PERFORMANCE OF PERCHED BEACH NOURISHMENTS

R. E. Musumeci[1], L. Cavallaro[1] and E. Foti[1]

Perched beach nourishments are popular measures to contrast beach erosion in the presence of steep beaches. Inspired by a real case-study, in the present work the performances of two configurations of the submerged barrier used to protect the toe of the beach are experimentally investigated. Measurements have been gathered concerning wave reflection and transmission, stability and scours around the submerged sill, and beach profile evolution. Both accretive and erosive wave conditions have been considered here. A comparative analysis on the evolution of the two configurations of the sill, shows that the armoring of the filter behind the rubble mound structure is a very effective measure to increase the level of beach protection (e.g. the shoreline retreat under erosive wave attack is reduced to a third). The comparison of the experimental results with an analytical model to predict the equilibrium profile of perched beaches shows that the key phenomena controlling the process are related not only to wave reflection but also to wave dissipation mechanisms at the sill. Moreover, the comparison of the experimental results with field data proves that notwithstanding the several simplifying assumptions considered in the physical modeling, several phenomena are reasonably predicted by the model (e.g. beach evolution, stability and scours).

Keywords: equilibrium profile; submerged breakwater; accretive waves; erosive waves

INTRODUCTION

In the presence of eroded steep beaches, beach nourishment projects are often coupled with a submerged reef to retain the beach in a perched position. The engineering community often favors such a solution, due both to the significant reduction of sand filling volume, during both construction and the following re-nourishment phases, and to the possibility of controlling offshore sediment losses. Moreover the presence of the reef allows to partially dissipate the incoming wave energy through wave breaking, thus reducing the erosive action of the incident waves on the protected beach.

It follows that for perched beaches, the overall response of the onshore beach profile depends on the complex interaction between the incident waves, the submerged structure and the beach. Therefore, wave reflection, wave transmission and wave breaking are key phenomena which need to be analyzed in conjunction with beach profile evolution, stability and scours around the structure.

In the past only few experimental investigations have been carried out to investigate perched beach response to normal and storm wave attack (Chatham, 1972; Sorensen and Beil, 1988; Dette et al., 2002). The above studies have been mainly focused on the analysis of the beach profile evolution and on the effectiveness of the location of the submerged breakwater in terms of distance from the shoreline.

Gonzalez et al. (1999) developed an analytical linear model to predict the equilibrium profile of a perched beach. In the model, the main assumption is that the most important modification of the beach profile is due to wave reflection at the seaward and leeward side of the breakwater, whereas the effects of breaking are taken into account through the hypothesis of constant breaker-to-depth ratio and uniform wave dissipation per unit water volume (Dean, 1991). The width of the barrier and the offshore and onshore water depths at the barrier control the flux of energy which reaches the perched profile.

It follows that although such a kind of beach restoration methodology is widely adopted in the field, a comprehensive investigation of the performances of such mixed solutions has received no great attention in the literature, compared, for example, to the investigation of simpler submerged breakwater (see, for example, the work done in the DELOS project, Sumer et al. 2005). A better understanding of all the hydro- and morphodynamics of perched beach is still needed in order to improve design criteria and make such solutions really effective.

Trying to contribute at filling the gap, inspired by an existing perched beach work, here the results of an experimental campaign are presented and discussed also through a validation of the analytical model of Gonzalez et al. (1999) and a comparison with field data. To this aim both accretive waves and erosive waves have been considered as a forcing to the physical model.

The paper is organized as follows: in the next section a brief presentation and discussion of the analytical model of Gonzalez et al. (1999) used for comparison is given, then the case study and the available field data which have inspired the study are summarized. Furthermore, the experimental set-up is described along with the experimental results. Finally, the main conclusions of the work are presented.

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BACKGROUND OF THE ANALYTICAL MODEL

Based on the linear model of Losada et al. (1992) for estimating the reflection coefficient of a vertical impermeable thin barrier, Gonzalez et al. (1999) developed an analytical model for predicting the equilibrium profile of a perched beach. Such a model is based on the following hypotheses: (i) in the region offshore of the rectangular impermeable submerged sill (Region 1 in Fig. 1), i.e. starting from the water depth h_e in front of the breakwater, the beach profile is an equilibrium profile and a constant breaker-to-depth ratio is assumed; (ii) there is no dissipation in the breakwater domain (Region 2 in Fig. 1) and the flux of wave energy is partially reflected offshore and partially transmitted onshore; (iii) onshore of the submerged sill (Region 3 in Fig. 2), there is also an equilibrium beach profile with water depth equal to h_i.

The main assumption of the model is that the flux of energy transmitted in the interior region F_i is simply given by the difference between the incoming wave energy flux F_e and the wave energy flux reflected by the barrier F_{er}.

$$F_i = F_e - F_{er} \tag{1}$$

Based on Eq. (1), assuming linear shallow water wave theory and that only the oscillating (non-breaking) part of waves contribute to the reflected energy flux (Baquerizo, 1995), the relationship between the internal and the external water depth at the barrier depends just on the value of the reflection coefficient Kr and it can be written as

$$h_i = h_e (1 - Kr^2)^{2/5} \tag{2}$$

To determine the internal water depth h_i, the reflection coefficient Kr must be found by matching velocities and pressures at the barrier as follows

$$\begin{aligned}
&\phi_1 = \phi_2 && x = 0, -h_e + a < z < 0 \\
&\frac{\partial \phi_1}{\partial x} = \frac{\partial \phi_2}{\partial x} && x = 0, -h_e + a < z < 0 \\
&\phi_2 = \phi_3 && x = B, -h_e + a < z < 0 \\
&\frac{\partial \phi_2}{\partial x} = \frac{\partial \phi_3}{\partial x} && x = B, -h_e + a < z < 0
\end{aligned} \tag{3}$$

where ϕ_1, ϕ_2 and ϕ_3 are the velocity potential in Region 1, 2 and 3, B is the width of the barrier and a is the water depth above the barrier. The interested reader is referred to the work of Gonzalez et al. (1999) for details on the iterative procedure needed to solve the problem.

