# Innovative Strategies, Monitoring and Analysis of the Coastal Erosion Risk: the STIMARE Project

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## ABSTRACT

Coastal erosion processes are often due to inappropriate coastal defense strategies. The construction of infrastructures that interfere with the coastal circulation and the sediment transport along the coast (piers, docks, etc.), the destruction of the dunes and other anthropogenic modifications to the beach, are some of the factors that limit the adaptability of the beach system and amplify the risk of erosion and flooding of the coastal land.

Coastal defense interventions have historically been based on the construction of rigid works (seawalls, groins, breakwaters, jetties, etc.), which, while protecting the territory, have often shifted the problem of erosion to the neighboring coasts.

The paper will present the contents and the first findings of the research project STIMARE (*Innovative strategies, monitoring and analysis of the coastal erosion risk*), financed by the Italian Ministry of the Environment and the Sea (MATTM), aimed to define strategies for coastal management, based on a strong involvement of the stakeholders, and on the use of innovative or low-costs technologies for coastal monitoring.

Methodology is based on data acquisition, numerical modelling, laboratory tests, physical and ecological monitoring. All the information and results will be discussed with the local stakeholders, in order to provide a comprehensive strategy for coastal protection, following the European Marine Strategy framework. The Project involves researchers from two important Universities in Italy (University of Bologna and Politecnico di Bari) and has a strong interdisciplinary approach, involving coastal engineers, urban planners, geologists, ecologists and mechanical engineers.

KEY WORDS: Innovation, Coastal management, Monitoring, Harbour siltation, Unconventional coastal structures.

## INTRODUCTION

In the coastal erosion processes anthropic activities and inappropriate human interventions frequently alter the littoral dynamics governed by natural factors.

Several factors limit the adaptability of the coastal system and amplify the risk of erosion and flooding of the land. Among them, the following ones can be mentioned: (i) the urbanization and the intensive use of the territory, which cause the stiffening of the coastal areas, (ii) man-made infrastructures (piers, docks etc.) interfering with the natural longshore sediment transport and the drainage basins and (iii) the reduction of sediment supply from drainage basins and the destruction of the dune belt. In the past, coastal defense interventions were commonly realized through the construction of rigid works (e.g., artificial reefs, groins and breakwaters), which, while protecting the territory, have often also shifted the problem of coastal erosion to the nearby littorals, creating a ‘domino’ effect.

In recent years, new observational and monitoring techniques , such as the visible (Archetti, 2009; Archetti et al., 2016; Archetti and Zanuttigh, 2010) and infrared (Archetti and Romagnoli, 2011) cameras, have been developed to investigate the effects on shoreline dynamics in presence of coastal defense works both in the medium term (Archetti and Romagnoli, 2011) and after single storm surges (Archetti, 2009).

Under regional policies of mitigation, coastal erosion processes are now more and more frequently addressed through "soft" approaches, by studying and analyzing defense systems with a lower environmental impact. Among them: (i) nourishment, (ii) innovative systems such as dune protection features, Beach Drainage Systems (BDS), able to reduce beach erosion and promote sediment deposition (e.g. Damiani et al., 2011; Saponieri and Damiani, 2015), and (iii) submerged structures such as WMESH, Reefball, Technoreef, geotube, sandbags etc., designed to reduce some of the impacts (for example by dissipating the wave energy, allowing some rate of crossshore sediment transport, reducing the sand sedimentation while favoring adequate water quality and environmental conditions) or to provide multiple functions (such as the creation of habitat for species of commercial or recreational interest (Dafforn et al 2015, Mayer-Pinto et al 2017).

Monitoring of the emerged and submerged beach is a fundamental step in the analysis of shore dynamics and in the evaluation of the effectiveness of the strategies applied for beach maintenance.

Another aspect that affects the choice of the most suitable strategies for protecting coastal areas concerns the risk assessment. It is necessary to address the limited resources available to contrast erosion in the most vulnerable areas, and to define optimal strategies able to limit the loss of value of the coasts and to increase coastal resilience towards extreme sea weather conditions.


