'BACK TO THE BEACH': CONVERTING SEAWALLS INTO GRAVEL BEACHES

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Abstract

During the 20th century, 5 km of hard structures (seawalls, detached breakwaters and groins) were built along 2.5 km of coast to stabilise the shoreline at Marina di Pisa (Tuscany, Italy). These reflective structures increased nearshore erosion and now a water depth of 7 m deep is found at the offshore toe of the detached breakwaters. Wave reflection pushes sediment flux offshore, inducing downdrift erosion. A project to reduce hard structures, based on their conversion into gravel beaches, is proposed here. The project layout was tested on a 2D physical model and proved to be effective as a coastal protection measure. Furthermore, it is less expensive than the maintenance costs of the present structure and produces a 30 m wide gravel beach, so offering economic benefits because of its recreational value.

1. Introduction

Italian coastlines began experiencing beach erosion during the second half of the nineteenth century, and nowadays more than 50% of the national shoreline is threatened by erosion (CNR, 1997; D'Alessandro and La Monica, 1999). The first response to this process was hard shore protection, favoured by the vicinity of the mountains and the fact that rock quarrying is a traditional industry. Consequently, rocky boulders are cheap and available everywhere and their use proliferated in the 1960s and 1970s. In addition, little was known about marine sand dredging for beach nourishment at the time due to the lack of fluvial and estuarine navigation. Today there are approximately 330 km of hard structures along our coastlines, drastically modifying coastal landscapes, inducing downdrift erosion, affecting sea water quality and circulation and, in many cases, not even providing efficient beach preservation.

Soft shore protection methods, such as beach nourishment with sand have recently been adopted in several projects, but they are not applicable where older structures such as seawalls, groins and breakwaters have dramatically changed the original coastal morphology. In these cases, water depth in front of the structures suddenly increases: as a consequence, incoming waves usually break over the structures, dissipating their energy on the structure itself and inducing scouring at the toe. Hypothetical beach nourishment with sand-like material would require an extremely large amount of sediment in order to restore a more gentle nearshore profile and thus at a cost rarely affordable for local and regional administration. In addition, ordinary maintenance of rock rubble/boulder constructions is extremely expensive, but

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necessary to protect urban and industrial settlements, coastal infrastructures and recreational areas.

Retention of these 'archaeostructures' clashes with the soft shore protection strategies recently adopted by national and regional administration. However, the skill and know-how for new solutions in these extreme cases is limited, the economic requirements are huge and the long time needed before reaping the advantages is at odds with the political life span, which needs short-term projects and results visible in 4 to 5 years.

'Back to the beach' is our slogan: hard structures have to be removed and converted into soft solutions, that is, gravel beaches. This process will require a relatively long period including intermediate phases and long rests to allow the environment to evolve gradually towards its new and more natural configuration.

2. Beach erosion and coastal protection at Marina di Pisa

Marina di Pisa is a seaside resort built on the southern wing of the Arno River delta (central Tuscany) (Figure 1) in the early 1800s. The Arno River delta has built up over the last 25 centuries, as a consequence of inland hill and mountain deforestation performed since pre-Etruscan times (Pranzini, 1984). The shoreline advanced more than 7 km at the river mouth during this time, while a 5 km-wide beach ridge and band of dunes formed alongshore from Livorno to Forte dei Marmi (46 km) (Figure 1).

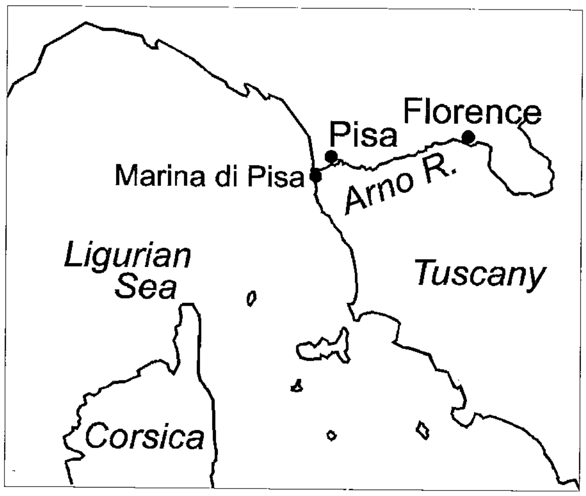

Fig. 1. Map of the area under discussion

Changes in land-use within the basin, and the practice of river bed quarrying, together with dam construction, have reduced the river sediment load from the estimated $5 \cdot 10^6$ m^3/yr in the seventeenth century to less than $2 \cdot 10^6$ m^3/yr in the last 50 years. Beach erosion began in the mid 1800s at the delta apex and gradually expanded to adjacent beaches (Pranzini, 1989). In the meantime the expanding Marina di Pisa was confronted by shoreline retreat.

