DETACHED BREAKWATERS AND THEIR USE IN ITALY

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1. Introduction

Detached (or "offshore") breakwaters of emerging type are a common and effective approach for beach protection, particularly for areas with small tidal oscillations. This kind of breakwaters aims at acting on sediment transport by decreasing the transport capacity of long-shore currents, thus locally causing settlement of sediments. Unlike groins, which act directly on long-shore currents, detached breakwaters act on incoming waves decreasing their height in the protected areas and thus also decreasing the strength of associated currents and causing settlement of sediments. Another functional aspect of detached breakwaters is that they influence not only long-shore transport, but also on-offshore transport of sediments.

The use of detached breakwaters is quite common along the coasts of the Mediterranean (particularly in Italy) and in Japan.

It is well known that, as for all protective structures of the "rigid" type, the benefit for the protected beach, following the increased deposition of sediment, is usually offset by reduced supply of sediments to and subsequent erosion phenomena of the downdrift beaches. Other shortcomings related to the construction of detached breakwaters of the emerging type may be observed:

- degradation of the quality of sand and water in the protected areas, particularly in cases when tombolos form;
- irregularity of the emerged beach and depth contours, the latter being dangerous particularly for inexperienced swimmers;
- degradation of the visual aspect of the beach, due to the presence of the emerging breakwaters.

To avoid some of the above shortcomings, in the last few years more attention has been directed towards the use of submerged structures for detached breakwaters. The advantages are:

- being invisible, they do not affect the natural aspect of the beach;
- their influence on waves is more selective compared to that of emerging breakwaters, larger waves being subject to stronger reduction than smaller ones (in this way, wave-induced water circulation is less affected during minor and moderate wave attacks);
- a softer and more regular impact on the protected and downdrift beaches is expected.

After a brief review of general characteristics and performance of detached breakwaters of emerging and submerged type, in this report some applications of this kind of protective system along the coasts of Italy will be illustrated and discussed.

2. Generalities on detached breakwaters

2.1. DETACHED BREAKWATERS OF EMERGING TYPE

Detached breakwaters of the emerging type consist of single segments or, more frequently, of series of segments separated by gaps. Their effect on incoming waves (and consequently on wave-induced currents and transport and deposition of beach sediments) is a complex three-dimensional phenomenon, in which wave energy in the protected zone is mainly transmitted by diffraction through the gaps and at the tips of the barriers and by overtopping above and transmission through the structure. Three-dimensional tests in the laboratory and direct field observations are the best tools for insight into these complex processes.

Literature on this kind of structures (for a comprehensive review of technical literature on detached breakwaters, both of the emerging and submerged type, see, e.g., Massel, 1989) refers principally to their effectiveness as shore protective structures. This depends on the geometry of the structure and on local environmental conditions.

Design procedures are still rather empirical, although recent improvements have been achieved in understanding the functional behaviour of detached breakwaters.

According to Toyoshima (1974), four types of detached breakwaters can be classified with respect to water depth d of the structure location:

a) shoreline systems, along the shore;
b) shallow water systems, d ˜ 1m;
c) median water systems, d ˜2.5-5.0 m;
d) deepwater systems, d > 6 m.

Median water systems are the most common for shore protection; in Italy, location depths generally vary between 2 and 4 m.

As regards breakwater geometry, main parameters are:

- breakwater length (B);
- gap width between breakwaters (G);
- distance of breakwater(s) from the original shoreline (X).

In Italy typical lengths are about 100 m or below, with typical gaps of 25-40 m.

According to the experiments of Rosen and Vajda (1982), ratio X/B between the distance of the barriers from the (original) shoreline is the basic parameter for the geometry of the beach in the protected zone. It is now generally accepted (Shore Protection Manual, 1984) that formation of tombolos occurs for $X/B < 1$ and formation of salients for $X/B > 1$, whereas breakwaters are considered ineffective for $X/B > 2$ (Herbich, 1990).

Investigations on the influence of geometry of breakwater systems and wave conditions on the volume of entrapped sand (Harris and Herbich, 1985) led to the relationship:

$$Q_b/XBd = f(X/B, X_{br}, H/L, G/B, \alpha \ldots)$$

where:

Q_b = volume of deposited into the sheltered volume of the breakwater, the latter being defined by (X)(B)(d)]

X = distance from original shoreline to seaward edge of breakwater

X_{br} = distance from shoreline to breaker line

G = gap between breakwaters

H = offshore wave height

L = wave length

α = angle of incident wave crests

d = depth of water at seaward edge of breakwater

For $X/B = 0.5 - 2.5$, the following formula has been proposed:

$$Q_b/XBd = \exp(0.31481 - 1.92187(X/B))$$

Detached breakwaters are usually of the rubble mound type, using natural stones, whereas concrete armour units are only used for larger depths. Various types of piled structures have also been used.

For rubble mound breakwaters, crest elevations of 0.5-1.2 m and offshore slopes between 1:2 and 1:3 are common, whereas steeper inshore slopes (up to 1:1) are frequently used in Italy (although this is in contrast with the Shore Protection Manual, 1984, which recommends no increase in shore-side slopes compared to seaside ones for breakwaters subject to overtopping).

2.2. SUBMERGED BREAKWATERS

Submerged breakwaters for shore protection may be conceived as long, continuous structures parallel to the shoreline: in this case, gaps are not strictly necessary for water exchange, which may occur over the section of the barrier. In any case, gaps may be provided for other reasons (e.g., to allow the passage of boats).

As regards the effects of submerged breakwaters on waves, which in the case of continuous barriers and normal incidence may be considered a substantially two-dimensional phenomenon, a number of theoretical and experimental investigations in flumes have been carried out.

Wave transformations induced by a submerged barrier depend on the geometry of the structure and the characteristics of incoming waves. According to Massel (1989), the effectiveness of a barrier may be measured in terms of reflection and transmission coefficients K_r and K_t which, from dimensional analysis, may be expressed as

$$\{K_r, K_t\} = f\{H_i/L_i,\ b/L_i,\ h_t/d,\ d/L_i,\ s\}$$

where H_i and L_i represent characteristics of incident waves, b is the top width of the structure, h_t its submergence (i.e., the depth of the structure crest below still water level), d the water depth at the structure location, and s a shape parameter.

On the basis of investigations on wave transformations on submerged structures, the most important parameters are submergence of the crest h_t and its width b.

As regards the effectiveness of submerged barriers as shore protection structures, the literature on this subject seems to yield little guidance for their design.

Some investigations carried out in flumes give indications of the effects of this kind of structure on beaches. However, no quantitative conclusions may be drawn on the basis of the technical literature, although improvements of beach conditions under erosive attacks and more stable configurations of the beaches compared to unprotected conditions are evident. Favourable effects on the stability of artificial fills are also reported.

As regards scouring effects on the barriers, movable bed experiments carried out by Aminti et al. (1983) reveal considerable scouring effects, particularly at the seaside foot of the barriers. Effects are especially severe in the case of low structures, whereas offshore seaside scouring becomes more important with increasing heights of the structures.

The importance of scouring phenomena on the stability of detached breakwaters has also been confirmed by field experience with submerged barriers in Italy. In several cases, as will be seen later, submerged barriers settled or even collapsed and anti-scouring devices were added in subsequent reconstruction or new works.

3. Applications of detached breakwaters along the Italian coast

Detached breakwaters of the emerging type are the most common shore protection measures along the coasts of Italy. Hundreds of kilometres of our coast have been protected in the last few decades by offshore breakwaters, usually starting from the most critically eroded beaches but often propagating for long stretches to downdrift beaches.

More recently, the concept of submerged structures, aiming at avoiding some of the negative environmental effects of emerging structures, has become more popular, and in the last few years most works on Italian beaches have been carried out using this kind of structure (usually in combination with artificial nourishment).

In the following, some examples of detached breakwaters built in Italy using emerging and submerged structures will be illustrated and discussed. Particular reference will be made to operations carried out on the beaches of three Adriatic regions (Veneto, Emilia Romagna and Marche; see fig.1). For each region, before examining the illustrated operations, some brief indications of general characteristics of the coast and of shore protection policies will be given.

