CHAPTER 151

EVOLUTION OF A BEACH WITH AND WITHOUT A SUBMERGED BREAKWATER: EXPERIMENTAL INVESTIGATION

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Abstract

In the present report experimental results about the efficiency of a submerged structure are presented. The experiment, carried out with random waves, covered about 2500 hours until equilibrium profile was reached. The most significant results are the good behaviour of the tested breakwater as a sand holding structure and its slowing effect produced on the shoreline backing, whereas the final position of the shoreline was nearly the same with and whithout breakwater.

1. INTRODUCTION

In coastal areas where tide excursions are limited, submerged breakwaters can be used to protect the beaches from the strong eroding wave action. This choice mostly depends on the better water exchange between the inner and outer zones of the submerged breakwater, which reduces the waterlogging area. Moreover it doesn't disfigure the seascape and allows to better enjoying the beach for all touristic activities, unlike emerged structures. Submerged breakwaters are also used to protect beach nourishment works. Many Italian researchers are involved in the study of this kind of structures (Aminti et al., 1983; Lamberti et al., 1981; Lamberti et al., 1984). This paper presents an experimental investigation about the cross-shore evolution of an unprotected beach subjected to random waves, as compared to the evolution of the same beach, protected by a submerged breakwater.

Trials showed significant results about the long-term evolution of a beach under the action of different wave attacks, and about the behaviour of each attack.

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2. EXPERIMENTAL SET-UP

Tests were performed in the wave channel of the Hydraulics and Hydraulic Constructions Institute of Bari Polytechnic. The channel is about 45 m long, 1 m wide and 1.2 m high (fig. 1). It was longitudinally divided into two equal parts by a thin glass wall, in order to simulate an unprotected beach on the first half of the channel and a protected beach with a submerged breakwater on the other half. Eighty gauging cross-sections, numbered from the shoreline to the wave generator paddle are located along the channel. The wave maker consists of a flat paddle which receives a rotatory-translational motion through a kinematic mechanism, able to reproduce any kind of waves.

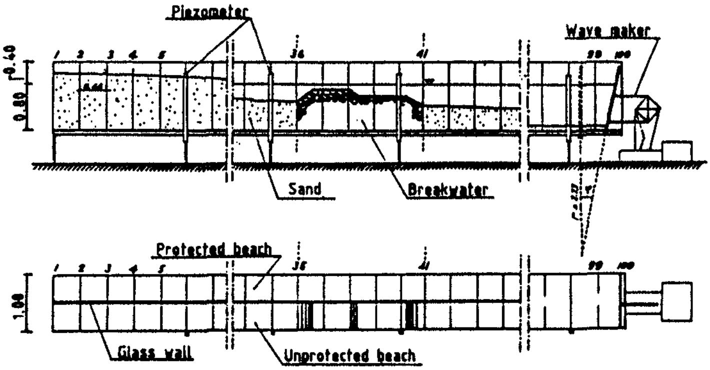

Figure 1. Experimental channel.

A beach of the Middle Adriatic coast was reproduced in the channel, in Froude Number similitude with undistorted 1:10 scale. The channel bottom is covered with a sandy layer of a pretty uniform size with $\mathbf{d_{50}=0.15mm}$, and fall velocity w = $\mathbf{0.018\ ms^{-1}}$. The mean water level in the channel was kept constant during the tests and the depth near the paddle was equal to 0.80 m.

Five wave attacks were chosen to simulate the sea wave conditions; they were characterized by JONSWAP energy density spectra with $\gamma = 3.3$ and $w = 0.07$ for $f < f_p$ and $w = 0.09$ for $f > f_p$. The wave attack characteristics, near the paddle, and their duration are reported in Table 1.

In the trials the attacks were grouped in a six-storm cycle with sequence 1-2-3-1-4-5 to simulate different energy sea conditions. The duration of the two attacks number 1 of the cycle was assumed equal to half the time reported in Table 1. The experiment covered 17 cycles over about 2400 hours, when the equilibrium profile was reached in both sides of the channel.