At first, groins were built, though they did not prevent the houses on the sea front being demolished by waves in the early twentieth century. Detached breakwaters and seawalls were built immediately after World War II and gradually expanded southward, running behind the erosion, though they were themselves one of the causes of this phenomenon. There were no settlements on the northern side of the delta and the shoreline was left free to retreat: as a consequence, erosion led to the loss of 1 300 m of land in a century, producing a sharp asymmetry at the Arno River mouth. At Marina di Pisa the coastline is now artificially stabilized for 2.5 km by a continuous seawall and by 10 detached breakwaters (Figure 2); in addition, a few groins divide the protected coast into five cells of different sizes. As a result, over 5 km of hard structures are defending 2.5 km of coastline.

Fig. 2. Seawall and detached breakwaters at Marina di Pisa

Mean water depth between the seawall and the detached breakwater is approximately 2 m, while on the offshore side of the breakwaters the water reaches a depth of approximately 7 m. The nearshore profile is almost horizontal with the breakwater for several hundred meters, although it is slightly convex, peaking at approximately 120 m from the breakwater (Figure 3). Farther offshore, the mean nearshore slope is approximately 0.4% down to the –15 m isobath. The nearshore profile, with its convex shape, demonstrates the offshore migration of sediments. As a consequence of this nearshore morphology, wave energy dissipation is very limited along the nearshore profile and the waves break directly over the structure. Sea bottom scouring is strong at the toe of the structure and maintenance costs high. In addition, wave reflection pushes the southward longshore drift coming from the Arno River offshore, so the fluvial sediments do not efficiently feed the downdrift beaches.

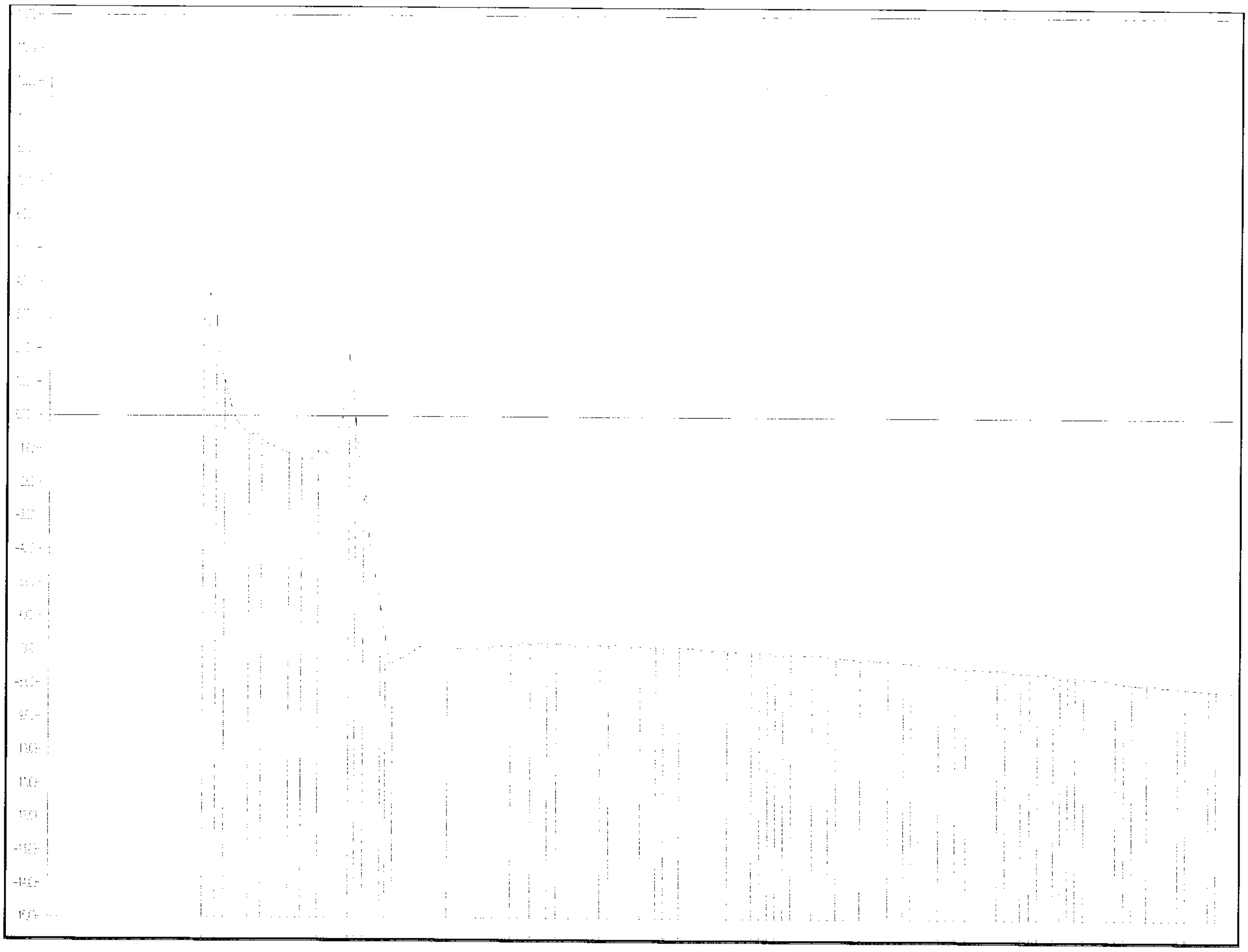

Fig. 3. Beach profile at Marina di Pisa.

