Dynamics of coastal currents and resilient beaches

Diego Paltrinieri[1,2], Giancarlo Faina[1,3] and Fabrizio B. Armani[1,4]

(1) CoReMa Spiagge srl, San Giovanni in Persiceto (BO), Italy
Tel: +393311053850
Email: catchall@coremaspiagge.it
(2) San Giovanni in Persiceto (BO), Italy
Email: dpaltrinieri@coremaspiagge.it
(3) Montefiore Conca (RN), Italy
Email: gfaina@coremaspiagge.it
(4) Milano, Italy
Email: fbarmani@coremaspiagge.it

Abstract

Worldwide coastal erosion is a topic of increasing impact. Coastal erosion in EU area is becoming a significant environmental, economic and social problem as its effects regard more than 20,000 km of coastline.

Actual coastal protection designs consider the wave actions as the main responsible for coastal erosion. In particular in Italy, on the basis of official national data over the past fifty years, the erosion problem of beaches has lead to a large increase of coastal hard structures as well as nourishment interventions. This fact has essentially caused a correlated increase of the coastal erosion stretches the majority of which always take place in the areas where coastal protection was intended. The search for a radical reconsideration of the coastal erosion issue is straightforward when perusing the historical data mentioned above.

A detailed knowledge of the complex coastal circulation of the bottom current is essential for the adoption of robust solutions to the erosion problems. The differential erosion/deposition maps, coming from more than 25 years of long-term monitoring of the Emilia-Romagna coastline, show the changes in the morphology of the submerged beach with the dynamics of the bottom current that cause them. The regular surveying of bottom current dynamics makes possible to plan interventions to restore beach equilibrium by implementing a monitoring/maintenance system that reflects the natural resilience of the coastal environment. The results of two pilot Italian case studies show that the transportation of sand to the beach is a natural consequence of the constructive action of wave-motion following the regularization of bottom current dynamics. This approach, which invokes a unitary vision of coastal environment, will need for a theoretical in-depth analysis aimed at the development of a new mathematical coastal dynamics modelling.

Introduction

According to literature (USACE, 2002), the movement of sediments along the coast is mainly due to the effect of wave-motion. Such model implies that the movement of sediment is caused by the wave-motion component parallel to the coast.

The direction and quantity of the moved material are determined by the angle between the waves direction and the beach and by their kinetic energy.

On the basis of this general principle, mathematical models have been developed to explain the erosion phenomenon regarding beaches. These models consider the reflexions and refractions of the wave-motion when obstacles are present on the coastline and forecast the effects on the shoreline and the seabed. This principle has inspired still today the planning of interventions aimed towards the reduction of the kinetic energy of waves. In order to do this, breakwaters are usually used in order to reduce the wave-motion or directly contrast the transportation of the sand along the coast with groynes perpendicular to the shoreline.

The protection of the coast with hard structures therefore, had the main goal of contrasting the wave-motion by reducing its kinetic energy.

In general, realization of protection structures have produced counter-productive effects over the medium-long term.

Although the longitudinal transport of sediment along coast is a well-known phenomenon, it lacks of a deep and systemic analysis regarding dynamics and energies involved in shallow water nearshore.

Limitations of mathematical models on coastal hydrodynamics

Nowadays a mathematical (and physical) model taking into account the real morphobatymetric variations due to the coastal bottom current is still missing. In particular, to the best of our knowledge, such a model validation based on long time data set has not be yet treated in literature.

Bascom, 1953; Komar and Inman, 1970; Dean, 1973; Stive and Wind, 1982, analysed the wave radiation stress in the nearshore region establishing a link between the driving longshore current and related sediment transport.

