ADAPTATION OF THE COASTAL PROTECTION SYSTEM AT MARINA DI PISA, TO EXTREME SEA CONDITIONS: EXPERIMENTAL ANALYSIS OF THE SUBMERGED BREAKWATER AND GRAVEL BEACH

Amanda Zannella, Andrea Esposito, Irene Simonetti, Lorenzo Cappietti

Abstract: The coast of Marina di Pisa has been subjected to strong erosion for decades. The current protective system comprises a large rubble-mound seawall, 6 emerged rubble-mound breakwaters, and 4 cells made up of a submerged breakwater and an artificial gravel beach framed by two groynes at the extremities. One of these cells experiences large amounts of water and gravel overtop onto the promenade and its two main components are studied through three design parameters: gravel nourishment width, gravel nourishment height, and width of the submerged breakwater crest. Fifteen configurations based on the design parameters were experimentally tested under the same wave motion and sea level. Three main outputs were analyzed: gravel overtopping, water overtopping, and final equilibrium profile which included the height and distance from the promenade of the crest formed due to wave action. The results also showed that an optimization between the increase in gravel nourishment width and breakwater width must be found as a large increase in one minimizes the effectiveness of the other. Additional observations on the amount of gravel added and the classification of gravel beaches are also made.

Keywords: Submerged Breakwater, Gravel Beaches, Marina di Pisa, Experimental Modelling

Amanda Zannella, University of Florence, Italy, amanda.zannella@unifi.it, 0009-0008-6057-5523
Andrea Esposito, AM3 Spin-off s.r.l., Italy, andrea.esposito@am3spinoff.com
Irene Simonetti, University of Florence, Italy, Irene.simonetti@unifi.it, 0000-0002-9263-0688
Lorenzo Cappietti, University of Florence, Italy, lorenzo.cappietti@unifi.it, 0000-0002-3957-5763

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Introduction

Marina di Pisa is a coastal town located on the Northern Tuscan coast on the Tyrrhenian Sea, at the south end of the mouth of the Arno River. The city has suffered from a long history of coastal erosion and coastal protection strategies which have contributed to its present state. The current coastal defense system at Marina di Pisa is composed of a large seawall along the coastal road, standing about 4 m above m.s.l. and extending south of the mouth of the Arno River for about 2.3 km. Additionally, about 50÷100 m offshore from the seawall, there are 10 rubble mount breakwaters ranging from 200÷270 m long and separated by a 15 m gap. Six of the breakwaters are emerged 1.0÷3.0 m above m.s.l. and the other four (in cells 7, 6, 5, 4, i.e. counting southward from the mouth of Arno River) are submerged about 0÷1 m below m.s.l. with gravel nourishment seaward of the existing seawall. Between the breakwaters, there are parallel rubble mount groins extending from the coast.

The present-day, heavily protected coast at Marina di Pisa is the result of decades of work and the implementation of various attempts at protection strategies, first through "hard" protection and slowly transitioned into a composition with "soft strategies". The first signs of erosion were evident right after the establishment of Marina di Pisa in 1872, when a large buffer of sandy beach still existed between the town and the sea. The first recording of a protective perishable structure against seen erosion is from a postcard of Marina di Pisa from 1915, which kickstarted a battle between the force of the sea and the attempt at land preservation with "hard" protective structures [12].

By the end of the 1960s the coast located south of the Arno's mouth was protected by groins, 2.3 km of seawalls (built in 1928), and 10 detached rubble mound breakwaters (built in the period 1935-1940 and 1965-1975), each 200÷270 m long, 3 m high above m.s.l., separated by 15 m wide gaps and about 50÷100 m off the shoreline [6] which can be seen in Figure 1a. The high investment in the protection of the coast has shown to be essential for the survival of Marina di Pisa. In Figure 1b, the erosion map recreated by Bini et al. [3] and the satellite image of Marina di Pisa in 1988 (Figure 1a) shows the difference in the evolution of the north and south of the mouth of the Arno River. A clear contrast in the erosion of the two sides of the river is evident as the south boundary was heavily guarded and the north side was left free to erode, losing more than 1 km of land.

