Coastal and Offshore Science and Engineering

Knowledge of the Past to Plan the Future: A Case Study of the Port of Catania

R. E. Musumeci[a,*], L. Cavallaro[a], M. Stagnitti[a], F. Castiglione[a], G. D'Agostino[a] and E. Foti[a]
[a]*Department of Civil Engineering and Architecture, University of Catania, Catania, Italy*

[*]*Corresponding author: provide full correspondence details here including e-mail for the corresponding author*

ABSTRACT: The strategic location of the Port of Catania (Italy), situated at the core of the Mediterranean Sea, underscores its importance in both national and international maritime trade. A comprehensive understanding of the port's historical development is essential to improving the quality of its commercial services while simultaneously enhancing its touristic and urban functionalities. The present study examines the evolution of the Port of Catania from its foundation to the present day, addressing the challenges faced by the international scientific community in preserving and upgrading this critical infrastructure. Constructed in 1785, the port has undergone several infrastructural transformations to expand its harbour basin, diversify maritime trade, and improve its safety measures. Notable milestones include the construction of the outer breakwater, designed by Fiocca in 1889, and the inner breakwater, completed in 1912. A defining moment in the history of the Port of Catania occurred during a severe sea storm of the 26th of March 1933, which resulted in the failure of the outer breakwater extension. Such an event cast doubt on the efficacy of the widely employed vertical-wall breakwater design, thus prompting international scientific research into more resilient alternatives. Ongoing research into design solutions for enhancing the outer breakwater, which was reconstructed as a rubble-mound structure, remains a focal point. Since 2019, the Department of Civil Engineering and Architecture (DICAr) at the University of Catania has been carrying out experimental and numerical studies, proposing new probabilistic design methodologies to fortify the outer breakwater against the anticipated impacts of climate change.

KEYWORDS: upgrading solutions, climate change, integrated design approach

1 INTRODUCTION

Port infrastructure is a cornerstone of social and economic development at local, regional, and global scales, thereby acting as the pivotal link between maritime and land-based trading networks (Camus et al., 2019; Izaguirre et al., 2021; Marino et al., 2023). Historically, the most prosperous and advanced civilizations thrived around ports, which were instrumental not only in the exchange of goods and cultures, but also in establishing and maintaining military dominance. The layouts of historical ports have been continuously adapted over time, either through the construction of new infrastructures or the modification of existing facilities, in order to meet the evolving demand of developing societies. Nowadays, existing harbors still need to undergo regular maintenance and upgrades to address the growing demand of port services. Moreover, there is an increasing emphasis on implementing long-term strategies to support the sustainable development of so-called "green ports" (Pavlic et al., 2014).

Maritime trade is strongly influenced by physiography and weather conditions, which constrain navigable routes. Maritime transport primarily relies on specific global shipping lanes, among which the circum-equatorial route holds particular significance. This vital corridor traverses the Mediterranean Sea, linking the Strait of Gibraltar and the Suez Canal.

In this context, the strategic importance of the Port of Catania, located in Eastern Sicily, Italy, becomes readily apparent. Centrally positioned within the Mediterranean Sea, it is equidistant from these strategic passages and serves as a pivotal hub connecting other European and African ports. The geographical significance of the Port of Catania is further emphasised by its influence on a regional area encompassing six of the nine Sicilian provinces, with a total population of approximately three million inhabitants (Foti et al., 2023).

The strategic importance of Catania in maritime trade was recognised as early as 1438, when king Alfonso D'Aragona initiated the construction of its first port infrastructure. This initial development included a reinforced and well-equipped outer breakwater, specifically designed to protect a basin capable of accommodating large warships and commercial vessels. Since then, the Port of Catania experienced continuous commercial growth, despite its infrastructure enduring repeated and severe damage caused by both natural phenomena, such as extreme sea storms, and anthropic events, including war bombings.

Therefore, it is not surprising that nowadays the Port of Catania spans an extensive area of approximately 24,000,000 m^2, comprising multiple water basins and significant land zones. Discussions regarding future development strategies aimed to improve the relevance of the port in maritime trade is open more than ever. However, any proposed development plan must take into account the port's historical origins and context to fully realise its unique potential.

This study provides a concise overview of the origins of the Port of Catania's strategic maritime role and examines its infrastructural evolution, driven by the increasing demand for port services. The complexity of this development has frequently required innovative technical solutions from the international scientific community, particularly in relation to the maintenance and enhancement of the outer breakwater. Accordingly, this research places particular emphasis on the scientific challenges associated with the port's development from its inception to the present, including potential impacts of climate change on harbour defence structures and port operations. Additionally, the study explores future perspectives for the Port of Catania, taking into account the Italian harbor reform introduced in 2015, as well as the port's touristic and urban potential. The emblematic history of the Port of Catania, as reconstructed in this research, offers valuable insights and inspiration for decision-makers and designers worldwide engaged in the modernisation and upgrading of port infrastructure.

2 HISTORY OF THE PORT OF CATANIA

2.1 *The Birth of the Port and Its Initial Expansions*

The Port of Catania, situated on the eastern coast of Sicily, occupies a strategic position, as shown in Fig. 1. Its central location relative to the Suez Channel, the Strait of Gibraltar, the European ports, and North-African ports establishes it as one of Italy's commercial ports of national significance.

The construction of the port commenced in 1785 under the initiative of Ignazio Paternò Castello, Prince of Biscari, who engaged the expertise of Zahra Buda, a Maltese engineer and professor at the University of Catania. This marked the creation of the so-called *Porto Vecchio* (i.e. the hold port), which initially featured an outer breakwater measuring 258 m in length, subsequently extended by an additional 122 m. In this configuration, the harbour basin covered an area of approximately 150,000 m^2. Fig. 2 presents a painting of the Port of Catania as it appeared in 1849.

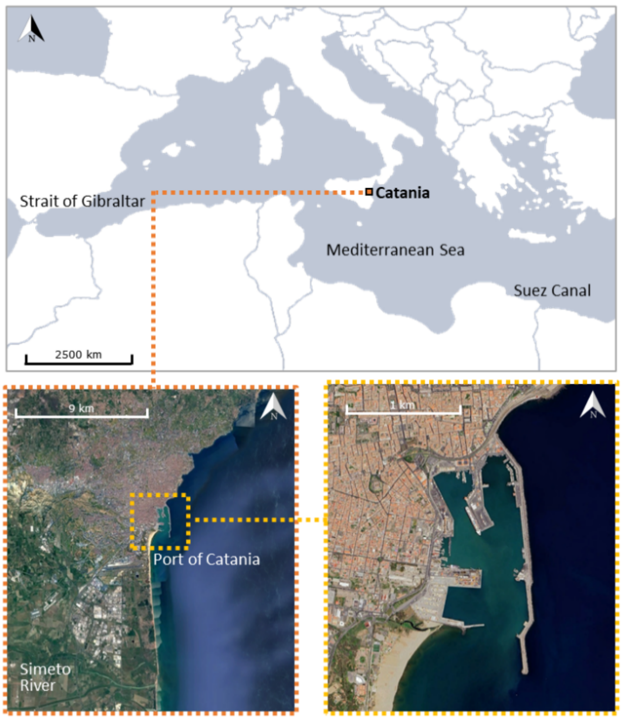

Figure 1. Location of the Port of Catania (satellite images from Google Earth 2024).

Figure 2. Picture of Catania in 1849. The Porto Vecchio designed by Zahra Buda appears in the foreground Source: Sonzogno (1864).

The outer breakwater, designed by Zahra Buda, was constructed using monolithic bottomless caissons filled with pozzolanic concrete. These caissons measured 20.64 m x 10.32 m x 9.30 m, with a total volume of 1980 m^3. They were embedded in rubble-mound structure composed of lava rock, which had a width of 33 m and a 6:1 slope on the seaside.

During the period 1861-1862, following the Unification of Italy, the Port of Catania handled an average of 2,581 ships annually, including departures and arrivals (D'Arrigo, 1947a). As a result of this substantial maritime traffic, the port was classified as a 2nd category, and I class in 1888. Between 1886 and 1890, it recorded an average annual trade volume of 370,000 tonnes of goods embarked and disembarked.

In response to the growing commercial demands, various proposals for the port's expansion were developed, which followed two main design concepts (Bruno, 1954 a,b,c), as illustrated in Fig. 3. The first concept proposed constructing a detached outer breakwater to shield the port from easterly waves, thus creating two entrances to the harbour basin. The second concept envisioned a new rooted outer breakwater, which would establish a single southern entrance to the harbour basin. After extensive deliberation, the municipal administration selected the second design and commissioned engineer Fiocca to complete the preliminary project. The project was finalised and approved in 1872, with construction works commencing in 1873.