It is worth pointing out that, because of the hypotheses introduced in the model, the controlling phenomena in the analytically modeled perched beach equilibrium profile is just wave reflection from the submerged barrier. Indeed, from the analytical point of view, it turns out that the parameter which controls the position of the perched beach is strictly related just to the internal water depth h_i and therefore to the reflection coefficient Kr. Such a result is mainly due to the fact that wave dissipation in the correspondence of the structure is considered negligible.

In particular, although the theory is generally valid, the model of Gonzalez et al. (1999) was validated using the quite restrictive assumption of narrow breakwater crest (B/L<0.06, with L being the wave length) in order to eliminate the dependency on the reflection coefficient. In the comparison of the present experimental results with the analytical results obtained by applying the above model, such a limiting hypothesis has been disregarded and the full version of the model is used in order to explicitly include Kr in the calculation of the shoreline advancement.

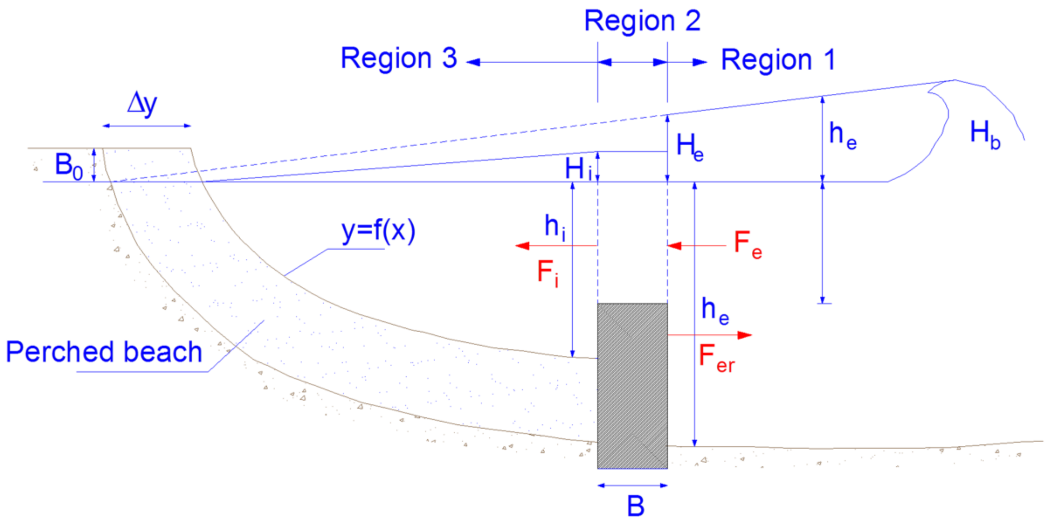


Figure 1.Sketch of the problem and definition of the variables of the analytical model (adapted from Gonzalez et al. 1999).

DESCRIPTION OF THE CASE STUDY

The experiments carried out in the present work have been inspired by the case of an existing beach nourishment project located at Belvedere Marittimo, on the Southern Tyrrenian coast of Italy. At such a location, in order to cope with the local beach erosion processes, 600000 m^3 of medium-coarse sand (d_{50}=3 mm) have been discharged within a 700 m-long cell, whose limits are made up by a submerged rubble-mound sill, on the offshore side, and two groins on the North and the South boundary of the cell. The barrier is made up by quarry-stones having mass in the range 1-3 ton. The barrier crest is located 2.5 m below sea level. To reduce off-shore sediment losses, a thick filter layer is present on the downstream side of the sill. Three granulometric classes of sediments have been used to ensure a gradual transition of the sediment diameter from the beach to the sill (d_{50}=5÷15 mm). Fig. 2 shows a sketch of the design section of the perched beach nourishment at the site of interest.

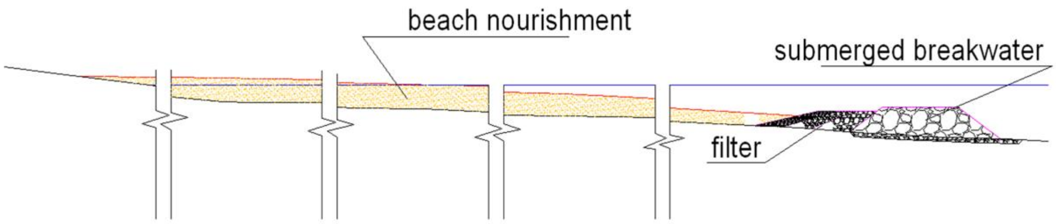
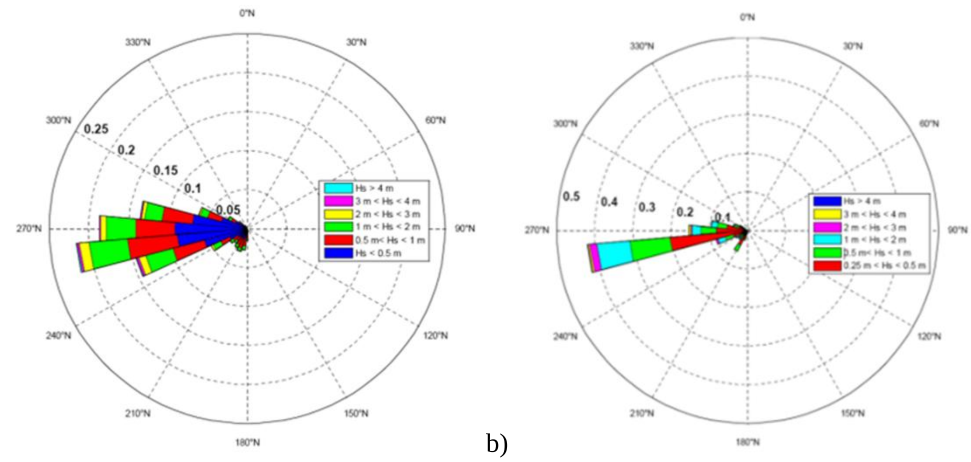


Figure 2. Design section of the beach nourishment intervention at the site of Belvedere Marittimo (Italy). The perched beach is protected by a submerged breakwater coupled with a filter system behind of the structure.