Fig. 1: Location of the study sites.

## The study sites

Three case studies are chosen on the coast of the Adriatic Sea, in the Mediterranean Sea in Italy. Their location is presented in Fig. 1. Two of the study cases are in the Emilia Romagna region, Cervia and Riccione (North Italy), and the third, Margherita di Savoia, in the Apulia region (South Italy). The selection was driven by the occurrence of unconventional solutions in place and/or by the strong interest that the coastal management plays for the local economy.

The first is the town of Riccione, whose littoral system is affected by strong sediment transport and erosive processes despite the frequent nourishment interventions made from the Regione Emilia Romagna, yielding the local administrators to study several solutions in order to mitigate the coastal erosion.

The net sediment transport in this coastal tract is directed South to North. A wave buoy working few kilometers North (managed by ARPAE) allows operative measurements offshore, and a spectral model for the wave propagation has been implemented in order to obtain the wave conditions at a very high spatial resolution and detect the occurrence of storm surges in the study site. Furthermore, two tide gauges located not far from this coastal site perform continuous measurements of the sea level.

Local authorities are carrying out experiments in order to counteract coastal erosion through the realization of non-conventional structures. A five-hundred-meter coastline has been protected with barriers made by sandbags, while reef-balls modules have been installed in a fifty-meter-long stretch of coast and three WMESH modules have been installed 200 m far from the shoreline. The design of these non-conventional works is experimental and has multiple objectives. They are thought to reduce the environmental impacts on sedimentary habitats (Heery et al 2017), to reduce the transmitted wave energy in order to limit the sediment transport offshore and to reduce the turbidity on the back of the barriers in order to maintain an adequate water quality for bathing. The monitoring of the stability and the evolution of the shoreline in presence of the different experimental structures installed, will allow to compare their response after storm surge events. The occurrence at Riccione of unconventional coastal defence methodologies and the interest in cooperating with research institutes, the local Municipality and stakeholders, made this site a prefect study site for the STIMARE project.

The second site is the harbour located in the town of Cervia (Fig. 1), whose littoral system is involved in a prevailing sediment transport from North to South.

The realization of a tourist Port in the ‘70s modifies the natural sediment transport, resulting in harbor siltation and southern beach erosion. In 2009 the docks have been lengthened, but with negligible effects. An innovative plant for sediment undersea transport is under realization at the harbour entrance. The technology has been already tested in the past in two experimental plants, located in Riccione (Amati and Saccani, 2005, see Fig. 2) and Portoverde (Bianchini et al., 2014; Pellegrini and Saccani, 2017) harbours. The main element of the plant, called “ejector”, is an open jet pump (i.e. without closed suction chamber and mixing throat) with a converging section instead of a diffuser. The ejector is installed on the seabed and once, fed with pressurized water, it transfers momentum from a high speed primary jet flow to a secondary flow. The primary jet flow contacts the suction fluid at the nozzle exit and drags it into the sea bottom, thus starting up and sustaining the secondary flow of suction fluid from surrounding water mass. If present, solid particles are entrained in the secondary flow, where jet stream and suction fluid are further mixed, exchanging momentum and recovering pressure. The water-sediment slurry then passes through a converging section and into a discharge pipe for delivery to a discharge point. The water for ejectors feeding is pumped from a pumping station placed near the ejectors installation area. The plant works 24 hours a day, 7 days a week, and by ejectors integration in series and in parallel it is possible to create and maintain over the time a seaway. The technology showed to be effective and robust, but a long term operation is required to fully evaluate the economic and environmental sustainability. Cervia installation represents the first demo installation and once in operation will be continuously and remotely monitored to evaluate energy consumptions, effect on the seabed, impact on marine flora and fauna, impact on underwater noise. The realization of the plant is financed by the LIFE MARINAPLAN PLUS project, which involves Trevi SpA (project lead), University of Bologna, Municipality of Cervia and ICOMIA. The project STIMARE will support further monitoring activities to evaluate siltation and erosion phenomenon near the harbor and will measure if the demo plant may have a positive impact on southern beach erosion mitigation.