Nevertheless, for the inhabitants of Marina di Pisa, these hard structures provide reassurance during severe storms, although the sea-front promenade is often closed due to overwash and a certain amount of damage is expected. Toe scouring induces the collapse and lowering of the breakwaters, which require frequent maintenance in the form of adding boulders to the tops of the breakwaters.

The study relating to a general plan for shore protection in the Pisa jurisdiction area revealed that these hard structures were no longer sustainable, but at the same time any proposed soft defence for the adjacent beaches was destined to fail due to the negative impact of the old works. The main task is to reduce wave reflection along the detached breakwaters in order to allow longshore sediment transport to reach the shoreline and feed the beaches to the south. This should also favour sedimentation in front of the breakwaters and thus anticipate wave shoaling and breaking. All these factors must be obtained without reducing the protection afforded by the seaside promenade and buildings.

3. A back to the beach project: presentation and discussion

While the members of the commission (P. Aminti, G. Berriolo, G. De Filippi, J. Oneto and E. Pranzini), appointed by the Pisa county administration to plan a new strategy for coastal conservation, were discussing this topic, the national agency for coastal defence (Genio Civile Opere Marittime) were about to raise two breakwaters (n. 6 and n. 7 from north) to a height of 3.80 m above the mean sea level, at a cost of approximately 3 billion Italian lira (1.5 million euro). This work was delayed and a different solution, aimed at reducing the reflective structures along the coast, was tested with a physical model. The project is based on lowering the detached breakwaters to mean sea level, and absorbing the overtopping wave energy with a gravel beach placed in front of the present seawall (Figure 4).