FIG.1. Map of Italy, with indication of regions examined

3.1. THE VENETO COAST

The Veneto coast (fig.1) extends along the Northern Adriatic for about 130 kilometres. It consists entirely of sandy beaches, interrupted by a number of river and tidal inlets, the most important of which are those connecting the lagoon of Venice to the sea.
As a consequence of intensive exploitation of the coast, a number of coastal structures were built, including protective structures to combat erosion (Liberatore et al., 1991).
Apart from the old and well-known "murazzi", built during the 17th century, and a limited number of detached breakwaters, most of the protective structures consist of systems of groins, often built in combination with shore parallel structures. Fig.2 gives a sketch of the eastern stretch of the Veneto coast, comprising some of the most popular resorts of the Northern Adriatic like Bibione, Caorle and Jesolo, and intensively covered by shore protection structures.

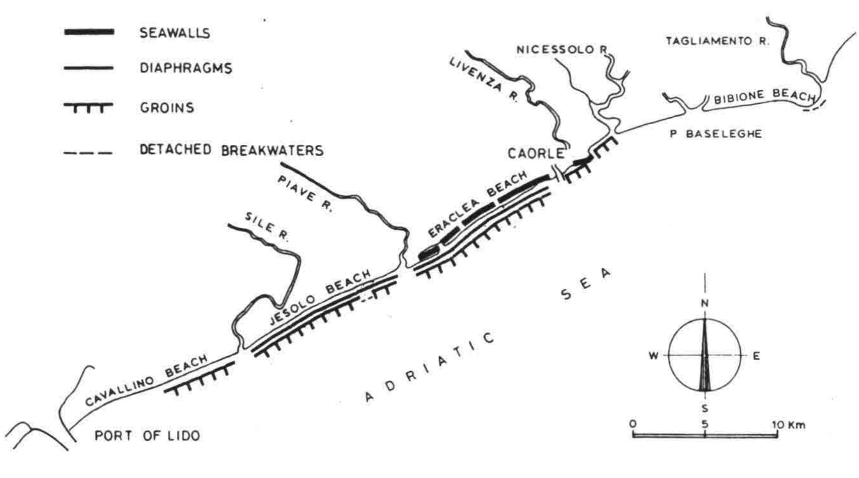

FIG. 2. Coastal defences of eastern stretch of Veneto.

The prevalence of groins, frequently built in combination with concrete seawalls and/or diaphragms, is evident from fig.2, whereas only a few detached (emerging) breakwaters were built at the inlet of the River Tagliamento and for a limited stretch along the beach of Jesolo.
The Jesolo breakwaters, of the rubble mound type, are part of a protective system built about 1967 to protect the beach against severe erosion threatening several buildings constructed along the beach some years previously. Due to the strong supply of sediments, the system of breakwaters was filled by sand in a few years.

3.1.1 Example of a submerged breakwater system.

This example refers to a submerged breakwater built recently to protect a fill

which was placed immediately west of the inlet of the river Livenza (fig. 3).
In this area, massive coastal protection already existed, consisting of a concrete wall with a concrete sheet pile diaphragm, protected by groins. This structure, built at the end of the 1960s mainly to protect the hinterland against flooding from the sea, extends for about 15 km (Fig.2) and is one of the most impressive examples of rigid coastal protections built in Italy.
Notwithstanding the presence of this protective system, erosion phenomena continued on the beach in several areas, including the stretch considered here, which suffered particularly from the recent extension of the updrift Livenza jetties. To improve the situation of this beach, in 1985 renourishment works were carried out for about 1.5 km, protecting the fill with a submerged barrier. This consisted of a Longard tube 1.80 m high, built at a water depth of 2 m, beyond the heads of the existing groins.
The operation was not successful, due to beach-side scouring of the tube, which caused it to sink and become ineffective.

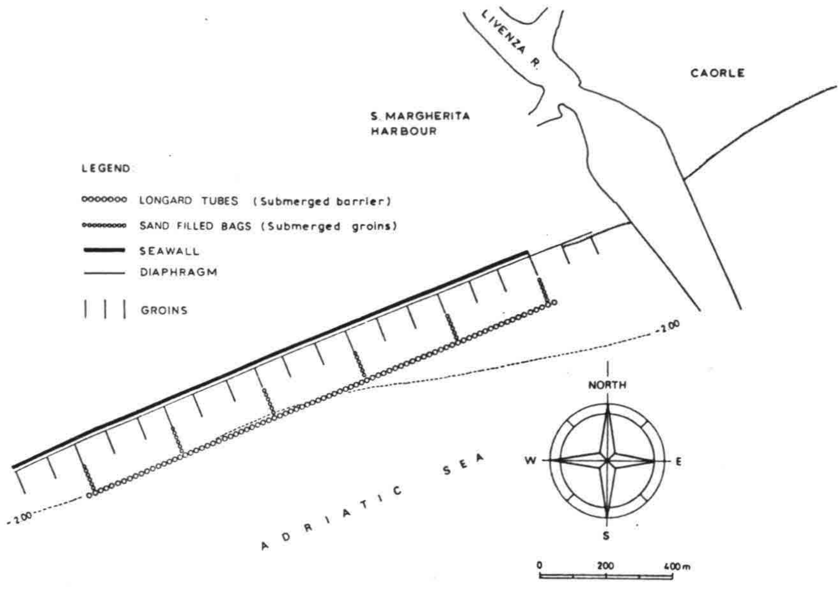

FIG.3. Protective structures at Caorle

After some modifications against scouring, this solution was again proposed in 1990 and carried out in 1991. According to the new design (fig.3) a series of submerged groins (built using large sand-filled bags) perpendicular to the tube was also built.

The scheme of the protective system, consisting of a longitudinal barrier and a series of submerged transversal elements, is similar to other works carried out in Italy to protect artificial fill. In this case, where protective structures were already present, further protection of the fill was deemed opportune due to the smaller dimensions of fill material (borrowed from the updrift area of the Livenza inlet, at water depths of 3-4 m) compared to the original material.

3.2. THE EMILIA ROMAGNA COAST

The Emilia Romagna coast extends along the Adriatic for about 135 km. It consists entirely of sandy beaches, with the only exception of its southern limit (the cliffs of Cape Gabicce, which separates Emilia Romagna from the Marche). Net longshore transport is generally directed north-west.
The coast is interrupted by a number of river inlets, generally protected by jetties to form channel harbours, which are characteristic of the coast of this region.

The Emilia-Romagna beaches are among the most famous in Italy and the whole Mediterranean. The pressure exerted by the tourist industry has led to intensive exploitation of the coast, which has mainly lost its original natural characteristics.
A long belt of buildings was constructed on the beach, removing dune systems and narrowing it. Further pressures from fishing and yachting activities, the latter again connected to tourism, led to stabilisation of the river inlets with jetties.
Apart from the jetties of the numerous channel-harbours, there are no harbour structures along the coast, with the only exception of the jetties of the port of Ravenna.

Emilia Romagna coast has suffered erosion since about 1930. This phenomenon has become more pronounced in the last few decades, main causes being:

- reduced contribution of sediments from the Po and other rivers feeding the beaches of this region;

- severe subsidence effects, which caused the land and beaches to settle by several cm/year in the last few decades and which is still continuing (the latest surveys, carried out by the Emilia-Romagna Region for the period 1984-87, confirmed subsidence for most of the coast, with maximum sinking of about 5 cm/year in the Cesenatico area);

- the presence of artificial obstacles, like jetties protecting the inlets, which disturbed the configuration of the coast.

As regards the last point, there are 15 couples of jetties (considering only those protruding into the sea for at least 10-15 m beyond the shoreline) present along this coast. They have produced important effects on the Emilia Romagna beaches, causing accretion of the southern beaches, which benefited greatly from the presence of the jetties: the most famous beaches in this area (like Rimini and Cesenatico) are situated updrift of inlets. Instead, the northern beaches suffered erosion effects, and were usually the first which had to be protected with detached breakwaters. These in turn produced erosion of downdrift beaches, with the necessity of further extending protection works. Jetties, as will be seen later, were a decisive factor in triggering off erosion effects and the evolution of the Emilia Romagna beaches.

