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On the stability of protected beaches

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Abstract

Beach replenishment in the presence of a submerged barrier has become a popular strategy in some countries, both as a coastal protection system and as a means to protect or increase recreational beach activities.
Whether the submerged barrier is meant as a proper breakwater system which reduces the wave energy or only as a way to retain the fill, its effects on both the wave hydrodynamic regime and the sediment transport are extremely important and complex.
Research in this field has been very active in the last few years, but no definitive solution has yet been found to correctly design perched beaches; the recent advances in the numerical simulation of cross shore transport processes, however, have improved the possibility of understanding the behaviour of these structures.
The paper reports on the results obtained by making use of a shallow water wave computation model coupled with a simple procedure aimed at evaluating bed load transport potential; this approach, while unable to produce a simulation of the actual bottom evolution, provides a measure of the stability of a given bottom configuration.

1 Introduction

While the use of submerged structures - be they simple toe protections as part of artificial beach replenishment schemes, or proper artificial reefs - is an ever increasing practise to protect sandy coasts from erosion, the tools available for their design are still far from being satisfactory.

The present paper is aimed at highlighting some problems which arise in connection with the design of such structures and at suggesting some possible improvements on the present methods. Three problems in particular are dealt with:

1) A large number of results is presently available on the wave energy transmission properties, which are usually synthesised in a transmission coefficient K_t, defined as the ratio between the significant incident (H_i) and transmitted (H_t) wave heights, H_i and H_t being usually estimated by measuring the time history of the water elevation η at some location on the wave side and on the lee side of the structure.

While the influence of the measuring position for H_i and H_t has been often examined and analysed, the underlying assumption that the wave energy in shallow water conditions should depend on the free surface elevation only, just as it does in Airy waves, has never been questioned or verified neither numerically nor experimentally.

2) The influence on K_t of the geometric parameters of the structure (mainly the crest elevation Rc and its length b) as well as that of the wave characteristics (Hi and some typical period T, or length L) has been thoroughly examined in a number of extensive research works, ranging from Powell and Allsop (1985) and Van der Meer and Daemen (1994) to the more recent results by Van Gent (2001) an Arcilla and Gironella (1999). Less attention, though, has been given so far to the problem of the influence of the same constructive parameters on the set up on the beach which the structure is supposed to protect, an effect that bears important consequences on the efficiency and on the acceptability of a submerged barrier; Verges and Sanchez-Arcilla (1999) suggest indeed that set up-current interaction should undergo further research; Chiaia and Damiani (1992) present some relevant if limited examples of laboratory tests, but the only result of some practical use seem to be the formulae given by Loveless and MacLeod (1999).

3) Beside, while attaining as low a K_t value as possible is probably a logical design objective, the connection between the reduction of wave energy thus obtained and the reduction of cross-shore beach erosion is not obvious at all. Cross shore beach morphology models are now widely available (e.g. SBEACH, UNIBEST etc) and they are often used to help in the design, but they are particularly weak in the simulation of the all-important swash zone, where the understanding of the sediment transport phenomena is still inadequate; an thus they cannot be fully relied upon to supply exact results.

The work presented in this paper is based on the use of Non Linear Shallow Water models (to produce some numerical results aimed at improving the present understanding of the problems stated in points 1 and 2, while a perspective way to tackle with point 3 is suggested in connection with the procedures and the parameters proposed in Giarrusso et al (2001a, 2001b).

2 Methodology

Non Linear Shallow Water Equations represent the most reliable way available so far to deal with swash zone problems and they have been tested in connection with coastal structures as early as 1989 (Kobayashi and Wurianto) even though their utility is restricted to a limited field of values for the Richardson number. Their formulation is well known and need not be recalled, while the particular version used here, as well as the numerical techniques employed for their solution are discussed in Dodd and Giarrusso (1998), and in Cavallaro et al (2002a,b)

The calculations were carried out for three basic geometrical configurations, as outlined in Figure.1, where the parameters are defined as follows:

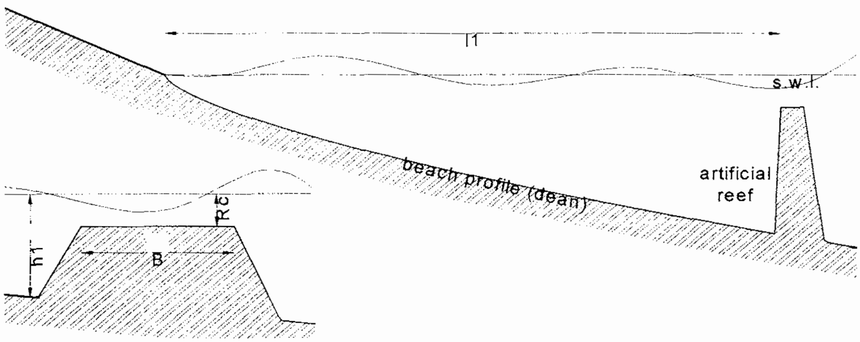

Figure 1

b: berm length

Rc: barrier depth at the crest

l1: distance of the barrier to the shoreline

h1: barrier depth at the lee side toe

The depth profiles follow a standard Dean profile ($y = A \cdot x^{2/3}$) with A = 0.13 (D_{50}= 0.3 mm), while the sub aerial beach is supposed to be flat with a 5% slope. "a" refers to a simple beach with no protection whatsoever; "b" to a replenished beach with a very low barrier at the toe (perched beach), and "c" to a proper artificial reef, aimed at reducing the energy of the highest incoming waves and thus the erosive effect of the sea action. The relevant parameters for the three configurations were the following:

Table 1. Parameters for the three configurations

	B (m)	R_c (m)	l1 (m)	h1 (m)
a:	-	-	-	-
b:	3,00	- 1,50	60,00	-2.50
c:	3,00	- 0,50	60,00	- 2,50

A number of wave attacks were numerically simulated for each configuration by making use of random wave spectra with offshore characteristics wave height H_c varying from 3 to 5 meters and a peak period given by $T = 6.6 \cdot \pi \cdot \sqrt{H/_{4 \cdot g}}$.

Since NLSW models can only be applied for high values of wave over depth ratio, H_s was modified, by making use of the linear theory transformation, from its offshore value to a depth h such that $H_s/h \approx 0.8$, where the computation was started. This restricts the analysis to storms of higher intensity which, on the other hand, are the most critical conditions; it is obvious though, that in further developments, a more advanced model will have to be matched to the NSLW in order to insure a correct computation of the wave transformation from offshore to the swash zone.

3 Results

As stated above, all the results refer to the three basic schemes outlined in Figure 1: "a", b" and "c", i.e. natural, perched and protected beach.
Figure 2 shows some useful results about the standard deviation σ_η of the water surface elevation η near the barrier; after some oscillations, it consistently decreases on the lee side to a fraction of its incident value, in agreement with Sassi et al (2002), Calabrese et al (2002), Sanchez-Arcilla et al (2000) just to quote some of the Authors who have most recently dealt with these problems.

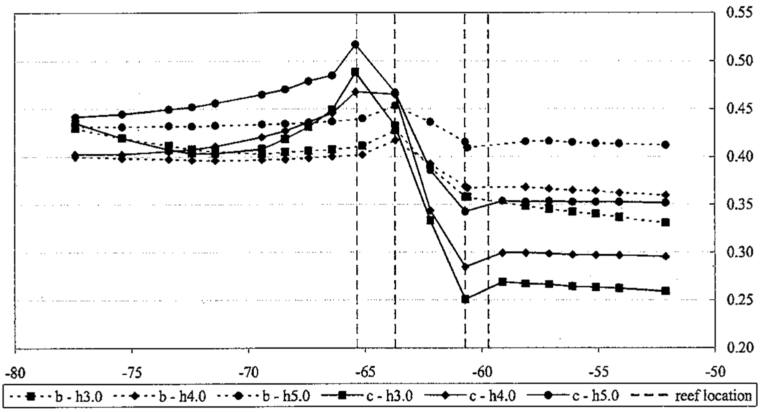

Figure 2

The ratio K_t for case "c" is well within the range to be expected from Van der Meer formulas, thus supporting the reliability of the model.

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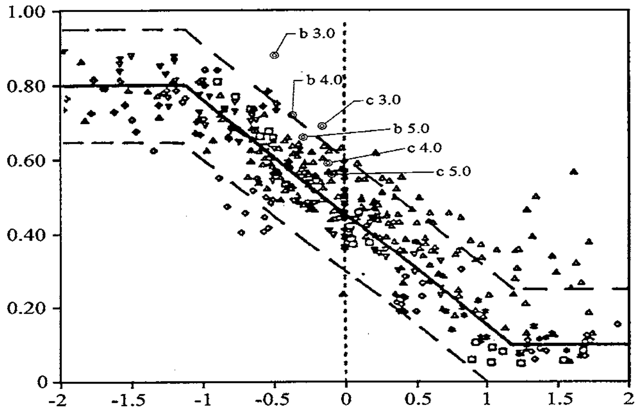

Figure 3

A parameter which is not normally considered in flume experiments is the kinetic energy that, according to the conventional linear wave assumptions, should be exactly equal to the potential energy, so that the total wave energy is usually evaluated by measuring σ_η.

Figure 4 shows that this is not always the case; $\sigma_v{}^2$ remains basically constant before and after the barrier.