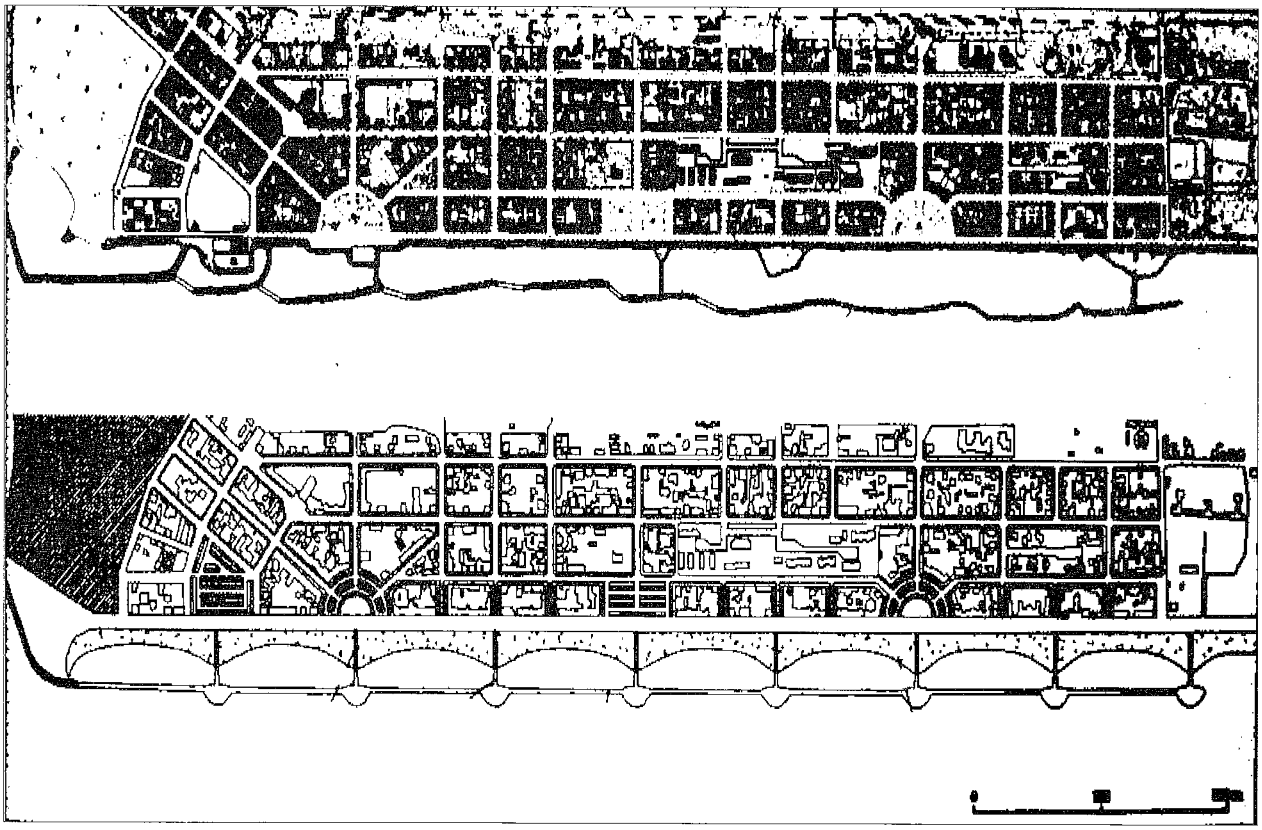

Fig. 4. Present (up) and proposed (down) coastal defences at Marina di Pisa

In the present situation, the breakwater berm is about 2 m above mean sea level and the transmitted wave height in the protected area is about 30% of the significant wave height under extreme conditions. Lowering the breakwater to mean sea level increases the transmission coefficient to 42% under the same incoming waves.

Energy transmitted behind the breakwater can be efficiently absorbed by coarse sediments, which have proved to be very stable both in nature and on artificially nourished beaches, thanks to their size, permeability and porosity (Pacini et al., 1997, 1999). These characteristics allow water to infiltrate during uprush, and return to the sea via sub-surface flow, eliminating the tractive forces acting during the backwash responsible for grain removal from the swash-zone. All this favours settlement of grain carried on the berm crest by on-shore fluxes, and the formation of a high berm (Orford, 1977; Orford & Carter, 1985). This behaviour was also confirmed by the available numerical modes (van Hijum & Pilarczyk, 1982; Van der Meer, 1998), although they probably overestimate the berm height which forms in gravel and boulder beaches.

One problem which still must be solved is the compatibility between the fine sediments of the nearshore and the coarser ones artificially dumped on the beach. On natural 'mixed sand and gravel beaches', the coarsest grains are found (Miller & Zeigler, 1958), where the last wave breaks, depositing fine sand in front of it, with the sudden reduction in grain size often occurring along a sharp line. The tendency of gravel to move onshore in mixed sediment beaches was also observed during recent beach nourishment performed in Sardinia (Pacini et al., 1997, 1999). In this case, fill material – gravel produced from hard rock – was pushed offshore three times with a bulldozer, forming a platform 30 cm below the mean sea level and each time the waves immediately brought it back to the shore. This helped to clean the material of its silt particles and provided preliminary rounding of the grains.

Another aspect that needs to be studied in more detail is the longshore mobility of gravel along sandy beaches.

The gravel filling performed at Marina di Cecina (Tuscany) south of the last groin along the coast is interesting in this respect. After four years, the material was found 15 km to the south! Similar results can also be observed at Lido di Policoro (Basilicata), where gravel and boulders discharged onto the unprotected shore are moving toward a fine sand beach downdrift.

All these factors suggest that while offshore dispersion of the filling will be very limited, strong lateral fluxes must be taken into account. Our project foresees a reduction in this longshore transport through the construction of short groins connected to the artificial reef by a submerged groin (Figure 4).

Cross-shore beach profiles were studied in gravel beaches with wave channel experiments at the Delft Hydraulics Laboratory (Van Hijum & Pilarczyk, 1982; Pilarczyk & De Boer, 1983; Van der Meer, 1988) and at the Wallingford Laboratory (Powell, 1990), producing parametric models of equilibrium profiles. Numerical models also allow the study of gravel beach profiles (CIRIA CUR, 1983). All these studies relate to beaches formed solely by gravel, reaching a depth where the breaking waves cannot cause any changes; no data exists for profiles where gravel lies over a fine sand bed.

In Italy, wave channel experiments aimed at supporting coastal protection projects have been done to study cross-shore beach evolution after artificial coarse nourishment has been carried out (Aminti, 1988; De Santis & Ruol, 1988). Although these experiments proved the stability of the model beach, we only have a small amount of data relating to natural beaches defended through coarse sediment nourishment (Berriolo, 1999; Pacini et al., 1999).

4. The physical model

To test the effectiveness of the project, a 2D physical model of the Marina di Pisa coast was performed on a scale of 1:25 at the Civil Engineering Department of the University of Florence. Here, a wave channel 50 m long, 0.8 m large and 0.8 m deep was used, equipped with an oleodynamic piston-type wave generator with a random input signal to reproduce a JONSWAP-type spectrum of pre-determined values of wave height $H_{1/3}$ and period $T_{1/3}$. A graduated tank collected the water overtopping the seawall or the beach thus allowing evaluation of the efficiency of the coastal protection.

In our tests, each wave was run for 45 minutes, representing 4 hours in nature according to the Froude law. Five sensors measured wave parameters along the channel as shown in Figure 5, and sampling at 20 Hz was processed both in the temporal (zero-up-crossing) and frequency (spectral analysis) domain. Generator performance was checked at gauge 1, whereas at gauge 2 the waves reaching the structures were measured (Table 2). Gauges from 3 to 5 produced data on wave height at the beach toe (Figure 6), while two piezometers allowed measurement of the sea level near the coast and the set-up in the protected area (Figure 7).

