SEA DEFENCE BY GRAVEL NOURISHMENT AND SUBMERGED BREAKWATERS: A CASE STUDY

Amanda Zannella, University of Florence, amanda.zannella@unifi.com
Andrea Esposito, AM3, andrea.esposito@am3spinoff.com
Irene Simonetti, University of Florence, irene.simonetti@unifi.com
Lorenzo Cappietti, University of Florence, lorenzo.cappietti@unifi.com

INTRODUCTION TO THE STUDY SITE

Marina di Pisa is a coastal town located on the Northern Tuscan coast on the Tyrrhenian Sea, on the south side of the Arno River delta. The first signs of erosion were evident right after the establishment of Marina di Pisa in 1872, when a large buffer of sandy beaches still existed between the town and the sea. The first recording of a protective perishable structure against erosion is from a postcard of Marina di Pisa from 1915, kickstarting a battle between the force of the sea and the attempt at land preservation (Pranzini et al., 2018).

By the 2000s the coast located south of the Arno River delta was protected by groins, 2.3 km of seawall, and 10 detached rubble mound breakwaters each 200-270 m long and 3-4 m high (above m.s.l.) and about 50-100 m off the shoreline (Figure 1A). The substantial protection of the coast was essential for the survival of Marina di Pisa. In Figure 1B, the shoreline map recreated by Bini et al. (2021) and the satellite image of Marina di Pisa in 2021 (Figure 1C), show the difference in the evolution of the north and south of the delta of the Arno River. A clear contrast in the erosion of the two sides of the river is evident as the south boundary was being heavily guarded stabilizing the shoreline and the north side was left free to erode until 2000 experiencing a coastal retreat of about 1 km.

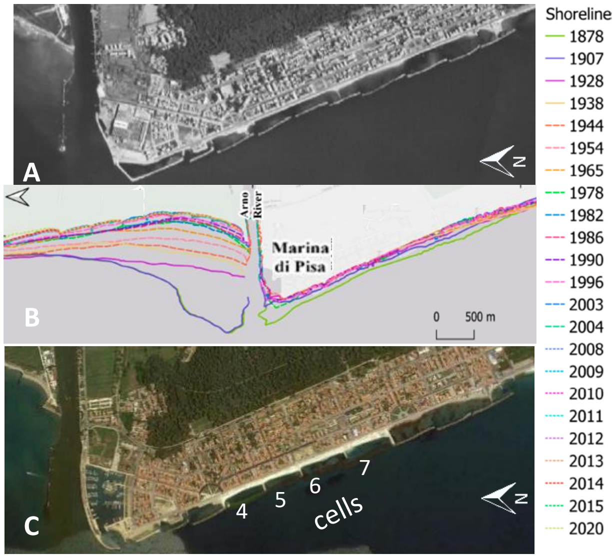

Figure 1A – Marina di Pisa 1988 (I.G.M., n.d.); B – Shoreline retreat map (Bini et al., 2021 (modified with the legend on right); C – Marina di Pisa 2021 (Google Earth).

In 2002, a new strategy began, guided by the University of Florence of adding gravel nourishment there where sandy beaches were already fully eroded and submerging the emerged breakwaters corresponding to the 7th cell (Aminti & Pranzini, 2000; Cappietti, 2011). The project aimed to reduce flood risk to the town of Marina di Pisa and return the area to a more natural environment, which added great value to the area and its residents. The project was finalized in 2007 for cells 7 and 6, and cells 5 and 4 in the following years. The varying coastal protection strategies through the years have contributed to its present state of mixed "hard" and "soft" strategies. The current mixed coastal defense system at Marina di Pisa varies from the state of 2000, by now having four submerged breakwaters, in cell 7,6,5,4 with gravel nourishment at the front and seaward of the existing seawall and the other six breakwaters emerged 1.0-3.0 m above m.s.l. (Figure 1C).

MOTIVATION

Gravel nourishment has the potential to become an integral part of protective systems due to its unique characteristics, such as: high permeability, porosity, and the higher grain inertia. The uprush of wave breaking is higher than the settling velocity of the gravel (Lorang, 2002) 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 (Austin & Buscombe, 2008; Buscombe & Masselink, 2006). This system of onshore transportation of gravel creates a crest, which naturally forms in response to higher energy, triggered by higher periods and higher waves, creating a protection barrier to the coast. The high permeability and hydraulic roughness of the gravel nourishment allow for large energy dissipation of waves while the crest acts as a barrier to stop high energetic waves from reaching the coast making it a valuable option as a coastal protection system.

In the case of Marina di Pisa, the three cells that used gravel nourishment have proven to be successful. However, cell 4 still suffers from large amounts of gravel and water overtopping on the promenade during major storms, despite the numerous reprofiling interventions that took place until the end of 2021. The unsatisfactory protection level at cell 4 can be linked to the following differences in the 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 toe seaward and shoreward; iii) the lower seawall crest level. The goal of this study is to analyze, through 2D experimental method, the impact of the two major components of the coastal defense system, namely: the submerged breakwater and gravel nourishment, on the behavior of cell 4 during major storms.