In 1889, the expansion of the *Porto Vecchio* was completed based on a project by Fiocca, subsequently modified by engineer Dionisio. The *Porto Vecchio* featured an entrance 330 m-wide, providing access to the harbour basin covering 180,000 m^2, with depths ranging from 5 to 6 m below mean sea level. The *Porto Nuovo* (i.e. the new port), enclosed by the Zahra Buda and Fiocca breakwaters, had an entrance 220 m wide, leading to a harbour basin spanning 685,000 m^2 and accommodating water depths of up to 10 m.

Between 1910 and 1913, the annual average volume of embarked and disembarked goods was approximately 800,000 tonnes, despite the harbour's limited equipment and inadequate protection against storm waves. Therefore, in 1912, construction began on the inner breakwater to mitigate wave agitation within the harbour basin and reduce silting caused by sediments transported from the Simeto river. However, these construction works were halted during the World War I.

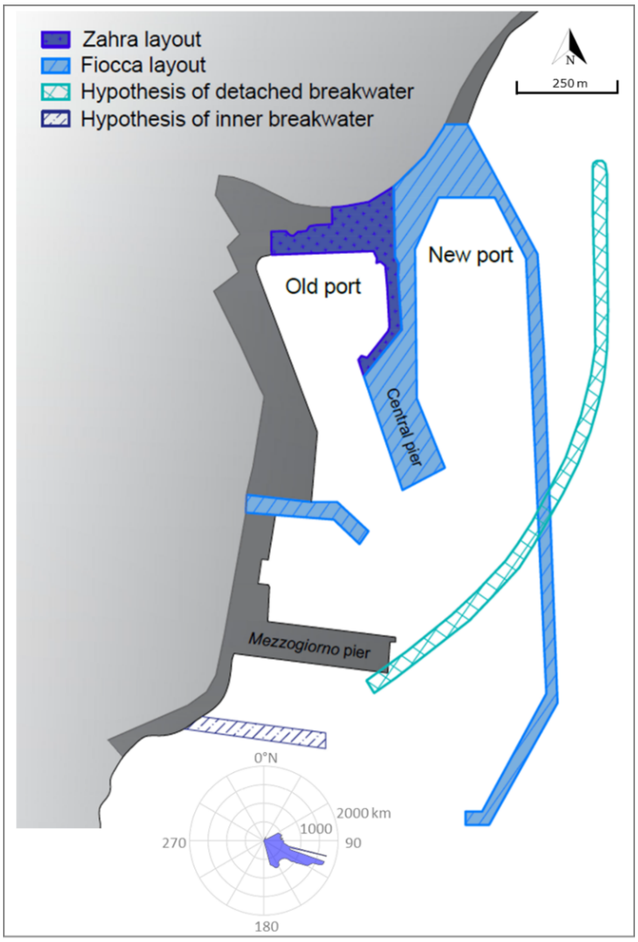

Figure 3. Proposed layouts for the expansion of the Port of Catania following the Unification of Italy. The sketches are modified from Bruno (1954a,b,c) and include an illustration of the geographical fetch.

On March 15th, 1919, the Italian National Council on Public Works approved an ambitious expansion project for the Port of Catania. This project was the outcome of an agreement signed by the Italian government, the municipality of Catania and the Italian Discount Bank, which was subsequently enacted into law in 1921. The above-mentioned project included:

- **Extension of the outer breakwater (Levante breakwater):** The breakwater was extended by 200 m using cyclopean blocks measuring 12.00 m × 4.00 m × 3.25 m, embedded in a rubble-mound structure at a depth of 12.50 m below mean water level. The structure was further protected by a guardian block measuring 6.00 m x 3.00 m x 2.00 m, as illustrated in Fig. 4.
- **Triangular service area:** A triangular zone for the storage of flammable substances was constructed at the connection between the outer breakwater and the above-mentioned extension (see Fig. 4).
- **Completion of the *Mezzogiorno* pier:** The *Mezzogiorno* pier, approximately 460 m long, was completed alongside the development of a mooring and a service area at its root.
- **Western mooring stations:** Mooring stations were constructed along 700 m of newly developed docks.
- **Inner central pier:** A central inner pier measuring 295 m in length and 100 m in width was constructed.
- **Increased water depth in *Porto Vecchio*:** The water depth in the *Porto Vecchio* area was increased up to 10 m.

It is notable that the maximum design wave height for the project was 7 m. The construction works were successfully completed in 1923, adhering precisely to the original schedule.

2.2 *The sea storm of the 26th of March 1933*

A severe sea storm occurred on March 26th, 1933. It caused extensive destruction to the extension of the outer breakwater, by reducing the cyclopean blocks that composed its vertical structure to rubble (Franco, 1994, 1996; Takahashi, 2002). This catastrophic event holds considerable significance for the international scientific community, not only because of the extraordinary magnitude of the sea storm, but especially because it represented the first recorded instance of a vertical breakwater's failure. At the time, vertical breakwaters were the most widely implemented type of harbour defence structure.

In 1932, the cross-section of the outer breakwater, extending from the triangular service area to the head of the structure, was configured as illustrated in Fig. 5a. regarding the cause of the collapse, Cunningham (1935) identified that during the construction phase, the outer breakwater had already sustained some damage from a sea storm on February 22th, 1930. This sea storm generated waves that reached 7 m in height and 200 m in length, displacing several horizontal blocks and partially destroying the armour layer. Although the damage was fully repaired, no significant modifications were made to the original project design. Subsequently, a more severe sea storm occurred on March 26th, 1933. The storm originated from the northeast, and it was characterised by waves 7.5 m in height and 230 m in length. It caused the complete destruction of the outer breakwater extension, with blocks displaced as far as 40 m.

As shown in Fig. 5b, the blocks comprising the vertical structure shifted and slid over one another, primarily due to the absence of vertical structural connections. Such connections are typically achieved through the use of vertical wells filled with concrete reinforced by steel bars, as depicted in Fig. 5c. Fig. 6 presents two photographs of the damaged breakwater, captured by F. Pesce a few days after the storm.

The collapse of the vertical breakwaters in Catania in March 1933 and Algiers in February 1934 (Cunningham, 1935), prompted an in-depth investigation into the causes of these failures. Professor Coen-Cagli conducted a detailed analysis, including physical modeling experiments. The experimental data pertaining to the Catania harbour breakwater, obtained through collaborative research by Professor Coen-Cagli and professor Stucky at the Lausanne Hydraulic laboratory, revealed the following findings, as reported by Minikin (1950):

- The upper portion of the structure, made up by cyclopean blocks, had been completely detached from the lower section.
- The physical model of the breakwater remained intact when subjected to wave conditions measuring7.5 m in height and 55 m in length, which were similar to the parameters recorded during the sea storm of March 1933.

Based on the above-mentioned experimental findings, Professor Coen-Cagli calculated the pressure distribution representative of wave forces acting on the Catania breakwater during the sea storm that resulted in its failure. Significantly, at the level of the sliding plane of the cyclopean blocks, the applied force of 30 tons exceeded the resisting force, which was only 25 tons. It is also noteworthy that the structural cross-section was deemed unstable even when assessed using the widely accepted Sainflou pressure diagram.

Figure 4. Photograph of the outer breakwater of the Port of Catania captured after the completion of its 200 m-long extension. The image shows the triangular service area located at the junction between the original outer breakwater and its extended section (source: F. Pesce, 1932).