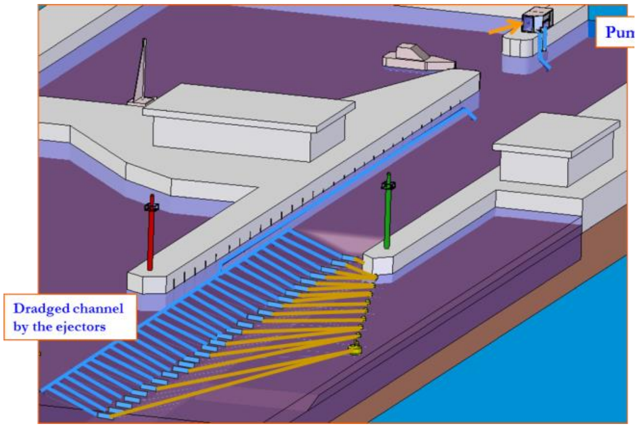


Fig. 2 Sketch of the ejectors system (Riccione)

The third site is located along the sandy beach stretching between the towns of Margherita di Savoia and Zapponeta in the Southern Adriatic Italian coast in Apulia Region.
In this site, the coastal evolution trend, since the mid-20th century, has been heavily influenced by the construction of the port of Margherita di Savoia. Over the following years, a severe shoreline regression has been observed downdrift of the harbor breakwaters and the hard coastal protection structures built in that area have failed to resolve the erosion problem.
In addition to coastal erosion issues, coastal area situation is often exacerbated by flooding hazard affecting also some inland areas. Due to the presence of low-lying and depressed areas, seawater invasion occurs also during ordinary storms (Bruno et al., 2014; Pasquali et al., 2019). Furthermore, sea storms are often associated with significant meteoric events, so, floods are worsened by river overflow.

At the three study sites the methods and activities described below are applied.

## Methodology

The Project will support a wide range of methods (Fig. 3) in order to achieve its goals.

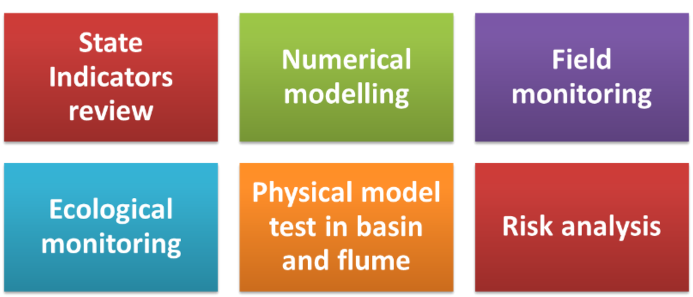


Fig. 3: Integrated methodologies applied in the STIPARE Project.

First, *the review of the relevant indicators* of the littoral state (so called Coastal State Indicators, CSI (Kroon et al., 2007, Davidson et al., 2007) will allow the evaluation of the impact of the coastal defense works, especially in conjunction with storm surges. The Italian "*National guidelines on the coastal defense from erosion and climate change effects*" report of the National Table on Coastal Erosion (TNEC) suggests the monitoring of some specific indicators: the rate of change of the shoreline, the beach width, the slope, the elevation of the beach and the volumetric variation of the sediments. Besides them, other indicators will be monitored before, during and after the storm surges: (i) the maximum wave run-up, (ii) the currents developed near the coastal defense works, (iii) the berm morphology. Additional sampling of sessile (iv) and mobile biota (v) will allow to compare the performance of the new structures relative to traditional rocky breakwaters and mainstream this ecological understanding into decision-making.

The effects of coastal risk depend not only on the nature of hazard and exposure but also on the management. Planning and management activities require both awareness of physical phenomena and participation of decision makers and local communities. The coastal risk, in fact, is usually ambiguously perceived: shoreline regression immediately influences the public risk perception, causing alarm amongst population and institutions but coastal protection structures face opposition in coastal communities.
For this reason, it would be useful a people-centered information system focused on reaching local communities risk perceptions, in order to develop a so-called "participatory monitoring" aimed to use stakeholders' and local communities' experience, integrated with scientific knowledge, in developing models able to support environmental phenomena analysis and define a priority scale.
The communities' risk perception will be considered by the treating of questionnaires and interviews administered to stakeholders, aiming at assessing the perception of both policy makers and tourists on coastal territory. Results of classical risk and perception risk analyses will be compared trying to evaluate the effects of people experience on coastal risk management.