About shoreline evolution and nearshore morphodynamics, Stephenson and Brander (2003) pointed out that synergistic studies incorporating specialized knowledge of field

measurements, laboratory and numerical modelling skills are unfortunately few and they should be further developed.
Large-scale coastal evolution analysed by Schwarzer et al. 2003; Cipriani and Stone, 2001, represents one of the most complex areas of research in coastal geomorphology.
Probabilistic approaches were first applied to coastal research by Vrijling and Meijer (1992), and Reeve and Fleming, (1997) assessed that stochastic modelling in coastal morphodynamics is preferable in respect to a forecast based on dynamics deterministic models.
In recent years, new approaches to coastal hydrodynamics have outlined furtherly the deterministic limits of classical modelling. Amoudry and Souza (2011), underline that numerical models of sediment transport are based on semi-empirical relationships, which are characterized by significant predictive uncertainty. Michaud et al. (2012) suggested to combine a Three-dimensional modelling of wave-induced current with a sediment transport model.
Margvelashvili et al. (2012) underline the importance of observational data because of the high complexity of sediment dynamics and limited understanding of key sediment processes. Radermaker et al. (2017), have highlighted how the presence of complex nearshore sand bar patterns (i.e. alongshore bathymetric variability) has an impact on local currents.
In Italy the last official publication by Environmental and Sea Ministry (Tavolo Nazionale sull'Erosione Costiera, 2016) highlighted that in the last decades many scientific problems concerns coastal hydrodynamics are still open especially regarding numerical solutions for turbulent fluxes. The document, moreover, stressed on the fact that there are too much simplifications due to a big complexity of coastal dynamics also in bi-dimensional models and in laboratory tests. In addition the report claims that the use of three-dimensional models which take into account the deterministic form of all the phenomena involved is unsafe for long time previsions regarding wide coastal application. The main limitations seem to be related to the correct description of turbulence induced by the breaking waves and the mechanism for the transport of the bottom sediment.

Status of the art of eroding coastlines in Italy

Many documents describe the increasing of coastal erosion in Europe (European Commission, 2004; Pranzini and Williams, 2013) and in Italy (De Marchi, 1970; CNR, 1986; ENEA, 2003; Pranzini, 1994; GNRAC, 2006; Tavolo Nazionale sull'Erosione Costiera, 2016; Pranzini, 2017).
In Italy in particular, the intervention procedures and the typology of the work carried out up till now have not solved the problem of erosion which has instead continued to increase despite the hard structures already accomplished.
The degree of artificialization of Italian coasts is one of the highest in Europe as strictly depending on projects realized in an emergency framework, thus highlighting the lack of intervention plans and their functional supervision over time.
Looking at official data about coastal protection in Italy, we have assessed that in the last 50 years, more than 1,300 km of hard structures alongshore have been built. Moreover, despite beach nourishment accounting for more than 35 million of cubic meters of sand,

the coastal erosion length – in the same territorial context - have increased from 600 km to 1,400 km.
Without a deep knowledge and analysis of the hydrodynamic costal context, the project of coastal protection (which up to now has costed to Italy a global sum estimated around 4,5 billion euros) could be useless or even worsen the coastal erosion. Nevertheless, even the strong decrease of the solid transport of the rivers towards the sea can be consider one of the key factors of the persistent erosion of the beaches. However, in the following sections we will give evidence that erosion phenomena are mainly due to the transport of sand along the coast caused by a particular nearshore bottom current.

<u>The waves create beaches and the bottom current transports the sediments</u>

As it is well-known, waves, by moving towards the beaches and breaking, collect the sandy material and carry it towards the shore. Hypothetically, if there were no waves there would be no beaches. After every storm the material with bigger grain size are pushed on the shore, while those with a lesser grain size, being suspended, are carried seawards. The sands of the beaches of the Emili-Romagna coast, for example, are becoming even thinner, in a linear way, as one moves away from the shore for about 1 – 1,5 kilometres. On the other hand, in the seabed at this distance only silts and muds are fund. The Adriatic seabed, with the exception of the coastal strip and of some paleo-beaches, are exclusively formed by silts and muds.
Due to the grain size, any sand movement will deposit at a certain distance from the coast. The twenty-five years monitoring campaign undertaken on the Emilia-Romagna coast seabed by the geologist Giancarlo Faina, has shown the presence of well-located erosive actions that happen parallel to the beach having the geometrical shape of a river route that runs under the coast (Fig. 1).