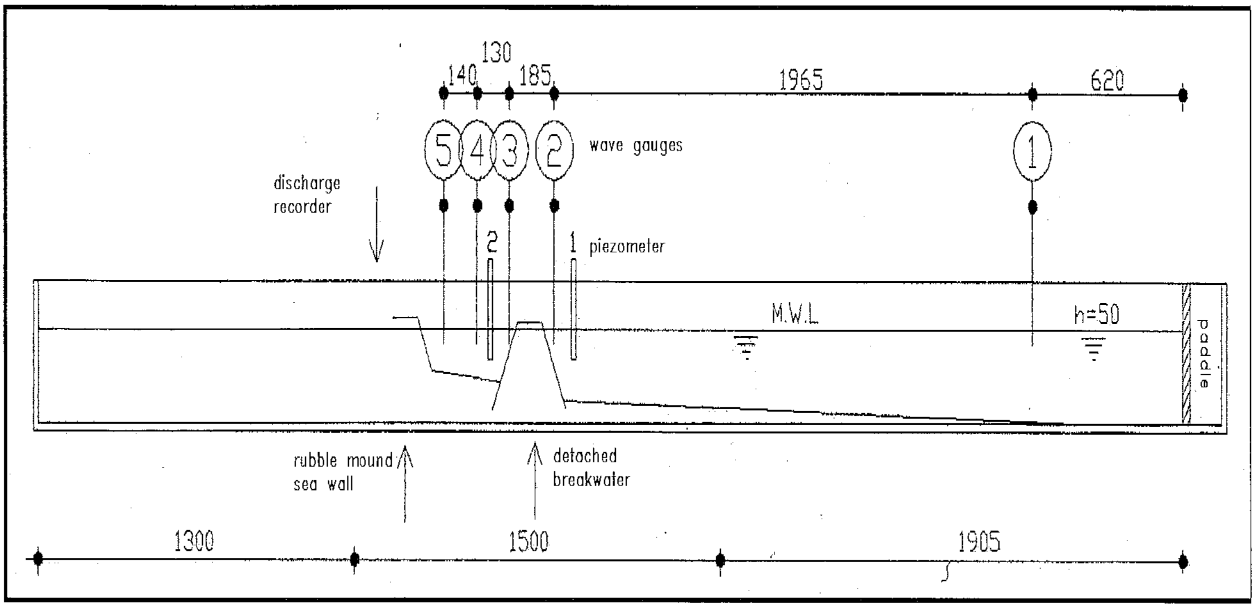

Fig. 5. Diagram of the wave channel used for the physical model of the coastal defences at Marina di Pisa

The main parameters to be considered when setting up a physical model of a beach are the Froude number and Dean's parameter (Dean, 1973; Gourlay, 1980; Vellinga, 1986)

$$N_0 = \frac{H_0}{VT}, \tag{1}$$

with H_0 = wave height in deep water, T = wave period, V = sediment settling velocity in still water.

These parameters allow size and density of the sediments to be included in the same relationship.