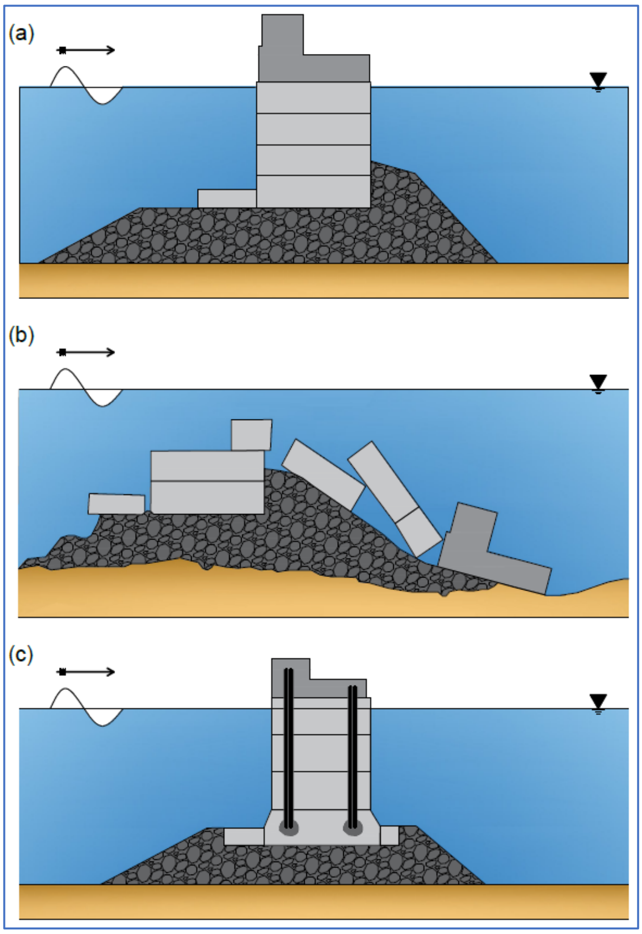

Figure 5. Cross-Sections of the Outer Breakwater of the Port of Catania: (a) typical cross-section as it appeared in 1932; (b) cross section following the destruction caused by the sea storm on March 26th, 1933. (c) typical cross-section of a vertical breakwater, highlighting the inclusion of metal components for vertical structural connections between the blocks, which were absent in the Catania Outer Breakwater. The sketches have been adapted from Cunningham (1935).

2.3 *The port at the end of the World War II*

In the aftermath of the sea storm on March 26th, 1933, the damaged section of the outer breakwater of the Port of Catania was rebuilt and redesigned as a rubble-mound structure featuring a parabolic profile, as illustrated in Fig. 7a (Benassai, 2006). Despite these modifications, the resilience of outer breakwater to extreme wave action, such as the conditions shown in Fig. 8, remained inadequate (Minikin, 1950). To address this vulnerability, Luigi Greco, then President of the Higher Council of Public Works, advocated for additional reinforcement of the outer breakwater. The updated design, as reported in Fig. 7b, incorporated a 3:1 sea-side slope from the mean sea level to the crest level (i.e. +5 m above mean sea level) and a 3:2 sea-side slope from the mean sea level to the bottom (Takahashi, 2002). The revised configuration demonstrated significantly improved performance, withstanding subsequent extreme sea storms, including the particularly severe event of October

Figure 6. Photographs taken on March 31st, 1933, a few days after the sea storm that caused the destruction of a section of the outer breakwater of the Port of Catania, extending from the triangular service area to the head (source: F. Pesce, 1933).

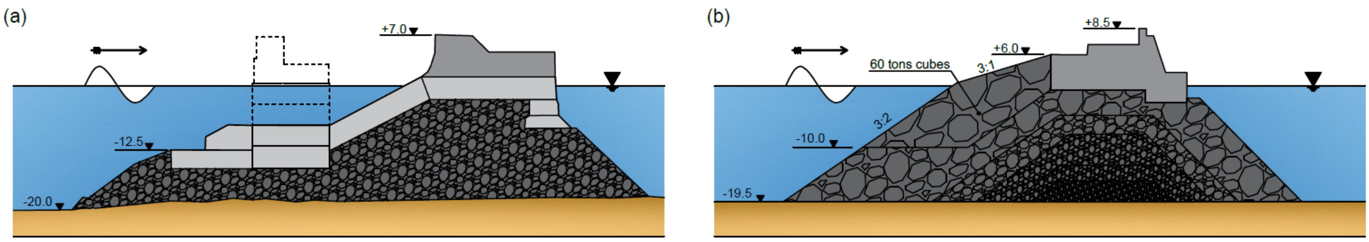

Figure 7. Sketch of the cross-section of the outer breakwater of the Port of Catania which was converted into a rubble-mound structure following the sea storm of March 26th, 1933: (a) configuration featuring a parabolic profile constructed immediately after the sea storm (adapted from Benassai (2006)); (b) reinforcement configuration proposed by Professor Greco to enhance the hydraulic performances of the outer breakwater (modified from Takahashi (2002)).

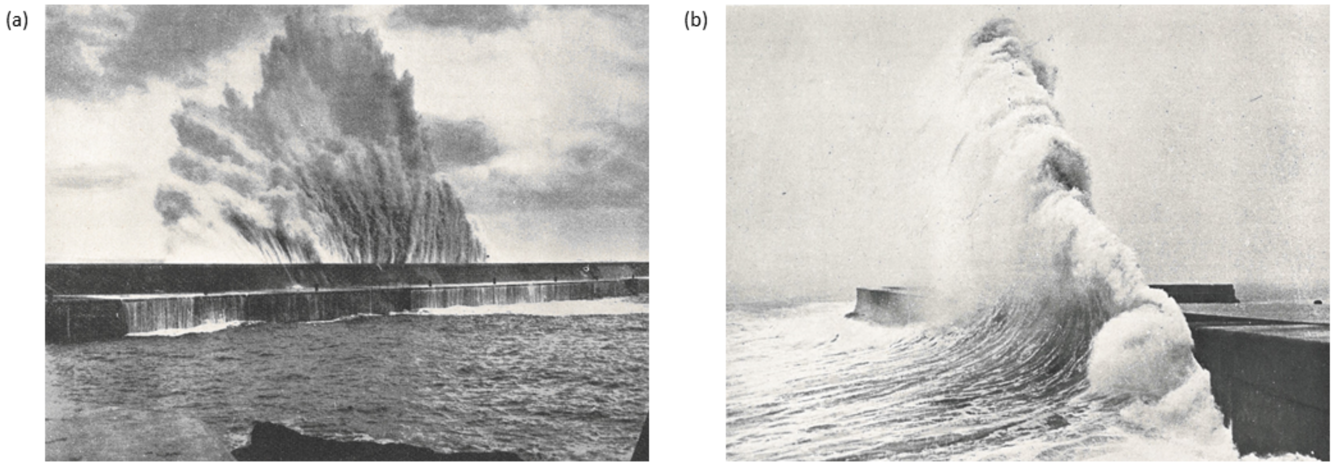

Figure 8. Pictures of the impact of an extreme sea storm occurred in January-February 1940 on the outer breakwater of the Port of Catania, which at the time featured a parabolic-shaped cross-section. Sources: (a)VV. AA. (1953); (b) Minikin (1950).

17th, 1951. The increased structural resistance facilitated the revitalisation of the import and export commercial activities at the port.

During World War II, the Port of Catania suffered extensive damage. More specifically, half of the 5 km of the wharves and the inner central pier were destroyed, along with critical infrastructure such as the machinery for loading and unloading goods, the lighting system, railway connections, service buildings, and a huge number of ships (VV. AA., 1953).

Despite these extensive losses, repair and reconstruction efforts commenced promptly, beginning with the removal of mines from the seabed. By June 30th, 1947, 98% of the planned restoration and reconstruction work had been completed (VV. AA., 1953), at a total cost of 300,000,000 Italian lire (D'Arrigo, 1947b,c).

The pivotal role of the Port of Catania in the revival of maritime trade in the Mediterranean Sea following World War II gained international recognition. This is exemplified by an article published in "The Dock and Harbour Authority" (London, September 1947, no.232, vol. XXVIII), which provided a comprehensive account of the port's foundation, as well as its technical, economic, and commercial development.

With reference to harbour traffic during the period 1900-1952, the Port of Catania recorded the following maximum quantities of embarked and disembarked goods (VV. AA., 1953): i) 556,036 tons in 1913; ii) 570,048 tons in 1927; iii) approximately 650,000 tons in 1934; iv) approximately 450,000 tons in 1949, reflecting the decline of maritime commercial activity caused by World War II. Until 1907, the quantities of exported and imported goods were comparable. However, from that year onward, imports increasingly surpassed exports in significance.

The main imported goods from foreign countries included hard coal, wood logs, sawn timber, wheat, lime stone, concrete marl, corn, chemical fertilizers, mineral oil, petroleum, gasoline, naphtha, paraffin, chemical products, raw hides, charcoal, paper and paperboard, oat, iron scraps, steel, cast iron, vegetable oils, olive pomace, marble and pozzolana, barley, coffee, sugar, cocoa, pharmaceuticals, leather dyeing and tanning products, dyes, paints, salted codfish, stockfish and other preserved fish, vegetable tallow.

The primary exports to foreign countries comprised citrus, sulfur, almonds, hazelnuts, walnuts, pistachio nuts, olives, fava beans, mustard seeds, wine, potatoes, olive oil, citrus peel, tomatoes preserves, bitumen and asphalt, dried legumes, licorice juice, raw cork, bricks, and cut lava stone.