Although Marina di Pisa has been protected by heavy interventions, erosion on the seabed south of the Arno River has not been controlled. Right after the construction of the emerged breakwaters, water depths immediately onshore of the breakwaters averaged approximately 2 m, whereas depths at the offshore foot of the breakwaters averaged 3 m. Because nearshore erosion has continued as a result of the decreased alongshore sand supply to the system, the offshore depths increased and are now between 5÷7 m. The increased water depths offshore of the breakwaters have allowed higher incident wave motions and have caused the breakwaters to frequently fail, requiring substantial maintenance and a complete reconstruction of the barriers with heavier rocks for the main armor layer. In this circumstance, the action of incident wave motions with increased energy caused higher mass flux through and over the detached breakwaters thus increasing the water level between the breakwaters and the seawall during storms, i.e., also called wave piling-up [6]. Under these conditions the seawall was frequently overtopped leading to flooding of adjacent streets and buildings, often causing the closing of the coastal road. In 2002, as a means to reduce overtopping and flooding, an artificial gravel beach (grain size D50=6 mm) was emplaced seaward of the seawall of cell 7. A severe storm in October 2003 (H_s=6.6 m, H_{max}=11.5 m, T_p=10.5 s at the La Spezia gauge) washed a substantial amount of water and gravel over the seawall and onto the streets, highlighting the nature of the problem [6]. The wave transmission at cell 7's emerged breakwater and the related wave piling-up in the breakwater's rear side was still too high, while the volume of gravel nourishment was still too low to relocate the shoreline at a safer distance from the promenade, even considering that the relatively small gravel grain size allowed their abundant displacement shoreward under the up rushing of waves on the gravel nourishment [7]. If the volume of the gravel nourishment was sufficiently larger and/or the wave transmission at the detached breakwater was sufficiently lower the gravel overtopping on the promenade would not have occurred. The response to the 2003 storm damage was to renourish in 2006 with larger grains, about 4÷8 cm and larger volume in an attempt to reduce the transport of sediment onshore of the seawall. Moreover, the detached breakwater was converted into a submerged breakwater and its crest was widened to enhance the dissipation of wave energy thus limiting the energy of the waves impacting the gravel nourishment [5]. In the following years, cell 7 has not experienced any further gravel overtopping on the promenade proving the effectiveness of this system in protecting Marina di Pisa.

Gravel nourishment became such an integral part of the protective system because its behavior under significant wave action differs greatly from sand due to many relevant factors, e.g. to its high permeability and the higher inertia of each sediment grain. The uprush of wave breaking is higher than the settling velocity of the gravel [10] which carries a large capacity of sediment transport onshore. The high permeability of the beach then allows for water infiltration which decreases the sediment transport capacity of the backwash [1, 4, 11]. This system of onshore transportation of gravel creates the most significant feature of gravel beaches, their crest, which naturally forms in response to higher energy from the ocean, triggered by higher periods and higher waves, creating a physical protection barrier to the coast. The high permeability and hydraulic roughness of gravel nourishment allow for large energy dissipation of waves [2]. The ability of gravel beaches to naturally form a protective barrier against coastal flooding, unlike sand that easily erodes, is the main characteristic that allows gravel nourishment to be a valuable option as a coastal protection system.

Currently, four out of the ten cells (cell 4, 5, 6, 7) at Marina di Pisa, starting from cell 7 in 2006 to cell 4 in 2018, have adopted the mixed "hard" and "soft" protection system, each composed of a submerged detached breakwater, gravel nourishment, sea wall, and groins framing the cell to prevent longshore transport of gravel (Figure 1c). Three of the cells have proven to be successful, but the protection level at cell 4 has been shown to still be unacceptable due to the persistence of large amounts of gravel and water overtopping on the promenade during major storms. In principle, the unsatisfactory protection level at cell 4 can be linked to the following differences in the coastal protection system's design concerning cells 5, 6, and 7: i) the smaller distance of the submerged breakwater to the seawall, ii) the higher water depths on the breakwater's seaward and shoreward sides toes; iii) the lower seawall crest level; and iv) the lower gravel nourishment crest level. The focus of this paper is to analyze, through 2-D experimental methods, the impact that the two major components of the current coastal defense system, the submerged breakwater and gravel nourishment, have on the behavior of cell 4 during major storms.

