EVOLUTION OF A PERCHED NOURISHED BEACH: COMPARISON BETWEEN FIELD DATA AND NUMERICAL RESULTS

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The morphodynamics of a perched nourished beach, located near the town of Belvedere Marittimo in the South-West coast of Italy, has been analyzed by means of the Xbeach numerical model. The results have been compared with several surveys available for this site. It has been found that generally the numerical results well reproduce the slope of the beach profile, though they over-predict the erosion in the onshore part of the beach. Such an overprediction is more important when the real wave climate measured near the site is used to run the numerical model, while the use of a yearly averaged wave produces results more in accordance with the field data.

Keywords: XBeach; submerged reef; equilibrium beach profile

Introduction

The beach nourishments with a protection at the toe made up by a submerged breakwater is becoming a widespread practice to extend the lifespan and the stability of beach nourishments. The goal is to reduce the offshore extension of the beach nourishment by intersecting the new beach profile with a submerged structure to retain the beach in a perched position. In this case, the presence of a submerged reef allows (i) a portion of wave energy to be damped; (ii) off-shore losses of beach sediments to be limited; (iii) the volume of sand requested for beach nourishment to be reduced, particularly in the presence of a steep beach (Raudikivi and Dette, 2002).

Several efforts have been made to determine the stability of a beach located in the proximity of a structure. Sawaragi (1988) carried out an experimental study on the effectiveness of submerged breakwaters to control cross-shore sediment transport. Sorensen and Beil (1988) investigated the storm effects on a beach profile, both in the presence and in the absence of a submerged breakwater, located at different distances from the shoreline. Gonzalez et al. (1999) proposed a semi-analytical methodology for the estimate of the equilibrium profile of a perched beach, which is based on linear wave theory and on the concept of equilibrium beach profile. The model assumes that wave reflection at the breakwater is the most important process that controls the evolution of the beach profile, as it modifies the amount of energy which can reach the beach itself; the consequent wave modification is used to determine the shoreline location of a perched beach. Dette et al. (2002) performed large scale experiments on a barred beach with different water depths above the crest of the sill, with the aim of analyzing wave energy conversion and the shape of the underwater profile of a surf zone.

Sumer et al. (2005) investigated experimentally the scour around submerged breakwaters, both at the trunk and at the roundhead. They found that substantial scour occurs at the toe of the structure, not only at the offshore side of the sill, but also at the onshore side. More recently Musumeci et al. (2011) performed an experimental investigation on the morphodynamics of a perched beach by using a physical model inspired by a real case study near the town of Belvedere Marittimo in the South-West coast of Italy. They analyzed the hydrodynamics at the back of a submerged reef and its stability under both the effects of a yearly-averaged wave and of low energy storms. However, as pointed out by Faraci et al. (2014), the physical model does not reproduce correctly the equilibrium profile and thus the shoreline retreat. A possible explanation for this drawback is the difference in the initial bed profiles between laboratory experiments and field data. However, the two beach profiles at equilibrium were so different that the issue of the initial conditions does not appear sufficient to explain the results. For more details regarding the comparison between field survey and physical model the interested reader is addressed to the paper by Faraci et al. (2014).

In this work the attention is rather focused on the possibility of predicting the morphological response of the perched beach of Belvedere Marittimo, by using the results of the morphological

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numerical model recently developed by Roelvink et al. (2009), known as XBeach. The reliability of the model is evaluated by comparing the numerical results with available field data.

XBeach has been extensively used at the storm event timescale (hours to days). Although this model has been validated and used extensively for erosive conditions, it has not been successfully validated or used to simulate post-storm beach accretion and recovery. Only recently, Pender and Karunarathna (2013) simulated storm and seasonal time scales to reproduce several features of the beach morphodynamics by using two different transport formulations, the Soulsby-van Rijn transport formula, used under storm erosive conditions, and the van Thiel-van Rijn formula (van Rijn, 2007), employed under post-storm recovery conditions. Moreover for recovery conditions calibrated factors applied to wave skewness and asymmetry were introduced to gain an agreement with field measurements.

In the present work XBeach has been used to simulate seasonal beach changes, without any attempt to modify its settings. By introducing the field measurements as initial conditions, the numerical results have been compared with several yearly surveyed profiles in order to understand the potentiality and the limitation of the morphological model.

In the following, first the case study is illustrated, then the morphological model XBeach is briefly described. Then, a section is devoted to comparisons between the in situ surveys and the numerical results. Conclusions end the paper.

Description of the case study

The beach of Belvedere Marittimo, located on the South-West coast of Italy (Figure 1), has been intensively exploited for recreational purposes and, in the last decades, it suffered a severe erosion.