It is noteworthy that the imported wood was also employed in the production of wicker goods and stringed music instruments. Catania, in fact, held national and international records for the importation of these materials.

3 THE PORT OF CATANIA FROM THE LATE 1990s TO THE PRESENT DAY

3.1 *Current state of the port*

Before the implementation of the harbour reform in 1994, the management of major Italian ports varied significantly. Historical ports, which had long-standing and widely recognised importance in maritime trade, were governed by specialised autonomous institutions (e.g. port authorities, autonomous consortia, or specific companies). In contrast, other harbors, including the Port of Catania, were administered by central institutions through local harbormasters.

In 1994, the harbour reform assigned one of the newly established port authorities to the Port of Catania. At that time, its commercial performance categorised it as a port awaiting confirmation. The reform introduced minimum thresholds for the volume of goods or passengers handled, which ports were required to meet in order to remain under the governance of a port authority. However, in order to uphold the meritocratic principles underpinning the establishment of these new port authorities, the reform allowed a ten-year period during which "newly-promoted" harbours could improve their commercial statistics to achieve permanent confirmation.

This reform marked the beginning of the modern era for the Port of Catania. The election of the first President of the Port Authority, Cosimo Indaco, in 1996 signalled a period of unexpected and rapid growth for the port, enabling it to exceed the required performance thresholds well before the deadline for the verification of the Port Authority's status.

The tenfold increase in the volume of goods handled over a span of just twenty-five years, however, came with significant challenges. The Port of Catania, a small port with a master plan dating back to 1978, struggled to accommodate this growth, as the plan did not support the necessary innovations. The port's capacity was stretched as the volume of goods handled surged from just over one million to eight million tons. These challenges were compounded by the city's renewed demand for a revitalised waterfront, which sought to integrate social and economic development with modernization, sustainability and inclusivity. Specifically, the port was tasked with initiating an urban transformation process similar to those undertaken by Genoa in Italy and several Spanish ports in the past decade.

It is important to note that the opportunities and available space to separate the commercial and recreational areas of the Port of Catania have always been extremely limited, owing to its deep integration within the city center. These constraints called for the implementation of upgrades, temporary solutions, and in some instances, compromises, in order to sustain the positive growth trend while meeting market demand. At the same time, innovative solutions were adopted to foster greater integration between the port and the city.

In this context, a passenger terminal was constructed to accommodate the transit of more than 250,000 passengers arriving aboard over 110 vessels. Moreover, a new commercial dock was built to handle Ro-Ro traffic, which grew so rapidly that the entire area designated for the storage of trailers and semi-trailers-central to the Port of Catania's operations- was completely filled within a few months. In few years, Catania became the leading port in Sicily port for container handling, processing approximately 60,000 TEUs annually and for the importation of new cars, with over 80,000 vehicles per year. Furthermore, one of the major international shipping companies, Grimaldi Lines, invested in the Port of Catania by introducing the first four Ro-Ro Hybrid ships, known as the "green giants" of the sea. More recently, the reform initiated by the National Strategic Plan for Ports and Logistic (PSNPL) in 2015 significantly altered the organizational structure of port governance and the planning processes established by the harbor reform of 1994. Legislative decree no. 169/2016, which enshrined the principles defined by the PSNPL, led to the creation of the Port Authority of the Eastern Sicily Sea in 2017. The new Port Authority replaced the previous Port Authorities of Catania and Augusta, thereby consolidating the administration of the two ports into a single institution headquartered in Augusta, a core port of the Trans-European Network of Transport (TEN-T).

Fig. 9 shows the evolution of the layout of the Port of Catania from 2000 to the present day. Moreover, Tab. 1 reports the annual quantities of exported and imported goods, along with the number of passengers recorded at the Port of Catania, thereby providing a quantitative measure of the port's development over time. Currently, the port encompasses a harbour basin of 24,000,000 m^2, with 6,560 m of docks, and 11,855 m of jetties. According to the 2023 official national records of maritime traffic, every year, the port handles: 1,409 vessels; 7,584,674 tons of goods; 4,682 Ro-Ro ship passengers;221,560 cruise passengers; 53,212 TEUs of containers.

In this context, the role of the outer harbor breakwater is of paramount importance. On the one hand, the outer breakwater is essential for safeguarding the inner harbour basin, thus ensuring accessibility, and facilitating the smooth operation of port activities. On the other hand, it plays a crucial role in enhancing the recreational utility of the port, with its over 2 km-long promenade running along its superstructure, offering views framed by the picturesque landscapes of the sea stacks of Aci Trezza and Mount Etna. However, as shown in Fig. 10, the outer armour layer of the breakwater has sustained severe damage due to its obsolescence and is no longer capable of accommodating wave overtopping discharges that are compatible with the operational requirements of the port.

3.2 *Design of the outer breakwater upgrade*

In order to improve the deteriorated hydraulic performance of the outer breakwater at the Port of Catania, the Port Authority of the Eastern Sicily Sea initiated a project to strengthen the existing armor layer. The design of the upgrade solution was strongly supported by the scientific contributions of the Department of Civil CS configuration, which consists in the addition of 62 tons cubes over the properly reshaped existing armour layer following a 2:1 design slope up to the crest level at +8.80 m above MSL, with a quarry stone toe berm to support the extra armour layer and the wave wall at +9.50 m above MSL (Fig. 11g).

Engineering and Architecture (DICAr) of the University of Catania. This collaboration involved both physical and numerical testing to evaluate the response of various upgrading options to wave actions.

3.2.1 *Detailed design phase*

During the detailed design phase, six configurations of the outer breakwater, proposed by the designers, were experimentally and numerically evaluated with reference to representative cross-sections no. 10 and no. 40, located at water depths of 16.50 m and 19.00 m , respectively (Fig. 11a). The configurations studied were the following:

1. E configuration, which is the existing 62 tons cube-armoured structure with a design wave wall at +8.50 m above MSL (Fig. 11b);
2. EM configuration, which is the existing 62 tons cube-armoured structure with a design wave wall at +9.50 m above MSL (Fig. 11c);
3. AS configuration, which consists in the addition of 30 tons Antifer blocks over the existing armour layer, following a 2:1 design slope up to the crest level at +8.80 m above MSL, with a quarry stone toe berm to support the extra armour layer and the wave wall at +8.50 m above MSL (Fig. 11d);
4. AD configuration, which consists in the addition of a homogeneous double layer of 30 tons Antifer blocks over the existing armour layer, with a quarry stone toe berm to support the extra armour layer and the wave wall at +8.50 m above MSL (Fig. 11e);
5. CM configuration, which consists in the addition of a homogeneous single layer of 62 tons cubes over the existing armour layer, with a quarry stone toe berm to support the extra armour layer and the wave wall at +8.50 m above MSL (Fig. 11f);

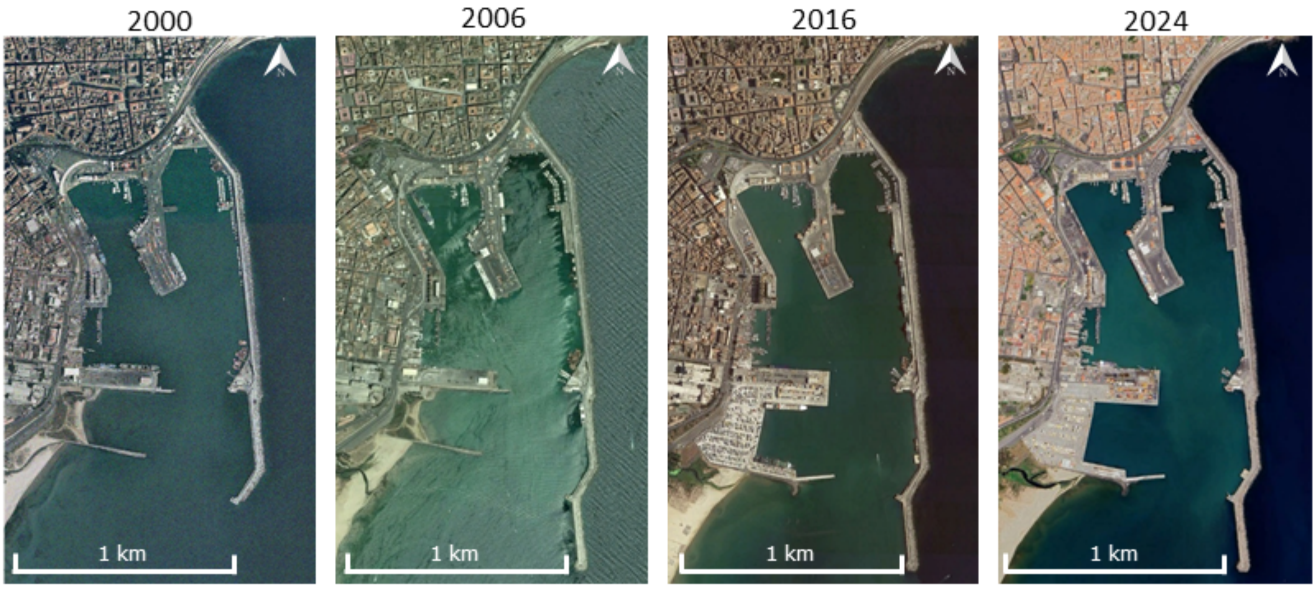

Figure 9. Evolution of the Port of Catania layout from 2000 to the present day. Sources: Sicilian Geographic Information System for the year 2000; Google Earth for the years 2006, 2016 and 2024.