ATTACK	m_0	f_p	t
	$[m * 10^{-4}]$	$[s^{-1}]$	$[h]$
1	3.0	0.63	88.0
2	15.5	0.47	12.5
3	6.0	0.47	32.2
4	30.5	0.38	5.5
5	15.0	0.38	11.2

Table 1. Wave attack characteristics and their duration.

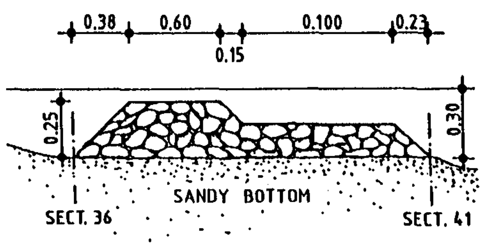

Figure 2. Tested submerged breakwater.

On the left side of the channel the submerged breakwater was located between sections 36 and 41; this position, with the characteristics of the selected wave attacks, is just outside the breaking zone and only the highest waves of attack n. 4 break offshore the structure. The breakwater face slope is about 1/1.5 and the submergency (h/d) is 0.17 (fig. 2).

The first results of the here presented trials were already discussed in previous papers (Lamberti et al., 1985; Chiaia et al., 1990).

3. PROFILE EVOLUTION IN THE LONG PERIOD

The starting profile (fig. 3) in the experiment was far from equilibrium so as to simulate an artificial filling action.

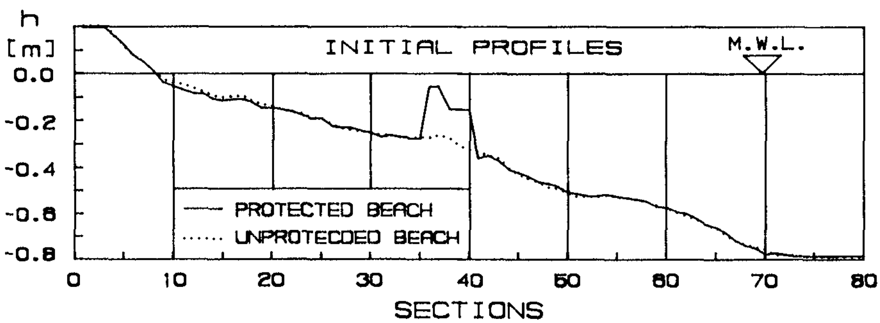

Figure 3. Comparison between protected and unprotected beach profiles.

Basically three constant slope zones may be observed: the first from section 70 to section 40 with 1.8° slope, the second between sections 40 and 13 with 1.08° slope and the third from section 13 to the shoreline with 2.33° slope. The zone close to the shoreline was concave with a maximum slope of about 5°. The initial profile, shown in figure 3, was obtained after the action of a low energy level wave attack, in order to simulate a sand compaction closer to reality.

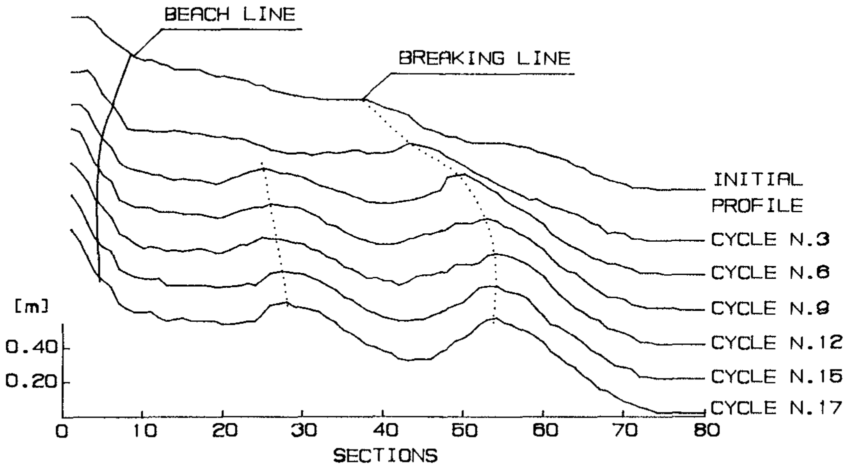

Figure 4. Unprotected beach evolution.