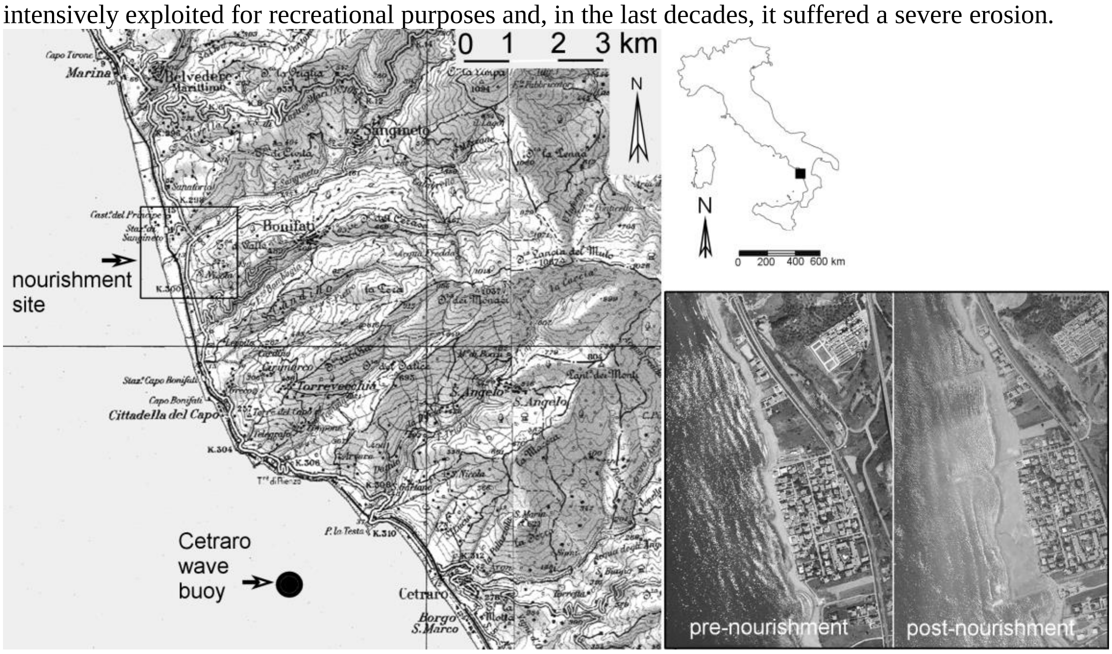


Figure 1. Overview of the investigated site. The ortophotos date back to 2000 (pre-nourishment) and 2006 (post-nourishment).

In order to contrast such a process, in 2006 a beach restoration project has been realized. In particular, in order to rapidly enlarge the beach, 600000 m^3 of quartz sand, with d_{50}=3 mm, were disposed on the beach face, for a longshore length of about 700 m and a cross shore length of about 230 m from the seawall that protects the seafront, up to a closure depth of 7.2 m (see Figure 1, showing the beach before and after the nourishment intervention). Considering the high slope of the beach profile at this location, the beach nourishment was coupled with a toe protection structure, parallel to the shoreline. Such a structure is made up by a quarry-stone submerged breakwater, with mass of the stones in the range 1-3 tons, and a filter on the onshore side of the sill, made up by three layers of shingles and small stones, whose diameter is in the range 5-15 cm. The water depth above the crest of the sill is about 2.5 m and the width of the sill is about 10 m. The filter was used to assure a smooth transition between the small size of the sand of the beach nourishment and the large stones of the barrier, thus avoiding large loss of sand. Moreover, the interested area was confined by two lateral groins, made up by the same material of the submerged sill, which allow lateral losses of sand to be controlled. Figure 2 shows the plan view of the site with the indication of the section 29 that has been reproduced in the XBeach model and the section 28 where the sediment surveys have been carried out; figure 3 shows a typical cross section of the intervention.

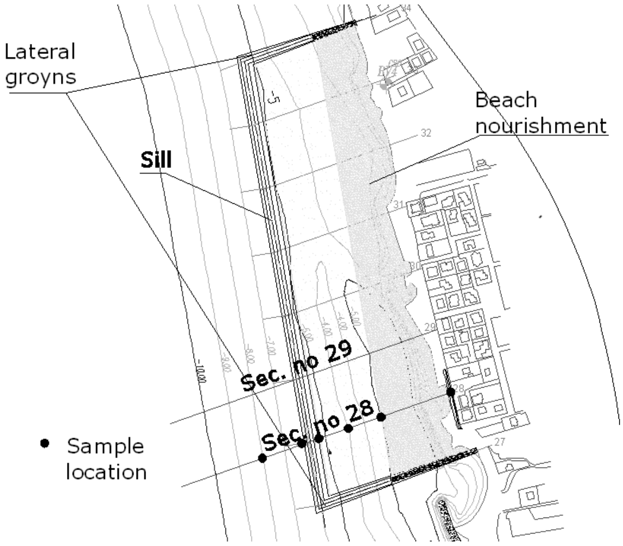


Figure 2. Plan view of the beach nourishment project with indicated the sections 28 (sediment sample carried out in 2006) and 29 (used as reference for the XBeach model)