Table 1. Quantities of exported and imported goods and number of passengers recorded at the Port of Catania from the second half of the 19th century to the present day. Sources: VV. AA. (1953) for the period 1996-1945; ISPRA (2009); official national records of maritime traffic for the period 2010-2023.

Period	Ships [no./years]	Goods [tons/years]	Containers [TEU/years]	Ro-Ro passengers [no./years]	Cruise passengers [no./years]
1886-1890	N.A.	370,000	N.A.	N.A.	N.A.
1890-1900	N.A.	450,000	N.A.	N.A.	N.A.
1900-1945	N.A.	544,662	N.A.	N.A.	N.A.
1999	N.A.	2,704,699	14,921	6,953	40,927
2000	N.A.	2,636,777	12,851	37,393	42,616
2006	N.A.	3,844,563	16,372	277,508	71,677
2010	3,269	4,876,699	20,560	251,167	186,613
2016	1,780	7,883,657	49,198	142,704	101,042
2018	1,984	8,617,406	59,764	99,157	123,985
2022	1,392	7,862,342	51,666	5,553	154,152
2023	1,409	7,584,674	53,212	4,682	221,560

In the framework of a scientific collaboration agreement between the Port Authority of the Eastern Sicily Sea and the DICAr, an extensive 2D experimental campaign was carried out from October 2019 to July 2020 in the wave tank of the Hydraulic Laboratory of the University of Catania (Stagnitti et al., 2020, 2023b). The wave tank was equipped with a channel measuring 18.00 m in length, 2.40 m in width and 1.20 m in height. The geometrically undistorted physical model was scaled according to Froude similarity, with a geometrical scale of 1:70. All of the above-mentioned configurations were tested for cross-sections no. 10 and no. 40 by subjecting the structure to progressive damage under irregular sea states, consisting of 1,500 waves. These waves simulated events with return periods of 5, 10, 50 and 100 years, as well as event corresponding to 120% of the wave height associated with a 100-year return period. It is important to note that the six configurations studied were defined during meetings between the designers and the DICAr, which were organised to review and discuss the intermediate results of the experimental campaign.

The experimental setup enabled the acquisition of data regarding the characteristics of incident and reflected wave motion, the damage levels of the outer armour layer, and the mean wave overtopping discharge. The reflection coefficients, calculated using the four-gauge method proposed by Faraci et al. (2015), range from 0.18 to 0.35 and exhibited close agreement with the predictions derived from the Zanuttigh and van der Meer formula (2008). This alignment persists despite a slight tendency to underestimate the theoretical values, which can likely be attributed to the unconventional shape and porosity of the tested structures.

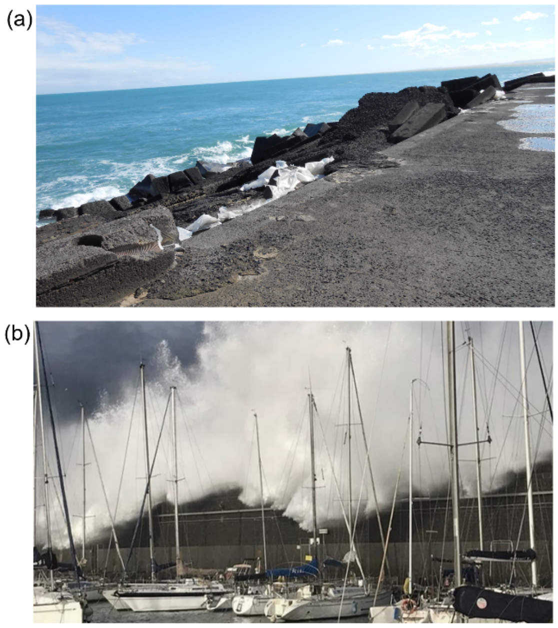

Figure 10. Current condition of the outer breakwater of the Port of Catania: (a) photograph of the damaged armour layer, taken in February 2014; (b) photograph of wave overtopping caused by the extreme sea storm occurred in February 2019.

The damage to the outer armor layer was evaluated using both traditional and innovative measurement techniques at conclusion of each sea state. For example, Fig. 12 presents models of AS (cross-section no. 10) and CS (cross-section no. 40) configurations at the beginning and at the end of the experiments. The traditional damage parameter, N_{od} (van der Meer, 1990), which refers to the number of displaced units from the armour layer within a strip of the breakwater slope of width equal to the median nominal diameter of the armour units (D_{n50}), was employed to assess the damage level relative to the initial, intermediate and total damage thresholds defined by The Rock Manual (Ciria, 2007). In addition, a novel measurement technique for the experimental analysis of damage mechanisms of cube-armoured breakwaters was developed. This technique is based on the quantitative characterization of the armour layer's surface roughness through the analysis of Structure from Motion 3D reconstructions of the tested structure at various stages of damage. Such a technique enables the quantification of reshaping modes and the automated identification of damage mechanisms experienced by the outer armour layer, which cannot be achieved by the traditional methods of counting displaced armour units or calculating the volume of eroded armour. Further details on this novel measurement technique for the analysis of armor layer surface roughness are provided by Stagnitti et al. (2023b). The experimental results on damage dynamics revealed that when additional armour units, either of the same size or smaller than the existing ones, are merely placed over the existing armour layer, the stability performance of the structure is inadequate. In any case, the additional 62-ton cubes exhibit greater stability than the extra 30-ton Antifer units, with cumulative N_{od} values in the range 0.5÷1.2 and 0.5÷6.0, respectively. Only the CS configuration, which involves appropriate reshaping of the structure toe, ensures damage levels below the acceptance limits suggested by Ciria (2007).

The mean wave overtopping discharge, measured using a purpose-designed automated system, was compared to the acceptance limits established by EurOtop (2018). For the design wave, all upgrading options provide at least a 30% reduction in mean overtopping rates relative to the E configuration. Moreover, these options exhibit mean wave overtopping discharges below the acceptance threshold for larger yachts (i.e. 5 l/s m). However, only the CS configuration ensures that the safety limit for smaller boats (i.e. 1 l/s m) is not exceeded. A non-dimensional analysis of the wave overtopping data revealed a good agreement with the predictions of EurOtop (2018) for configurations involving the existing armour layers or additional cubes of the same size as the existing units. On the contrary, EurOtop (2018) tends to overestimate the mean wave overtopping discharge for configurations with additional Antifer units smaller than the existing cubes. This discrepancy is likely attributable to the unconventional positioning of the extra units, whose mutual interaction may lead to unexpected energy dissipation processes.

The results of the combined analysis of damage and wave overtopping experimental data are graphically summarized in Fig. 13. The CS configuration is the only one that simultaneously achieves a reduction in wave overtopping and a minimization of cumulative damage to the outer armour layer, irrespective of the considered cross-section. This outcome can be attributed to the preliminary reshaping of the existing armour layer, which provides a uniform surface for the placement of additional armor blocks at each cross-section. Therefore, the CS configuration was selected as the basis for the detailed design of the upgrading solution for the outer breakwater in Catania.