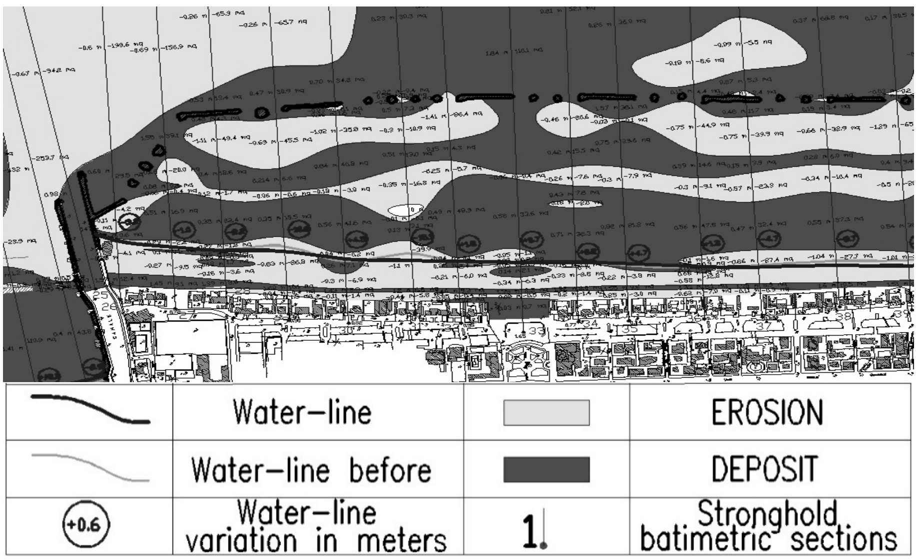

Fig. 1 : Example of an erosion-deposit differential map

The analysis unveiled the presence of a real current (influenced in its direction by the Coriolis law) whose planar components move in the clockwise direction (in the Northern Hemisphere) while its vertical component head towards the seabed.
According to the monitoring performed in long stretches of the Marche and Emilia-Romagna coast, the general circulation of this bottom current seems to develop over an order of magnitude of hundreds of kilometres.
This bottom current is normally located among the submerged dunes and the shoreline.
The presence, on the coast, of obstacles opposing to the main flow of the bottom current (groynes, piers, ports, barriers, etc), modifies the linear development of the current itself, creating local inclinations that skirt such obstacles.
Assuming that the bottom current is the main element that is responsible for the longitudinal solid transport, then a new broad range of studies may be developed.
Many phenomena that are difficult to explain by the effect of waves-erosion only are now easier to understand. With this new hypothesis, the hard structures result to be the cause of inclinations and acceleration of the bottom current and are even responsible for erosion phenomena that can deploy even at great distance from the structure itself.
During the coastal storms, this current acquires a remarkable consistency with an associated speed capable of carrying away the sandy and/or pebbly material determining a dynamic evolution of the morphology of the seabed. The bottom current locate itself in different flow-lines among the shallows. The shape of the seabed and the position of the submerged dunes are decisive for the dynamic balance of the coastal line. It's well known that the submerged dunes get close to the shore during the summer months (Fig.2a) while in the winter months they move towards the sea (Fig 2b).
In the summer season the submerged dunes are closer to shore and the bottom current passes on a minimum hydraulic surface while the winter period, coastal storms increase the speed of the bottom current.

