

## MODEL TESTS FOR EVALUATING BEACH NOURISHMENT PERFORMANCE

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### Abstract

After having shortly discussed about the nourishment fundamentals, focussing the attention on the benefits and on the factors promoting the beach fills, some specific questions on fill design, on related processes and on the temporal aspects of such beach-protecting intervention were addressed and tentatively answered.

In the second part, the physical-model tool, as a way for answering to the suggested questions is presented and three different case studies are discussed.

### Introduction

In the last decades the use in coastal protection of soft intervention schemes such as beach nourishment has largely substituted the use of “hard” intervention approaches like seawalls and groins, because of economic reasons and mostly because of the lower impact on coastal resources and activities.

Nowadays the first task of a project manager is the quantification of the on-going beach erosion phenomenon. This involves the identification of the relevant morphological processes and the consideration of the aspects related to local interests such as safety, recreation, environment and economy.

Once the problem has been defined, the protective measures must be carefully

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selected. The increasing need of solutions at low environmental impact suggests the choice of soft intervention schemes, which may be integrated with some supporting hard structure. However, "soft" projects need some additional experience in order to derive consistent evaluation criteria for technical problems, economic matters and public policy issues. A beach nourishment project, in fact, includes design considerations on the following aspects: frequency and duration of the fills, pre- and post-fill erosion rates, post-fill profile equilibrium, project length, volumetric requirements, grain size compatibility, protective dunes, long-term sand resources, placement location, "hybrid" projects and downdrift impacts. Because of its relatively short design life, a beach nourishment project needs to be periodically refinanced for maintenance, rehabilitation and environmental permitting.

The first part of this work deals with the choice of the "most suitable" solution. A general framework for comparing the possible solutions is presented in terms of morphological impact and economic aspects that define a number of "objective evaluation criteria".

The determination of the design life is important because it gives the designer the chance of a long term management of the interventions. The long-term evaluation of beach nourishment performance can be obtained by means of numerical or physical modelling. We focus here on the physical modelling approach, which will be proven to be valuable when mutually interacting physical processes are to be taken into account.

The second part of the paper presents the results of three sets of model tests, performed referring to different beach nourishment projects in Italy.

#### Basic considerations on beach nourishment

For a number of reasons, not lastly historical and legislative, the coastal zone was seen as a "low cost" resource. The adoption of hard engineering practices, heavily based on concrete and steel structures, results in a completely artificial set of forcing factors and boundary conditions, further exacerbating the problem. This has led to the present tendency of developing "soft defence techniques" as a tool to be used in Integrated Coastal Zone Management (ICZM). Among these techniques, periodic artificial nourishment is widely regarded today as an environmentally acceptable method of beach and dune protection and restoration for short-term urgencies (viz. storm-induced erosion) as well as long-term issues (i.e. structural erosion and relative sea-level rise).

Beach nourishment or fill can generally be defined as the artificial addition of suitable (in terms of beach quality) sediment to a coastal area that has a sediment deficiency in order to rebuild and maintain that beach at a certain width and height which provides storm protection and/or a recreation area (CBNP, 1995; Delft Hydraulics, 1987). This definition encompasses restoration (an initial and major sediment contribution to widen the beach) and periodic renourishment (an additional, usually smaller, sediment contribution necessary for the preservation of project integrity). Frequently, nourishment projects include an artificial dune for additional protection against storm surge and waves.

The most important benefits of beach nourishment can be summarised as follows:

- reduction of erosion and flood damage;

- resetting of the long-term erosion trend;
- enhance of recreation and tourism;
- spreading of cost outlays over time;
- reduction of downdrift impact of coastal protections;
- increasing of sand budget for global coastal stability;
- project reversibility.

For these reasons, over the past several decades the beach nourishment has become a preferred coastal hazards management tool. In the future, this reliance is expected to increase mainly for the following reasons:

- increasing of coastal populations
- increasing use of beach for recreational purposes
- increasing public awareness of coastal hazards
- increasing concern about the impact of hard structures.