The scientific collaboration agreement between the Port Authority of the Eastern Sicily Sea and DICAr encompassed the numerical modelling of the outer breakwater. In particular, the open-source CFD software OpenFOAM was employed to simulate wave-structure interaction, focusing on the E and CS configurations (Figs. 11b and 11g) at cross-section no.40 (Fig. Fig. 11a). The simulations employed the Reynolds-Averaged Navier-Stokes (RANS) and Volume-Averaged Reynolds-Averaged Navier-Stokes (VARANS) equations (Higuera et al., 2014a,b), in conjunction with the Re-Normalisation Group (RNG) $k-\epsilon$ turbulence model (Argyropoulos and Markatos, 2015; Yakhot et al., 1992). Two-dimensional, prototype-scale simulations were conducted within a numerical channel measuring 500 m in length and 33 m in height. Irregular sea states, consisting of 260 waves representative of a 100-year return period event, were reproduced. The computational grid featured a uniform vertical mesh size of 0.26 m, and a horizontally variable mesh size, ranging from 0.50 m to 1 m along the offshore direction. Calibration of porous media parameters was achieved using experimental data on wave reflection and mean overtopping discharge, aligning with the established state-of-the-art methods (Losada et al., 2016).

The outcomes of numerical model complemented the experimental findings by offering additional insights into the development of dynamic pressures acting on and within the porous structure. Notably, the maximum mean dynamic pressures were observed at and immediately below the MSL, in accordance with the experimental data related to the outer armour layer damage.

Building on this foundation, the numerical model was further refined and utilised to perform supplementary analyses, specifically examining the influence of the porous media parameter β on the observed mean wave overtopping discharge. Results revealed that variations of 10÷20% in β would lead to changes of approximately 150% in the estimated overtopping discharge. For a comprehensive discussion of the simulations and their findings, readers are referred to Castiglione et al. (2023).

Within the framework of the scientific collaboration agreement, the issue of the laying phase of additional armour units was also examined. A digital 3D model of the cross-section no. 40 of the outer breakwater was developed using both the commercial software *Rhinoceros* (www.rhino3d.com/it/) and the open-source software *Blender* (www.blender.org). This model was employed to simulate the placement of additional armour blocks and assess the potential reshaping of the existing armour layer. The application of the digital model to the AS and CS configurations (Fig. 14) highlighted the need of a detailed laying plan to ensure the irregular placement of the blocks, a requirement for effectively dissipating the incident wave energy. This process can be supported by the use of the digital model itself, which supports the optimization of block arrangement. The plan should account for the effects of initial block inclination and reciprocal block collisions on the final positioning of the armour units.

Upon the conclusion of the scientific collaboration agreement between the Port Authority of the Eastern Sicily Sea and DICAr, additional numerical investigations were undertaken to further examine the wave overtopping phenomenon. These studies focused on the E and CS configurations at cross-section no. 40, which had been identified as the least and most effective configurations, respectively, based on experimental findings.

The two-dimensional CFD model, IH2VOF was used to solve the 2D RANS and VARANS equations. This approach decomposed the instantaneous velocity and pressure fields into their mean and turbulent components (Lara et al., 2011) and applied the $k-\epsilon$ turbulence model. A total of 300 simulations, conducted at an experimental model scale (i.e. 1:70), were performed within a numerical channel 1.60 m in length and 0.40 m in height. The channel was discretized by a uniform mesh with cell sizes of 0.02 m in the horizontal direction and 0.01 m in the vertical direction. Six random realizations of twenty-five sea states, each comprising 1500 waves, were simulated by varying significant wave height, peak wave period, and mean sea level. Once again, experimental data on wave reflection and mean overtopping discharge were employed to calibrate the porosity parameters.

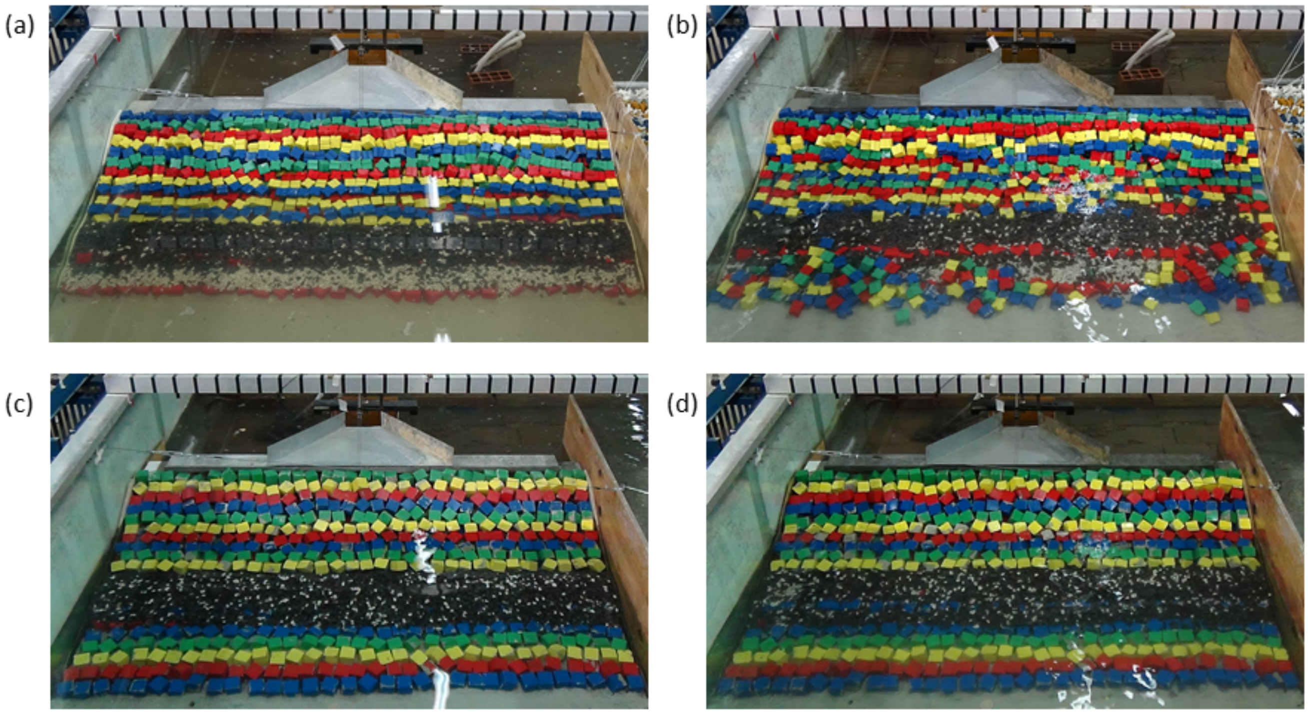

Figure 12. Physical model of the outer breakwater of the Port of Catania: (a) initial and (b) final condition of the AS configuration at cross-section no. 10; (c) initial and (d) final condition of the CS configuration at cross-section no. 40.