An analysis of the wave climate has been carried out in order to determine the wave characteristics at the site, both offshore and onshore. Fig. 3 shows the rose diagrams of the frequency of the significant wave height distribution offshore and at the depth of closure, which is equal to 7.2 m. The most frequent and energetic wave attacks come from 240°N and 290°N offshore of the site. Due to the bathymetric characteristics of the site, such a sector is much narrower (260°N- 270°N) close to the coast, the wave attack being almost orthogonal to the coast. Therefore a 2D physical modeling of the site seems to be appropriate and it has been adopted in the present case.



a) b)

Figure 3. Directional distribution of significant wave height at the site of interest. a) Frequency of significant wave height in deep waters. b) Frequency of significant wave height at closure depth (h=7.2 m).

Yearly bathymetric surveys as well as data on the dimension of beach material along some transects, prior, right after and for two years after construction, are available. In particular, the recorded bathymetric profile right after construction shows that the beach nourishment has been realized by disposing two sediment mounds, one on the shoreface and one close to the submerged breakwater. The analysis of the sediment samplings right after construction exhibits a strong uniformity of the sediment sizes (d_{50} is about 3 mm everywhere, but on the swash zone and offshore of the sill). The following surveys show the tendency of the beach profile toward an uniform equilibrium slope, at the same time a sediment sorting occurs with finer sand (d_{50}=0.26÷0.60 mm) in the submerged beach and coarser sand (d_{50}÷3.1-3.8 mm) on the emerged shoreface.

EXPERIMENTAL SET-UP

The experiments have been carried out at the Hydraulic Laboratory of the University of Catania, on a 2D physical model, scaled 1:30 compared to prototype. The experimental wave tank is 18 m long, 3.60 m wide and 1 m deep (see Fig. 4). Froude similarity has been used for wave scaling. A "SAND model" (van Rijn, 1993) has been considered for scaling the beach material, by checking through the mobility number that a similar sediment transport regime occurred both in the prototype and in the model (Van Rijn et al., 2011). The elements of the barrier have been scaled by considering the similarity of the Hudson number. Several simplifications have been made when building the physical model. For example, the three types of granulometric classes of the different layers of the filter have been reduced to one class. Moreover, sediment sorting of the real beach along the profile has not been considered and a well-sorted quartz sand has been used considering a d_{50} equal to 0.24 mm, which is similar to the smallest sand diameter observed in the field. Table 1 summarizes the materials and the dimensions of the stony elements used in the present physical model.

Table 1. Characteristics of the materials used for the physical model of the beach and of the submerged breakwater.

Element	Material	Size
Beach	Quartz sand	d_{50}=0.24 mm
Sill	Basaltic quarry stones	20 mm<d< 30 mm
Filter	Calcareous shingles	3 mm<d<5 mm

Both hydrodynamic and morphodynamic measurements have been carried out.

From the hydrodynamic viewpoint, three resistive wave gauges have been used. Two of them have been located in front of the sill, in order to measure the reflection coefficient by means of the two-gauges method proposed by Goda and Suzuki (1976). A third gauge has been located shoreward of the barrier, to measure the transmission coefficient. Velocity profile have been measured in front of the barrier by means of a micro-ADV.

Moreover, the stability of the submerged sill has been measured optically by means of two computer vision methodology: a stereo-head produced by VidereDesign, located in front of the barrier and a 2D structured light approach. By using the latter method, a section of the barrier is continuously visualized by means of a laser sheet which is projected onto the barrier. A calibration procedure is used to convert the data from pixels to centimeters. A review of the application of computer vision techniques in the field of coastal engineering laboratories has been recently presented in Foti et al. (2011).

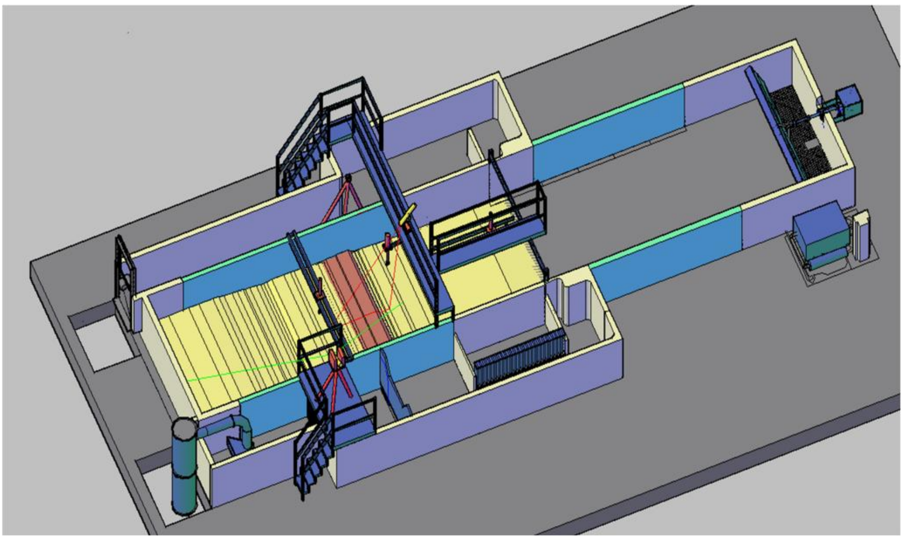
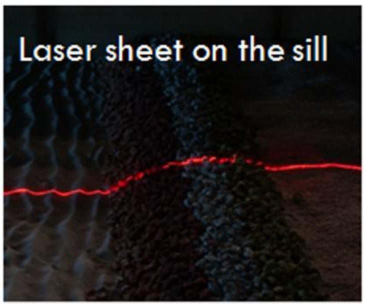


Figure 4. Experimental wave tank and location of the physical model of the perched beach nourishment (the barrier is in red), and of the measurement instruments.