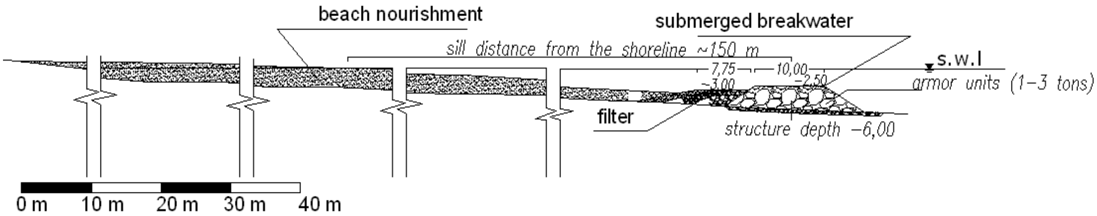


Figure 3. Typical cross section of the beach nourishment.

The site has been yearly monitored along several sections from 2005, i.e. the year before construction, up to 2008, i.e. two years after the work was completed.

Figure 4, where the field measurements are plotted all together, shows a greatly eroded beach at year 2005, before the beach nourishment works. In 2006, the submerged sill and the beach filling can be easily recognized. It may be noticed the presence of a large dip in the beach profile onshore of the breakwater. Such dip is induced by the procedure of sand disposal during the works and it completely disappears after two years.

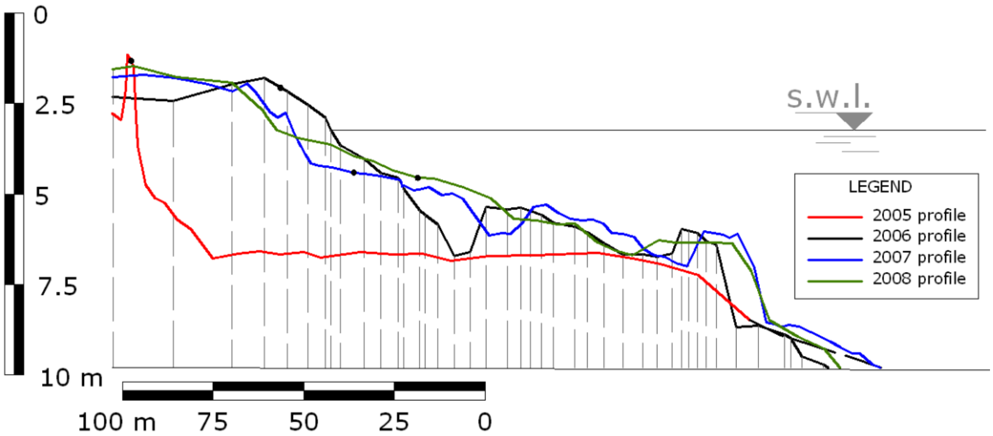


Figure 4. Bathymetric surveys of the cross-shore evolution of the beach profile before (2005) and after construction (2006-2008) at section no. 29.

Figure 5 shows the mean sediment diameter at various depths along the profile of section 28. Before construction the sediment diameters are greatly variable, in the range of 0.25-7.4 mm. Since the beach filling was made in 2006 by using quartz sand having d_{50}=3 mm, at this time the field data show mainly the presence of the new beach material except on the foreshore, where coarser grain sizes appeared. The origin of such a coarse sand is not very clear but it may be related to the occurrence of storms just before the surveys, which caused the accumulation of large sediments at certain locations. However in the following year such a large material disappeared again. After a couple of years the sediment characteristics were again largely mixed up by the action of the waves. Coarser sand was found landward, probably because of the occurrence of storms before the surveys, while finer sand was found offshore. The presence of finer sand landward the sill in 2007 and 2008 (Figure 5, h=0÷2) could be due to the effect of waves which mobilize finer sediments which bypassed the sill and then were trapped between the shoreline and the sill.