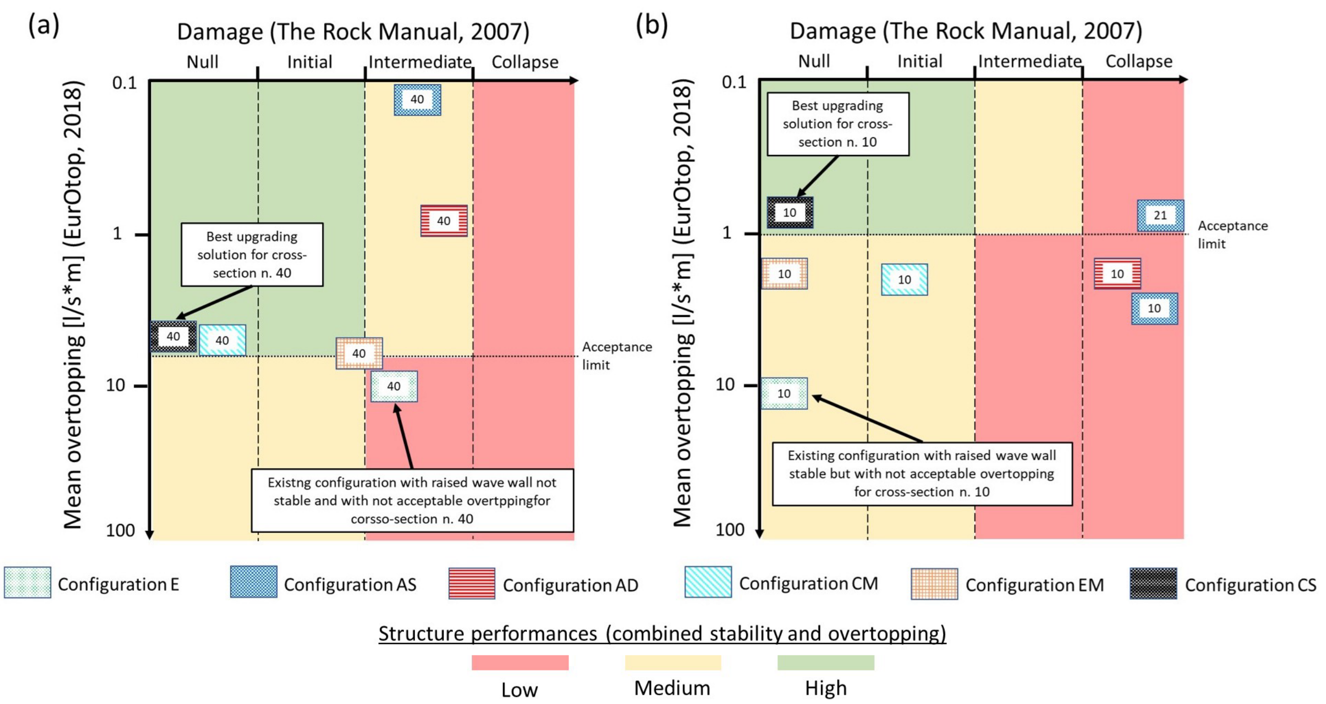

Figure 13. Physical model of the outer breakwater of the Port of Catania: summary of the experimental results for cross-sections (a) no.10 and (b) no. 40 in terms of outer armour layer damage and mean wave overtopping discharge. The results are compared against the acceptance limits recommended by the Rock Manual (Ciria, 2007) and EurOtop (2018), respectively. The red, yellow and green backgrounds denote the structure overall performance levels (i.e. low, medium, high).

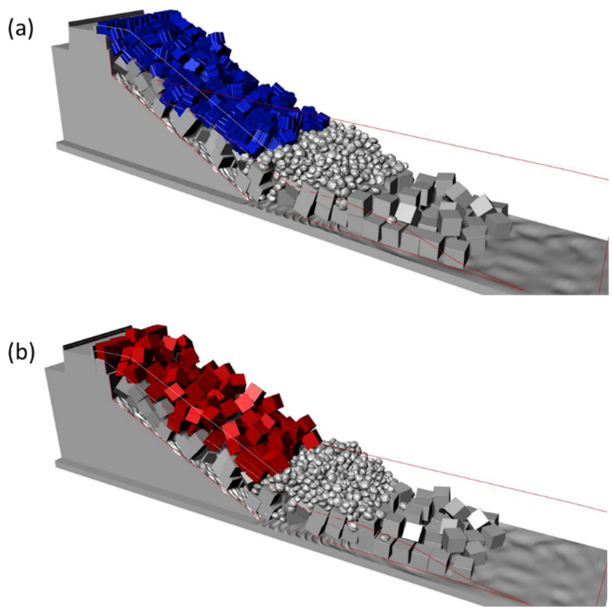

Figure 14. Digital model of cross-section no. 40 of the outer breakwater of the Port of Catania: (a) AS configuration; (b) CS configuration.

The wave overtopping phenomenon was characterized by measuring not only the mean discharge, but also the probability of overtopping and the distribution of individual volumes. Therefore, results from the 300 simulations were used to examine the effects of wave sequence and series length on the uncertainty of the overtopping measurements. Additionally, the simulated overtopping data were compared with existing literature formulations, typically calibrated for newly built structures. In line with findings reported in the literature, the wave sequence was shown to significantly influence the uncertainty of overtopping estimates for the tested non-conventional structures. Moreover, the minimum requirement of 1000 waves, as suggested by EurOtop (2018) for overtopping evaluations, was found to yield stable results only for the most energetic sea states. A comparison of wave overtopping measurements with state-of-art predictions highlighted the necessity of employing specifically calibrated formulas to estimate mean wave discharge and overtopping probability when addressing existing or upgraded rubble-mound breakwaters. A more comprehensive account of the numerical model setup and the obtained results is provided by Stagnitti et al. (2023a).

3.2.2 *Executive design phase*

Subsequent to the awarding of the general contract for the executive design and construction of the upgrade of the outer breakwater of the Port of Catania in June 2023, the company DUOMI s.r.l., as the leader of a temporary consortium comprising Duomi s.r.l., Technital s.p.a., and AT advanced s.r.l., was appointed to carry out the executive design. The consortium engaged DICAr to perform numerical investigations on wave overtopping for the newly optimized upgrading options.

The numerical analysis focused on cross-section no. 40 of the outer breakwater, and considered the following upgrading configurations:

1. A variant of CS configuration (Fig. 11g) with the crest level elevated to +9.80 m above MSL (Fig. 15a), which corresponds to a minor modification of the detailed design configuration.
2. An optimized configuration proposed by the executive project designers. This configuration entails raising the height of the crest promenade by 1 m, , wave wall, and rear side wall by 1 m, incorporating a smaller and flatter toe berm, and relocating the emerged additional blocks over the submerged structure, to create an S-shaped breakwater (Fig. 15b).

The two-dimensional CFD model IH2VOF, mentioned in Section 3.2.1, was employed to simulate the interaction between waves and structure, as well as to estimate the wave reflection and mean overtopping discharge at both the seaward and rear side walls. Moreover, a 2D hydraulic model of the crest promenade was developed, based on the solution of the continuity equation. Such a model uses the wave overtopping discharge obtained from IH2VOF as input and generates output values for the drain discharges and the discharge flowing over the rear side wall.

Concerning the setup of the IH2VOF model, preliminary simulations were conducted to define the computational domain and grid, as well as to calibrate the porous media parameters based on the experimental results for wave reflection and overtopping presented by Stagnitti et al. (2020, 2023b), as briefly summarized in Section 3.2.1. The final channel dimensions are 350 m in length and 45.5 m in height. A trade-off between result accuracy and computational time required a combined calibration of the non-uniform computational grid cell size and the porous media parameters. This calibration was based on two cases, differentiated according to the energy content of the simulated sea state, which is represented by the ratio between the structure's crest level (R_c) and the significant wave height (H_s). Specifically, for more energetic sea states, a coarser grid resolution is sufficient. In the case of R_c/H_s <1.4, the cell size along the horizontal and vertical directions ranges from 1.00 to 2.00 m and 0.78 to 0.50 m, respectively. For R_c/H_s ≥1.4, the cell size along the horizontal and vertical directions ranges from 0.70 to 1.85 m and 0.30 to 0.82 m, respectively. The values of the porous media parameters are consistent with those reported in the existing literature (Losada et al., 2016).

A total of 12 simulations were conducted for the upgrading solutions of the detailed and executive designs, considering two random realizations of the three hydrodynamic conditions specified by the designers, including a 100-year return period event with a mean sea level raised by 0.66 m. The results obtained from the application of the modelling chain indicated that the executive design configuration yields a 20% reduction in wave reflection compared to the detailed design option. As for the mean wave overtopping discharge at the wave wall, no significant differences were observed between the two configurations. However, the executive design solution exhibited lower mean and maximum wave overtopping discharges at the rear side wall, probably due to the primarily vertical development of the overtopping jet. As an example, Fig. 16 shows the typical overtopping jets generated in both the final design and executive design configurations.

The numerical results discussed provide valuable insights for the ongoing conclusion of the executive design phase.

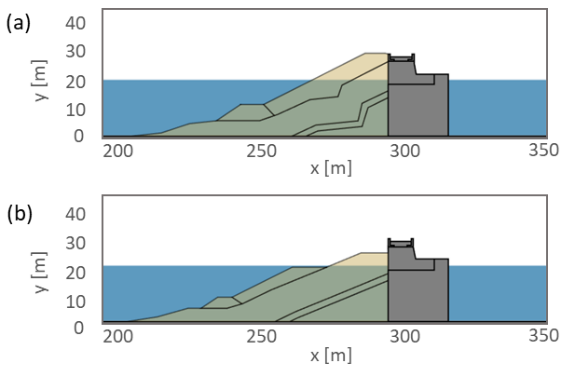

Figure 15. Sketches of the upgrading solutions for the outer breakwater of the Port of Catania numerically investigated to support the executive design phase: (a) final design configuration; (b) optimized configuration proposed by the designers of the executive project.

3.3 *Probabilistic assessment of the upgraded outer breakwater*

The design of upgrading solutions for existing harbour breakwaters, such as the Port of Catania, is influenced by numerous uncertainties. These uncertainties mainly stem from limited knowledge regarding the current condition of existing structures, the stochastic nature of external forcing, and the empirical nature of the formulas used to describe interactions between wave motion and coastal structures. Additionally, the impacts of climate change further exacerbate uncertainty in the characterization of external loads acting on the structure. Traditional design methodologies, which rely on the assumption of stationary forcing, are insufficient to directly address such uncertainties (Foti et al., 2020). On the contrary, probabilistic design approaches enable the explicit incorporation of stochastic variables into the calculation of the failure probability of the structure- defined as the likelihood of the structure reaching a specific limit state.