### Technical issues in beach nourishment planning

The technical issues in nourishment planning have been in depth analysed in a previous paper of the authors (Ruol et al, 1997; Capobianco and Stive, 1997) which discusses the beach fill management, focussing on the requirements of fill-design, the correct definition of active processes and the planning of a beach-fill timing strategy. For the benefit of the further discussion, some results are summarised in tables 1-3.

TOPICS	SPECIFIC QUESTIONS ON FILL DESIGN
<i>Design of beach fill</i>	will the expected erosion phenomena be related to longshore transport, cross-shore transport or both?
<i>Shape of planform</i>	what will be the optimal shape of the nourished beach?
<i>Along-shore position</i>	what will be the best technique for placing sand into the beach? <ul style="list-style-type: none"> <li>• direct placement;</li> <li>• stock-piling;</li> <li>• continuous nourishment</li> </ul>
<i>Volumetric requirements</i>	what is the depth of closure and the post-placement profile?
<i>Project length</i>	Is there a minimum project length longshore? Will hard structures be necessary to protect the toe or the ends of the nourished beach?

Table 1

TOPICS	SPECIFIC QUESTIONS ON PROCESSES
<i>Determination of erosion rates</i>	How should future erosion rates be estimated?
<i>Grain size compatibility</i>	What will be the best choice for the grain size of the nourishing material?
<i>Areas downdrift of projects</i>	Should the downdrift benefit (if any) be considered while designing a beach fill?

Table 2

TOPICS	SPECIFIC QUESTIONS ON TEMPORAL ASPECTS
<i>Design life</i>	What is an appropriate (minimum/maximum) design life for a project?
<i>Design frequency</i>	Should design frequency be quantified? Should design imply a coupled analyses of storm probability and erosion processes?
<i>Periodic maintenance requirements</i>	Should design include a time schedule to optimise periodic nourishment cycles, with regard to beach requirements? Should a flexible approach be adopted?
<i>Vulnerability</i>	Should the designer carry out an analysis of risks, with regard maintenance schedule? Should alternative solutions for coastal protection be adopted?
<i>Post-fill profile equilibration</i>	When should projects be accredited (after fill placement or after fill equilibration)?

Table 3

### Physical model tests as a tool for beach nourishment behaviour evaluation

Physical model tests represent a technique to answer to those questions in tables 1 to 3. This technique is used most appropriately when a decision problem under analysis is too complex to be solved by analytical models. Simulation through physical models is a quantitative procedure that describes morphodynamics process by constructing a model and then observing how the model behaves in order to learn how the process itself might behave. As a general rule, physical simulation should be used only as a last resort and never as the first option. There may be theory or analytical techniques available to solve a problem. When there are, they should be used.

We should also not forget that "communication and involvement" increasingly play a fundamental role in environmental protection activities in general and nourishment interventions in particular. The adoption of physical model tests have a strong potential also because can be immediately understood (even if only partially) by a large audience. The advantages of physical model tests are:

- The effect of interaction between the different forcing agents can be taken into account;
- complex boundaries can be reproduced;
- wave conditions vary continuously according to seabed modifications;
- up to now, other modelling techniques are not as useful as physical models in morphological analysis where cross-shore and longshore sediment transport together must be taken into account,

while the limits of physical model tests are:

- they are expensive and time consuming;
- the analysis of different situations or the repetition of tests often implies a new setup of the model;
- scale effects are not always assessable.

As a general approach, fixed bed models are suitable for the study of:

- wave propagation;
- sediment transport patterns (particle tracks);
- armour stability;
- forces on structures,

while movable bed models are suitable for the study of:

- planform beach evolution;
- longshore sediment transport;
- beach profile evolution;
- cross-shore sediment transport;
- scour.

Where physical models are probably giving signs of their limits is in the context of long-term and large scale modelling. Such limitation is however still largely compensated by their intrinsic ability to handle complex situations.