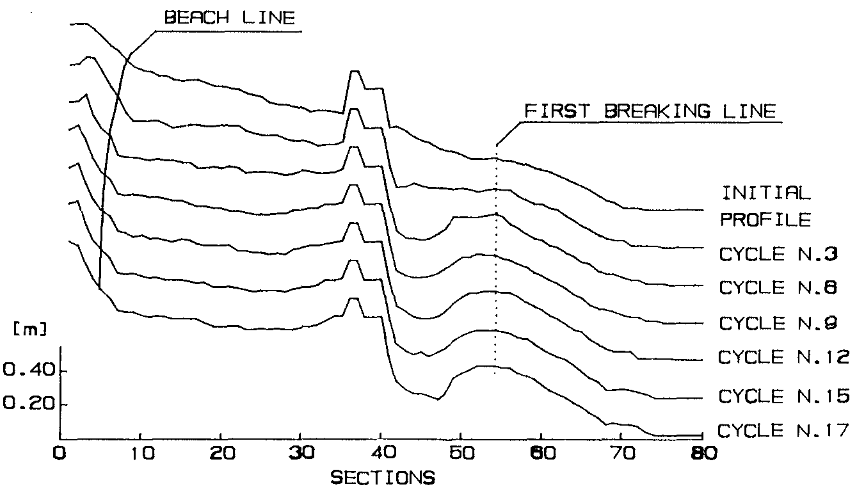

Figure 5. Protected beach evolution.

The global evolution both in the protected and unprotected beach are reported in figures 4 and 5 in which the backing of shoreline and the formation and migration of bars are clearly shown in both configurations.

The efficiency of the tested submerged breakwater was firstly studied by comparing the profiles observed both on the unprotected and protected beach at the end of each wave attack. The beach profiles obtained at the end of some cycles are shown in next figures.

The behaviour of the two beach profiles starts becoming substantially different at the end of the first storm cycle (fig. 6). A notable offshore transport is observed in the unprotected beach resulting in a sharp backing of the shoreline and the formation of a bar.

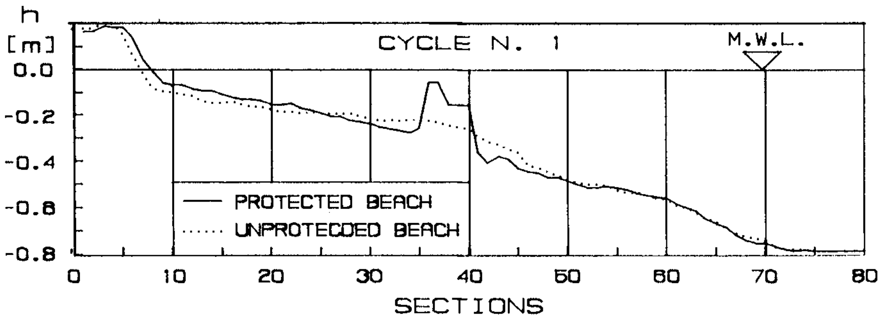

Figure 6. Comparison between protected and unprotected beach profiles.

Sand transport is far less marked in the protected beach, although its characterstics are the same as in the unprotected one (shoreline backing and offshore transport). However, the action of the submerged breakwater in reducing the offshore transport is noticeable since the beginning.

Such a behaviour is clearly shown in fig. 7, in which the profiles at the end of the 4th cycle are reported.

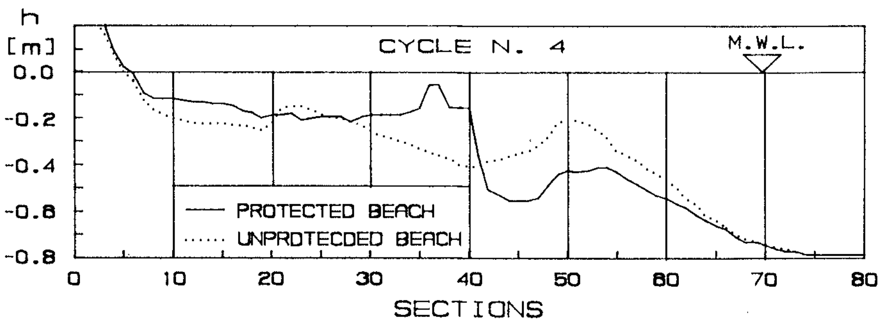

Figure 7. Comparison between protected and unprotected beach profiles.