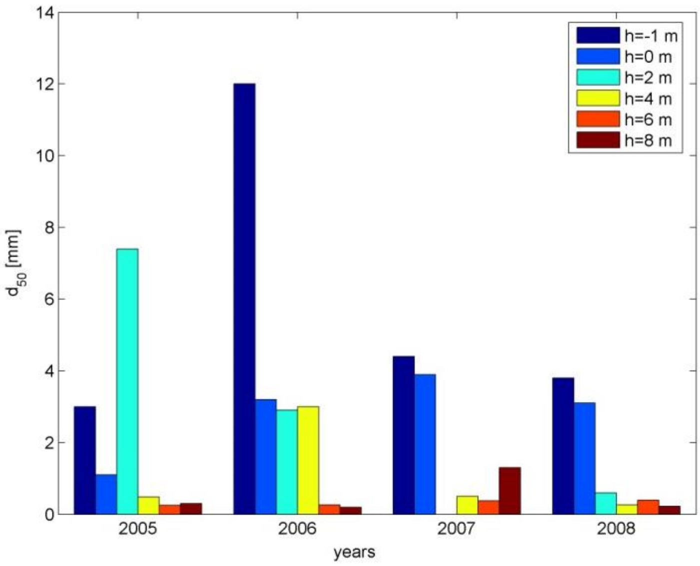
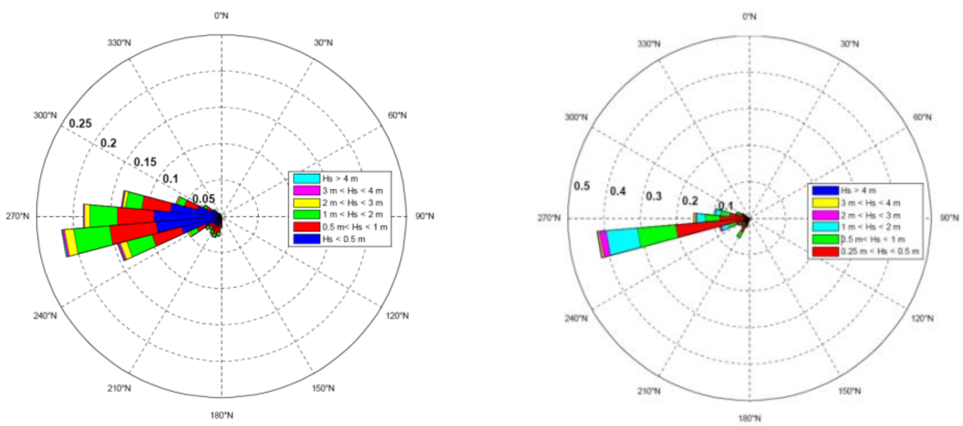


Figure 5. Survey on the mean diameters of beach sediments along a cross-shore section both before and after the nourishment.

The analysis of the wave climate was carried out on the basis of the data provided by the Buoy of Cetraro, belonging to the Italian National Wave Measurement Network (ISPRA). The data were geographically transferred from the buoy to the site of study and then were propagated close to the coast by using SWAN (Ris et al, 1994). The analysis showed that the wave motion is mainly orthogonal to the coastline. Moreover the site can be classified as microtidal, since the maximum tidal excursion for a return period of 10 years is 0.27 m. Figure 6 shows the wave climate at deep water and at the closure depth (7.2 m) close to the investigated site.



(a) (b)

Figure 6. Wave climate at (a) deep water offshore Belvedere Marittimo and at (b) the closure depth (7.2 m).

The morphological model

XBeach is an open source numerical model aimed at analyzing the morphodynamics of coastal areas (Roelvink et al. 2009). XBeach concurrently solves the time-dependent short wave action balance, the roller energy equations, the nonlinear shallow water equations of mass and momentumand computes the bed morphodynamics on the scale of wave groups.

The wave boundary conditions can be applied as time series of the instantaneous wave height including wave grouping, or alternatively, the time-steady wave forcing can be used, which may still result in unsteady currents and surface elevation (Roelvink et al., 2009).

The inputs of the applied numerical model can be subdivided in bottom profile characteristics and wave data. As regards the bottom, the profile measured in May 2006, i.e. immediately after the construction of the protected nourishment, was considered. The main characteristic of such a profile is that the nourished sand has been collocated, for constructive reasons, with a steep slope and therefore a pit is present before the submerged breakwater. An additional simulation was carried out by using the 2007 profile and reproducing its evolution during one year. The profile measured in 2008 is used for validating the model results.

As regards the sediment characteristics, the median grain size adopted for beach nourishment (d_{50} =3 mm and d_{90}=4 mm) has been provided as input. Even though the field surveys showed that the submerged breakwater has been modified by the waves, giving rise to a progressive widening and lowering of its shape in time, a hard layer option has been used, thus implementing a non erodible condition in correspondence to the sill.

The input wave data were those recorded by the buoy of Cetraro (see Figure 1 for reference) and geographically transferred to the area of interest (Contini and De Girolamo, 1998). The wave data were treated in order to determine the modification of height and direction of waves during their propagation toward the coast. In particular, due to the huge amount of data, the refraction and shoaling were computed under the more simple assumption of straight and parallel bathymetric lines, by applying the well-known formulations of Wilson (1966) and Goda (2000) respectively.