In many practical situations, while waiting for the latest developments in the field of morphological modelling and particularly long term morphological modelling, the contribution that physical model tests can give is still of paramount importance, being implicitly integrative of all the (scaled and complex) processes that determine the evolution of the nourishment interventions. In particular they can when the validity of numerical models is limited by large uncertainty in the relevant input parameters which propagates to the model output.

### Case studies

The following paragraphs describe how physical model tests have been applied for evaluating the performance of three beach nourishment projects.

The general purpose of physical modelling was to assess if the planned interventions were able to protect the infrastructures located on and behind the beaches and if the beach fill maintenance cost was acceptable.

The projects hereafter presented (fig.1) deal with two protected beach nourishments located close to Rome (Ostia) and in Northern Sicily (Capo d'Orlando), and with a "self nourishment" induced by a coastal protection intervention located in the Po river delta (Barbamarco).

### Beach nourishment at Capo d'Orlando (Sicily)

The first application of physical modelling is a protected beach nourishment designed for a 1200 m long beach located close to Capo d'Orlando and facing the Southern Tyrrhenian Sea.

The project area is today characterised by an increasing beach erosion caused by an unbalanced longshore sediment transport condition. This erosion is exposing the street and the buildings to the wave attacks; the picture in fig. 2 shows the present condition of the village and underlines the need of a quick intervention.

The design requirements for this project were mainly:

- safety of infrastructures behind the beach;
- availability of a larger beach area for recreational activities.



Figure 1. Project sites.



Figure 2. Capo d'Orlando beach.

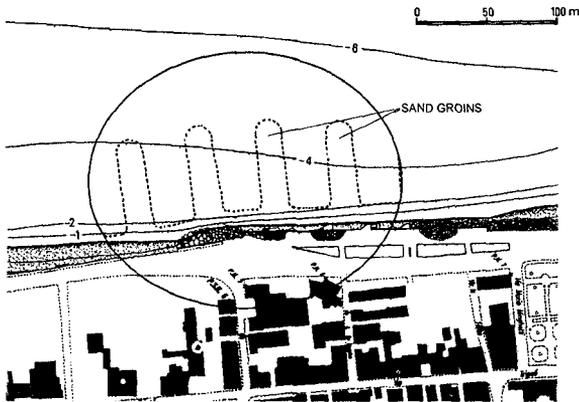


Figure 3. Beach fill technique at Capo d'Orlando

The design solution of the 1200 meters long protected beach nourishment prescribes a sand fill of about  $205 \text{ m}^3/\text{m}$  of sand operated by means of building 39 sand groins (fig. 3) followed by the placement of 6 quarry groins spaced about 200m.

The general interest was to evaluate whether the designed project was suitable to protect the urban area behind the beach and if the beach fill technique (sand groynes) was really effective. These questions have been answered using mobile bed physical models: a number of tests have been planned to study the two- and three-dimensional sand transport phenomena occurring on the beach.

The models have been designed according to the Froude criterion, whereas the bed material has been scaled according to the Dean criterion (in the model and in the prototype a constant ratio between the wave height and the fall velocity times the wave period has been imposed).

The specific questions on the beach fill design for Capo d'Orlando project can be summarised as follows:

- which short term evolution of the Capo d'Orlando littoral without any additional beach protection is expected?
- is it the beach fill technique effective?
- does the designed construction sequence optimise the effectiveness of the beach fill?
- is it possible to define a construction schedule that does not interfere with the tourist activities?

The physical modelling program designed for the study of Capo d'Orlando beach erosion phenomena included:

- 2D model 1:25 (cross-shore profile)
- 3D model 1:25 (representative cell reproducing the beach delimited by two rubble mound groynes)
- 3D model 1:60 (whole project area);

The waves used for modelling the local climate have been selected from local wave hind-

casting by the UKMO (United Kingdom Meteorological Office). In particular, the waves to be reproduced in the 3D models were obtained respecting the energy flux criterion.

The study of the cross-shore profile (2D-model) started with the simulation of beach evolution from the present condition; the results clearly demonstrated that the surveyed profile are indeed in critical condition and can not be maintained without adding new sediments. The nourished profile and the erosion rate related to cross-shore sand transport have been studied through the simulation of the two nourishment phases planned in the project.