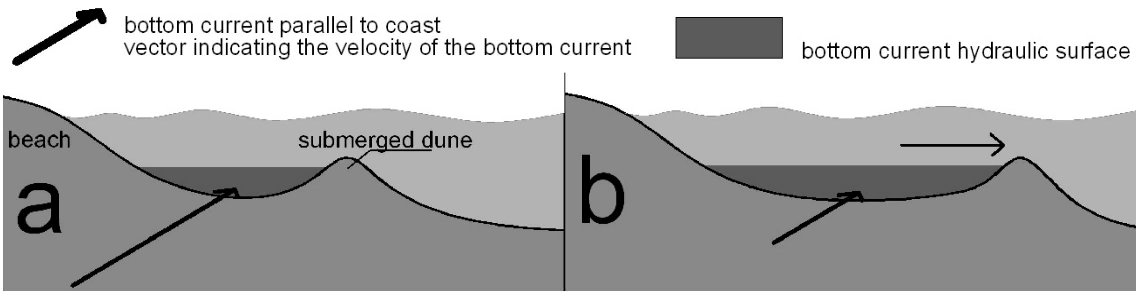

Fig. 2 : Morphodynamic of coastal seabed with the bottom current

Data confirm that during a coastal storm, the seabed current's speed increases remarkably, and consequently the possibility of carrying sands.
The increasing bottom current speed moves the submerged dune seaward producing an enlargement of its hydraulic surface and an increase of transported sediment. Then the slowing down effect of the bottom current causes a decrease in solid seabed transport.
The sea then finds a natural equilibrium through the movement of the seabed responding to the different seasonal energetic balances.
With the construction of any hard structure there is a tendency to remarkably limit such a natural balance transforming the system from dynamic to static.
A static system accepts moderate changes implying that any attempt to increase the width of the beach artificially (e.g. through nourishments) have a great chance of failing as the

true cause of erosion is still acting. On the contrary, if the seabed and the dunes are free to move (dynamic system) they will tend to settle down conforming to the new balance with the greater change of maintaining the new artificial beach (resilient effect).
The shape of breakwaters parallel to the beach (such as those in South Riccione and in Misano Adriatico) led to a decrease of the kinetic energy of the wave-motion. Such breakwaters produce the hardening of the whole system no longer allowing for the natural movement of the shallows when the energetic conditions of the coastal bottom current change.
The anti-erosion barrier turns to be the cause of the erosion itself.
The hard structures planned to stop the wave-motion, regardless of the bottom current, will produce adverse effects of both environmental and economic nature.

Erosion and silting up phenomena produced by the bottom current diverted by a pier

The peers and the hard structures that protrude into the sea modify the hydrodynamic balances creating inclinations of the bottom current and producing erosion and sedimentation. Fig. 3 shows these dynamics: the current that naturally travels parallel to the coastline, when coming against the obstacle (i.e. a pier), it is partially forced to reverse its direction especially during the coastal storms.

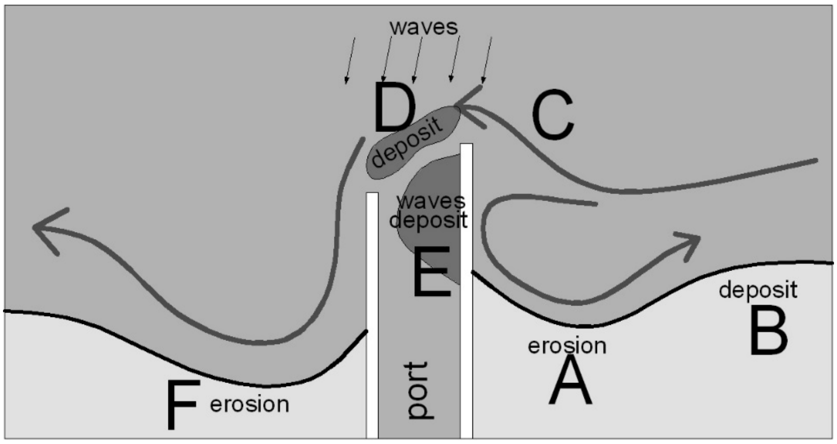

Fig. 3 Dynamics of seabed current around a pier, creates an erosion (point A) due to the local centrifugal force and a sedimentation (point B) as its kinetic energy dies down. The main current turns around the pier moving quickly towards the land producing the erosion (F) before adapting itself. On the top of the pier, the current behaves like a fluvial meander that settles on the inside producing a sedimentation (D). The movement of the waves carries this sediment inside the canal producing silting up (E)

Adverse effects of the sandy nourishments on erosion areas

To recreate and protect the beaches from erosion, nourishment works are often carried out. Nevertheless, without taking into account the background bottom current dynamics, these nourishments do not produce the expected result and may create other erosive spots (Figg. 4,5,6,7).