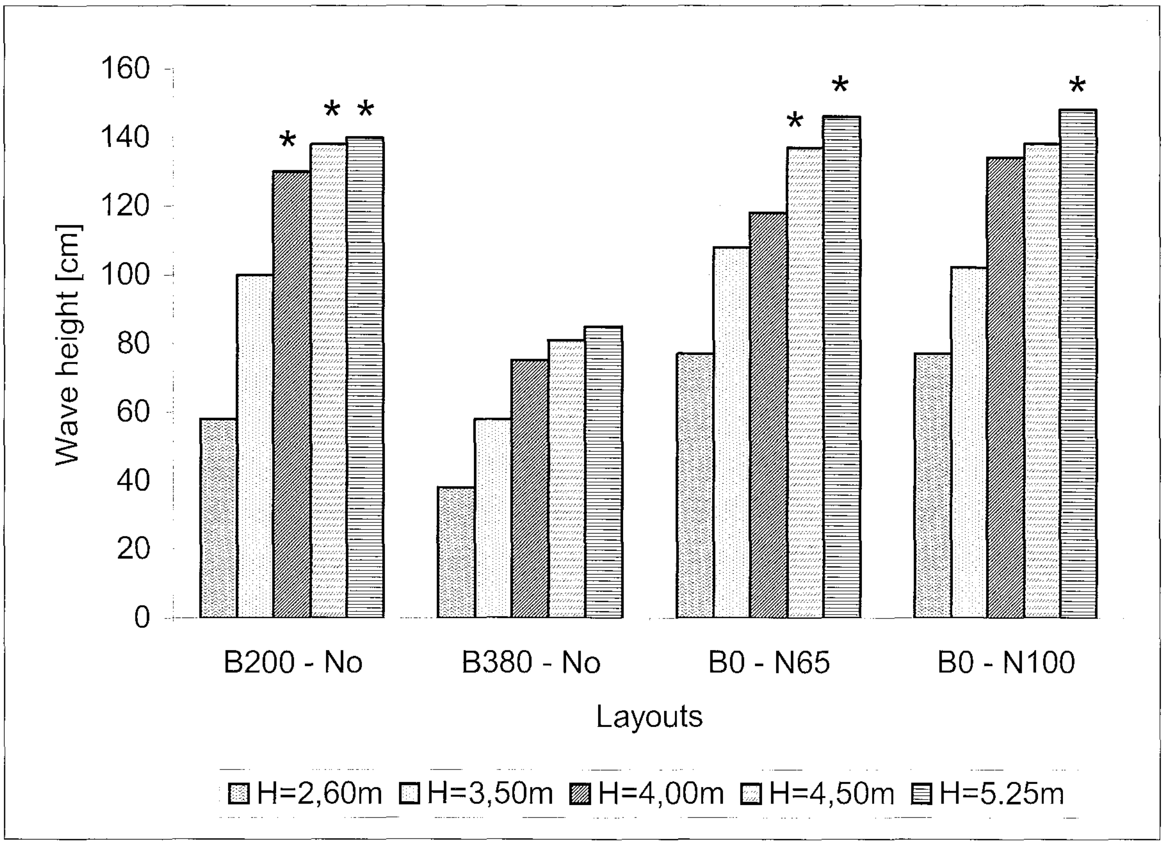

Fig. 6. Wave height at the beach toe for different waves for the different tested layouts $(H_{1/3})_3$

Table 1. Sediment physical characteristics in the prototype and the model at 1:25 scale.

Material	Density (g/cm^3)	D_{50} in the model (mm)	Settling velocity in the model (m/s)	Scaled settling velocity (m/s)	D_{50} in the prototype (mm)
Sand	2.65	1.20	0.12	0.60	16

Table 2. Wave parameters at location 1 and 2 (see Figure 5).

H_0 [m]	$(H_{1/3})_1$ [m]	$(H_{1/3})_2$ [m]	$(T_{1/3})_2$ [s]
2.60	2.34	1.89	6.3
3.50	3.36	3.00	7.7
4.00	3.81	3.32	8.4
4.50	4.25	3.45	8.9
5.30	4.98	3.69	9.95

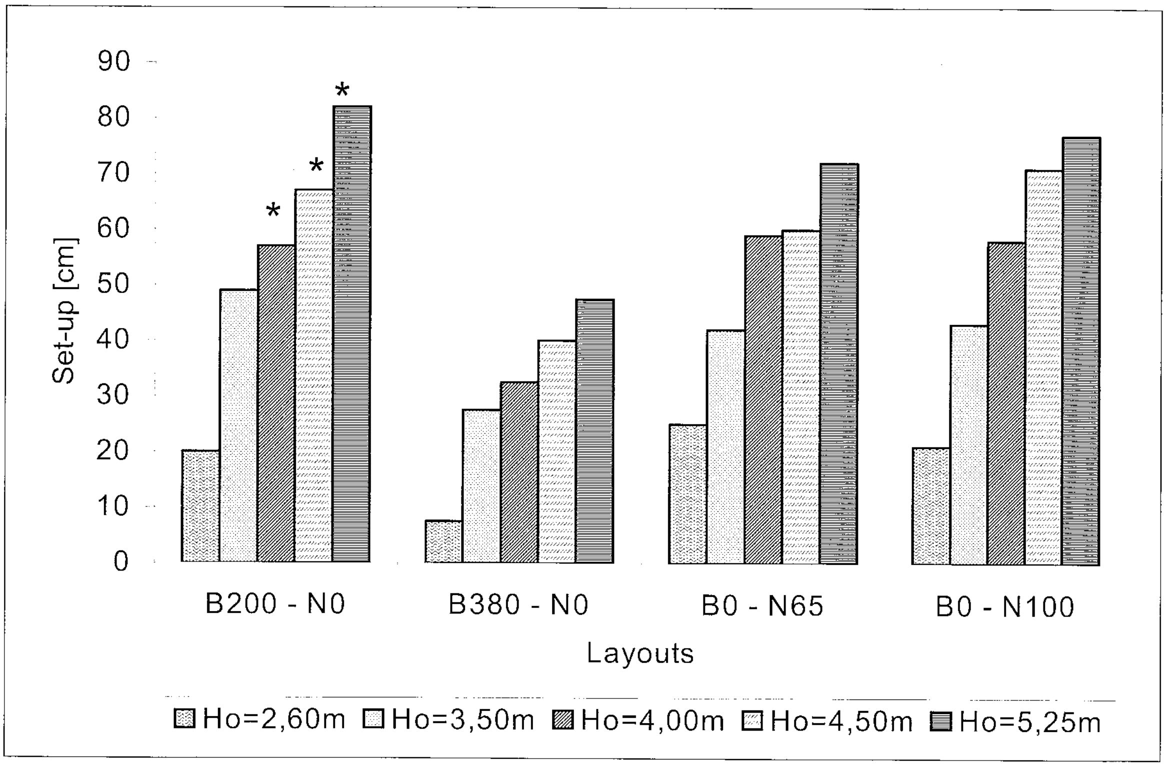

Fig. 7. Set-up values at the fill toe for the various layouts under different waves

The present configuration of the breakwater was tested first (B200) and then tested with its height raised to +3.8 m as proposed for the maintenance works (B380); no nourishment (N0) was simulated at this stage.