The surf-zone in the protected beach is, on the average, less deep if compared to the unprotected one and a deposit area forms just at the back of the breakwater which increases until equilibrium conditions are reached. This behaviour confirms the efficiency of the breakwater in reducing the offshore transport.

Figures 6 and 7 show an erosive trough at the toe of the structure which tends to become deeper and to stabilize when the equilibrium profile is reached. Most of the eroded material is deposited offshore forming a bar (sketched in figs. 6 and 7), and a part of it is found out, as indicated later on, in the surf-zone. This does confirm that, despite its selectivity, the breakwater allows onshore transport, under given conditions (Aminti, 1986).

For the unprotected beach, figures 6 and 7 show the formation of two bars; the offshore bar moves in deepwater direction till it reaches a stable position, thus defining the surf-zone width. As the surf-zone width becomes stable, the shoreline reaches a condition close to equilibrium, at about the 7th cycle, as shown in figure 4.

After the 7th cycle of attacks, in the protected beach a sharp deepening of the erosion trough is noticed (fig. 8), as observed in the previous cycles together with the formation of a well-defined bar which causes the breaking of the highest waves and thus a further erosion of the trough until equilibrium is reached.

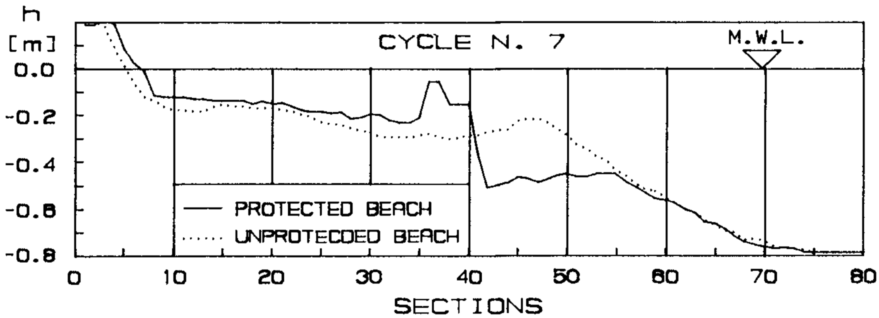

Figure 8. Comparison between protected and unprotected beach profiles.

Starting erosion at the offshore toe of the structure can be mostly related to the back currents coming from the onshore zone. Indeed at the beginning of the experiments only few waves broke before reaching the structure. Therefore, wave breaking cannot be the major active mechanism in the trough formation.

Into the surf-zone of the protected beach a substantial flattening of the profile is observed, with a sharp backing of the shoreline tending to the same position as in the unprotected beach.

In the subsequent cycles (fig. 9) the re-alignment of the shoreline between the unprotected and protected beach, as well as the deepening of the erosion trough and the bar formation in the protected beach are more pronounced until a substantial equilibrium condition is reached.

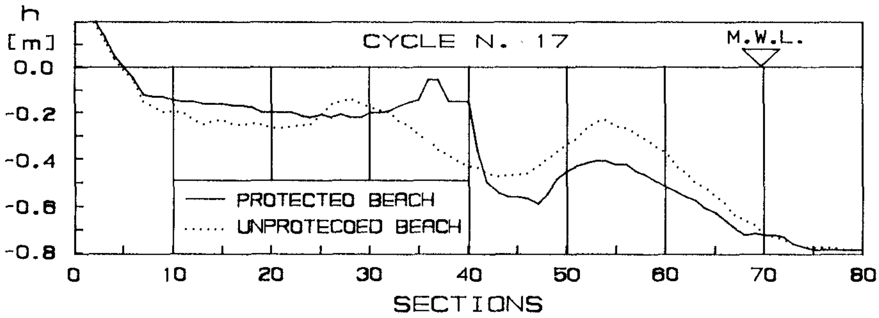

Figure 9. Comparison between protected and unprotected beach profiles.