To protect the beaches from erosion, a number of structures were built along this coast. Fig.4 indicates the various protective structures built along the coast, as a result of several decades of concern with shore protection.
About 40 km of beach are now protected by detached breakwaters of the emerging type, 13.4 km by submerged breakwaters, 1.6 km by groins, 3.5 km by land-based shore parallel (parallel shore) structures. A further 40 km of coast is defended by structures to protect the land from flooding from the sea (artificial dunes, seawalls, etc.). For some stretches, there are different kinds of protective structures in combination.
On the whole, about 100 km of coast are protected by structures, whereas only 35 km are unprotected.
As fig.4 shows, detached breakwaters are by far the most widespread defensive measure in this region, with a total of 53.5 km of coast protected by barriers of emerging and submerged types.

Emerging breakwaters were the preferred solution until about 1980, when their shortcomings became clear (erosion of downdrift beaches, which led in several cases to the

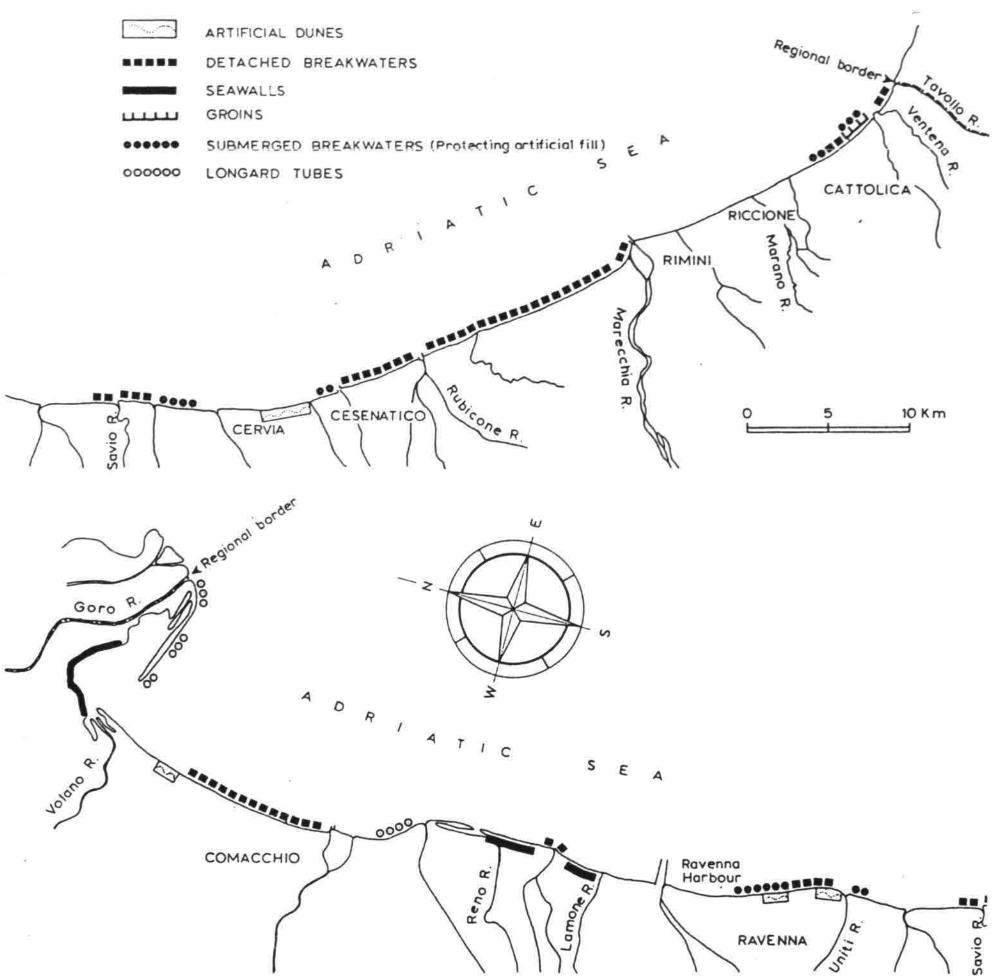

Fig.4. Coastal defences of Emilia Romagna (from Idroser, 1991)

necessity to "propagate" downdrift protections; unfavourable environmental effects, etc.; even effects on the protected beaches were not always satisfactory, for lack of sediment transport and continuing subsidence).

In the last decade, there has therefore been a change of approach, and an important turning-point was the decision of the regional authorities to carry out thorough investigations on the conditions of the entire coast and to propose solutions for the eroding beaches which would carefully consider consequences on the adjoining beaches and on the coastal environment, thus avoiding "case by case" solutions as in the past. As a consequence of the investigations and proposals of Idroser (1982), commissioned by Emilia Romagna Region, artificial beach nourishment was recognised as the best solution for shore protection, and most new works carried out since then follow this indication.

However, artificial nourishment was never accomplished alone and

complementary structures were always built to reduce losses of fill material.
This was favoured by the scarcity and cost of fill sediments, always borrowed from land pits, and also by some inadequacies of Italian laws on coastal protection and a traditional mentality, rather widespread in Italy, for which it is difficult to conceive coastal engineering without construction of rigid structures.
The typical basic solution for auxiliary structures consists in submerged barriers parallel to the beach, with submerged groins perpendicularly connecting the beach to the barriers. The submerged structures are composed of sand-filled textile bags.
At first, low barriers with high submergence were used, whereas a tendency towards solutions with less submergence and greater sections is evident in new designs.

3.2.1. Examples of detached (emerging) breakwaters

Detached breakwaters of the emerging type have been built along the Emilia-Romagna coast since about 1933 and were the preferred solution for coastal protection until about 1980. Then, as a consequence of the new trends in coastal protection policy, new works relating to emerging breakwaters were limited in practice to repair of damaged structures or minor completion works.

The usual structures consist of rubble mound breakwaters located at water depths of 2.5-3 m.
The typical section (fig.5) has an offshore slope of 1:2 and inshore slope 2:3; the crown height is about 1.0-1.5 m above m.s.l., and its width is about 4-5 m (corresponding to the width of 3 armour stones). The weight of the armour stones is 3-7 (metric) tons. The length of the segments is about 100 m with gaps of 30-40 m. The breakwaters are either parallel to the shoreline or inclined south-east.

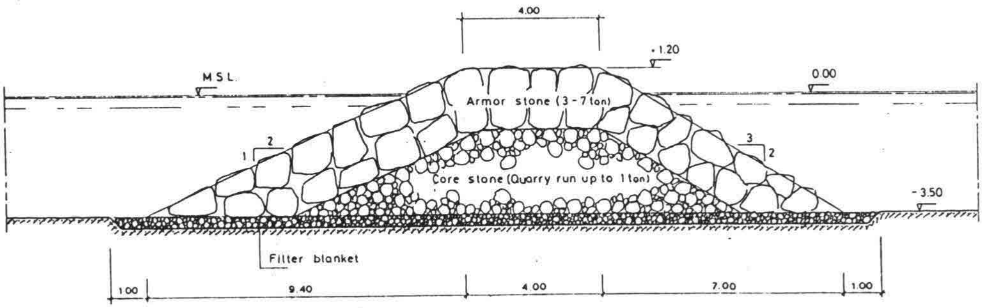

Fig.5. Section of a typical detached (emerging) breakwater used in the Emilia Romagna coast

As an example, the system built to protect the coast between Rimini and Cesenatico (fig.6) is considered in particular.
This stretch of coast, with a total length of about 20 km, is protected by a continuous belt of detached emerging breakwaters, which represent the longest continuous protective system of detached breakwaters present in this region and perhaps in Italy. This is composed of about 180 segments.
As seen in fig.6, the beach is downdrift of the port of Rimini, and suffered considerable erosion after the last extensions of the jetties, which were completed in 1925. These extensions caused a shoreline offset of about 500 m, with accretion of the beach of Rimini and erosion of the downdrift beaches for several kilometres (more than 30 km according to the estimate by Idroser, 1985).