The stereo-head allowed to control the movement of the elements of the barrier and to evaluate the damage of the barrier in terms of the relative displacement $D=N_{dis}/N_{tot}$, where N_{dis} is the number of displaced elements and N_{tot} is the total number of stones. The 2D structured light approach has been used to measure the damage by means the relative eroded area $S=A_e/D_{n50}^2$, with A_e being the eroded area and D_{n50} the characteristic size of the elements of the sill. At the same time, the 2D computer vision system has been used to measure the scour induced by the wave in front and behind the barrier. Fig. 5a shows a typical image obtained by projecting the laser sheet on the sill, while Fig 5b) explains how such an information is interpreted by comparing the measurement of the initial and final profiles, to determine the eroded area A_e and the scour depth.

a) 

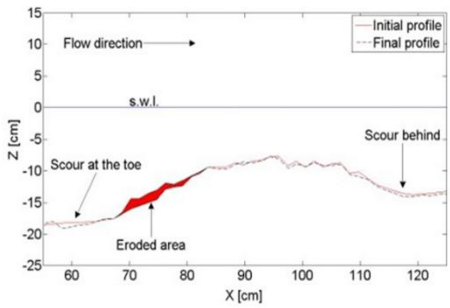
b) 

Figure 5. 2D computer vision system for recovery the damage to the submerged barrier and the scour depth close to it. a) formation of the image; b) interpretation of the image to measure the eroded area and the scour depth in front and behind the sill.

Finally the evolution of the beach profile has been measured both by using a set of rods located along a section of the tank and by means of a 3D laser scanner.

Fig. 6 shows the two configurations of the tested physical model. In particular, in the modified configuration the filter introduced by the designer shoreward of the submerged structure to reduce sand losses has been covered by an armor layer made up by the same type of element of the barrier.

a) b)

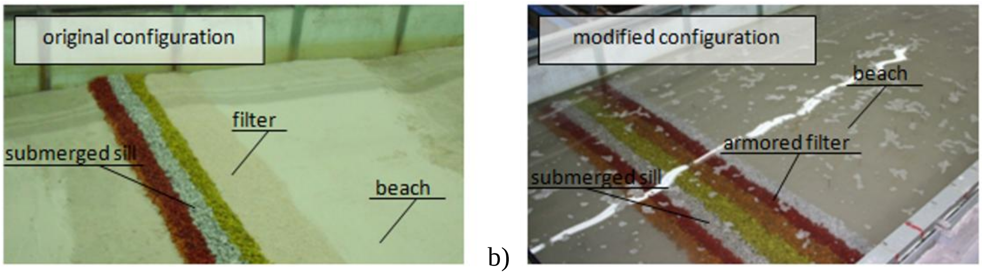


Figure 6. Investigated configurations of the perched beach nourishment: a) original configuration; b) modified configuration (where the filter has been covered with a layer of elements similar to those of the submerged sill).

EXPERIMENTAL CAMPAIGN

The experiments have been aimed at analyzing: (i) the long-term evolution of the beach profile; (2) the resilience of the beach to the effects of small storm wave attack in two cases, namely right after construction, starting from the initial profile after sand disposal, and after an equilibrium beach profile was achieved due to morphological wave attack; (iii) the effects of an alternative design of the sill, with the armoring of the filter layer.

In the lab, the irregular waves have been generated by using Jonswap spectra with the same significant wave height and medium wave period compared to prototype. The significant wave height, H_s, the mean wave period, T_m, and the duration of the event considered in the present work are summarized in Table 2, both at prototype and laboratory scale. In particular the morphological wave conditions correspond to an accretive condition, while the storm wave is a small storm, characterized by about 2 years of return period at the site of interest, which is representative of erosive conditions.

During the accretive tests, in order to reach an equilibrium beach profile the overall duration of the morphological wave was about 22 hours, which corresponds to 4 years real time. The erosive wave conditions have been experimentally simulated by considering a storm profile, i.e. a series of sea-state having increasing significant wave height and wave period.

As mentioned before, two kind of erosive wave tests have been performed: (i) erosive waves attacking the beach after an equilibrium condition was achieved; (ii) erosive wave attacking the initial beach profile of the beach, thus simulating a storm which attack the perched beach right after the construction of the beach nourishment. For brevity sake, in the present work the results relative to the latter erosive conditions are not discussed.

Table 2. Hydrodynamic targets considered in the present experimental campaign

	Prototype scale			*Laboratory scale*		
	H_s [m]	T_m [s]	*Duration* [h/years]	H_s [m]	T_m [s]	*Duration* [h/years]
Morphological wave	1.49	8.01	29.66	0.05	1.46	5.41
Storm wave	4.20	12.38	21.00	0.14	2.26	3.83

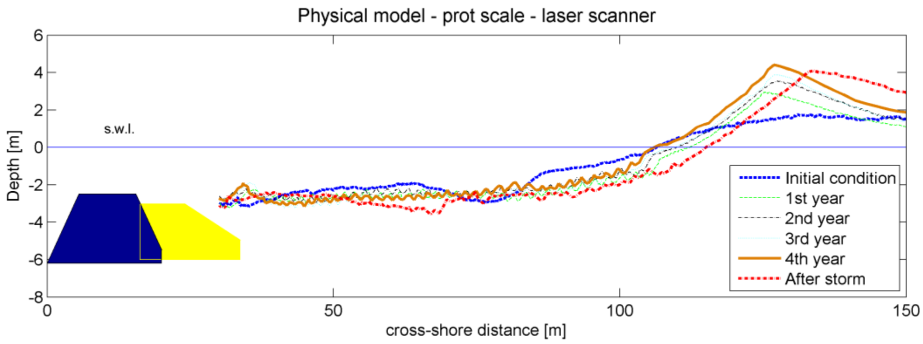
EXPERIMENTAL RESULTS

The hydrodynamic, stability and morphodynamic behavior of the two configurations of the perched beach described above has been analyzed. Reflection and transmission coefficients have been measured along with the damage to the submerged breakwater in terms of both the relative displacement of the rubble mound elements and of the relative eroded area. From the morphodynamic point of view, measurements on the wave scour both at the toe and on the lee side of the sill and the beach profile evolution have been gathered.