The activities of the Project also include the implementation and validation of a *numerical approach to study* the three sites identified in the presence of the coastal defense works, assuming several possible scenarios. For each site, sea conditions (i.e. the wave climate), storm surges and the climate change scenarios will be analysed based on the available data and on the most updated IPCC (2018) report. The efficiency of multipurpose coastal structures aiming to increase flood mitigation and coastal defence of the area will be investigated following the approaches presented in Archetti and Gaeta (2018) and Gaeta et al. (2018), with the implementation of coupled wave-hydrodynamics models at coastal (high) resolution, in order to simulate waves, currents, water levels and sediment transport and to estimate the morphological shoreline evolution. Current configuration of the area and alternative defence schemes to improve coastal protection will be simulated and results will be given in terms of wave load, inundation rate and bed level change. The comparative numerical analysis under the different scenarios and configurations will be a useful tool in estimating the optimal coastal protection scheme both in terms of flooding mitigation and erosion reduction.
By means of a numerical approach based on multiple nested modeling approaches as the one implemented and validated in Gaeta et al. (2016), prediction of sea conditions at very high resolution, i.e. coastal scale of meters, offshore the defence structures in Riccione and the harbor mouth in Cervia will support the investigation of the performance of the new installation, in relation to sea and environmental conditions.
Modelling will be performed with the commercial suite MIKE21, with the use of modules Sea wave (SW), Hydrodynamics (HD) and the shoreline modeling (SM), in order to simulate the presence of the unconventional structures. The transmission coefficient of the structures, which is an important parameter in the modeling input, is taken by results of previous test in laboratory and by results of CFD simulations.
In order to investigate the stability of one single module, and the transmission coefficient, CFD simulations were performed, solving validated RANS equations (Antonini et al., 2016).

The computational results were elaborated in order to estimate forces acting on the structures induced by the waves and hydrodynamic field in presence of the structures. An example of the velocity around the WMesh structure under the most extreme condition is presented in Fig. 4.

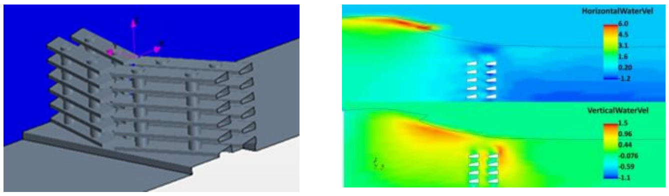


Fig. 4 3D sketch of one WMESH module as modeled and Velocity field around WMESH under the extreme simulated wave attack.

One of the key aspects in the STIMARE's project will be the integrated use and development of coastal monitoring techniques. We will perform a topo-bathymetric monitoring of both emerged and submerged beach using traditional topographic survey techniques by means of a differential GNSS (Global Navigation Satellite System) station and high-resolution multi-beam bathymetric surveys in front of the coastal protection structures. We will compare the overall results of the topo-bathymetric surveys (which will constitute the topographic inputs for numerical models) with data obtained with other monitoring approaches. We will survey the shoreline by applying traditional methods (following the indications of the Italian TNEC), and through the application of new methods such as thermal imaging cameras. The low altitude photogrammetric surveys (UAV) for the reconstruction of the coastal morphology (shoreline and beach sediment area and volume) will also allow the evaluation of the sediment shifts during different seasonal wave climate and in response to high energy events, i.e. strong storm surges. We will also use UAVs both for a periodic monitoring and to take video and photo shootings in case of extreme events, in order to ascertain the real-time response of the coastal protection systems. We will also use TLS (Terrestrial Laser Scanning) surveys on coastal sites affected by the interventions in order to create a 3D reference model, and to cross check surveys realized with other techniques. One of the goals of this project is to use low-cost survey methodologies that non-expert technical staff could perform. Several encouraging results have already been obtained in the past (Mancini et al., 2013) and the objective now is to obtain similar precisions using commercial low-cost UAVs. Furthermore, we will use TLS surveys as a verification method, being this technology is considered as a reference method. Taking benefit from previous experiences, we will pay attention to the correlation between the topographic and bathymetric surveys in order to eliminate any possible errors related to the use of the different methodologies. Giambastiani et al., 2016, Scarelli et al., 2017).