It was observed that the equilibrium profile of the unprotected beach in the onshore zone before the bars, may be interpreted by Dean's equilibrium profile (Dean, 1977):

$$\mathbf{h} = \mathbf{a}\,\mathbf{x}^{\mathbf{b}} \tag{1}$$

where **h** is the bottom depth in the section considered, **x** is the distance from this section to the shoreline and **a** is a parameter which, as shown experimentally, mainly depends on the sand beach particle-size (Moore, 1982). Assuming a constant energy dissipation per unit volume in the whole surf-zone, Dean obtained the law (1) theoretically with $\mathbf{b} = \mathbf{2/3}$. In a beach with a particle-size characterized by $\mathbf{d_{50}=0.15mm}$, the same researcher (Kriebel et al., 1986) found an equilibrium profile which is well interpolated by the law $\mathbf{h=0.075\ x^{2/3}}$.

Based on many laboratory and field experimental data, relating to beaches of different sand particle-size, Vellinga (1986) found that the law $\mathbf{h = 0.35\ w^{0.44}x^{0.78}}$, where w is the fall velocity, does well interpolate the onshore equilibrium profile for a wide range of particle-sizes. On the other hand, the same author disproves the constant dissipation assumption made by Dean, stating that coefficient **b** can have different values, especially when the sea state is variable and the profile is bar-shaped. Indeed, in the presence of bars, the onshore profile follows the experimental law (1) only in the proximity of the shoreline whereas, approaching the bar, depths tend to be first constant and then to decrease.

Our trials showed that till section 20 the profile is well interpolated by the law $\mathbf{h = 0.125\ x^{0.44}}$ which is quite different from the one found by the previous authors on a beach with the same sand mean particle-size.

In figure 10 the unprotected beach profiles, observed in the last storm cycle, and the above indicated interpolation laws are reported; it may be observed that the equilibrium profile shows a greater erosion in the onshore area, near the shoreline.

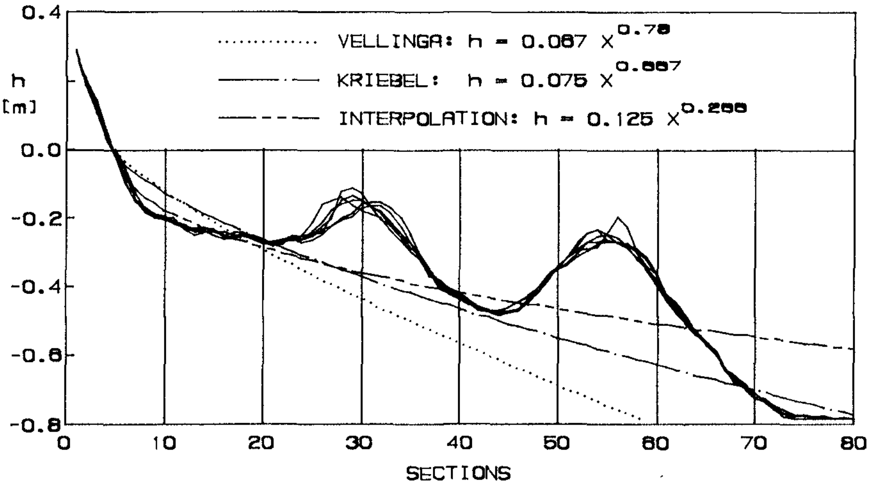

Figure 10. Profiles measured after each wave attack of the last cycle and theorctical and intepolation laws for equilibrium profile.

The behaviour observed in our experimental results is in accordance with those found by other authors (Swart, 1974; Larson 1988), who tested bar-shaped beach profiles. In accordance with Vellinga, it may be stated that this behaviour, which deserves further attention, is to be attributed to the change in the dissipation mechanism in the surf-zone in the presence of a bar on the profile.

In order to evaluate the efficiency of the submerged breakwater under study, for all beach zones, some global parameters of the profile were introduced which enable assessing structure effects on emerged and submerged beaches.