However, in the present work, we focus our attention mainly on the performances of the perched beach nourishments in terms of beach profile evolution both in accretive and erosive conditions. The interested reader is referred to Musumeci et al. (2011) for more details on the experimental results on the hydrodynamics, stability and scour around the sill.

Fig. 7 reports, at prototype scale, the measurements of the evolution of the perched beach subject first to 4 years of morphological wave attack followed by a small storm characterized by a return period of about 2 years, on site. As mentioned before the first condition corresponds to accretive waves, whereas the second one is representative of mildly erosive waves. Results are shown both on the original configuration of the sill, with the unprotected filter, and on the modified configuration, with a stone apron located on top of the filter.

a)



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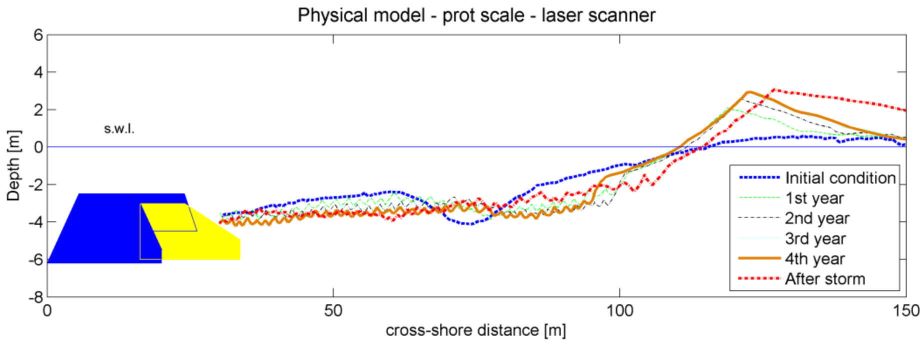


Figure 7. Evolution of the beach profile measured at the end of several series of accretive waves (1st year, 2nd year, 3rd year and 4th year, each year is made up by about 12500 waves) followed by a series of erosive wave (small storm having about 2 years return period). a) original configuration; b) modified configuration. Measurements are reported at prototype scale.

The initial profile corresponds to the profile measured in situ during 2006, i.e. the first one after sand disposal. Such an initial profile is characterized by the presence of two mounds of sediments coming from the two different placements of sand, one close to the barrier and the other one close to the shoreline. The dynamics of the beach observed during the experiment can be summarized as follows.

Initially, under accretive waves, the sediment transport is directed onshore. Nevertheless, after the 1st year, the shoreline retreats because part of the available sediment volume is used to compensate the discontinuity located in the central part of the initial profile. Moreover, another part of the sediment volumes is used to start building a berm. After the first year the sediment transport is still directed onshore, the berm height keeps increasing but the shoreline movement reverses and it starts moving offshore, thus increasing the width of the emerged beach. A sediment budget along the profile shows that the volume of sand moved after the first year tends to decrease becoming negligible after the 4th year. Indeed, in Fig. 7 in the correspondence of the 3rd and of the 4th year it is clear the tendency toward an equilibrium profile.

Under erosive waves the sediment transport is mainly directed offshore but in the swash zone. The shoreline position retreats, the berm is slightly eroded and part of the sediments are lost within the gap of the barrier or offshore.

Both the original and the modified configurations show a similar dynamics. However, in the second case the dynamics during the accretive wave conditions is faster, since the profile reach earlier a quasi-steady condition. Moreover, it turns out that the presence of the stone apron on top of the filter allow for a more efficient protection of the beach from storm wave attack.

Table 3 summarizes some of the main morphological parameters of the beach profile evolution, such as the shoreline advancement or retreat, the height of the berm and the average beach slope, in order to allow a comparative analysis on the performances of the two type of perched beaches. It turns out that the simple use of the stone apron allow a much greater protection of the beach nourishment, as for example the shoreline retreat is reduced to a third of the one measured in the absence of filter protection.

Table 3. Comparative analysis of the perched beach nourishment evolution at prototype scale

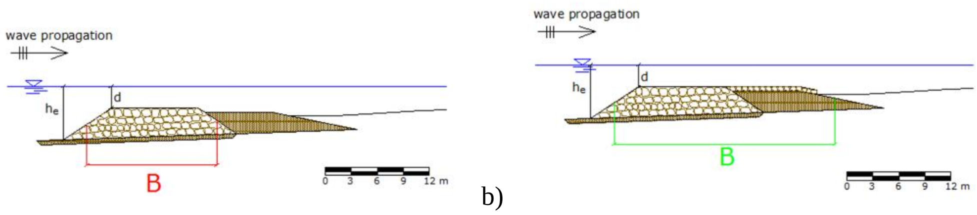
		Original configuration	Modified configuration
Accretive wave	Shoreline advancement [m]	0.60	5.00
	Average slope of the shore face [%]	22.6	18.5
	Elevation of the berm crest with respect to the s.w.l. [m]	4.42	2.92
Erosive wave	Shoreline retreat [m]	9.10	3.70
	Elevation of the berm crest with respect to the s.w.l. [m]	4.10	3.09

Comparisons between experimental and analytical results

The results of the present experiments have been compared with the prediction of the analytical model of Gonzalez et al. (1999). To this aim, following the indications provided by Gonzalez et al. (1999), an iterative procedure has been implemented on purpose. However, before considering the comparison between experimental and analytical results, the main differences between the two approaches have to be pointed out.