In the sites where the sand bags and the WMESH modules are installed, a high-resolution georadar will verify the integrity and the position of the structures during the monitoring period, in order to evaluate if high-energy events would affect the original installation.
The Project includes also the monitoring of the stability and the evolution of the shoreline in the two coastlines where WMESH and sand bags are installed, in order to compare their response during storm surges.

At the sites video-monitoring stations will be installed. with low-cost instruments technology (Raspberry-Pi), which has never been used before for this purpose. At the site of Margherita di Savoia, fully-automated video stations will be installed with the support of low-cost microserver. Video-monitoring will allow the continuous survey of the shoreline and the wave run-up. These indicators will be analyzed in order to evaluate the impact of the single storm surges and compared with the physical parameters of the beach. The SDM for the shoreline extraction developed in Valentini et al. (2017) will be implemented and modified according to specific site characteristics. The tool is composed by specific routines, addressed at the images processing (e.g. shoreline extraction and geo-rectification) and data analysis, inspired by the global Probability of Boundary (gPb) concept and the seed-based segmentation. Results and main analyses will be shared in quasi-real time with a web-application.

The monitoring of the ecological status will be conducted. The aim is to evaluate the effects of novel designs of coastal defense interventions on the composition and structure of their associated assemblages of flora and fauna, estimate whether these effects differ from those of other traditional hard engineering used in the region (Bacchiocchi and Airoldi 2003) and ultimately evaluate the possible consequences in terms of ecosystem functionality and provisioning of ecosystem services (Mayer Pinto et al 2018). A precise monitoring of the ecosystems evolution will be also performed in order to evaluate the possible alteration of their functionality due to the presence of the coastal defense works (Dafforn et al., 2015). The monitoring of the quality of the marine ecosystems will be set in the initial stage of the Project, in order to identify possible alterations according to the type of interventions planned and to prepare and adequate experimental design for the quantification of the ecological characteristics of the ecosystems. The benthic population will be analyzed for the assessment of the environmental quality. For the non-conventional interventions (sand bags, "sand-duct" and ejectors), the components of the sandy-bottom populations will be taken into consideration. For the installation of the WMESH modules, the structure of the populations settled on the structure will be also analyzed in order to evaluate the composition and the biomass. The monitoring of the populations will be adequately replicated over space and time. It is important to note that artificial structures differ vastly from original ecosystems (Airoldi et al 2005), so efforts to quantify their ecological outcomes must adopt an 'objectives-based' strategy, focusing on achieving the desired ecological, social and economic targets (Mayer-Pinto et al 2017). In this specific case, due to the highly tourist economy of the study regions, the expected objectives include the maintenance of ecological services provided by marine systems such as food production, and recreation, therefore information will be collected on functioning of the system that underpin those services (e.g. abundance of macroalgae, filter feeders and fish populations). Data will be analysed using univariate and multivariate statistical methods to compare the performance of the new designs with that of other traditional structures