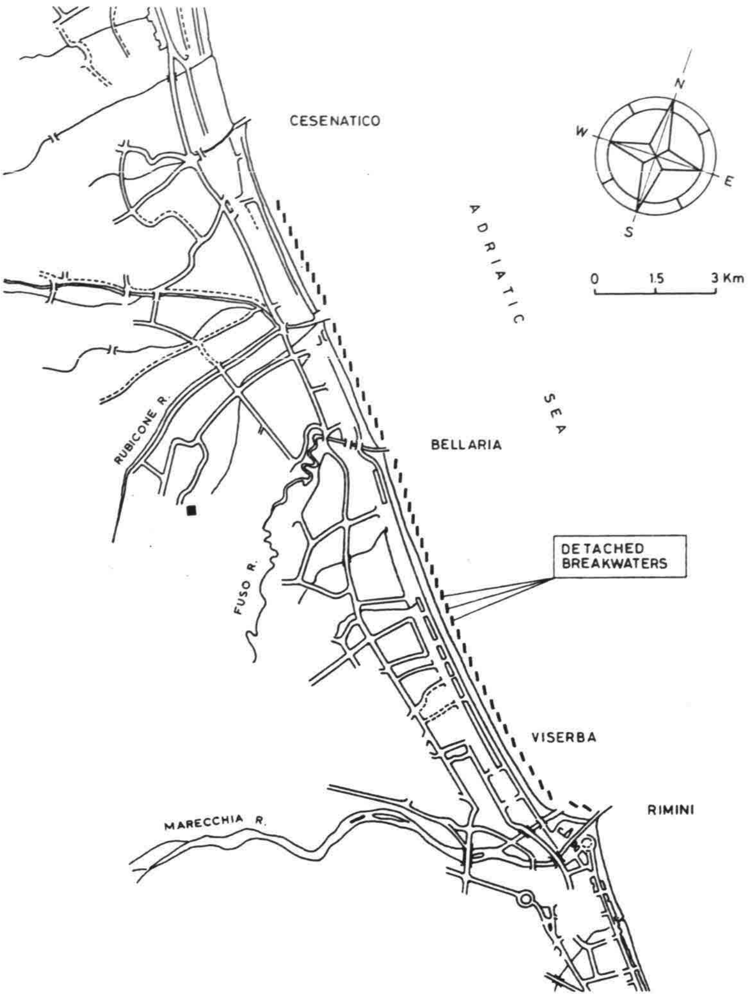

FIG.6. System of emerging detached breakwaters protecting the coast between Rimini and Cesenatico (Idroser, 1982)

As a consequence, a number of offshore breakwaters were built to protect the beaches: the first five were completed at Viserba in 1950; ten segments were built between 1952 and 1956. Twenty segments were built at Bellaria between 1958 and 1962. Breakwater construction continued until 1972, protecting the whole coast between Rivabella and Marina di Cesenatico and, after a halt of a few years, it started again in 1978, leading to completion of protection between Rimini and Rivabella in the south, and along the beach of Cesenatico in the north.

The protective system certainly helped in facing erosion, at the least in the short term. However, beach accretion was considerable only near the river inlets, especially at the northern (downdrift) side. Few effects were obtained on the most downdrift beaches, and in some cases the protection afforded by the breakwaters was unsatisfactory, as in the case of Gatteo a Mare, where renourishment works were deemed necessary and carried out in 1972 to improve the conditions of the beach: this was an anticipation of a trend which now seems obvious.

Apart from the high capital investment, we must also consider the difficulties and costs of maintaining such a system over time: continuous maintenance works are necessary to repair and reshape the barriers, subject to damage by storms and to subsidence effects; continuous modifications are also necessary in an effort to combat local erosion phenomena. In many cases this has resulted in shortening the gaps or in adding segments of breakwaters, or even in closing the gaps with submerged barriers.

3.2.2. Examples of systems of submerged breakwaters

3.2.2.1. First-generation works

For the first works, carried out since 1983, low submerged structures were used, using 1-m^3 bags.

A typical scheme of this kind of work is shown in fig. 7. The barriers were usually laid at water depths of up to more than 3 m, whereas the height of the structure was about 1 m. Transversal structures were also generally provided, aiming at reducing loss of sediments by longshore currents.

A number of beaches were renourished and protected in this way: Misano, Riccione, Cesenatico and Cervia, for a total length of 5.6 km and a fill volume of 100 m^3/m (a total of about 400-500,000 m^3 for all works).

The Emilia Romagna Region has carried out a number of surveys since 1986 to check the effects of the new works on the protected beaches and the behaviour of the new structures.

From a functional point of view, the surveys showed a general improvement of conditions on the beaches where the new works had been carried out. Only at Riccione were the results unsatisfactory, and this was ascribed to the lack in this case of transversal elements (submerged groins connecting the longitudinal barrier to the emerged beach). Transversal elements appeared to be an important complementary element for the success of this solution, as also shown by the nearby beach of Misano, where the effects of the works were positive.

As regards the behaviour of the structures, considerable scouring phenomena at the beach-side foot of the barriers and some damage to the structures were observed, due to displacement or breaking of the bags.

So, whereas the behaviour of new works was considered quite satisfactory from a functional point of view, some weak points of the barriers from the structural point of view had become evident.

One problem was the insufficient resistance of sand-bags as armour units against/to wave forces, which caused their displacement (though in some cases it was not clear if bag displacement also depended on their defective laying during construction of the barriers). Another problem was the mechanical strength of the textile bags, some of which broke for various reasons, including the activity of mussel-gathering boats and also vandalism. A last problem was scouring at the beach side of the barriers, which caused sinking of the structure.

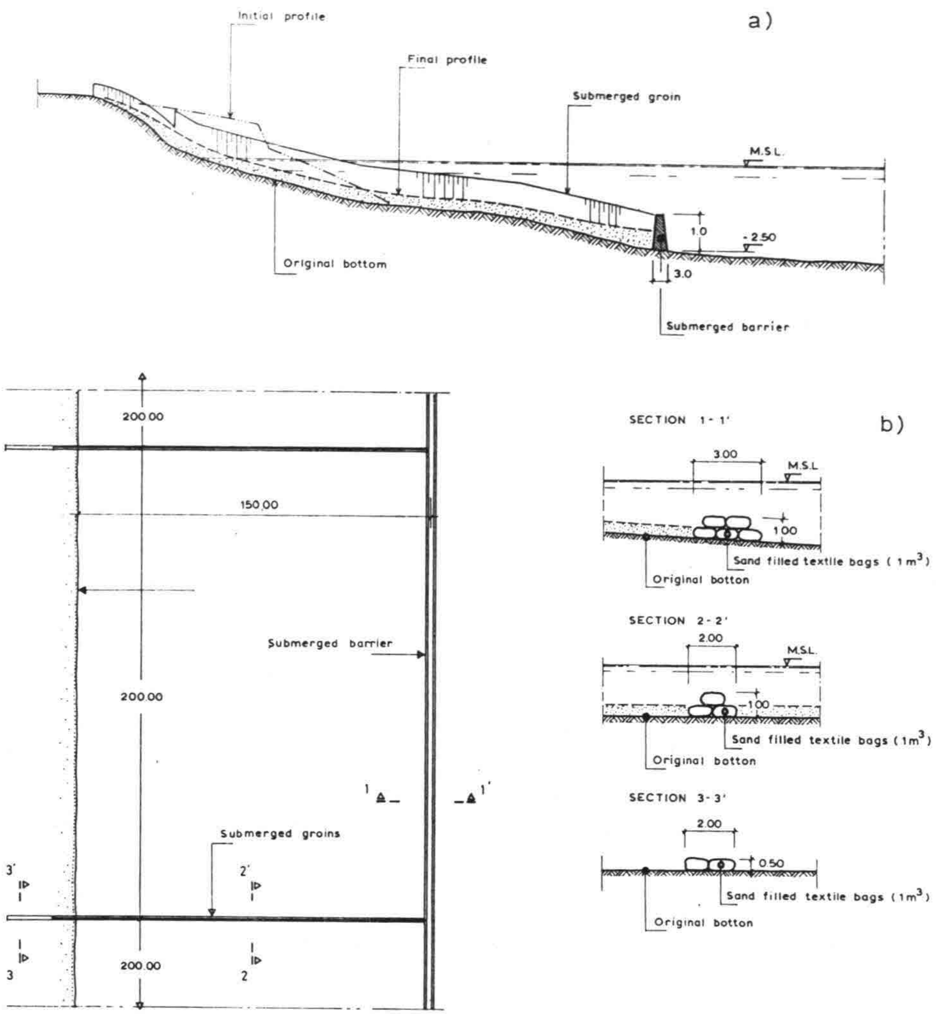

FIG.7. Sketch of a typical protective system for beach renourishments used in Emilia Romagna (Idroser, 1982).