First of all, the analytical model treats the submerged breakwater as an impermeable rectangular element, whereas in the physical model the rubble-mound structure is porous and it has a trapezoidal shape. In the case of the original configuration of the model, the presence of the filter exposed to the wave action cannot be properly taken into account and the filter is considered a part of the inner beach profile, made up by the same beach material. Even more complicated, in the case of the modified configuration a stone apron is used to protect the underlying filter.

In order to perform the comparison with the above described model, a reasonable compromise seems to consider an equivalent width of the barrier equal to the mean width *B* of the structure, as indicated in Fig. 8 for both cases. Besides the differences in the geometry of the protection of the toe of the beach, another more important difference arises among the analytical approach and the experimental one. Indeed, in Gonzalez et al.'s model the effect of wave dissipation induced by the presence of the structure, i.e. the effect of wave breaking and of porosity, is neglected, the controlling phenomena being wave reflection of the incoming waves.



a) b)

Figure 8. Sections of the submerged barrier at the toe of the perched beach and indication of the mean equivalent width B considered for the comparisons with Gonzalez et al. (1999). a) original configuration; b) modified configuration.

Fig. 9 reports a comparison between the calculated and measured reflection coefficients *Kr*, for all the tested hydrodynamic conditions and configurations of the physical model. It appears that in most of the cases the analytical model tends to overestimate the reflection coefficients, but in the case of erosive waves attacking the modified configuration. Table 4 points out the mean relative absolute errors grouped by type of tests (i.e. original or modified configuration of the barrier, accretive or erosive waves). It can be noticed that the errors are much smaller when the modified configuration of the barrier is concerned. Indeed in such a case the structure is much more rigid than in the first case and the hypotheses of Gonzalez et al. (1999) are better fulfilled.

In particular, in the case of the original configuration, both the analytical and the physical models agree that the more energetic the waves, the higher *Kr*. The opposite occurs in the case of the more rigid and larger structure, where the filter has been armored, the reflection coefficients are larger in accretive conditions and smaller in erosive conditions. This behavior seems to be representative of the fact that in this case a relatively larger portion of the wave energy is able to penetrate up to the shoreward part of the beach profile, being transmitted onshore.

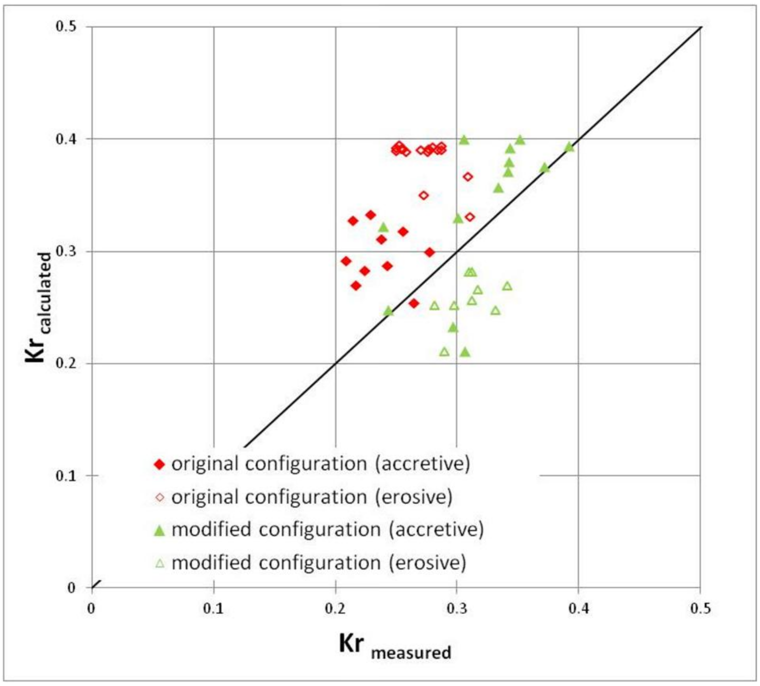


Figure 9. Comparison between the reflection coefficients measured and calculated by using the analytical model of Gonzalez et al. (1999).

Table 4. Comparison between the analytical and the experimental results on the prediction of the reflection coefficient

Physical model	Wave condition	Mean relative absolute error [%]
Original configuration	Accretive Erosive	27 41
Modified configuration	Accretive Erosive	14 17

Once the value of the reflection coefficient Kr has been determined, the analytical model predicts the beach profile simply assuming along the perched beach an equilibrium profile which starts at the back of the barrier at the water depth h_i. Such a water depth is determined by using Equation (2).

In the present work a comparison between the predicted equilibrium beach profile and the measured one has been carried out. To this aim, the beach profile measured along the central section of the tank after a long series of accretive waves (i.e. about 50000 waves, which correspond to 4 years of morphological wave attack in the field) has been considered here as a benchmark. In order to determine the sediment scale parameter A of the well-known Dean’s equilibrium profile equation ($h=Ay^{2/3}$, where h is the water depth, and y is the distance from the shoreline), the following relationship has been used

$$A = 0.21(d_{50})^{0.48} \tag{4}$$

The value of the d_{50} has been chosen equal to that of the quartz sand used in the lab, i.e. 0.24 mm.