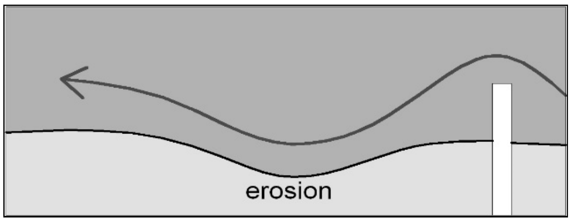

Fig.4 - An erosion area is usually caused by anomaly due to an obstacle (ports, groynes, silting up, etc.) that diverts the bottom current producing an inclination of the same

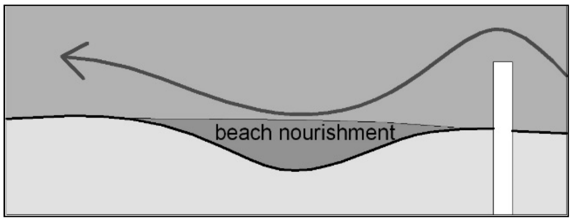

Fig.5 - To restore the usability of the beach, a nourishment is created

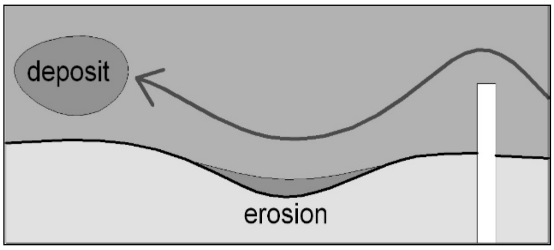

Fig.6 – As no action is taken to mitigate the cause of the erosion - caused by an alteration of the bottom current stream - the sand of the nourishment is collected by the current itself and deposited a bit further away, creating a silting up

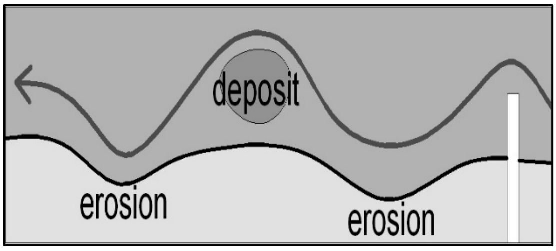

Fig.7 - The silting up does not allow the current to flow freely thus creating a new inclination of the current that then may generates a new erosive area

In order to effectively and permanently contrast the erosion of the beaches, it is important to act first of all on the hydrodynamic balance of the bottom current and then eventually plan for nourishment.

Planning and intervention based on the observation of the bottom current

The case study of Viserba (Rimini, Emilia-Romagna Region - Italy)

An application of the observations herewith described is the intervention carried out in Viserba located in the municipality of Rimini in February 2011.
The area under analysis, after the construction of the marina of Viserba, has underlined different problems: the south area of the marina had a strong erosion allowing the presence of muds in the bathing area within the breakwaters which were built to protect the whole coast of North Rimini.

From the studies that have been carried out with a systematic comparison of the local bathymetry, a coastal bottom current that goes from South-East towards North-West was revealed. Due to the obstruction of the marina and to the silting-up of the seabed close to the breakwaters, the bottom current couldn't flow naturally and was forced to partially reverse its direction creating an erosion on the south side of the marina and a sedimentation of sand even further southwards (Fig.8)

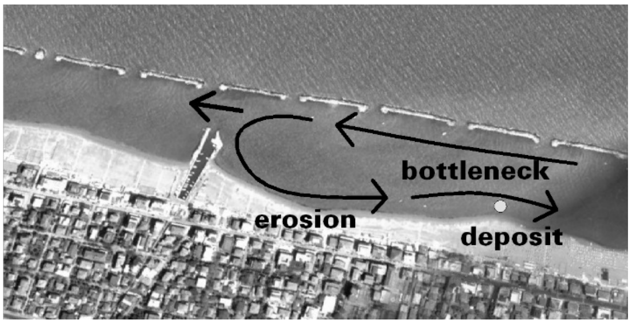

Fig. 8 Viserba beach (Rimini) before the intervention

The current, by reversing its direction and eroding the beach, led also to the creation of submarine canyons on the seabed close to the shoreline. In addition to that, the mud and the suspended fine materials coming from costal storms during the summer season settled inside these hollows making the seabed muddy and thus creating bathing problems.
Starting from these premises, the intervention project envisaged the lowering of the breakwater in the south side of the marina at the medium sea level. (Fig. 9)