Later, an artificial gravel beach was constructed and the detached breakwater lowered to the mean sea level (B0). The equivalent of 65 m^3/m (N65) and 100 m^3/m (N100) nourishment were tested. Although sediments of various size were tested, our data here only refer to 16 mm equivalent grains (1.20 mm in the model; Table 1). Some considerations relating to the other tested materials are reported in the conclusions to this paper. As far as wave climate is concerned, tests were carried out with increasing H_{0S} values, up to 5.30 m (Table 2), which correspond to a wave with a return period of 30 years. The offshore wave conditions have been reproduced in 12.5 m deep water $(H_{1/3})_1$ and measured at a depth of 7 m in front of the breakwater $(H_{1/3})_2$.

In the bidimensional model it was not possible to measure the sediment loss produced by the flow occurring between adjacent breakwaters due to the different mean sea levels. Set-up values for the area between the seawall and the detached breakwater can help in estimating this effect.

5. Results

5.1 WAVE HEIGHT IN FRONT OF THE ARTIFICIAL BEACH

Significant wave height $(H_{1/3})_{3,4,5}$ at the beach base was related to the transmission coefficient of the breakwater and the reflection index of the work near the beach. The former was strictly determined by the height of the breakwater above the sea level (Van der Meer, 1992). On a low reflectivity beach, the increase in wave height produced by lowering the breakwater is only partially balanced by the reduction in wave reflection by the nearshore structures, and wave heights in the protected zone are quite similar in any layout with low offshore breakwaters (Figure 6).

5.2 SET-UP

The extreme set-up value behind the detached breakwater (Figure 7) was 83 cm when the latter was in its present configuration, with the top at 2.0 m above m.s.l., and fell to 48 cm with a 3.5 m high breakwater, when levels were balanced by filtration through the rocks. Low breakwaters were more easily overtopped, but offshore fluxes more efficiently restored the water levels and set-up was reduced (70-75 cm). This data can be considered the maximum values, since 3-dimensional processes were not simulated and longshore fluxes could render the prototype very different to the 2D model. During severe storms, the waves were actually observed to pass over the detached breakwater, running over a higher sea level and easily reaching the coastal road.

5.3 OVERTOPPING VOLUMES

In the present configuration (B200 N0) overtopping occurred when Hs reached 4.0 m (Table 3, Figure 7), and when the waves were strong, the coastal road was completely flooded (2.07 l/s/m). Raising the detached breakwater to 3.8 m above m.s.l. (B380 N0) overtopping did not occur under any wave condition. This was largely to be expected, since behind other recently raised breakwaters, no problems with the coastal road have been reported, not even during severe storms.

When the breakwater was lowered to the mean sea level (B0), a fill volume of 65 m^3/m (N65) prevented overtopping by waves with Hs lower than 4.5 m. In extreme conditions (Hs = 5.30 m) waves reached the seawall and reflection occurred, preventing the berm crest from forming: a concave profile directly connected to the seawall evolved. With a 100 m^3/m fill, a large berm was formed (equivalent to 30 m in nature), with a crest well distant from the seawall preventing road flooding in all sea states tested. The highest waves, however, did overtop the berm, but the water was absorbed by the backshore, which rose in elevation.

6. Discussion and conclusion

A gravel beach proved to be effective in reducing the overtopping of the present seawall and inundation of the coastal road. This was also the case with a significant lowering of the detached breakwaters. As observed in natural beaches (Orford & Carter, 1985), coarser sediments stay on the nearshore and no mixing occurs with the fine sand constituting the present shore-face. Marked grain size discontinuity occurs, at the step base (Figure 8).

Table 3. Overtopping, for each layouts, under different wave conditions.

Layout	Hs [m]	Overtopping
B200 N0	4.00	0.10
B200 N0	4.50	0.43
B200 N0	5.30	2.07
B380 N0	5.30	0.00
B0 N65	4.50	0.04
B0 N65	5.30	0.14
B0 N100	5.30	0.00

Sometimes the sand was seen to slightly cover the gravel: this could choke up the pores and reduce beach permeability and porosity. As this phenomenon, together with grain size, is a conclusive characteristic, this aspect should be analysed in detail.

Our results prove that it is possible to lower the detached breakwaters along our coast, with a direct gain in nearshore water quality. Gravel beaches could substitute seawalls, even without an external breakwater, as proved in other tests performed by the authors (Aminti et al., in prep.). Additional tests, not reported here, show that there is no significant gain in efficiency by changing the grain size, as long as we are inside the gravel–pebble range.