The first phase of the nourishment consisted in building-up a first series of sand groynes and in placing a certain amount of sand directly on the beach (fig. 4).

A three-month long (all time data are referred to prototype units) wave attack (simulating an average wave climate) has been simulated on this artificial beach and a first nourished profile has been obtained; in the second phase, again sand groynes have been built on the new cross-shore profile and a second 3 months long wave attack has been simulated.

In order to compare the final condition (fig. 5) with the surveyed starting profile (summer profile), a new 1.5 months long mild wave attack has been performed to simulate the summer wave conditions. The summer profile obtained after this test is shown in figure 6.

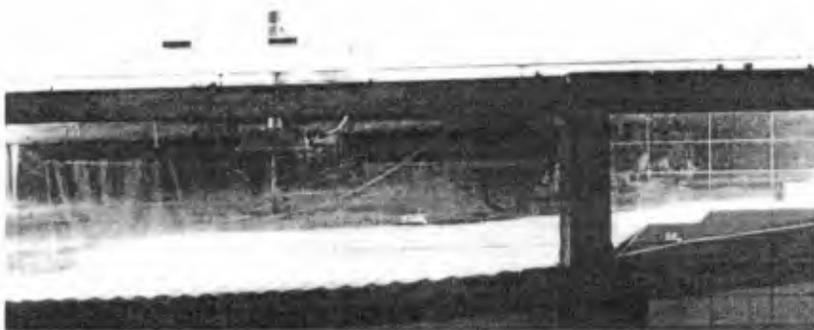


Figure 4. Beach nourishment 2D – Phase 1(sand groynes and beach fill)



Figure 5. Beach profile after beach nourishment and wave attacks

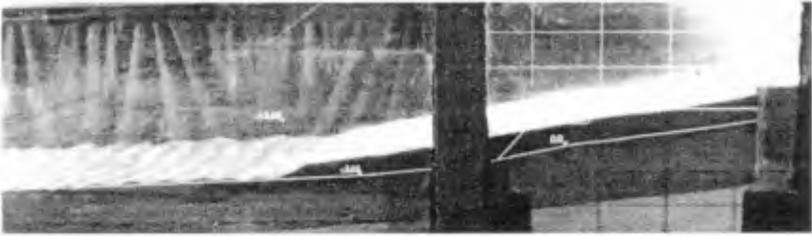


Figure 6. Final beach profile (summer profile)

The results of the 2D modelling can be summarised as follows:

- beach profile is indeed in critical condition: after having simulated 1.5 months of waves, the retreat of the shoreline (cross-shore transport) was about 8 m;
- after the nourishment a quasi-equilibrium profile was reached, with the shoreline moved about 12 m seaward;
- since the existing profile is far from an equilibrium condition, most of the sand supplied from the sand groins moved offshore, without significant contribution to shoreline advance.

Both the 3D models (the “cell-model”, scaled 1:25 and the global one scaled 1:60) followed the wave schedule already used for the 2D model; the longshore energy flux has been analysed in order to obtain a set of 4 wave spectra reproducing the existing sand transport conditions. Figure 7 shows the experimental layout for the 3D “cell model”.

In figg. 8 and 9 the final results obtained after the construction of the quarry groins built up after the reshaping of the beach operated by the wave attacks.