3.2.2.2. Second-generation works

After several years of experience with beach filling protected by submerged breakwaters, this kind of solution has been confirmed in the new designs, e.g., those at Cesenatico and Ravenna.

Differences from the first projects consist of:

- larger quantities of beach fill per metre of beach (200 m^3 instead of 100);
- barriers with larger sections and larger sand bags (2 instead of 1 m^3).

The importance of transversal elements in guaranteeing the stability of the fill has been recognised, based on previous experience, and these elements are now always provided in the new projects.
As regards the location depth for barriers, depths between 2.5 and 3 m are now considered preferable, whereas previously designed barriers were built in water depths of up to 3.5 m.

As an example of the new design criteria, fig.8 schematically shows the works recently carried out at Ravenna.

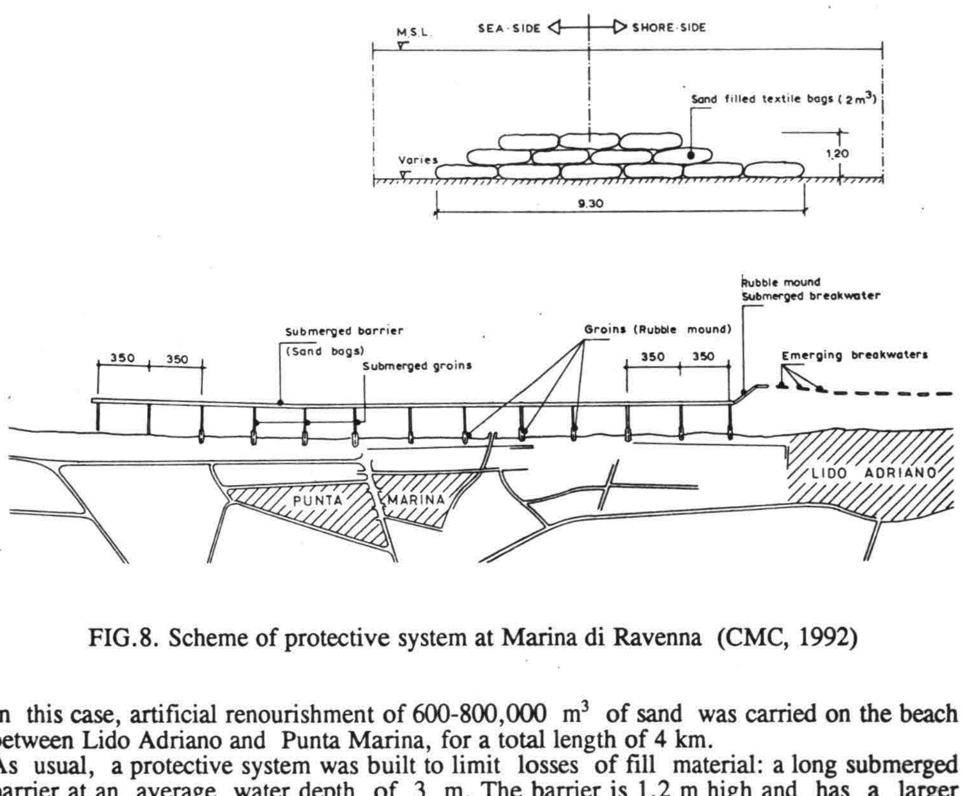

FIG.8. Scheme of protective system at Marina di Ravenna (CMC, 1992)

In this case, artificial renourishment of 600-800,000 m^3 of sand was carried on the beach between Lido Adriano and Punta Marina, for a total length of 4 km.
As usual, a protective system was built to limit losses of fill material: a long submerged barrier at an average water depth of 3 m. The barrier is 1.2 m high and has a larger section than previous designs (see fig.7), with a base width of more than 9 m and a top width of about 5m. A single bag has been added to the shore-side of the barrier to prevent scouring at the toe of the structure.
The protective system is completed by a series of groins built at intervals of 350 m, thus comprising 12 cells; the groins consist of short inshore segments of emerging rubble mound structures and offshore submerged segments built, as usual, with sand-filled bags.

3.3. THE MARCHE COAST

The Marche coast has a total length of 172 km. Rocky coasts comprise 19% of the total, sand and gravel beaches the remainder. The beaches are mostly supplied with sediments from rivers which, rising in the nearby Apennines, have limited hydrographic basins and are generally seasonal.
The coast is divided by the cliffs of Monte Conero into two stretches with different orientation and beach characteristics. In the north, sandy beaches (about 45% of the total length) prevail, while gravel beaches represent 35% and sandy-gravel beaches 20%. In the south, gravel beaches prevail (64%), with 14% sandy-gravel beaches and 22% sandy beaches.
Net longshore transport is directed north-west; this is more evident for the northern than for the southern stretch, where it is subject to local inversions (particularly at river mouths). The theoretical estimates by Aquater (1982), based on CERC formula and offshore measured wave climate and refraction models for estimating nearshore wave conditions, give average values of 200,000 m^3 for the north and 60,000 m^3 for the south.

There are a number of harbour structures along the Marche coast: generally channel harbours stabilised with jetties, but also in a few cases convergent jetties and external harbours.
About 56% of the beaches are now protected by defensive structures (Dal Cin et al., 1989; Aquater, 1992). These are most frequently detached breakwaters (40% of beaches) and rubble mound seawalls (16%). The latter are usually emergency defences, protecting railways, roads and buildings from wave attack. Groin systems are generally not used as shore protection measures in this region.

Most of the unprotected beaches are eroding, particularly at the river mouths. The primary cause of erosion is generally the decrease in sediment supply; subsidence effects are in this case negligible. According to Aquater (1982), supply decreased by 30-40% after 1966: quarrying from rivers was one of the principal causes, with about 12.7 million cubic meters of sand and gravel quarried from 1966 to 1975 (greater than the potential transport of all of the Marche rivers during that period).

Until about 1980, detached breakwaters of the emerging type, together with rubble mound seawalls, were the only protective measure for eroding beaches.

After 1980, new types of protection were also emplaced, such as artificial nourishments protected by submerged breakwaters of various kinds. In this case, the new approach was encouraged by the investigations and consequent work proposals carried out by Aquater on behalf of the Marche Region.

In this case, small volumes of fills - of the order of a few thousand cubic metres - were used to protect short stretches of beach; rubble mound structures were also often used as submerged breakwaters. This was at least partly due to the steeper slopes of the submerged beaches, and to the heavier attacks of waves compared to those occurring along the coast of Emilia-Romagna.
Furthermore, in this region construction of emerging breakwaters was not almost completely abandoned as in Emilia Romagna, but continued, although at a reduced rate compared with the past.

3.3.1. Examples of detached (emerging) breakwaters

A number of systems of detached breakwaters were built along the Marche coast .
From the structural point of view, their geometry (section, length of elements, etc.) is about the same as in Emilia Romagna.

In this case, the length of the resulting breakwater systems is less impressive than in the case of Emilia-Romagna, the longest uninterrupted system of detached breakwaters (built to protect the beach of Senigallia) having a total length of 4.5 km.
This system was built as a consequence of erosion which had appeared since the

beginning of this century but which became particularly severe in the period 1948-1978, when works were decided. After construction of the protective systems, the situation for the protected beach improved markedly; however erosion worsened in the downdrift beaches.

A number of new systems of emerging breakwaters has also been built in the last few years, particularly in cases where, due to urgency in facing erosion, it was not deemed safe to resort to traditional systems but rather to "softer" solutions such as submerged barriers. In fact, more than half of the new protective systems carried out to protect 19 km of beach (Aquater, 198?) consist of detached breakwaters of the emerging type.

For the new works, care was taken to avoid some disadvantages of the past and new barriers have been built at greater distances from the shoreline to avoid the formation of tombolos and to help water exchange. In some cases, old barriers have been removed and new ones rebuilt farther offshore. In other cases, artificial fill has been laid on the beach protected by the new barriers.

3.3.2 Examples of submerged breakwaters

Submerged breakwaters have been used in Marche both for simple protection of the coast and, more frequently, in combination with artificial beach nourishment.