All the amount of data collected in such a way have been reduced in order to be considered as input of the used model, sampling every 6 hours and filtering the waves heights lower than 0.5 m. In Figure 7 the actual sequence of storms, after removing the calms is shown. Its duration corresponds to the fraction of waves over 0.5 m occurring during the two years between 2006 and 2008. In particular about 125 days of storm events are obtained for the two years, seven of these being characterized by a wave height higher than 3 m and four by a wave height higher than 4 m. These wave conditions have been input in the model as a sequence of stationary sea states. Due to the limitation of XBeach which does not allow simulations longer than 10^6 seconds to be run, all the wave data have been divided in sequences of 993600 s each in order that the output profile of the n^{th} simulation was provided as input for the $(n+1)^{th}$.

A specific simulation has been run using as input a yearly-average wave. The yearly-averaged wave height H_s and period T_m have been calculated for the site of Belvedere Marittimo by Aristodemo (2008). This wave is representative of the energetic content for the considered sector; in principles it should be able to induce the same effects on the littoral as the whole data set of waves accounted for its calculation. Starting from significant wave height H_{si} and period T_{pi} of the i^{th} component of N events, the yearly-averaged wave can be calculated as:

$$H_s = \left(F^2 \cdot R\right)^{1/5} = \left[\left(\frac{1}{N}\sum_{i=1}^{N} H_{si}^{\ 2} \cdot T_{pi}\right)^2 \cdot \frac{1}{N}\sum_{i=1}^{N}\frac{H_{si}}{T_{pi}^{\ 2}}\right]^{1/5} \tag{1}$$

$$T_m = \frac{F}{H_s^{\ 2}} = \frac{\frac{1}{N}\sum_{i=1}^{N} H_{si}^{\ 2} \cdot T_{pi}}{\left[\left(\frac{1}{N}\sum_{i=1}^{N} H_{si}^{\ 2} \cdot T_{pi}\right)^2 \cdot \frac{1}{N}\sum_{i=1}^{N}\frac{H_{si}}{T_{pi}^{\ 2}}\right]^{2/5}} \tag{2}$$

F being the energy flux and R the mean wave steepness.

Absorbing boundary conditions have been set for back and front of the domain; default settings have been left for wave breaking and roller setup. The same setting was used for the simulation carried out using the 2007 profile as initial condition.

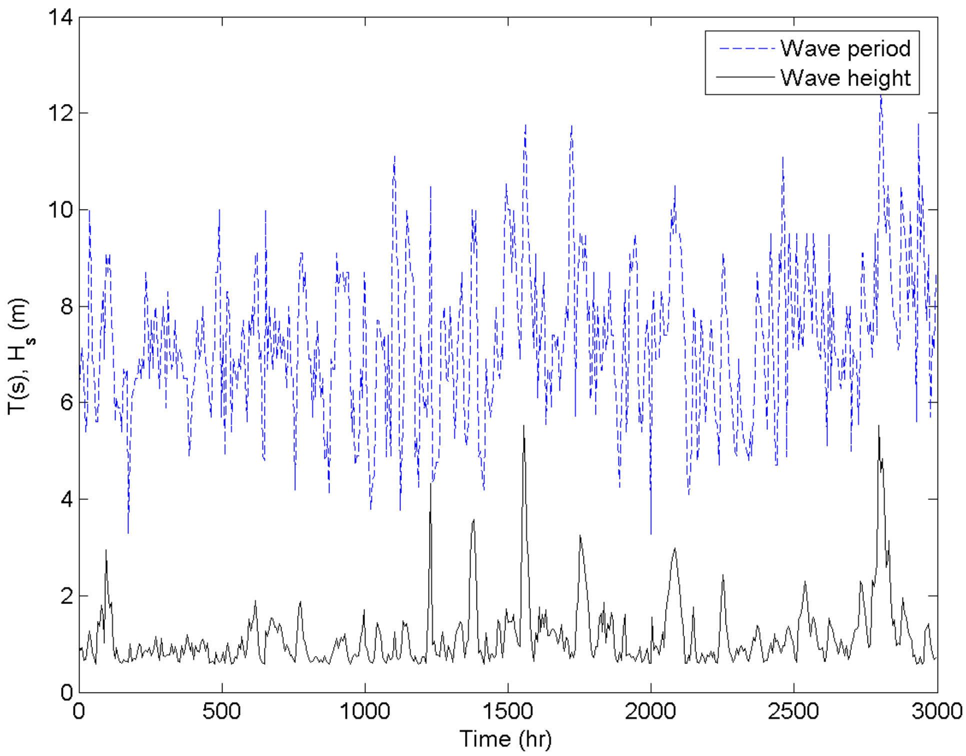


Figure 7. Wave data registered at the buoy of Cetraro, geographically transferred to the site and sampled every 6 hours filtering waves heights smaller than 0.5 m.