Despite the theoretical foundations of the probabilistic design approach being established during the 80's and90's (e.g. CIAD project group 1985; van der Meer 1988; Burcharth 1993; Oumeraci et al. 1999), the widespread adoption of these methods has been limited. This is largely due to the relatively recent availability of affordable, high-performing computing resources capable of performing complex probabilistic calculations. As a result, only a few contemporary design guidelines explicitly account for the use of probabilistic methods (e.g. US Army Corps of Engineers 2002; TECH-JAPAN 2009; Puertos del Estado 2010). While numerous studies have examined the calculation of failure probabilities for harbour breakwaters, only a limited number have investigated the implications of climate change (Takagi et al., 2011; Kim and Suh, 2014; Galiatsatou et al., 2018). Moreover, these studies often adopt simplistic approaches and lack robust methodologies for the quantitative comparison of structural performance across different climate scenarios. Within this context, the outer breakwater of the Port of Catania serves as a case study for developing a probabilistic methodology aimed at designing upgraded rubble-mound breakwaters that account for the impact of climate change. Furthermore, the study introduces novel performance indices to facilitate the immediate comparison of alternative design solutions under varying climate scenarios.

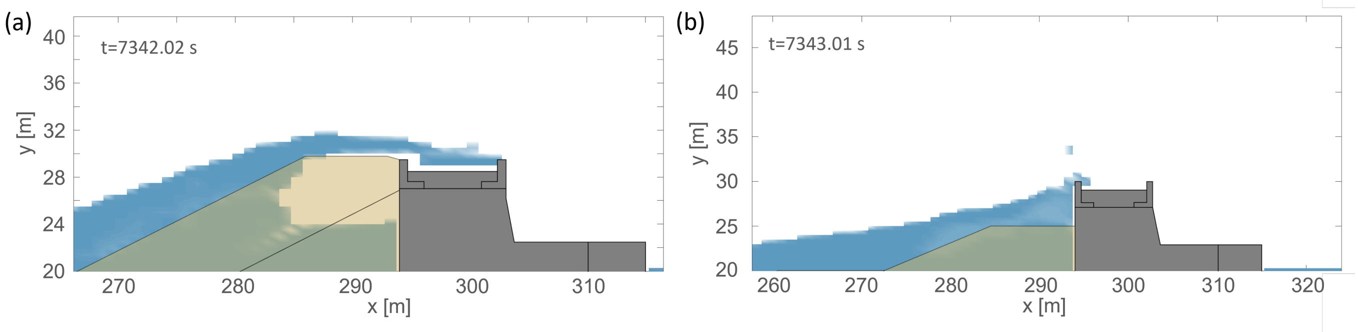

Figure 16. Frames from numerical simulations supporting the executive design of the upgraded outer breakwater of the Port of Catania: (a) detailed design configuration; (b) optimized configuration proposed by the designers of the executive project.

As elaborated in detail by Stagnitti et al. (2022a) and Stagnitti et al. (2022b), the proposed methodology employs Monte Carlo simulations to estimate the failure probability, i.e. the likelihood that the reliability function associated with a specified limit state assumes a negative value over the structure's lifetime. The generic reliability function, derived from either site-specific data or conventional design formulas (e.g. formulas describing the damage progression or mean wave overtopping discharge as functions of sea level and incident wave motion) is expressed as follows:

$$Z = R - S \tag{1}$$

where R and S denote the resistance and solicitation terms, respectively. Therefore, negative values of the reliability function correspond to the condition $R < S$. The assessment of both R and S involves stochastic variables (i.e. geometry and material parameters for R and wave and sea level characteristics for S), which are defined by probability distribution functions. A marine climate emulator is used to generate random sea storms and sea levels based on the probability density functions of mean sea level and of significant wave height. Additionally, site-specific relationships are applied to link the latter with the peak wave period, the sea storm duration and storm surge height. The effects of climate change are incorporated through the factor of change method (Peres and Cancelliere, 2018).

To enable a comparative analysis of failure probabilities over the structure's lifetime, calculated for different upgrading options under both present and future climate scenarios, the following performance indices are defined: i) the failure index, which is the ratio between the failure probability over the structure's lifetime and the maximum acceptance limit (r); ii) the rate of growth of the failure probability throughout the structure's lifetime (s).

The probabilistic design methodology was implemented for the outer breakwater of the Port of Catania, focusing separately on the ultimate limit state (ULS), associated with the collapse of the additional armour layer, and the serviceability limit state (SLS), linked to excessive mean wave overtopping discharge. Reliability functions were developed based on both traditional and site-specific design formulas. In particular, the ULS site-specific formula was calibrated using experimental data on damage progression obtained for the upgraded configurations featuring an additional armour layer. Similarly, the SLS formula was calibrated using experimental data on mean wave overtopping discharge for the E and CS configurations (see Section 3.2.1).

The findings revealed that the use of reliability functions calibrated only for conventional breakwaters results in an overestimation of the stability and hydraulic performances of the upgraded structure. However, when both traditional and site-specific formulations were considered under the present climate scenario, the failure probability of both the existing and upgraded structures remained below the acceptance threshold of 10^{-1} (Puertos del Estado, 2010). Moreover, under future scenarios derived from climate projections provided by the Copernicus Climate Change Service (Caires and Yan, 2020; Yan et al., 2020), the failure index and the rate of growth of the failure probability for the E and CS configurations were found to be, on average, 30÷40% lower than the present values. This indicates an expected improvement in the performance of the structures in the future. This enhancement correlates with the predicted reduction in future significant wave heights at the Catania site, which exerts a more pronounced influence on the structure's response to external loads than the anticipated rise in sea level.

4 CONCLUSIONS

The historical analysis of the Port of Catania, as reconstructed in the present study, highlights its pivotal role in Mediterranean maritime traffic. This infrastructure has always functioned as a strategic flywheel for the development of Eastern Sicily, supporting and sustaining the socioeconomic growth. Notably, the port has supported the area where the majority of the island's productive activities are concentrated.

The challenges associated with the reconstruction or upgrading of the port in response to extreme sea storms have also inspired and mobilized the international scientific community. The damage sustained by the vertical outer breakwater during the severe sea storm of March 26th, 1933, significantly undermined the confidence in vertical wall breakwater technology, which was then widely employed worldwide. This event catalysed research into more effective, wave-resilient technological solutions. Moreover, the current obsolescence of the structure, coupled with the effects of climate change, introduces new complexities that are being addressed through interventions grounded in an integrated design approach. This seeks to ensure adequate safety levels by combining the expertise of designers and harbour managers with insights from physical and numerical models. In accordance with the latest international design standards and guidelines, the integrated design methodology should incorporate probabilistic approaches for the assessment of the structural performance, a field currently undergoing significant development.

The future challenge will be to develop a highly sustainable and technologically advanced port, one that not only enhances and diversifies its commercial sector, but also offers valuable new spaces for urban life. Achieving this goal will require a comprehensive understanding of the history of the infrastructure, which will be crucial for effectively highlighting the intrinsic characteristics of the Port of Catania. In this context, the harbour reform started in 2015, through the issuance of the National Strategic Plan for Harbours and Logistic (PSNPL), represents a significant opportunity. The involvement of the Port Authority of the Eastern Sicily Sea enables the consideration of broader areas beyond the Port of Catania itself, extending to the districts of the ports of Augusta and Pozzallo. This opportunity fosters integrated planning in line with the philosophy underlying the harbour reform, which envisions the establishment of multiple logistic platforms along the Italian coastline, capable of providing a wide range of services to global markets.

For instance, relocating the container terminal to Augusta presents an opportunity to attract new operators to the Port of Augusta, thanks to the newly available space. The shift will not only revitalize the currently underused Port of Augusta but also ease the operational burden on the Port of Catania. It will also facilitate the reorganization of spaces and foster a new relationship between port and the city. The current proposal for the new master plan of the Port of Catania invests on its role in tourism and urban development. In conjunction with improvements in infrastructure to support the growth of commercial, ferry, cruise, and general cargo traffic, this will create new spaces in the transition zone between the port and the city. These developments will pave the way for the long-awaited establishment of a sustainable and vibrant waterfront.

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