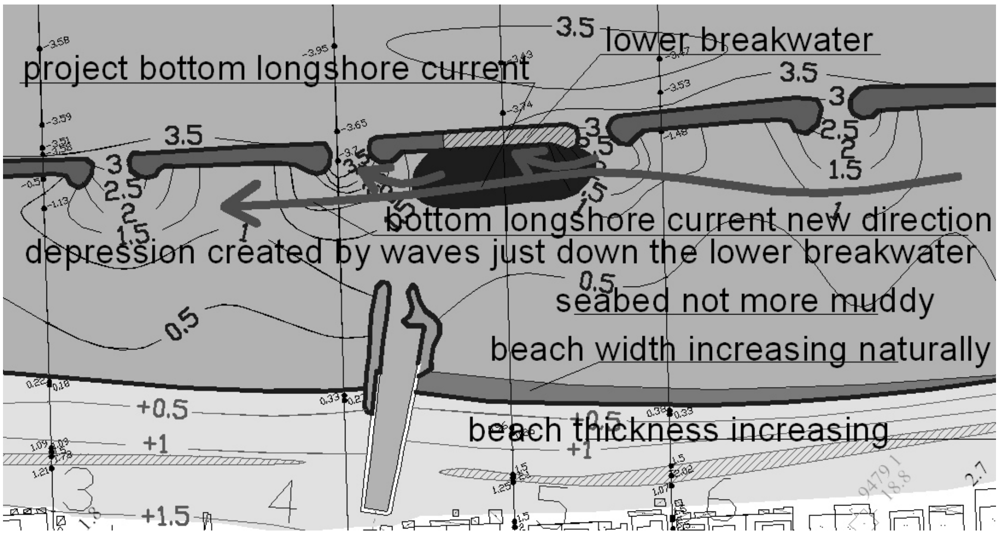

Fig. 9 Viserba beach (Rimini) planning project

The function of this lowering was to make the waves break just behind the breakwater creating an hollow of about -2.00 meters along the opening. This hollow would become the new site of the bottom current that would continue its path without being forced to reverse its direction.

In February 2011, the City Hall of Rimini decided to approve the project concerning the opening of the breakwater.
As soon as the project was carried out, there was an immediate increase of the beach width and after the big coastal storm of March 2011 the beach size increased by about 12 meters decreasing the erosion stride and levelling the shore. (Fig.10)

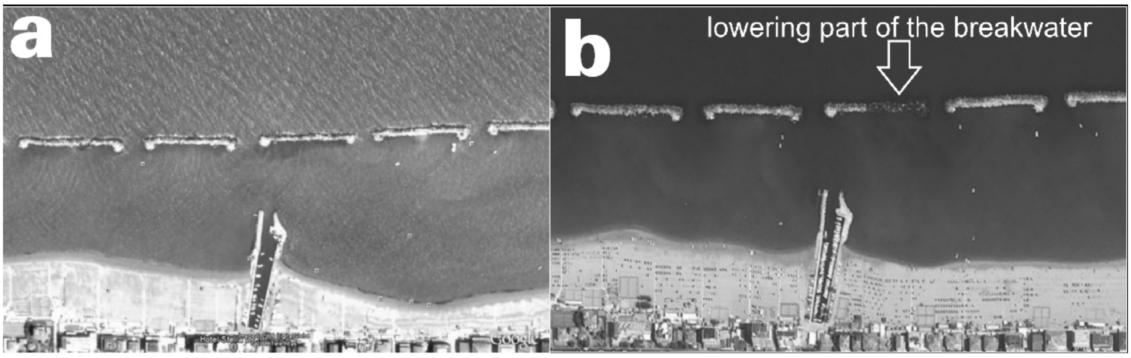

Fig.10 - Satellite pictures of the Viserba beach (before **a** and after **b** the intervention for the lowering breakwater)

Therefore, by opening the breakwater at the medium sea level the following results were achieved:

- A seabed of about -2.00 meters close to the breakwater with the possibility of swimming while before bathing was limited as the seabed was about 40-50 cm;
- As the bottom current does not reverse its direction, there are no submarine canyons on the seabed that is now sandy and hard thus improving bathing conditions. Waves, by carrying sandy material to the ground, have increased both the width and the thickness of the beach;
- A better view on the open sea was created with a remarkable aesthetic improvement of the beach;
- Thanks to the regularized bottom current the water is cleaner.