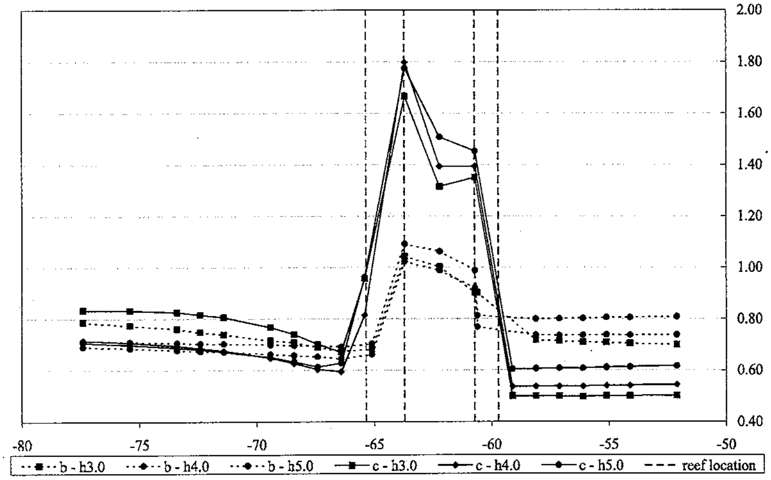

Figure 4

Since the total wave energy depends on both $\sigma_v{}^2$ and $\sigma_\eta{}^2$, this result suggests that the actual energy reduction might be less than what could be expected by simply considering the classical K_t parameter (equal to $H_t/H_i = \sigma_{\eta t}/\sigma_{\eta i}$) as a measure of the energy ratio. Given the importance attached to such a parameter in engineering applications, this result seems to be of some practical relevance.

Coming to the second problem outlined in the introduction, i. e. the set-up effect, figures 4 and 5 show how the average value $< \eta >$ of the water elevation will substantially increase in presence of an artificial reef, both at the shoreline and near the barrier itself.

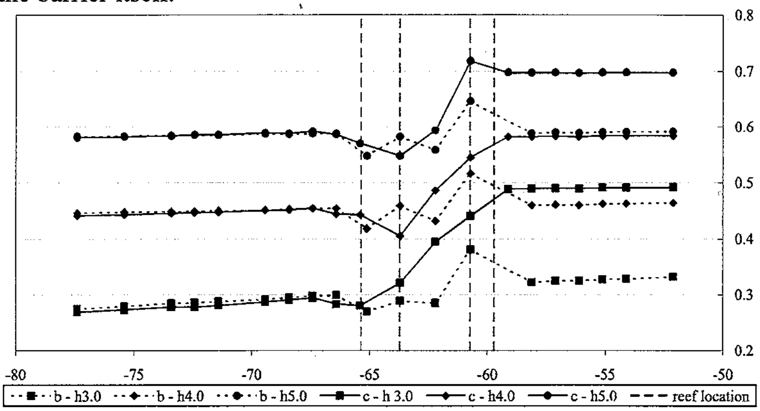

Figure 5: $< \eta >$ Average water elevation increase – Near the barrier

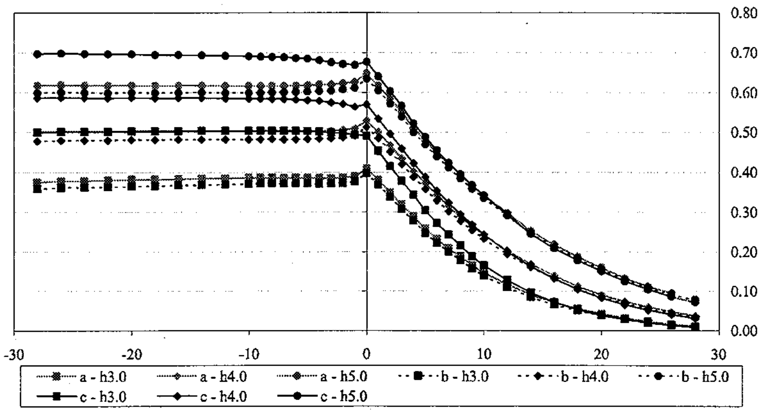

Figure 6: $< \eta >$ Average water elevation increase – Swash zone

It is interesting to see that a perched beach will not substantially differ in this respect from an unprotected one. To our knowledge, the only operational formula to compute this effect has so far only been developed by Loveless et al. (1999). Of course the values obtained by the procedure employed here will have to be added to the conventional set up deriving from wind and wave effects well offshore of the barrier.

Finally, the problem of assessing the performance of submerged barriers in protecting the coast is far from being solved; even if K_t were a reliable index of the wave energy reduction there would still no clear evidence on how the erosive effects are connected with it; engineering practise as well as some recent research (Damiani et al 1992, Sanchez-Arcilla et al 2000) seem to suggest that in some circumstances artifcial reefs might even enhance the erosion processes. There are thus no simple and safe guidelines available to the designer of such structures. The use of cross shore erosion models such as USACE's SBEACH is of course a possibility; the hydrodynamic assumptions of these models, however, are very crude specially in the swash zone, which is all-important in restoration projects, whose objective is nearly always to stabilise or to enlarge the subaerial beach.