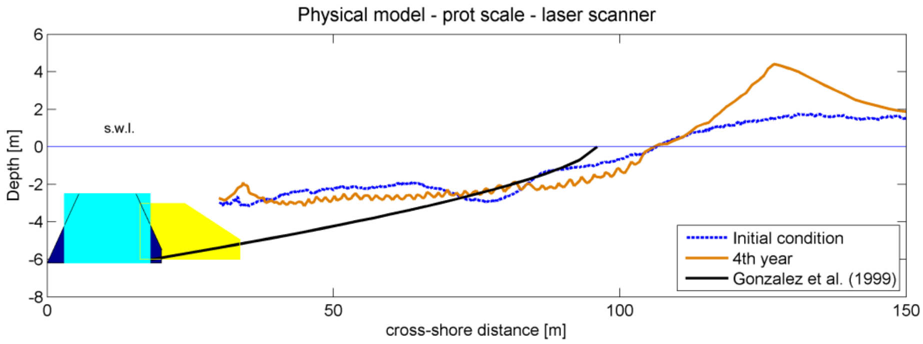
Fig. 10 shows the initial beach profile, as measured in the lab; the equilibrium beach profile measured after 4 years of accretive wave attack and the analytical equilibrium beach predicted by the model of Gonzalez et al. (1999). The top and the bottom panels of Fig. 10 are referred to the original and the modified configuration results respectively. It can be noticed that, when applying the analytical model considered in the present work, the difference between the two cases is translated just into a difference of the width of the equivalent rectangular barrier (cyan area in the plots).

It appears that in both configurations there is a great discrepancy between the analytical and the experimental results. Indeed, while the experimental results show a tendency to reshape the beach profile toward an equilibrium profile and to form a berm on the shoreface without a significant movement of the shoreline, the analytical results provide a much larger scour behind the submerged structure and in turn a much larger advancement of the shoreline itself.

Such a discrepancy is mainly due to the differences between the calculated and the measured value of the water depth h_i at the back of the submerged sill. Indeed such a value is a constraint for the position of the equilibrium beach profile in the model of Gonzalez et al. (1999). For both configurations, Table 5 reports the calculated and the measured values of h_i along with the relative error and the distance Δy between the measured final shoreline and the predicted one. It turns out that the water depth h_i is greatly overestimated by the analytical model. Moreover it can be noticed that, in analogy with the results on the reflection coefficient, the errors are larger in the original configuration case compared to the modified case.

Such a difficulty of the model to properly predict the water depth shoreward of the submerged structure should be related to the differences between the theoretical structure itself and the real one. Moreover the present version of the analytical model does not include energy dissipation over the sill, whereas in reality a great portion of the wave energy is dissipated both by waves breaking over the structure and by turbulence within the porous medium. It follows that the analytical model must overestimate the energy flux transmitted onshore. Such an interpretation is partly confirmed by the smaller errors observed when comparing the analytical model results with the results obtained on the modified configuration, which has a more reflective behavior with respect to the original one. Another difference is the presence of the filter in the original configuration of the model which cannot be taken into account analytically. Indeed the sediment of the filter, being much coarser than the beach sediment, are also less mobile, thus tending not to be eroded by the incoming waves and justifying smaller water depth behind the structure.

a)



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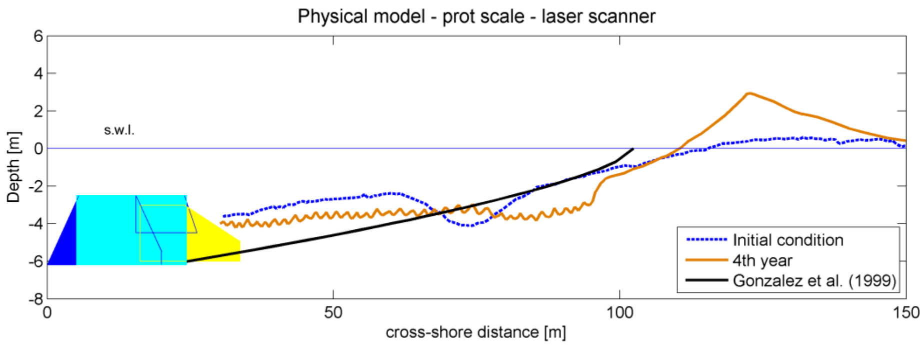

Figure 10. Comparison between the beach profiles measured and calculated by using the analytical model of Gonzalez et al. (1999) at prototype scale. The initial beach profile in blue is reported as a reference condition. The blue structure is the rubble mound sill, the yellow area represents the filter, the cyan region is the equivalent impermeable rectangular barrier considered in the application of the analytical model. a) original configuration; b) modified configuration.

Table 5. Comparison between the analytical and the experimental results on the prediction of the equilibrium beach profile (accretive waves)

	$h_{i\ calc}$ [m]	$h_{i\ meas}$ [m]	err_{hi} [%]	Δy [m]
Original configuration	5.91	3.76	57	10.61
Modified configuration	5.85	4.12	42	7.90

Comparisons with field data

The results obtained on the original configuration inspired by the real perched beach nourishment realized at Belvedere Marittimo have been also compared with the available bathymetric field data.

In particular Fig. 11 reports on the top panel the results measured in the lab and on the bottom panel the field measurements. All the beach profile have been measured in situ yearly in the month of May, right after construction (2006) and two years afterward (2007, 2008).

Obviously the situation simulated in the lab is much simpler then what occurred in the field. Indeed the hydrodynamic forcing in the field is much more complex than the idealized wave forcing considered here (e.g. more than one storm has occurred, there can be effects of oblique wave attack, etc.). Moreover, the beach material itself is quite different. Indeed, the sediments cannot be properly scaled in the lab and it has been stated before that a SAND model has been used here, by ensuring that the mobility number was in the same regime (stability of small-scale bedforms and suspended load) in the lab and in the field. Furthermore, from the analyses of the sampled sediments in situ, the granulometric sorting in the field is quite large (d_{50} is in the range 0.20÷12 mm), whereas in the lab well-sorted sand has been used (d_{50}=0.24 mm).