The partners have a wide and consolidated experience on physical models and agree with the need to couple small scale laboratory tests with fields monitoring and numerical modelling (Sancho et al., 2001). *An experimental study* is being conducted on a two-dimensional physical model at the LIC laboratory of the Polytechnic of Bari, in order to evaluate the efficiency of a BDS integrated with other coastal defense structures. At present, several BDS trials have been carried out both in the field and in the laboratory, showing a limited efficiency of this technique. The limits of the BDS are certainly due to an incomplete knowledge of the design parameters that determine its best functioning. On the other hand, the studies conducted on the BDS so far suggest its use in conjunction with other coastal protection interventions. For instance, in the presence of submerged barriers filtering the most energetic waves propagating towards the shoreline, the BDS could be more effective in stabilizing sediments transported to the shore, mitigating the loss of sediments. The effects of a submerged sill on BDS efficiency is being investigated on a small-scale physical model at the laboratory of Coastal Engineering of Politecnico di Bari (Bari, Italy) (Fig. 5). The mixed system is tested under wave erosive conditions in order to study the effects on both hydrodynamics and moprhodynamics in different beach configurations (Saponieri et al., 2018).

Fig. 5 The small scale 2D-physical model at the Coastal Engineering Laboratory of Politecnico di Bari, Italy. Upper panel: submerged sill, Bottom panel: the drainage system.

Another option could be the use of the BDS with the aim of increasing the “lifetime” of artificial nourishments. In the case of new sediments inputs, as in the site of Margherita di Savoia, the implementation of a BDS should help to understand the potentialities of such systems in improving economical sustainability of the nourishment. The main aim is to investigate the capability of the drainage system in increasing sediments stability and, consequently, make the beach erosion slowly, in order to reduce the periodic refilling, without affecting the environmental sustainability of the intervention.

*Risk analysis*. The overall data, information and results obtained during the Project will allow to formulate relations between the forcing (storm surges energy, duration, sea water level) and the effects of the impacts of the littoral structures already defined as indicators. In particular, the approaches suggested by previous literature (Mayer-Pinto et al., 2017; Archetti et al., 2016) will be followed. The analysis aims to quantify the impact of the coastal defense interventions and to compare the different methods adopted for the coastal protection.

**Discussions and conclusions**

The project STIMARE presented here foresees three main research lines, by involving both laboratory experiments and field activities on 3 study sites, characterized by the presence of innovative interventions. The research is intended to increase sandy beaches resilience against erosion and flooding by means of alternative and innovative works without affecting coastal environment.

In order to address these issues, a preliminary risk assessment is needed in order to quantify the risk index at regional scale, for which both physical indicators and experiential learning variables will be considered.

The coastal dynamics will be analyzed in the 3 study sites in the presence and absence of the innovative works (WMESH, sandbags, BDS, ejectors), through in situ surveys, numerical and physical modeling. This will allow to evaluate the effectiveness of the interventions and promote management strategies.

The monitoring of such interventions will play a relevant role in the project, since it will give the possibility of testing different approaches (e.g. video cameras, UAV, SAR) and procedures to extract main indicators for morphodynamics and hydrodynamics investigation and risk assessment, with the aim of seeking the right balance between the quality of the result and costs.

Moreover, the project involves a continuous dialogue and involvement of local stakeholders interested in coastal area management and defense, in order to provide a comprehensive strategy for coastal protection, following the European Marine Strategy framework.

The STIMARE Projects is indeed very ambitious, with the following objectives synthetized:

- Definition of the intervention’s strategies for the coastal management, in order to mitigate the erosion and to enhance the sustainable use of the territory.
- Monitoring of the indicators at the three study sites where different coastal protection systems are installed, in order to verify their effectiveness and to define survey techniques that are easily repeatable and effective.
- Improvement of the knowledge of innovative and low impact intervention methodologies (BDS, barriers in sand bags, WMESH) in conjunction with traditional coastal defense works.
- Validation of the ejectors system for the remodeling of the seabed,

as an instrument integrated with the existing costal defense structures against coastal erosion.
- Verification of the feasibility of coastal protection interventions combining multiple BDS and submerged breakwaters.
- Development of easy-to-use and low-cost methodologies and tools for coastal erosion monitoring, in order to promote the creation of a "Coastal Observatory".
- Industrialization of techniques for a continuous monitoring of the beach: low-cost video stations, surveys with thermal camera, with drones, with infrared camera for low visibility conditions.
- Optimization of works to reduce the impact on coastal ecosystems and preserve environmental quality and ecosystem functionality as indicated by the Marine Strategy Directive.

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