Model results

The application of XBeach model covered two years, i.e. from May 2006 to May 2008. Nevertheless, the availability of yearly bottom profile measurements allowed to consider an intermediate result, in order to compare it with the field survey of year 2007. In such a way a more reliable indication about the correspondence between numerical model and field data has been obtained.

Figure 8 shows the measured profiles for the years 2006 and 2007 along with the results of the simulation named XB06, which is obtained starting from the field profile acquired in 2006 (initial condition) after one year of simulation (XB06 2007). Main aim of this plot is to compare the results of the simulation with the survey of 2007.

The main outcome of this simulation is that the slope of the beach is well estimated by XBeach model during the first year. Looking more closely at the cross-shore profile, proceeding from offshore to onshore it is possible to notice that:

i) the sill, that has been set as a non erodible layer, has not been shifted or deformed while in the field it undergoes a reshaping, due to the modeling effect of strong waves;

ii) the numerical model predicts the disappearance of the pit which is located at about x=80 m already after the first year, thus even more rapidly than in the field;

iii) the dune partial destruction is also well reproduced by the model but it appears to be rather overestimated. This latter result can be attributed to the fact that the model has been developed for predicting storm effects along the coast, thus it does not take into account the accretive effect due to small waves, causing an erosion stronger than that observed in the field.

iv) notwithstanding the previous drawbacks, the shoreline retreat computed by the numerical model for this first year is somewhat similar to that measured in the field (about 11 m), since the dune erosion takes place mainly above the mean water level.

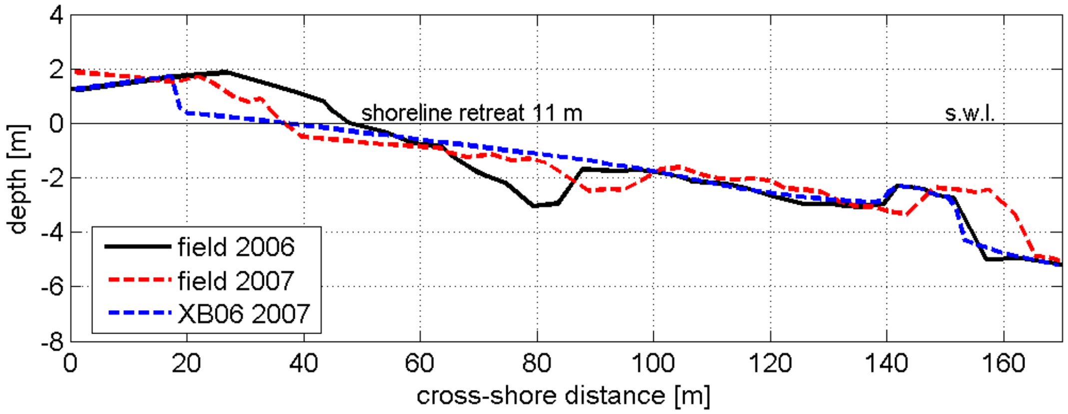


Figure 8. Comparison between the beach survey of 2007 and the results of one year of numerical simulation. The beach survey of 2006 has been used as initial condition for the XBeach model.

The results of a simulation performed considering as input a unique sea state, made up by the yearly-averaged wave previously described, for a duration of 30 hours per year (XB06 av.wave) is reported in Figure 9 along with the results of the run XB06 after two years of simulation (XB06 2008). For the run XB06 av.wave, as for the XB06, the initial conditions correspond to the 2006 surveyed field profile. Moreover, in order to make easier cross-comparisons, the final 2008 profile as obtained from the field survey has been plotted along with the results of the XB06 2008 and XB06 av.wave simulations.
As previously observed for one year simulation, the beach profile is well reproduced, however:

i) the sill in the field appears to be strongly deformed by the wave action, while in both simulations it remains unchanged due to the 'non erodible layer' setting;

ii) the pit due to the procedure of sand disposal completely disappears in the field after two years; in the numerical simulation XB06 it was wiped out already after the first year, while in the average wave simulation it is still visible after two years;

iii) the dune destruction after two years seems definitely overestimated with respect to the field data. A much better prediction is provided by the average wave simulation.

iv) the shoreline retreat after two years is overestimated by the numerical simulation XB06 (the retreat in this case is about 21 m) with respect to the field measurements (slightly reduced with respect to the 2007 conditions), also in this case a better prediction is provided by the average wave run.