METHODOLOGY

The 2D experiments were carried out in the 37 m long, 0.80 m wide, and 0.80 m deep wave flume at LABIMA. The model was scaled at 1:36 to the prototype, based on Froude's similarity. The section at most risk was selected for the model design, a sketch of the model design with the current configuration in black and the tested parameters in red are shown in Figure 2.

The gravel nourishment width (BW) was tested at 40 m, 50 m, 60 m, and 70 m; the height of the nourishment (BH) was tested at 2 m and 3 m; and lastly, the breakwater crest width (BWW) originally at 20 m was tested at 30 m, 40 m, and 50 m extending seaside. The parameters were matched within 15 configurations all tested under the same wave conditions of significant wave height of 4.1 m, period of 12 s, sea level at 0.4 m, and a 6-hour storm (at prototype scale).

The outputs for each test were: gravel and water overtopping beyond the seawall and the final profile after the test.

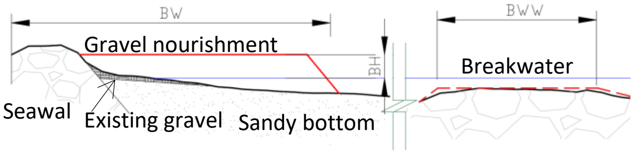

Figure 2 - Sketch of the model design, with the definition of basic parameters

RESULTS AND CONCLUSION

Sensitivity analysis has shown that an increase in gravel nourishment width and height and an increase in submerged breakwater width decrease both water and gravel overtopping. If the gravel nourishment volume was not enough to create a sufficiently large beach, then the morphodynamics would lead to the formation of the crest on the promenade, due to gravel overtopping. It was also evident that while the submerged breakwater and gravel nourishment worked together to decrease the amount of overtopping, an increase in one of the parameters eventually decreased the effectiveness of the other, e.g. an increase of breakwater crest with nourishment width at 60 m (BW) makes no significant difference in water overtopping (Figure 3).

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, which in turn has great importance in controlling the occurrence of gravel overtopping on the promenade, a larger crest further from the promenade will provide greater protection. 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 (Figure 4, green and purple). 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. Future studies will be carried out to further analyze the general response of gravel nourishment as a coastal protection strategy in climate change scenarios.

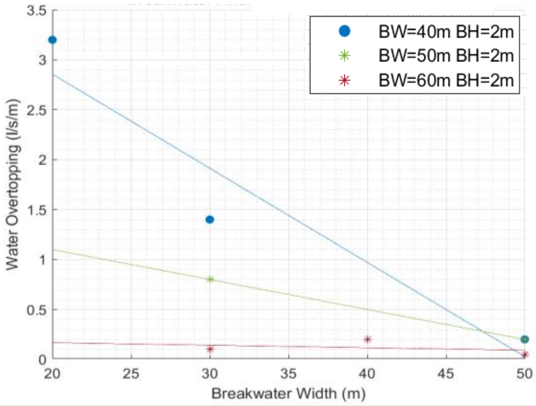

Figure 3 - Effect of breakwater width BWW on water overtopping for different gravel nourishment width BW.

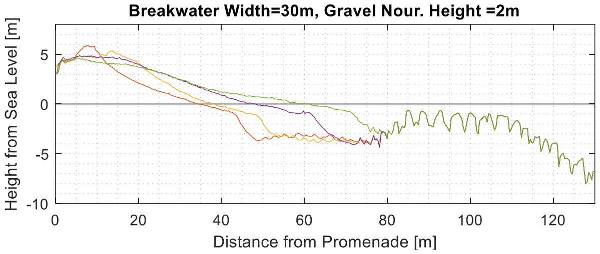

Figure 4 - Effect of the gravel nourishment width BW on the final profile for a fixed breakwater width BWW=30 m; width of gravel nourishment: orange=40 m, yellow=50 m, purple= 60 m, and green=70 m

REFERENCES

Aminti, Pranzini (2000): Indagine sperimentale per la ristrutturazione delle difese di Marina di Pisa, STUDI COSTIERI, vol.3, pp.57-70.

Austin, Buscombe (2008): Morphological change and sediment dynamics of the beach step on macrotidal gravel beach, MARINE GEOLOGY, vol. 249 (3-4), pp.167-183.

Bini, Casarosa, Luppichini (2021). Exploring the relationship between river discharge and coastal erosion: An integrated approach applied to the Pisa coastal plain (Italy). REMOTE SENSING, vol.13 (2), pp. 1-22.

Buscombe, Masselink (2006). Concepts in gravel beach dynamics, EARTH-SCIENCE REVIEWS, vol. 79(1-2), pp. 33-52.

Cappietti (2011). Converting emergent breakwaters into submerged breakwaters, JOURNAL OF COASTAL RESEARCH, pp.479-483.

Lorang (2002). Predicting the crest height of a gravel beach, GEOMORPHOLOGY, vol. 48(1-3), pp.87-101.

Pranzini, Anfuso, Cinelli, Piccardi, Vitale (2018): The marble beaches of Tuscany, GEOGRAPHICAL REVIEW, vol 98(2), pp. 280-300.