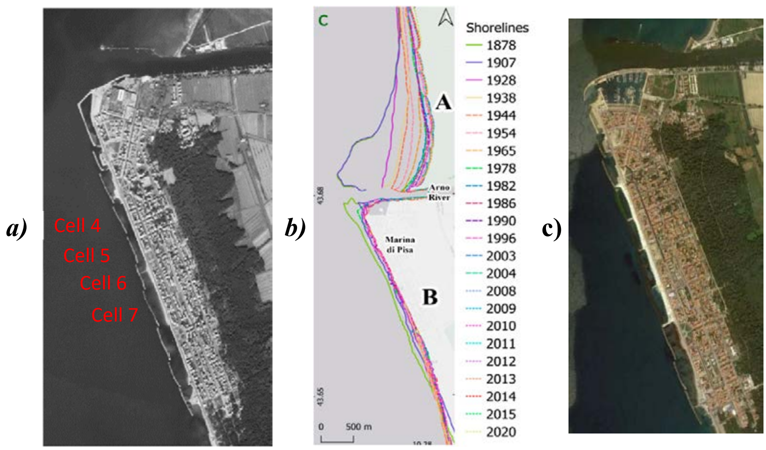

Figure 1– a) Marina di Pisa 1988 [8], b) Historical evolution of the coastline position at the Arno River mouth from 1878 to 2020 [3], c) Marina di Pisa 2021, with a naming convention for the cells (Google Earth).

Materials and Methods

The experiments were funded by the Region of Tuscany and were performed in one of the Wave-Current Flume (WCF) in the Laboratory of Maritime Engineering (LABIMA) at the Civil and Environmental Department of the University of Florence. The wave flume utilized is 37 m long, 0.80 m wide, and 0.80 m deep. It can produce a maximum wave height of 0.35 m within periods ranging from 0.4÷1.25 Hz [9], with a piston-type wavemaker. Due to the restrictions imposed by both the wave flume and the components of the model, the chosen scale for the model is 1:36. The section chosen for the 2-D experiment was retrieved by a bathymetric survey of cell 4, where the section, in relation to cell 7 had the following parameters: 1) smaller beach width; 2) deeper seabed on the submerged breakwater's shoreward side due to the presence of a hole; 3) deeper seabed at the submerged breakwater's seaward toe.

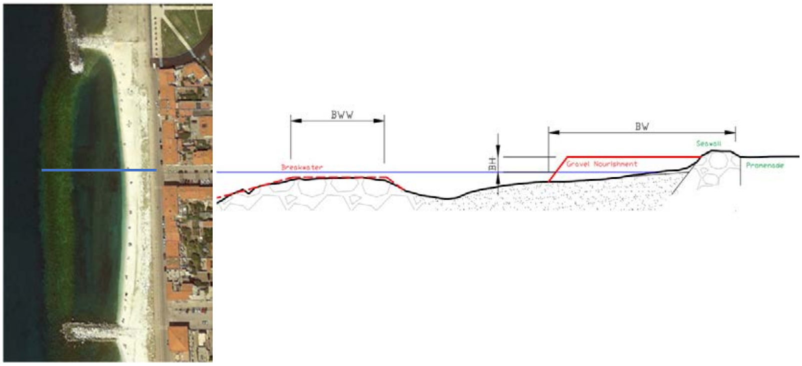

Figure 2 – Cell 4 2021 (Google Earth) (left), Configuration parameter (right).

The components of the model were designed based on Froude similarity. The current configuration at cell 4 on the chosen section, is composed of about 11.5 m of gravel nourishment from the promenade with a characteristic size of 4÷8 cm and it was represented by 1-2 mm gravel in the model with the extension of nourishment varying in height and width. The seawall stands at 4.5 m above m.s.l. with a crest of 4 m and stones of 1÷4 tons, it was represented as scaled-down dimensions in the model with 21÷84 g stones. The submerged breakwater has a crest of 20 m, -1 m below m.s.l. with stones of 5÷10 tons that were represented in the model with unchanging elevation but varying lengths of increasing crest width and with 105÷210 g stones in the model.

The test configurations were composed of the variation of the two main protective components of the cell: the submerged breakwater, and the gravel nourishment. For the fifteen tests carried, three main parameters varied: the extension of the current 20 m submerged breakwater (BWW = 30 m, 40 m, and 50 m seaside), the width of the gravel nourishment (BW = 40 m, 50 m, 60 m, 70 m) and the height of gravel nourishment (BH= 2 m and 3 m), Figure 2. The combination of varying parameters can be seen below in Table 1. The model was calibrated by reproducing the current state of the cell and testing it with a wave action that represented three recent storms, that caused gravel overtopping, with a maximum incident significant wave height of 4.1 m at the toe of the submerged breakwater, period of 12 s and sea level set up of 0.4 m.