The results of the 3D-models can be summarised as follows:

- the three-month long simulation from the present condition (without additional protections) shows that the shoreline position reaches the seawall, endangering houses and infrastructures;

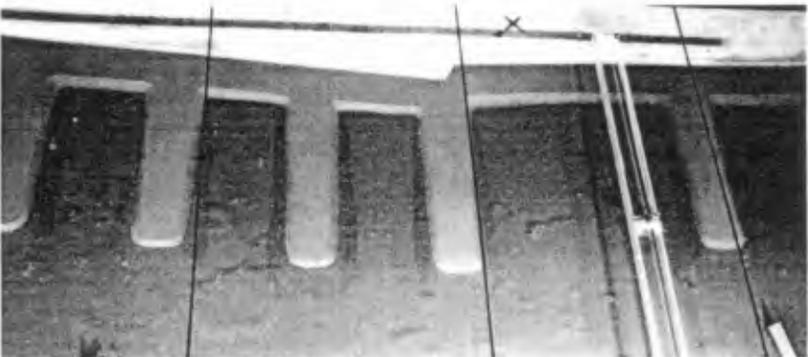


Figure 7. Beach nourishment 3D – Phase 1 (sand groynes and beach fill)

- the beach fill forces the shoreline to move 15 m (average displacement) seaward, even if in critical points the shoreline advance appears negligible;
- the late construction of the rubble mound groins allows beach fill material to move downdrift before being protected;
- the model results show that the reshaping of the sand groins will occur in a very short time (e.g. 1 day, if a 2.5 m high wave is used). The beach fill does not need to be ended long time before summer. If operated in wintertime, it is very likely that the wave action will destroy the groins before the end of their construction.

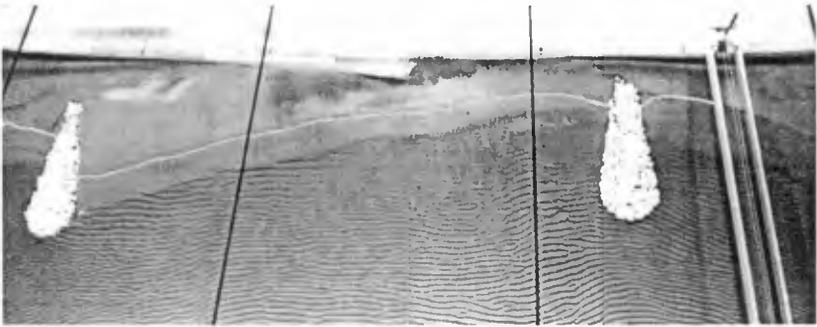


Figure 8. Final beach condition 3D

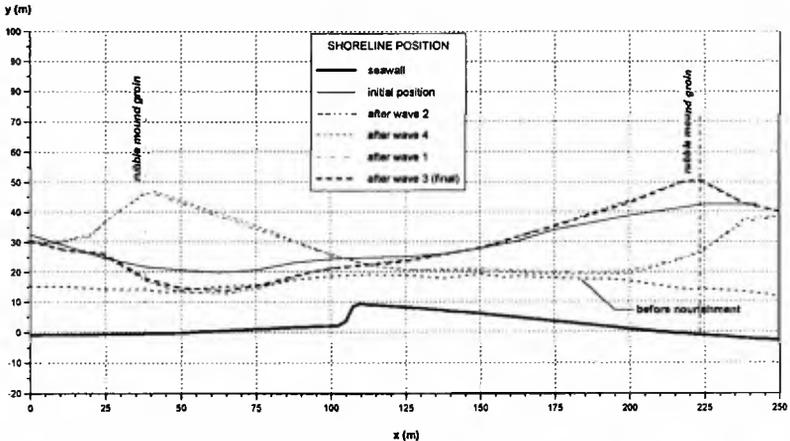


Figure 9. Shoreline beach evolution 3D – Phase 1(sand groynes and beach fill)

### Beach nourishment at Ostia (Lazio)

The project consists of the build up of a submerged breakwater, distant some 80 m from the shoreline, located in a water depth of about 4 m, with the top at  $-0.5$  m from m.w.l.; the area delimited by this parallel-to-the-shoreline structure and the shoreline is going to be filled with an amount of  $250 \text{ m}^3/\text{m}$  of sand (fig. 10, upper panel).