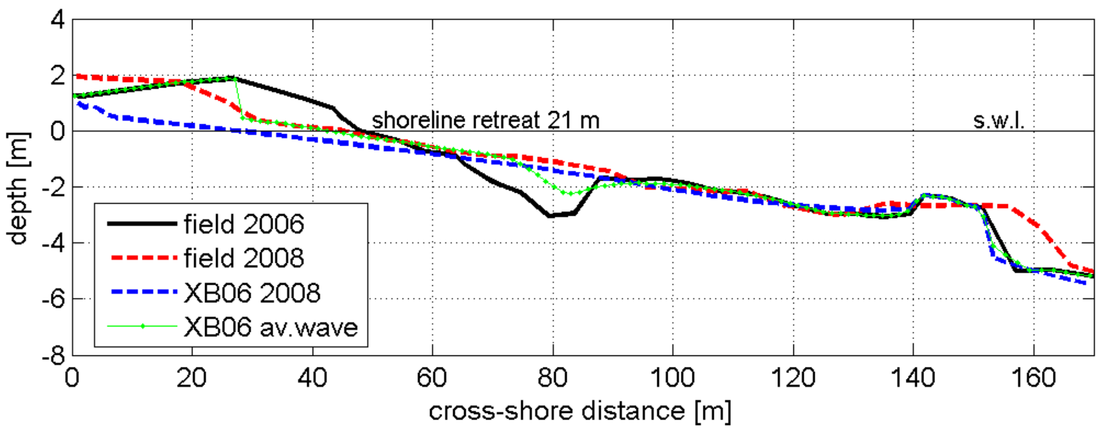


Figure 9. Comparison between the beach survey of 2008 and the results of two years of numerical simulation and the average wave simulation. The beach survey of 2006 has been used as initial condition for both the XBeach model simulations.

In Figure 10 the results of the run XB07 are reported. For this simulation the initial conditions have been set to coincide with the field survey of 2007. The simulation has been run for one year, and thus compared to the field survey of 2008. The average wave simulation has been also carried out starting from the same initial conditions. Considerations similar to the previous cases can be performed.

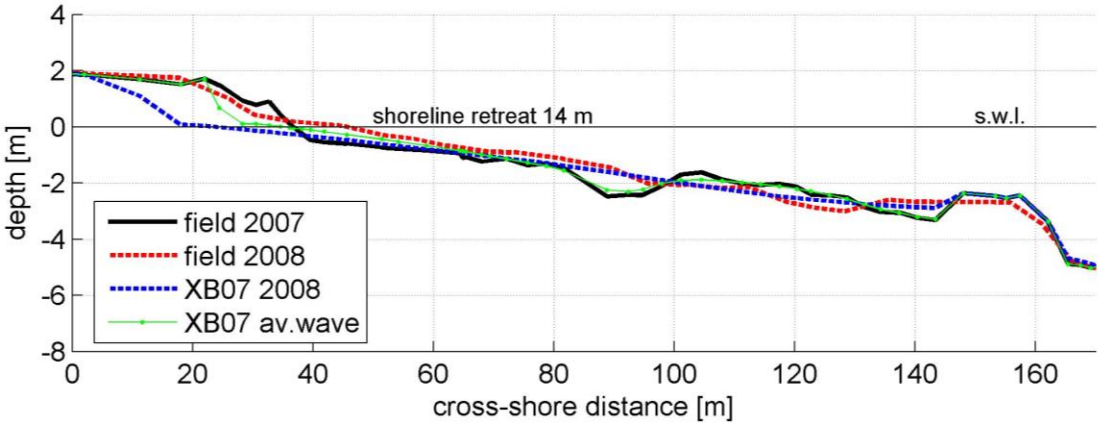


Figure 10. Comparison between the beach survey of 2008 with the numerical results obtained after one year of simulation. The beach survey of 2007 has been used as initial condition for both the XBeach model simulations.

From the comparison between XB06 2008 and XB06 av. wave simulation, and between XB07 2007 and XB07 av.wave simulation, one may conclude that, due to the fact that the XBeach model has been developed for predicting storm effects along the coast, a stronger erosion than that observed in the field is obtained by using the real sea states. However, if the average wave is substituted to the actual wave climate, a better agreement with the field data is obtained. Indeed the average wave though energetically equivalent to the wave climate, seems to have a smaller impact from a morphodynamic point of view, causing a slower filling of the depth gradients, but an erosive condition more similar to that observed in the field. Thus the average wave produces overall a rather good approximation of the beach morphodynamics. This result shows that the procedure adopted to determine the yearly-averaged wave is consistent with the field data.