Once the model was validated, all the other configurations were tested under the same extreme wave action that represented the worst-case wave motion that is physically possible in the 7 m water depths at the toe of the submerged breakwater. Therefore, the storm was represented by an incident significant wave height of 4.3 m at the toe of the submerged breakwater, a period of 12 s, and a set-up of 0.8 m with a duration of 6 h (significant height of 0.139 m, a period of 2 s, setup of 0.022 m and 1-hour test in the model). It is important to state that the tests were carried out with the initial profile of a flat and horizontal emerged berm of the gravel nourishment as it has been just nourished, which showed to be the worst-case scenario for overtopping for the specific nourishment lengths we tested as the gravel had not given time to form its crest, but the crest formation was forced to take place during the storm.

Results

The outputs of each test included an initial survey of the set configuration, a final survey conducted after the wave action, the amount of gravel overtopping in l/s/m, and the amount of water overtopping in l/s/m (Table 1).

Table 1– Parameters and outputs of test in Prototype

Test	Lab Code	Breakwater crest width [m]	Nour. Width [m]	Nour. Height [m] m.s.l.	Measured Gravel Overtop. (l/s/m)	Measured Water Overtop. (l/s/m)
1	C1	20	40	2	0.8	3.2
2	C2	20	40	3	0.3	1.4
3	C3	20	50	3	0.1	0.7
4	C4	20	60	3	0	0.1
5	C15	20	70	2	0.1	0.1
6	C7	30	40	2	0.1	1.4
7	C6	30	40	3	0	0.2
8	C8	30	50	2	0.2	0.8
9	C5	30	50	3	0	0.2
10	C9	30	60	2	0.1	0.1
11	C10	30	70	2	0	0.1
12	C11	40	60	2	0.1	0.2
13	C14	50	40	2	0.2	0.2
14	C12	50	60	2	0	0
15	C13	50	50	2	0.1	0.2

*The sea level considered during each test was +0.8 m above the m.s.l.

Discussion

Effects on Overtopping

The configurations accepted as effective are those in which the gravel overtopping was 0 l/s/m, and water overtopping was less than 0.1 l/s/m. Sensitivity analysis of both water and gravel overtopping against the increase of the width of the submerged breakwater as well as the increase in gravel nourishment was completed by keeping two out of the three parameters constant and analyzing the change in overtopping within the change of the third parameter. The analysis showed some expected results. With an increase in gravel nourishment width and height, there was a decrease in both water and gravel overtopping. Furthermore, an increase in the submerged breakwater width resulted in a decrease in water and gravel overtopping, although values of overtopping suggest that the effect of the increase of the extension of gravel nourishment is greater than that of the extension of the breakwater. Throughout the sensitivity analysis, it was also evident that while the submerged breakwater and gravel nourishment worked together to decrease the amount of gravel and water overtopping, an increase in one of the parameters eventually decreases the effectiveness of the increase of the other.

Figure 3 shows the decrease in effectiveness of an increase of breakwater width, as the gravel nourishment width (BW) increases.

Therefore, when working with this approach of coastal protection, it is imperative to have a combination where the effectiveness of both components is optimized. Interestingly, analyzing the nourishment with the same volume of gravel (Test 9 and Test 10) but different configurations of height and width showed that the initial profile does indeed have a direct impact on the amount of gravel overtopping, as the configuration with the greater height had less amount of gravel overtopping.

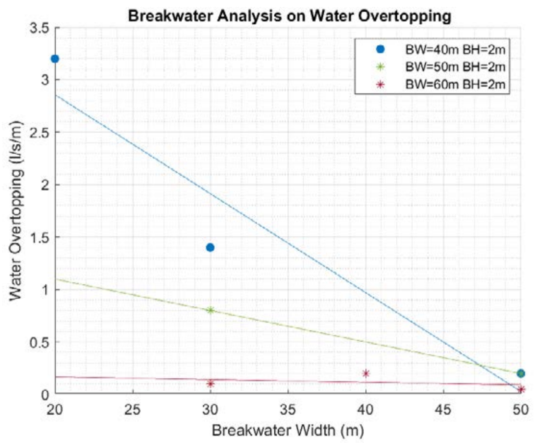

Figure 3 – Breakwater Analysis on Water Overtopping.