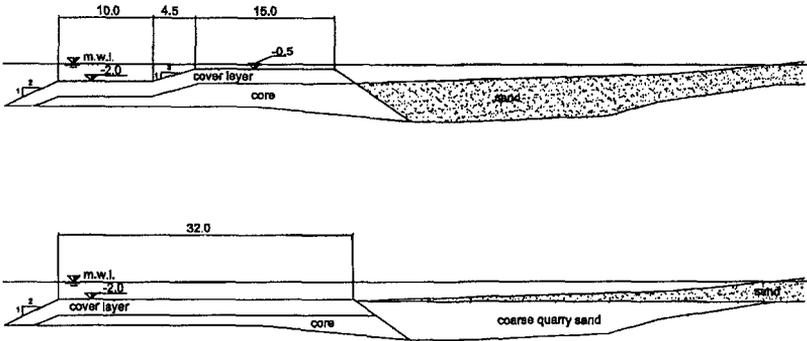


Figure 10. Beach fill technique at Ostia

The specific questions on the beach fill design tried to be answered by means of physical model tests were:

- is it the hard structure suitable for beach fill protection?
- is it the hard structure suitable for recreational purposes?
- are there any alternative solution that suits both beach protection and recreational purposes?
- which is the life expectancy of the beach fill (or the expected maintenance schedule)?

Based upon the waves recording of the site, it was possible to reproduce a morphological period corresponding to about 3 months in nature; the sequence of waves: summer, autumn, winter, spring was used.

The results obtained by mean of 2D-physical model tests can be outlined in the following list:

- the model tests demonstrated a good stability of the nourished beach (upper panel of fig. 10), with only small variations from the initial beach profile;
- a considerable increase of the water level in the region between the submerged breakwater and the shoreline (ranging between 13 to 43cm, referred to prototype) was measured and, as a consequence,
- very "dangerous" return currents have arisen over the top of the submerged structure (this behaviour seems not to be acceptable in the framework of a safe utilisation of the beach).

As a consequence of the described results, a different solution (fig. 10, lower panel), with the top of the structure protecting the "perched beach", placed at  $-2.0\text{m}$  from m.w.l.

was reproduced and studied in the 2D-model. In particular with the analysed solution the stability of the artificial nourishment was increased using a double layer fill (lower coarse-quarry-sand covered with fine sand, suitable for beach activities). The results of this second round of tests is outlined in the following:

- the model tests demonstrated a lower effectiveness of the structure in protecting the beach fill (fig. 11);
- the coarse-quarry-sand layer was not reshaped by the wave action;
- an initial sand loss of about  $25 \text{ m}^3/\text{m}$  was evaluated in a 3 months period, with a retreat of 10 m, but further simulations showed that the beach profile is close to equilibrium (expected retreat 5 m/year);
- return currents over the breakwater are much lower than in the previous case and seem to be acceptable in the framework of a safe utilisation of the beach;

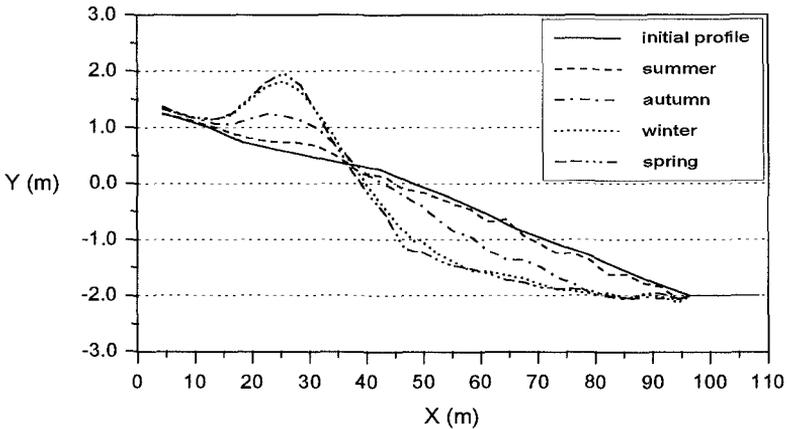


Figure 11. Beach profile evolution after the wave attacks

#### Beach reshaping and inlet stabilisation at Barbamarco (Po delta)

This project (located at Barbamarco, Northern Adriatic Sea) deals with the stabilisation and reshaping of a deltaic lagoon inlet. This stabilisation, obtained placing sand filled geosynthetic tubes for limiting the inlet fill up, induces the accretion of the updrift beach. The beaches adjacent to the inlet have also been nourished using the sand dredged from the channel, which has been dredged up to  $-3.0 \text{ m}$ . The investigation area is sketched in fig. 12.