4. ANALYSIS OF BREAKWATER EFFICIENCY

4.1 Shoreline Zone

The parameters selected to describe this area are the swash-zone slope and the shoreline position, both determined after each wave attack. As to the slope, the mean value observed in the first cycle of attacks (about 8.5°) kept stable with some fluctuations (5° ÷ 14°), due to the different action of single wave attacks; at the end of the trials, however, slope fluctuations in the swash-zone are reduced.

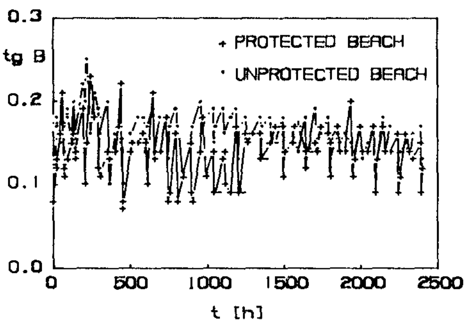

Figure 11. Evolution of swash-zones slope.

Figure 11 shows that, regardless of the type of beach profile considered, the beach slope in the swash-zone is basically affected by the characteristics of the wave attack it is subject to; it is indeed poorly influenced by transformations of waves in their transfer from offshore to the shoreline, although in the case of unprotected beach, slope values are generally a little higher and fluctuations are lower.

Experiments did confirm that the beach slope is inversely proportional to the wave attack energy, and its variations are very rapid; in fact, the slope observed after each storm is reached few minutes after the action of the attack.

The shoreline, at the end of trials, tends to reach more or less the same position both in the presence and in the absence of the breakwater (Fig. 12). Therefore, when the breakwater is used to reduce erosion of the emerged beach, it has no effectiveness in the long period, whereas it proves to be useful in slowing down its backing.

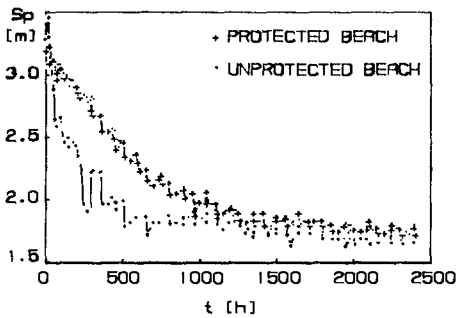

Figure 12. Evolution of shorelines position.

In fact, while in the unprotected beach equilibrium is achieved after about 600 hours, the protected beach needs a double time. The analysis of the action of each wave attack on the shoreline shows that attack 1 is reconstructive, attacks n. 2 and n. 4 are destructive whereas attacks n. 3 and n. 5 are characterized by an intermediate behaviour. These results were observed in both sides of the channel.

4.2 Surf-Zone

Sand transport from the surf-zone to the outer zone of the breakwater was evaluated using the B_0 parameter, i. e. the water volume contained between the breakwater and the first section of the channel, complementary to the sand volume.

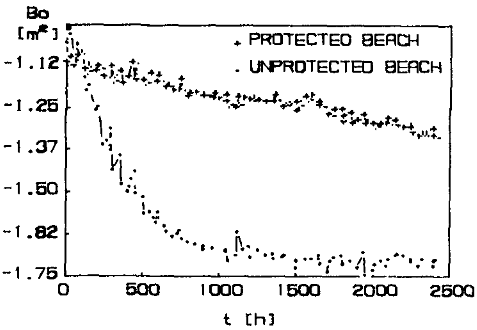

Figure 13. Evolution of water volume conteined in the first 40 sections of the channel.

The temporal evolution of B_0, evaluated assuming a negative depth, is reported in figure 13.

For the unprotected beach, B_0 decreases sharply thus indicating an intensive sand flux offshore, whereas in the presence of the breakwater, sand transport is slower and less marked. The breakwater is clearly shown to be an effective holding structure.

Moreover, under equilibrium condition, B_0 is decreasing in the protected beach, whereas in the unprotected beach, despite some fluctuations, B_0 is constant.