It’s important to point out that this result was achieved by changing the natural balance of the bottom current without doing any nourishment.
During the summer season of 2011 the shore continued to increase in width by 10 meters more. In the following years the width of the new beach was maintained and no more erosion phenomena took place.

The case study of Valverde (Cesenatico, Emilia-Romagna Region - Italy)

The second case study concerns Valverde of Cesenatico in an area starting from “Bagno Matteo” beach facility for about 350 meters southwards. In the seventies of the past century heavy erosion was formed following the construction of emerged breakwaters parallel to the coast at about 350 meters from the shoreline seawards. This erosion phenomenon was opposed with riprap linings and subsequently with groynes to protect the beach facilities but the erosion process continued.

Nevertheless the riprap linings didn’t block the sand transport and also represented an obstacle to the access to the sea for bathing. In addition the groynes contributed to the formation of strides of erosion (Fig. 11).

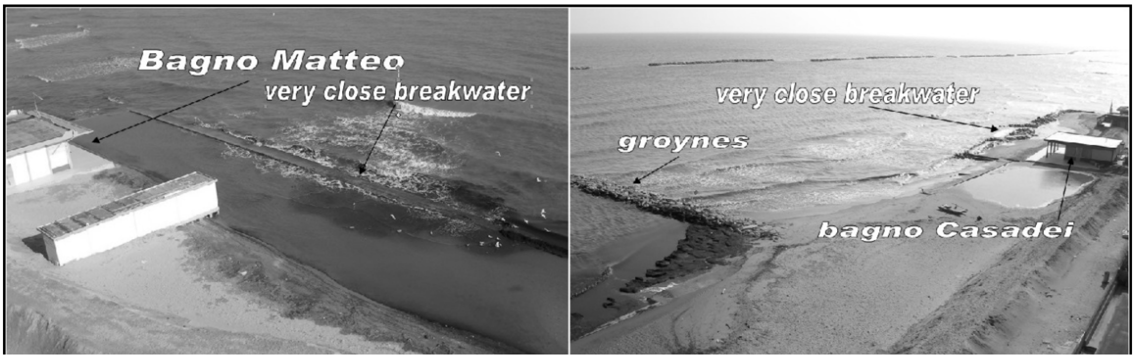

Fig.11 - Pictures before the interventions in Valverde, Cesenatico

In 2010, following the detailed study of coastal bottom current, a solution was proposed. It consisted in the removal of the all riprap linings and of the groynes. Just from the first coastal storm, thanks to the constructive action of the wave-motion, new sand was brought from offshore towards the beach, confirming the hypothesis that many times the hard structures cause and/or increase erosion.

After such intervention a natural beach of about 30 meters was naturally formed in front of “Bagno Matteo”. Moreover, in the locations where the groynes were removed, the beach width increased by 15 meters. The rebalancing of the natural profile of the beach protects still today the beach facilities from coastal storms and it has improved the environmental and aesthetic aspect of the coast. (Fig. 12).

Fig.12 - Pictures after the interventions in Valverde, Cesenatic

Conclusions

The empiric knowledge coming from more than 25 years of morpho-batymetric monitoring of Emilia-Romagna coast has shown the existence of a primary effect of the bottom current flowing near the shoreline. The sand transport and the general direction of such a current in this area is always from south to north regardless of the direction from which waves come. The bottom current could be compared to a "river in the sea" and seems to play a fundamental role in many of the most critical problems characterizing the artificial littoral such as beach erosion and harbours' silting up. A new planning concept for the conservation infrastructures of the coastal environment based on the dynamic of the bottom current and not exclusively to the wave-motion has been introduced.

The interventions that can be carried out by applying this planning method can solve many problems often interrelated to each other: from the silting up of ports to the coastal erosion. The improvement of the bathing waters and the aesthetic of the waterfront are granted as secondary effects of the main issue just cited.

Further studies and modelization of the bottom current need to be carried out in order to develop a theoretical and integrated framework of this branch inside the general coastal dynamics literature.

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