Effects on Final Profile

The amount of gravel nourishment and width of the submerged breakwater also had a direct impact on the position of the crest on the final profile, that in turn has great importance in controlling the occurrence of gravel overtopping on the promenade. If the gravel nourishment volume was not enough for creating a sufficiently large beach, then the morphodynamics would lead to the formation of the crest on the promenade which results in gravel overtopping. As seen in Figure 4, the parameter that most affected the position of the crest is the gravel nourishment width, as it increases the crest moves away from the promenade. The submerged breakwater has also been shown to have a similar effect but with a much lower effectiveness than the nourishment. Furthermore, the configurations that included a large amount of nourishment width and large breakwater form no crest, often starting with nourishment larger than 60 meters. This phenomenon can be due to large energy dissipation and the lack of space between the breakwater and nourishment that allows the waves to propagate in a way in which its interaction with the gravel nourishment is less effective in creating the crest.

a)

b)

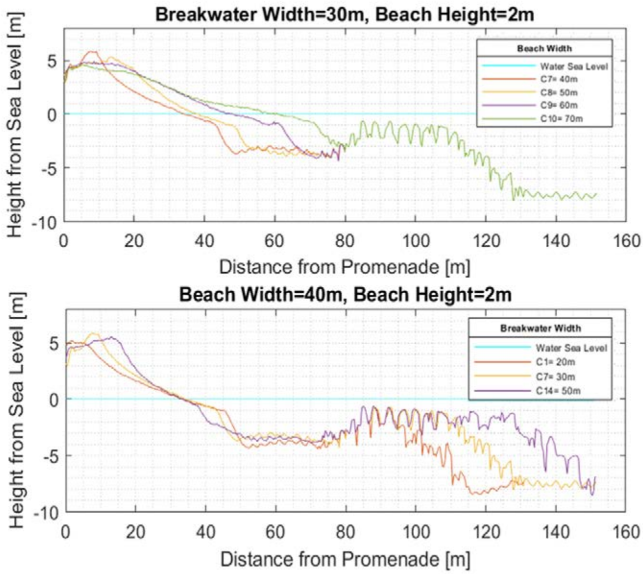

Figure 4 – Final Profile: a) beach width analysis; b) breakwater width analysis.

Conclusion

Marina di Pisa is a Tuscan coastal town (in Italy) that has endured years of coastal degradation with various attempts of diminishing erosion by coastal protection systems. The implementation of “hard” and “soft” protective structures has led to a large seawall against the coastal road standing about 4 m above m.s.l. and ten cells based on ten rubble-mound offshore breakwaters 50-80 m from the seawall. Six of the breakwaters are emerged standing 3 m above m.s.l., and the other 4 breakwaters (cells 7, 6, 5, 4) are submerged (-1 m below m.s.l.) and with gravel nourishment offshore of the seawall. Cell 4 at Marina di Pisa has not reached a satisfactory design as large amounts of water and gravel overtop onto the promenade during large storms. A laboratory experiment on a wave flume was designed and tested to examine three design parameters on the two main protective components, the submerged breakwaters and gravel nourishments of cell 4. The three design parameters tested were additional gravel nourishment width, gravel nourishment height, and addition to the submerged breakwater crest. Fifteen configurations based on different combinations of the design parameters were tested under the same wave storm action, and their effects were analyzed against three main outputs: gravel overtopping, water overtopping, and final equilibrium profile including height and position of the final crest formed by the gravel nourishment during the tests. The experiments have shown interesting results involving the combination of submerged breakwater and gravel nourishment. As expected, the enlargement of both the nourishment and breakwater results in less amount of gravel and water overtopping. Interestingly, the combination of a large enlargement in one of the components has shown to lower the need to also adopt the other component, therefore it is important to reach an optimal design where the effectiveness of all the components is equalized under the premise of economic affordability. The initial profile of the nourishment encompassing the initial gravel volume also has shown to have major effects on its final profile, especially the beach nourishment width that was correlated with the shift of the final crest away from the promenade. A combination of a large extension of the breakwater and beach nourishment also showed to have final profiles without a crest but a steady slope, as the short length between the breakwater and the nourishment did not allow for further wave propagation. The final crest position both in height and location has been shown to have an impact on the amount of overtopping. Lastly, the volume of gravel added as nourishment to the beach had a direct impact on the profile evolution and behavior as it mixed with sand, with the smallest amount of gravel creating mixed sand and gravel beach and changing the desired behavior of the gravel. It is important to notice that although the engineering component is key to a functional design, a successful design also includes social, economic, and environmental factors that are not discussed in this paper.

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