Examples of the first kind of intervention are the works carried out to protect the cliffs north of Pesaro (fig.9) and south of Ancona (fig.10) from wave attack.

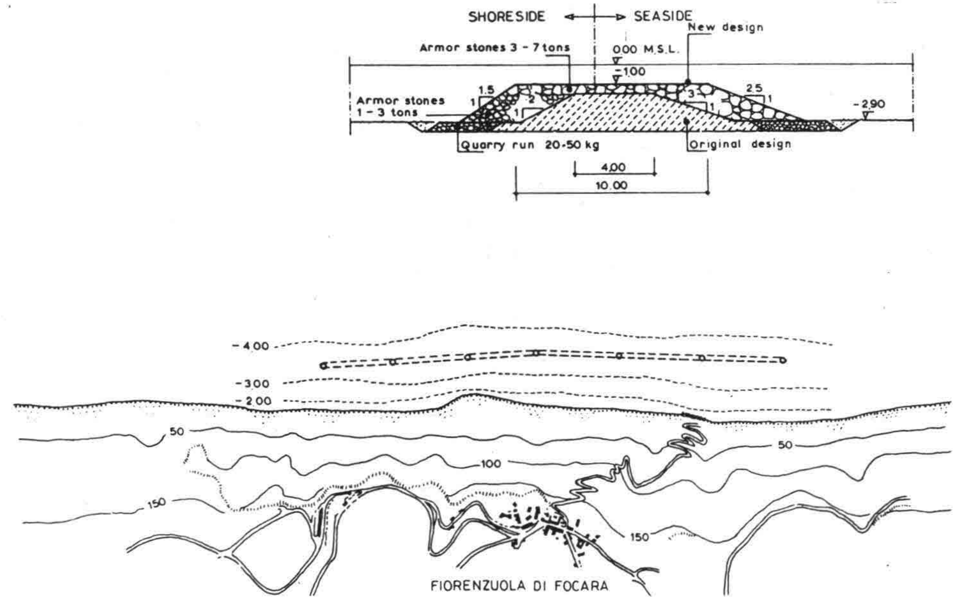

FIG.9. Protective system at Fiorenzuola di Focara (north of Pesaro; Aquater, 1985 and 1992)

In both cases, this solution with submerged barriers was particularly suitable because of the high environmental value of the coast, which would otherwise have been disfigured by the presence of emerging structures.

Rubble mound structures were used in both cases. For the barriers north of Pesaro, the rubble mound structures, which had suffered damage from wave attack, were rebuilt a few years later using a larger section and a smaller submergence.

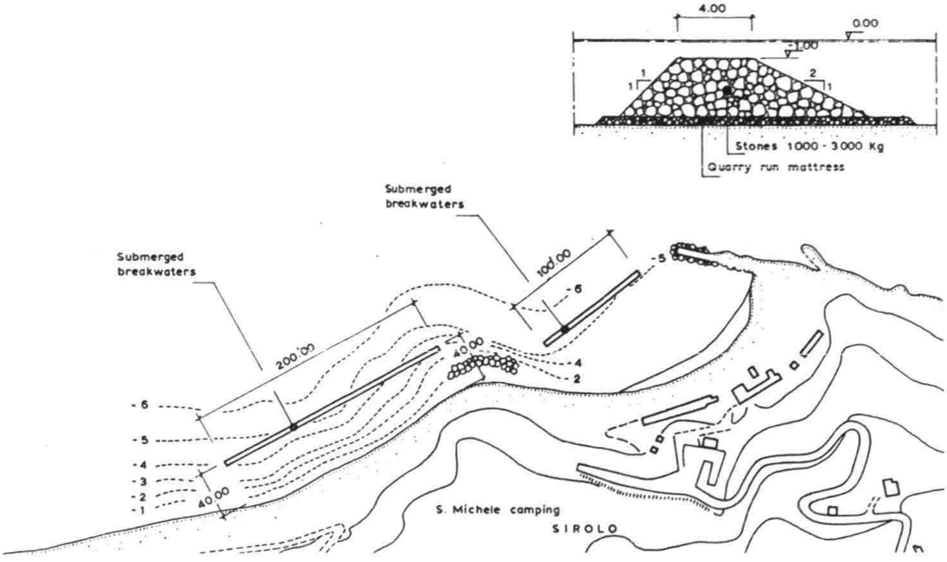

FIG.10. Protective system at Sirolo (south of Ancona; Aquater, 1985)

As regards submerged structures built as complementary structures for artificial beach nourishment, a number of solutions have been adopted in the Marche.
Most of them are rubble mound structures, as at Grottammare, S. Benedetto and Porto Recanati (Lorenzoni et al., 1987), S. Elpidio, Lido di Fontespina (Aquater, 19) and Torrette di Fano (Aquater, 1992).
At Porto Recanati (fig.11) and Grottammare (fig.12), the protective systems consist of segments of submerged barriers (70 m long at Porto Recanati and about 90 m at Grottammare, with gaps of 20 m in the first case and 15-25 m in the second). The barriers protect artificial fills of 16,000 m^3 for about 700 m of beach at Porto Recanati and of 23,000 m^3 for about 1,200 m of beach at Grottammare. Emerging signalling islands are also present.
Both structures are reported to have been subject to damage not long time after they were constructed. In fact, some weak points appear from the sections of Figs.11 and 12. One is the rather low weight of armour units used, particularly for the Porto Recanati barriers, built in a water depth of about 5 m, and therefore presumably subject to breaking wave heights of about 4 m. Another is the very steep shore-side slope (1:1) of the barrier: slopes steeper than 1:1.5 are not recommended (see, e.g., Shore Protection Manual, 1984), particularly for breakwaters subject to overtopping, in which case it is advised not to increase shore-side slopes compared to seaside ones.
As regards the planimetry of the works, it is not clear why so many separated segments have been built, since a long continuous barrier would probably have been more suitable (with only a few gaps, if deemed necessary for the passage of shipping).
For all the above structures, good results as regards functional performance are reported.

Another example of the use of rubble mound submerged structures is that of Torrette di Fano, where a low barrier about 1 m high was built at a water depth of about 2.5 m. In this case, transversal structures were also built (rubble mound submerged groins). Renourishment of 12-14,000 m^3 was also carried out on the beach.

Other types of submerged barriers have also been built in the Marche as complementary structures for beach nourishment, as in the case of Marina di Montemarciano, where two different types of structures have been used.