The specific questions on beach fill design to be answered using physical modelling were the following:

- is it the longshore sediment transport able to fill the area close to the geosynthetic tubes?
- how long will it take to reshape the beach?
- what will be the filling rate of the dredged channel?

The physical modelling programme designed to answer the previously mentioned questions implied the construction of a 3D model in a 1:100 scale, reproducing the whole project area. The 3D physical model tests designed to evaluate the performance and the time schedule of the project were carried out using light bed material (anionic resin CPN80-bayer®, see tab. 4 for a detailed characterisation). This bed material allows to reproduce the prototype sediments behaviour with respect to the Dean criterion also using very small scale models.

grain size class	D (mm)	w (m/s)	s
1	0.51	1.15	1.13
2	0.72	1.63	1.11
3	1.02	2.01	1.09

Table 4. CPN80-bayer® characteristics (w: fall velocity; s: specific weight)

The model has been calibrated using field data obtained by means of a successive bathymetric campaigns and allowed to determine a morphological model time scale.

The rate of sand bypassing the tubes and filling the dredged channel has been evaluated in the physical model using sand traps located within the channel; a value of about 2000 m<sup>3</sup>/year was found.

The calibrated model has been used also for evaluating the beach accretion rate updrift the inlet; it was determined that, by the end of 1997, the coastline south of the inlet should have reached the edge of the tube groin (a recent inspection confirmed this forecast).

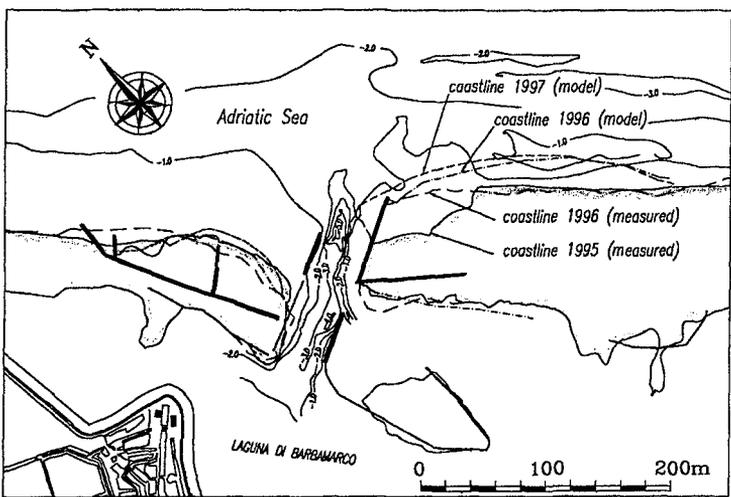


Figure 12. Barbamarco inlet (tubes are sketched with solid lines).

### Final remarks

After a brief survey of the still open questions related to the beach nourishment performance evaluation, three cases studies has been presented and analysed by means of physical model tests. This methodology allowed to give satisfactory answers to some practical questions not easily manageable with numerical techniques.

The experimental study of the nourishment design of Capo d'Orlando allowed to point out some useful information concerning the temporal aspects of sand groins remodelling phenomenon induced by the wave attacks.

From the tests on the Ostia littoral nourishment, it was possible to obtain interesting results concerning both the most suitable design of the submerged detached breakwaters and the behaviour of a double-layer supply of material.

Finally, the Barbamarco study evidenced the effectiveness of light bed material in describing transport phenomena when using very small model scale.

As a final remark, it can be stressed that the contribution of physical model tests is still of paramount importance, being implicitly integrative of all the (scaled and complex) processes that determine the evolution of the nourishment interventions.

### Acknowledgements

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