This means that, in the unprotected beach, once the two bars have formed, sand displacements are moderate, because of the action of wave attacks which compensate each other within the cycle.

On the other hand, for the protected beach, although an equilibrium condition is reached in the emerged beach (see Sp and tg ß), a further evolution of the profile is observed in the onshore area. Indeed, due to the sand accumulation at the back of the breakwater, return currents cause an off-shore transport which goes on slowly even when the profile is substantially under equilibrium.

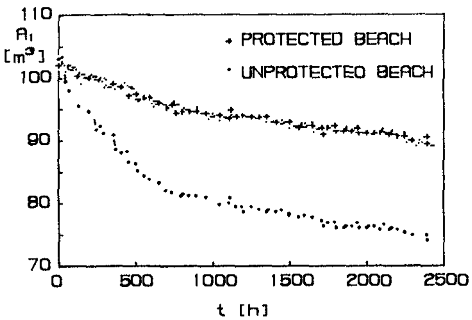

Figure 14. Evolution of integrals of the moments of depths respect to channel central section.

During the trials it was observed that the breakwater under study acts as a filter also to the nourishment action of summer waves, but it allows some onshore transport by the highest waves which suspend the material offshore the breakwater, particularly at the start of experiment.

The behaviour of parameter A_1 (integral of the moments of depths observed in each section with respect to the channel central section 40) (fig. 14) shows offshore sand displacement and does confirm the above interpretation of its evolution. Really it can be observed that also in the unprotected beach, A_1 goes on decreasing until the end of tests, denoting a sand displacement inside the surf-zone.

An interesting indication is provided by parameter B_1 (integral of moments of depths in the first 40 sections of the channel with respect to section 20). Fig. 15 shows that, for the unprotected beach it first decreases sharply and then it shows a fluctuating evolution (caused by the onshore bar displacements), whereas for the protected beach it decreases and, under equilibrium, tends to a constant value.

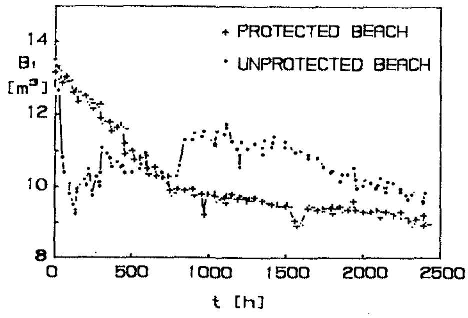

Figure 15. Evolution of integral of the moments of the first 40 section depths with respect to section 20.

This is due to the presence of a well formed deposit area, close to the breakwater, and to the achievement of a stable and flat configuration of the beach profile in the surf-zone.

4.3 Offshore Zone

By offshore zone we mean here the zone outside the breakwater which is not necessarily the outer zone of breaking waves; in fact, as previously indicated, under equilibrium conditions, both protected and unprotected beach profiles show a bar around section 53 which causes the breaking of the highest waves, thus dividing the surf-zone from the offshore zone.

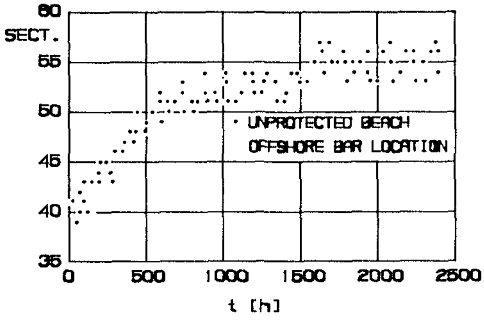

Figure 16. Evolution of offshore bar location in unprotected beach.

The profile of the zone under consideration is indeed characterized by the presence of the bar and by an erosion trough at the toe of the breakwater.

The first difference observed between the protected and unprotected beach concerns the bar position.

Figures 4 and 5 show that, for the unprotected beach, the offshore bar does form initially around section 40 and then migrates offshore and gives a stable length to the surf-zone; on the other hand, the bar on the protected beach does start forming initially in a position close to the final one, without any notable displacement.