More advanced models are possible whereby the hydrodynamic part is dealt with Shallow Water Equations while the solid phase problem is simultaneously solved with numerical procedures to supply a constant updating of the bottom geometry and various researchers are developing and testing such procedures (Cavallaro et al., 2000), but even when the numerical problems are solved, the number of physical parameters required to provide a solution makes them difficult to calibrate and to use as a design tool.

A simpler possibility which is being tested by the Authors, is to make use of the existing and well proven NLSW hydrodynamic numerical models over a fixed bed in order evaluate a limited number of parameters which in turn could be directly connected to the physical processes of erosion and reconstruction in the swash zone. An adimensionalised form of the bottom stress was proposed in Giarrusso et al (2001a), while water height and flooding duration were proposed in Giarrusso et al (2001b).

In the following bottom stress is evaluated as the time-averaged value of the square velocity

$$\tau_0 = \frac{1}{T} \int_0^{T_d} K_s \cdot V \cdot |V| \cdot dt \quad (1)$$

K_s being a friction factor .

Figure 7 shows the behaviour of the τ_o with K_s *taken as unity,* the cases quoted above:

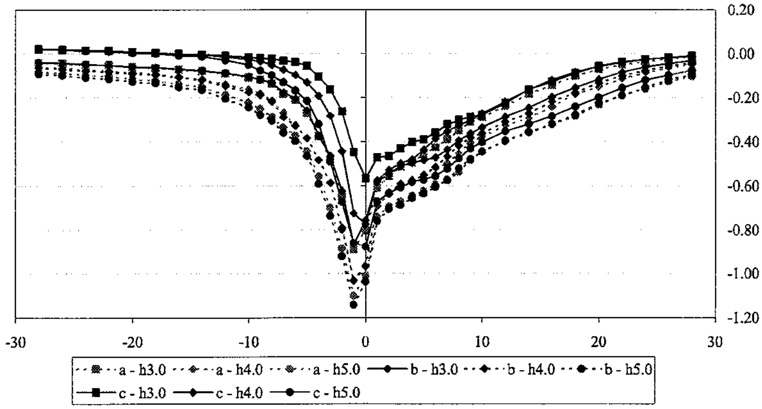

Figure 7

as it was to be expected, the τ_o value decreases for the protected beach while there is no relevant difference between the "natural" and the perched beach. In order to consider a more sintethic parameter, it is useful to compute the bottom stress index τ_i, defined as integral value of τ_o.

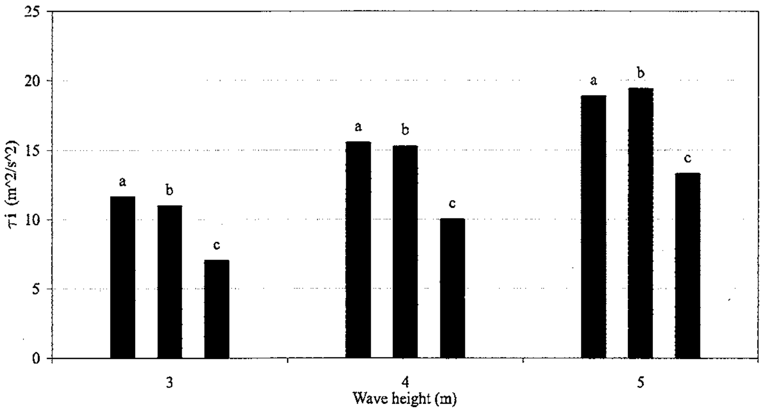

Figure 8

over the whole swash zone length.

Figure 8 visually summarises the results, which are physically consistent; the same procedure can then be applied to laboratory or field experiment results in order to correlate τ_i, or other synthetic parameters, to the advancement or erosion of the beach. Of course the real bottom and subaerial beach profile will have to be supplied to the model in place of the schematic example provided here.

4 Conclusions

Simple and well-proven hydrodynamic models of the swash zone provide useful insight on various aspects of the performance of protected and perched beaches.

According to the calculations, the classical K_t parameter does not fully account for the wave energy loss caused by a submerged barrier; moreover, a substantial set up is shown to appear on the lee side in presence of an artificial reef, both at the shoreline and near the barrier itself, thus confirming the so far scarce previous results.

Finally, a procedure has been proposed whereby a numerical model can be used to evaluate a simple parameter which in turn could be directly connected to the physical processes of erosion and reconstruction in the swash zone.

Besides the obvious necessity of testing and calibrating the procedure with real data, an extension of the numerical model in order to overcome the limits of NSLW equations seems to be necessary in order to improve the performance specially for low wave heights and deeper water depths.

5 Acknowledgements

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