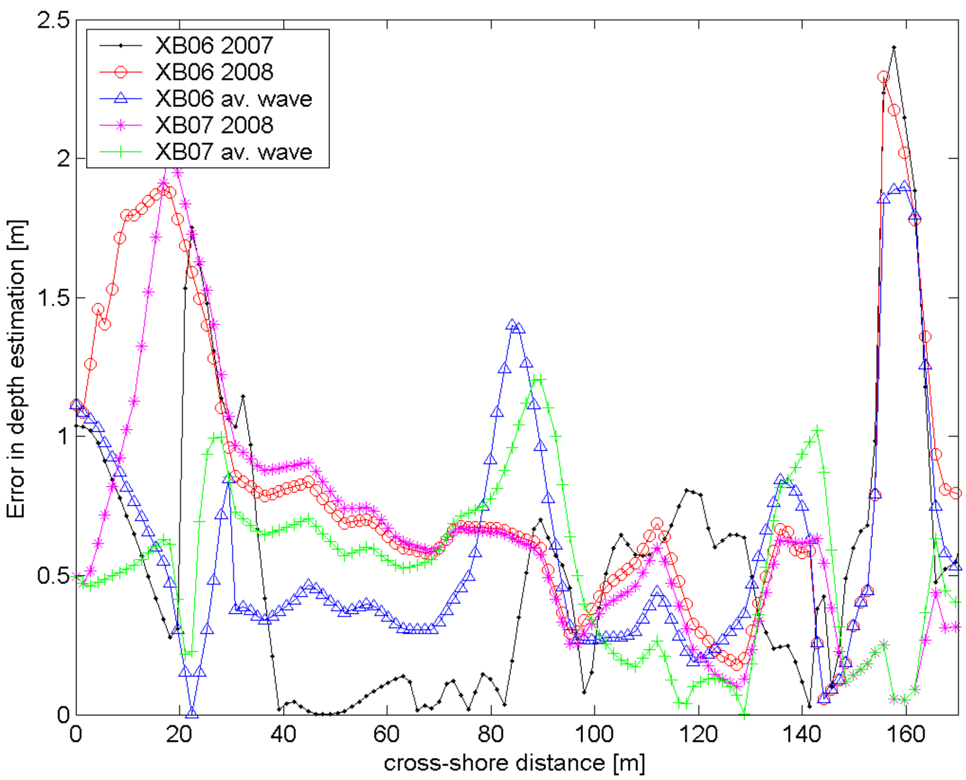


Figure 11. Differences between the numerical and the field beach profiles along the cross-shore distance.

Finally In Figure 11 the error obtained subtracting the numerical beach profile from the field survey is plotted for XB06 and XB07 and average wave simulations. The error is generally low and smaller than 1 m along the profile. It is higher at the sill, where the XBeach simulations are not able to describe properly the adjustment of the barrier under the wave action, as above mentioned, and at the back of the dune, where XBeach overestimates the erosive effects of the wave field.

In addition, the errors of the XB06 and of XB07 simulations are really close to each other except near the sill. This cross-validation is particularly interesting as it confirms the coherency of the XBeach results.

As regards the XB06 and XB07 yearly-averaged wave simulations they show large differences with respect to the other simulations, where the yearly-averaged wave does not well describe its filling, as mentioned above, and onshore, where it provides less erosion than the whole set of wave data.

Conclusions

The morphological response of a perched beach located in the South-West coast of Italy has been investigated by means of the well known XBeach numerical morphological model. By using the field data as initial conditions, the numerical results have been compared with several yearly surveyed profiles in order to understand the potentiality and the limitation of the morphological model.

The analysis of the wave climate was carried out on the basis of the Buoy of Cetraro (ISPRA), after being geographically transferred and propagated close to the coast. The wave data were sampled each 6 hours keeping off the wave heights lower than 0.5 m. A yearly-averaged wave representative of the energetic content for the considered sector has also been considered for the site.

It has been observed that:

i) the morphological model generally well reproduce the beach profile slope;

ii) the morphodynamics of the sill, that in the model has been set as a non erodible layer, cannot be properly described, as in the field it undergoes a reshaping, due to the modeling effect of stronger waves;

iii) the numerical model predicts the disappearance of the pit which is present in the initial profile, due to the procedure of sand disposal during the works, more rapidly than in the field;

iv) the dune erosion is not well reproduced by the model as it appears to be rather overestimated. This latter result can be attributed to the fact that the model has been developed for predicting storm effects along the coast, thus it does not well reproduce the accretive effect due to small waves, causing a stronger erosion than that observed in the field.

v) the shoreline retreat after two years is overestimated by the numerical simulation with respect to the field measurements.

It has been observed that the erosion overprediction is large when the whole set of wave data is used to run the numerical model, while the use of a yearly averaged wave produces morphological results more in accordance with the field data.

ACKNOWLEDGMENTS

This work was supported by PRIN 2012 project (2012BYTPR5 - Modellazione di processi idromorfodinamici costieri per applicazioni ingegneristiche). Field surveys were carried out in the framework of POR Calabria 2000-2006 project “Low impact solutions for littoral protection”.

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