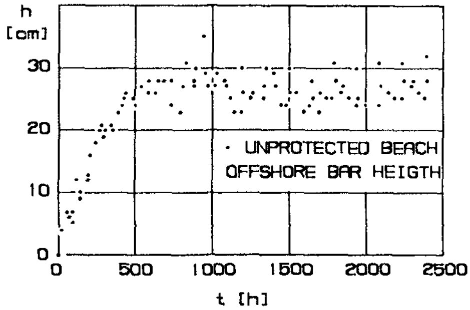

Figure 17. Evolution of offshore bar depth in unprotected beach.

Figure 16 shows the offshore bar displacement on the unprotected beach along its evolution, whereas figure 17 reports the depth on the bar, taken as the difference between the initial and actual depth. The end position of the bar is comparable in both sides of the channel, while depth is higher in the case of the protected beach (Fig. 18).

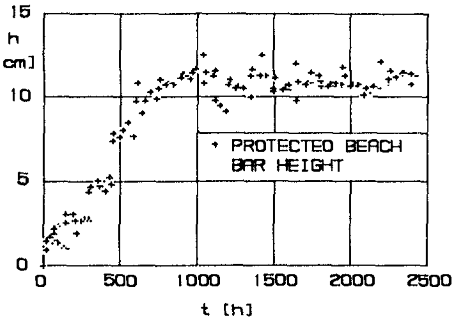

Figure 18. Evolution of bar depth in protected beach.

This is due to the fact that the bar in the unprotected beach is formed with all the material eroded in the surf zone, while in the protected beach sand mostly comes from the trough.

Another parameter used to describe the offshore region is, as already mentioned, the erosion trough at the toe of the breakwater, whose genesis needs further studies.

Fig. 19 shows a good correlation between the pit deepening and the depth reduction on the bar.

This shows that one of the active mechanisms for the trough formation is the presence of the vortex (site of dissipation) produced by the breaking occurring on the bar. This mechanism is the same acting on the unprotected beach.

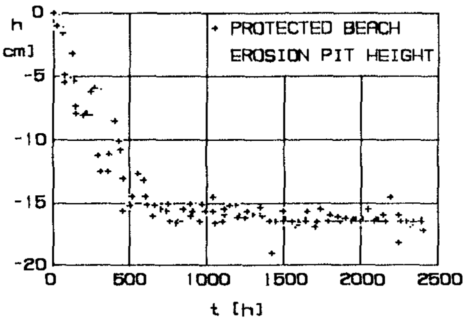

Figure 19. Evolution of depth of eroding trough at the offshore toe of the structure.

In addition to the previously described mechanism, a contribution to the trough formation in the initial stage of trials is given by return currents as above mentioned.

However, it should be noted that, regardless of the causes which produce erosion at the toe of the breakwater, the pit depth reaches a maximum equilibrium value so that, to prevent any failure in the foundation, either the bearing surface should go below that depth, or the breakwater should be displaced offshore.

5. CONCLUSIONS

Laboratory experimental results enabled assessing the efficiency of the tested submerged breakwater relating to the cross-shore transport action. Breakwater proved to be an excellent holding tool for the sand contained in the surf-zone, although it does not seem selective at all to offshore transport.

On the other hand, the protective action from erosion in the swash-zone is not equally effective; the presence of the breakwater did not reduce the backing of the shoreline which reached almost the same position both in protected and unprotected beach profiles. Nevertheless, it should be pointed out that the breakwater caused a notable slowing down of the wave eroding action on the emerged beach, in fact the time taken for equilibrium to be reached in the protected beach is double as compared to the unprotected one.

In the outer zone of breakwater, the configuration is similar both in the protected and unprotected beach (bar-trough conformation). Some interesting considerations can be drawn from the results relating to the erosion trough. Indeed, although the study on pit formation needs further research, it has been observed that it reaches a constant depth at equilibrium. Such a result can be helpfully used for design, in that the bearing surface of the structure should go below that level to prevent any subsidence which could jeopardize the breakwater stability.

Experimental results need being further processed so as to provide indications on the action of each wave attack and to understand the hydraulic behaviour of the breakwater through the study of the reflection, transmission and dissipation coefficients and the wave set-up in protected and unprotected beach profiles.

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