Nevertheless, the physical model results can provide a series of both qualitative and quantitative indication on the perched beach evolution. Similarities between field and lab data can be summarized as follows: (i) in both cases the beach tends toward an equilibrium condition; (ii) the instability of the filter material under the action of the waves has been observed both during the experiments and in the field; (iii) the submerged sill appeared to be unstable both in the lab and in the field. Concerning the beach profile evolution, it should be pointed out that the main differences between field data and laboratory results are related to the beach slope and the height of the berm. Indeed in the field a milder sloping shoreface is obtained at equilibrium and the location of the berm crest, if any, should be onshore of the observed area. Such differences are probably due to scaling effects of the sediment diameters and to the fact that in the field several storms have attacked and modeled the beach during the observation time. However, it is encouraging the fact that, in quantitative terms, the final shoreline retreat observed during the experiments was about 9 m (at prototype scale), whereas during the monitored two years in the field the measured shoreline retreat is in the range 12.7÷20.8 m.

CONCLUSIONS

In the present work the performances of perched beach nourishments have been investigated by means of a physical model, inspired by a real case study. Indeed, for such a case-study several information were available on the geometry, on the wave climate and on the beach material characteristics, both at the initial stage after construction and during the evolution of the intervention.

In the lab, the model has been scaled 1:30 with respect to the prototype. In particular two different configurations of the toe protection have been studied, i.e. with and without a stone apron used as a protection of the filter located on the leeside of the structure. Both accretive and erosive wave conditions have been considered and a comprehensive analysis has been carried out on the hydro- and mophodynamics of the perched beach. Indeed, reflection and transmission coefficients, stability and scour around the sill and the beach profile evolution have been measured.

A comparative analysis on the two configurations of the submerged structure shows that the use of the stone apron is a quite effective measure in protecting the beach. Indeed, under accretive waves the shoreline advancement of the beach profile close to equilibrium with respect to the initial condition is about 8 times larger compared to the case with the uncovered filter. Moreover, under erosive conditions, the shoreline retreat is almost 3 times smaller.

The experimental results have been compared also with the prediction of the analytical model of Gonzalez et al. (1999). In particular, the reflection coefficient is overestimated by the analytical model in the majority of the considered cases, but in the case of erosive waves attacking the barrier with the armored filter. Moreover, smaller relative errors are registered considering such a configuration (mean relative error in the range of 14%÷17 %) with respect to the other one (mean relative error in the range of 27%÷41%). Concerning the comparisons of the measured and predicted equilibrium profile due to accretive wave conditions, several differences arise due to larger values of the scour behind the sill predicted by the analytical model and different beach slopes. Also in this case, the comparison with the structure in the presence of the stone apron is relatively more satisfactory. From such a comparison, it appears that the analytical model is not able to properly mimic the experimental data, mainly because it considers wave reflection as the key phenomenon and it disregards the effects of wave dissipation in the correspondence of the submerged breakwater. Such a energy dissipation is mainly due to wave breaking over the sill and to the permeability of the barrier. This explanation is confirmed by the smaller errors obtained when comparing experimental and analytical results in the presence of the armored filter. Indeed, in such a case the structure is more rigid and the reflected wave energy flux term contributes more significantly to the energy flux balance.

The experimental results have been compared also with field data. Notwithstanding the many simplifications considered in the physical modeling of the perched beach, such as simplified wave forcing, unscaled beach sediments, different granulometric distribution, the experimental results can provide reasonable prediction of the phenomena which occur in the field, i.e. instability of the submerged breakwater, strong erosion of the filter, tendency toward an equilibrium beach profile. In particular, the physical model is able to predict shoreline retreats which are similar to those observed in the prototype.

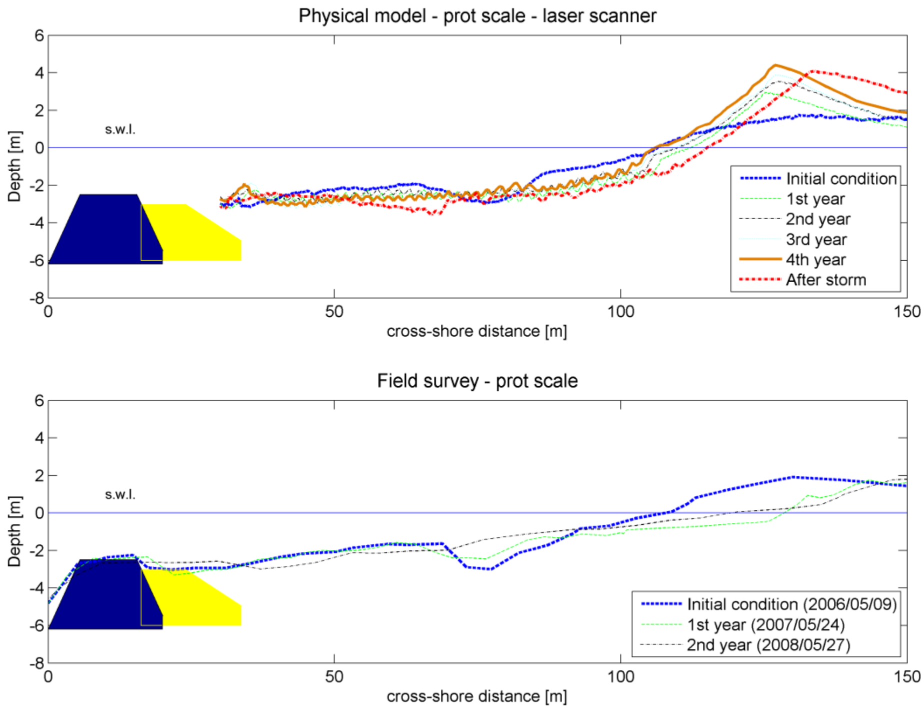

Figure 11. Comparison of the beach profile evolution with field data. Top panel: beach profiles measured during the present experimental campaign; bottom panel: beach profile measured during field bathymetric survey.

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