricated elements, and protective surface coatings. In contrast, more recent and complex structures (Cases 4-6) required advanced methods such as elastomeric bearing replacement, polymer-cement based reprofiling, and composite CFRP strengthening of load bearing members. Particularly noteworthy was Case 6, the Reinforced Pier, where the external strengthening of reinforced concrete beams using carbon fiber composites was an innovative solution at the time. This approach became a reference model for subsequent reinforcement projects in marine environments, demonstrating that well designed strengthening (without unnecessary major reconstruction) can extend service life significantly, even for structures showing critical signs of structural fatigue.

Overall, the analysis confirms that successful rehabilitation of marine concrete structures requires not only knowledge of material technologies but, more importantly, a tailored engineering approach. Each intervention must take into account the structure's operational history, accessibility, loading conditions, and environmental exposure in order to achieve long-term durability and performance.

Table 4. Comparative Table of Rehabilitation Case Studies for Marine Hydrotechnical Structures

No	Case Study	Type of Degradation	Scope of Repair Works	Applied Technologies
1	Breakwater Constructed in the 1920s	Cap corrosion, concrete losses, timber degradation, rockfill migration	Partial demolition, RC panels installation, new parapet	RC prefabs, C30/37 concrete, dry-mix shotcrete
2	Caisson-type Breakwater	Rebar corrosion, cracks, leakage, baffle damage	Chamber reconstruction, shotcrete, prefabs, protective coatings	GRC, polymer concrete, reinforced shotcrete
3	Caisson Quay Structure	Cover delamination, rebar corrosion, tidal degradation	Cleaning, PCC repairs, edge protection installation	PCC R4, GRC prefabs, flexible surface coatings
4	Access Platform	Bearing corrosion, concrete loss, damage to piers and spans	Reprofiling, bearing replacement, waterproofing, joint repairs	PCC, injection, protective mats and coatings
5	Port Authority Quay	Equipment damage, concrete degradation, corrosion	Demolition, new mooring path, fenders, prefabs, new bollard blocks	GRC, rubber fender beams, C35/45 concrete, anchors
6	Reinforced Pier	Support cracking, cover delamination, rebar corrosion	Reprofiling, external CFRP strengthening, anchoring	CFRP strips and mats, epoxy adhesives

Based on the conducted analysis and case studies, the following recommendations can be formulated for the design and implementation of repair works for concrete and reinforced concrete hydraulic structures operating in marine environments:

1. Early damage diagnosis should be an integral part of maintenance strategies, enabling repair interventions before critical structural deterioration occurs.
2. Selection of repair technologies must be preceded by thorough assessment of environmental exposure, access limitations, and site specific operational constraints.
3. In cases of structural damage, external strengthening using CFRP composites can be a highly effective alternative to traditional methods provided the system is properly designed and anchored.
4. GRC prefabricated elements are well suited for use in impact zones and should be considered in

rehabilitation projects involving ice or mechanical wear.
5. For facilities operating continuously, staged construction and minimal disruption to service are essential to ensure uninterrupted port functionality.
6. It is recommended to maintain detailed repair documentation that captures materials used, techniques applied, and technical outcomes, thus facilitating knowledge transfer for future retrofit projects.

7 CONCLUSIONS

Most marine hydraulic structures operate both above and below the water surface throughout their long service life. Repairs, local refurbishments, large scale modernisations, reconstructions, and structural reinforcements represent an ongoing challenge for hydraulic engineers. The most demanding projects are those in which it is necessary to ensure the stability of the structure during the repair process while also maintaining operational continuity or readiness of the facility.

In the case of marine structures, it is difficult to speak of standard repairs or renovations. Each facility is treated individually, taking into account environmental factors, the types of loads acting on the structure, the materials used in the original construction, and, above all, the type and extent of damage to individual components. Typically, failures and damage in hydraulic structures are caused by the corrosion of marine concrete or the degradation of other key load bearing elements. The durability of marine concrete is determined by damage resulting from the simultaneous action of self-weight, operational loads, and environmental influences such as chloride ingress, sustained high humidity, temperature fluctuations, dynamic loading from wave action and cargo-handling operations, and cyclic wetting and drying. These destructive factors often act synergistically, leading to carbonation, reinforcement corrosion, cracking, delamination of the concrete cover, and, ultimately, loss of structural capacity and water tightness.

The case studies analysed in this paper confirm that successful rehabilitation of marine structures is achievable through accurate identification of degradation mechanisms and the application of repair technologies tailored to the specific type of structure and extent of damage. For older structures, the primary measures included surface reprofiling, crack sealing, application of protective coatings, and the installation of prefabricated GRC panels. More complex and heavily loaded facilities required advanced techniques such as polymer-cement concrete (PCC) reprofiling, elastomeric bearing replacement, low pressure crack injection, and external strengthening with CFRP composites. Of particular significance was the strengthening of crane rail beams at the reinforced handling pier using carbon fibre strips and mats, a pioneering solution at the time, which has since become a reference model for subsequent marine rehabilitation projects. The comparative analysis shows that the effectiveness of selected repair technologies depended not only on material performance but also on foundation conditions, repair staging, and accessibility to the damaged components.

In all six documented cases, the adopted repair strategies successfully restored both the structural integrity and operational capacity of the facilities, with no recurrence of damage observed in the rehabilitated areas. These findings demonstrate that effective rehabilitation of marine concrete infrastructure requires more than knowledge of materials; it demands a comprehensive engineering approach that takes into account operational history, environmental exposure, loading regimes, and site-specific constraints. When executed correctly, such interventions can successfully mitigate the effects of corrosion and significantly extend the safe service life of critical port and coastal infrastructure.

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