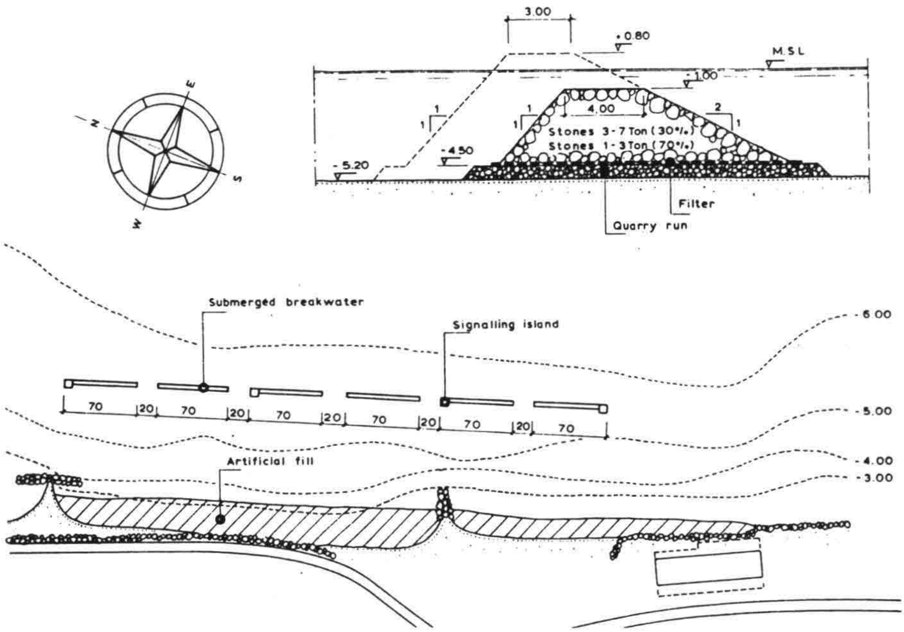

FIG.11. Protective system at Porto Recanati

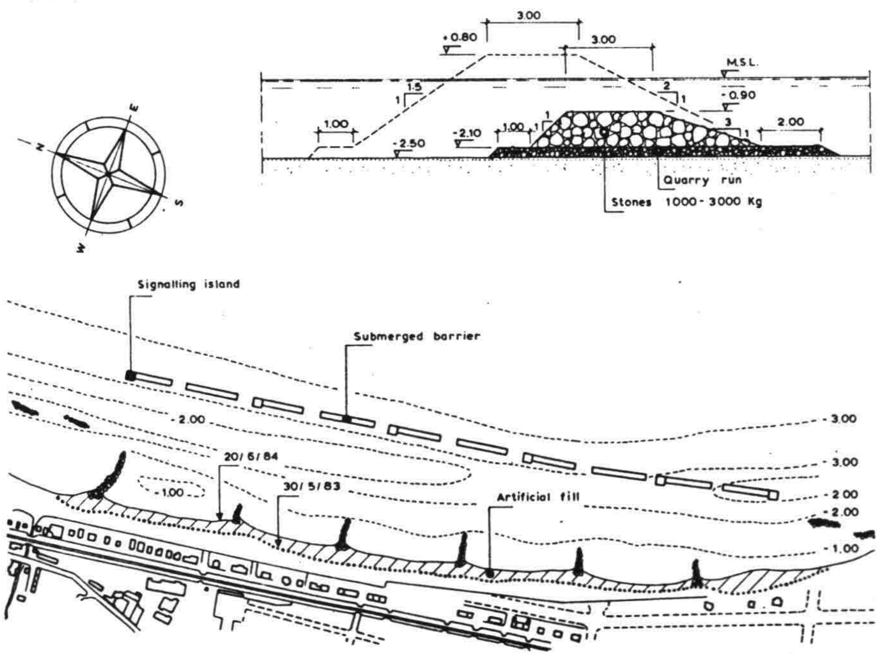

FIG.12. Protective system at Grottammare

In the first (fig.13a), 1 m^3 sand-filled bags were used to build the very low barrier (0.5 m high on a water depth of 2 m) and the submerged groins connecting the barrier to the beach. This kind of work is similar to those seen for Emilia Romagna.
In the second (fig.13b), sand-filled Longard tubes were used to protect a stretch 1.7 km long which had suffered erosion and to enable the use of road parallel to the shore. Two rows of segments built with Longard tubes of different lengths and gaps were used in this case.

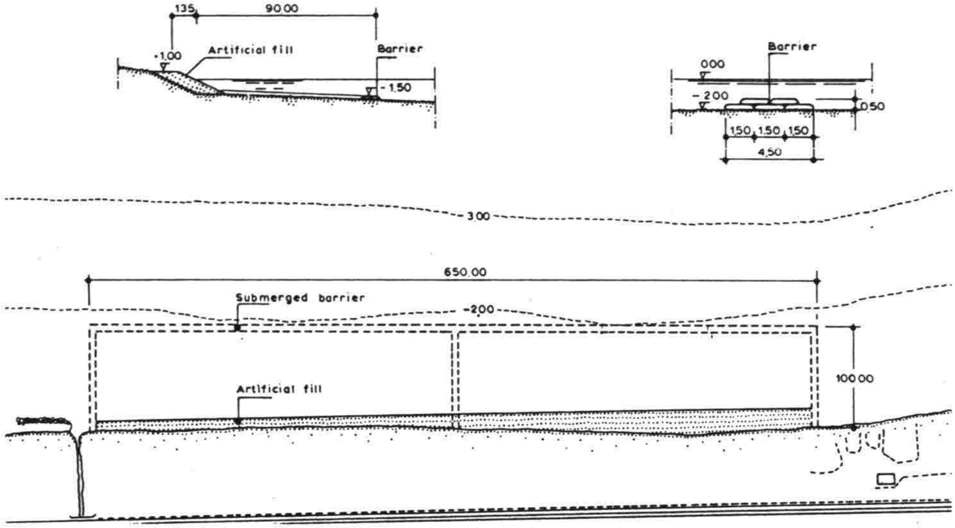

FIG.13a. Protective system at Marina di Montemarciano

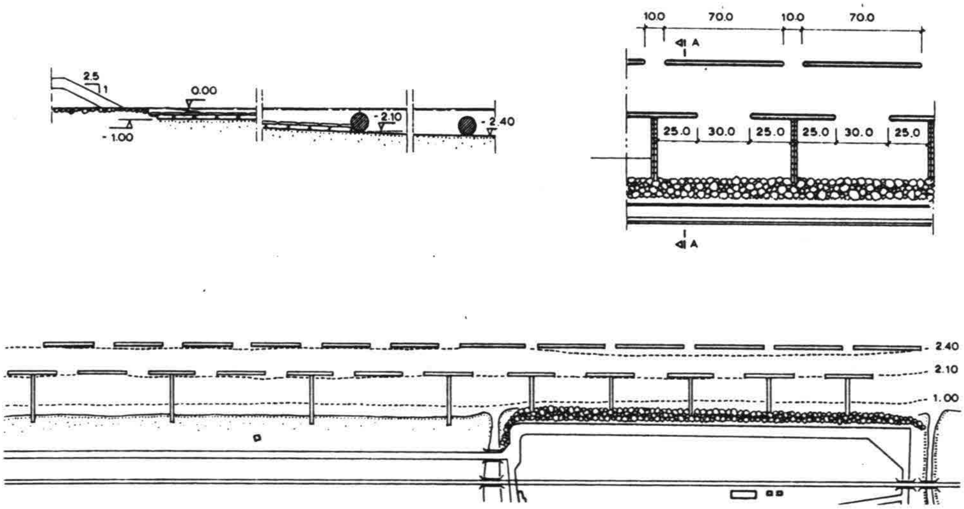

FIG.13b. Protective system at Marina di Montemarciano

4. Conclusive remarks

From the above descriptions, we have seen that a large number of shore protective structures have been and continue to be built in Italy in an effort to combat erosion.

Among shore protection structures, detached breakwaters are the most common measure, not only along the coasts considered here, but for the whole length of the Italian coasts (about 7600 km). Compared with other types of fixed structures, in Italy detached breakwaters have proved in many cases to be an efficient method of shore protection. They offer immediate protection to the beach to be defended, even before the trapping effect of sediments has widened the beach. From this point of view, they present advantages compared to groins (which have little influence on wave attack before significant accretion of the beach has occurred) and also, obviously, to seawalls, which afford protection to the land behind, but which do not help in accreting the beach.

However, as already seen and well known by coastal engineers, serious drawbacks are associated to the extensive use of detached breakwaters (as, more generally, of any type of rigid structure interrupting littoral drift). Apart from serious "local" environmental problems like water exchange and quality of sediments in the protected area (which can be partly reduced by not building the barriers too near the shoreline, thus avoiding the formation of tombolos), the main problem is that of the downdrift shift of erosion phenomena, and thus the necessity of protecting the downdrift beaches too. This is clearly shown, e.g., by the long uninterrupted sequences (up to 20 km long between Rimini and Cesenatico) of detached breakwaters built along the coasts we have examined. Furthermore, also on protected beaches results have been sometimes unsatisfactory, particularly in cases of insufficient sediment transport and strong subsidence, as for Emilia Romagna.

As seen above, the inadequacy of this kind of protection to solve the problem of coastal erosion satisfactorily has been recognised in the case of the Emilia Romagna and Marche, and a more general approach has appeared necessary, by considering the coast as a whole and aiming at avoiding "case by case" solutions which have caused the proliferation of rigid structures along the coast in the past.
Artificial nourishment of beaches was then recognised as the best solution for beach erosion problems. However, as already seen, in Italy this concept must combat against inadequacies of Italian laws on coastal protection and also traditional mentality, according to which it was hard to conceive coastal protection without fixed structures . Another problem was the difficulty of obtaining suitable fill materials, generally borrowed from land deposits. So the concept of protected nourishment prevailed, using submerged structures as complementary structures protecting artificial nourishment. Most of the new protective systems proposed in the last decade obey this concept.