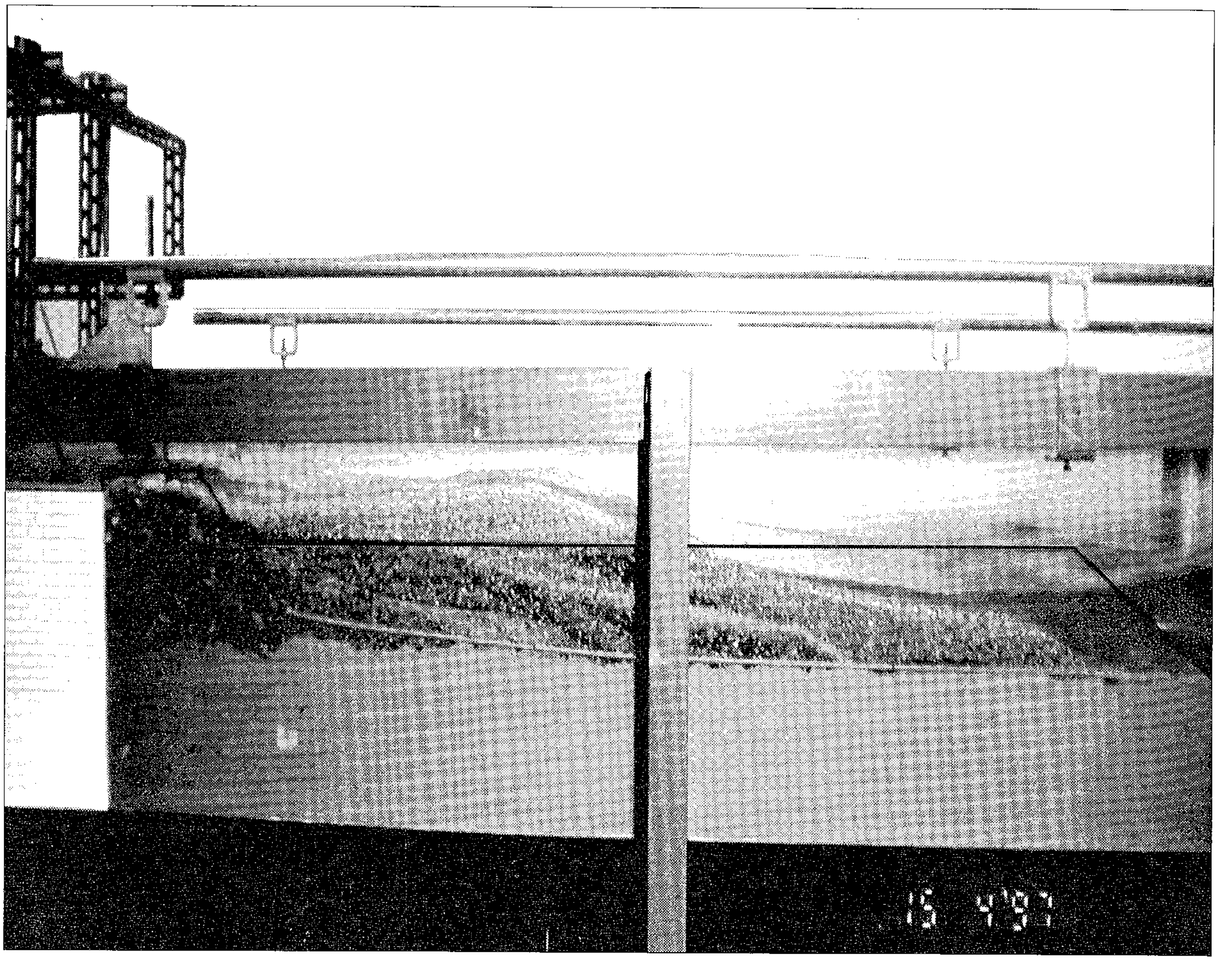

Fig. 8. Gravel beach formed by nourishment in the physical model. The horizontal line shows the top surface of the material laid initially; the beach profile was shaped by Hs = 5.30 m waves.

These results convinced the national agency to approve our project and order a cost analysis. The new project cost was estimated to be 2 200 million Italian lira (1.1 million euro), which is approximately 30% less than the cost of raising the breakwater (3 000 million Italian lira; 1.5 million euro). A 30-meter-wide dry beach is also obtained, which, in a site developed for tourism in Italy, is far more valuable than the cost of construction. Lowering the detached breakwater should reduce near-shore water pollution, and the reduction in wave reflection should reduce offshore dispersion of longshore drift. The forecast nearshore accretion should induce wave shoaling and energy dissipation. In the future, this could allow lowering of the detached breakwater even further, or reducing of beach grain size. Work on this project will begin in the near future, together with detailed monitoring. If the results prove to be positive, the entire sea-front side of the town will be modified in the forthcoming years (Figure 9).

Fig. 9. New look of the coast at Marina di Pisa according the project of hard structure reduction

Acknowledgements

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