As regards the types of submerged structures used, in the case of Emilia Romagna, the most frequent solution was that of systems of longitudinal barriers and transversal elements (groins) built with sand-filled bags. Low submerged barriers were used initially, whereas higher and wider barriers were adopted in later designs, and the size of the bags was also increased. Particular care against scouring problems at the beach-side foot of the barriers has been taken in more recent designs.

For the Marche coast, rubble mound structures have frequently been used for the submerged barriers, although sand filled bags and Longard tubes have also been used in some cases. Rubble mound submerged barriers have also been used to protect cliffs from erosion, thus affording good protection against wave attack and at the same time minimising unfavourable aesthetic effects.
In the case of the Marche too, the tendency of new projects is to use larger structures, with higher and wider sections than those built earlier.

From a functional point of view, the type of solutions adopted for submerged barriers, considering the high values of submergence, particularly for first-generation works, evidently aims at increasing stability of fill sediments rather than influencing waves.

As regards the effectiveness of the various systems of submerged structures seen

above, it is certainly not easy to make definite judgements, which would require thorough investigations in the field and in the laboratory, aiming at comparing the behaviour of protected and unprotected beaches.
The final aim of such investigations would be to compare total costs for simple artificial nourishment and protected nourishment, including capital and maintenance costs for both beach fill and protective structures; due consideration of effects on downdrift beaches should also be taken.

At the present moment, before the results of above investigations are available and carefully examined, we can only rely on the impressions and experience of those involved in the projects. These indicate, in general, good performance of the works carried out using artificial beach nourishment protected by submerged structures; the effectiveness of the protective structures is expected to improve with increased dimensions of the barriers, as in the more recent works.

From the structural point of view, several barriers, particularly the submerged ones, have suffered damages under wave attack due to structural "weakness" of first designs. For the new works, more robust sections have been designed, also considering scouring problems (particularly at the seaside foot) more carefully. In any case, more research appears necessary regarding stability of submerged barriers.
As regards the two kinds of structural solutions most frequently adopted for submerged barriers, i.e., sand-filled bags and natural stones, they have both advantages and drawbacks. On one hand, natural stone elements are certainly more durable and not subject to breaking as textile bags are; furthermore, they have a greater volume weight than bags.
On the other hand, sand-filled bags are more regular than stones, and thus allow better and more precise shaping of the structures; for bathers they are also certainly more suitable than rubble mound structures. Furthermore, textile sand-filled bags (or other similar elements) represent an interesting solution for cases in which quarried rock is not easily available or not economic. The progress of bag technology is also expected to improve the mechanical resistance of bags in the future, thus making this solution still more appealing.
As regards solutions based on large sand filled "sausages", which have been used for some of the above works, they may be considered as interesting alternatives to small sand-bags. The use of single large "sausages" instead of small elements certainly simplifies barrier construction; however, repair is much more difficult and if the envelope breaks the whole structure has to be rebuilt. Particular care must be taken of scouring, particularly at the shore-side foot, which has caused serious problems in some of the above applications.
From a hydrodynamic point of view, circular sections do not appear to be particularly efficient and have high reflection coefficients. From this viewpoint, solutions using hydrodynamically profiled sections, like that proposed by Larsen (1990), seem preferable.

Coming back to the problem of coastal protection in general, a few considerations may be made on shore protection policy for the coasts examined here. Due to better environmental impact and softer effects on downdrift beaches, submerged barriers certainly represent an improvement compared to detached breakwaters. However, doubts remains regarding their level of effectiveness, particularly for the first works (characterised by a high submergence).

In the writer's opinion, they should only be used where their usefulness can be reasonably demonstrated, and not as a panacea for any coastal problem, as is going to happen in Italy. More attention should be paid to the main operation, which is artificial nourishment itself. This problem should be solved in a more satisfactory way: first of all, finding suitable borrow deposits with large scale surveys, as done, e.g., in Emilia Romagna (Idroser, 1990), where large humps of sands where discovered offshore. Only with large sçale nourishment operations could erosion dealt with in a more satisfactory way.

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References

AMINTI,P., LAMBERTI,A. and LIBERATORE,G.(1983). Experimental studies on submerged barriers as shore protection structures. *Proc. 1st Int. Conf. on Coastal and Harbour Eng. in Develop. Countries, Colombo Sri Lanka*

AQUATER(1982). Studio Generale per la Difesa delle Coste. Vol.I: Relazione Generale, Regione Marche

AQUATER(1982). Studio Generale per la Difesa delle Coste: Vol.II: Rapporti di Settore, Regione Marche

AQUATER(1985). Interventi di difesa della costa realizzati con fondi F.I.O. '82, Regione Marche

AQUATER(1992). Personal communication.

C.M.C.(Cooperativa Muratori e Cementisti, Ravenna)(1992). Personal Communication

CORTEMIGLIA,G.C., LAMBERTI,A., LIBERATORE, G., STURA,S. and TOMASICCHIO,U.(1981). Effects of harbour structures on shoreline variations along the coast of Italy, *PIANC Bull. no.30, Vol.II*, 10-36

DAL CIN,R. and SIMEONI,U.(1989). Coastal zoning: application to the Middle Adriatic, *Proc. Sixth Symp. on Coastal and Oc. Management, ASCE*, "Coastlines of Italy"

DAL CIN,R., Pedone,F. and Simeoni,U.(1984). Morphological evolution and sediment distribution on the coasts of the Marches, *Societe` Hydrotechnique de France, XVIII Journees de l'Hydraulique, Marseille*

DAL CIN,R. and SIMEONI,U.(1987), Analisi ambientale quantitativa dei litorali marchigiani fra Gabicce ed Ancona, *Boll. Soc. Geol. It.* 106, 377-423

HARRIS,M.M. and HERBICH,J.B.(1986), Effects of breakwater spacing on sand entrappment, *Journal of Hydraaulic research,* , Vol.24, No.5

HERBICH,J.(1990). Pile and Offshore Breakwaters, Chap. 19 *in* "Handbook of Coastal and Ocean Engineering", J. B. Herbich Ed., Gulf Publishing Company, Vol.1, 895-920

IDROSER(1982). Piano progettuale per la difesa della costa adriatica Emiliano-Romagnola: Relazione Generale, Regione Emilia Romagna, Bologna (Italy)

IDROSER(1982). Piano progettuale per la difesa della costa adriatica Emiliano-Romagnola, Vol. V: Il regime del litorale e le alternative di intervento, Regione Emilia Romagna, Bologna (Italy)

IDROSER(1985). Piano progettuale per la difesa della costa adriatica Emiliano-Romagnola, Vol. VI: Le opere a mare: caratteristiche ed effetti sul litorale, Regione Emilia Romagna, Bologna (Italy)

IDROSER(1990). Ricerca di depositi sabbiosi sul fondo del Mare Adriatico da utilizzare per il ripascimento delle spiagge in erosione, 2ª Campagna di Ricerca, Bologna (Italy).

IDROSER(1991). Carta dei litorali in erosione e interventi di difesa realizzati, Bologna (unpublished)

LARSEN, O.F.(1990). Development of a low-cost system for non-disfiguring large scale coastal protection, *Proc. Symposium Littoral 90, Marseille (France)*

LIBERATORE,G., MURACA,A. and CAMPANALE,F.(1991). Effects of coastal structures on the beaches of the Veneto (Italy), *Proc. 3d Int. Conf. on Coastal and Harbour Engineering in Developing Countries, Mombasa (Kenya)*

LORENZONI, C., PERUCCI P. and RICCIONI, M.(1987), Ripascimento artificiale di alcuni litorali marchigiani: criteri di progetto, modalita` di esecuzione e conseguente evoluzione delle spiagge, *IV Coll. AIOM, Ancona(Italy), 1987*, 196-221

MASSEL, S.(1989), Detached breakwaters, Report on literature study and practical guidelines, Polish Academy of Sciences, Institute of Hydroengineering, Gdansk (Poland)

POPE,J. and DEAN,J.(1986). Development of design criteria for segmented breakwaters, *Proc. 20th Coastal Engineering Conference*,ASCE, 2144-2158

Shore Protectional Manual(1984). U.S. Army Waterways experiment Station, U.S. Government Printing Office, Washington DC

TOYOSHIMA, O.(1974). Design of adetached breakwater system. *Proc. 14th Coastal Eng. Conf.*, Vol.2, 1419-32