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Published in:
Coastal Engineering

DOI (link to publication from Publisher):
10.1016/j.coastaleng.2005.09.010

Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com
SCIENCE DIRECT®
Coastal Engineering 52 (2005) 841–866
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
www.elsevier.com/locate/coastaleng

European experience of low crested structures for coastal management

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Abstract

This paper aims to describe selected study sites monitored and analyzed during the DELOS project. All the selected sites are protected by Low Crested Structures (LCSs) under various environmental conditions.

In the first part of the paper the characteristics of the European structures are presented and the results of the inventory are summarized with statistical comparison with LCS characteristics in the worldwide scenario (Japan and USA).

In the second part a description of the sites and prototype observation of the impact of LCSs is given: a description of the site, environmental conditions and response to its construction based on existing literature and on activities performed during the project are summarized and the research results are reported. Where available observation on ecological impacts and socioeconomic effects are provided. The descriptions are introductory to other DELOS Special Issue papers dealing with prototype observations and experiments.

The geometric characteristics of the sites are very wide-ranging: deeply submerged LCSs perform well when groins are present (Pellestrina), whereas for semi-submerged LCSs (Lido di Dante) particular maintenance has to be planned for vulnerable parts, such as gaps and roundheads, where strong currents are responsible for erosion. Emergent LCSs show the formation of salients (Altafulla) or tombolos (Lønstrup) depending on the shoreline distances. In macro-tidal beaches (Elmer) tidal currents can control the salient development and the overall performance of the scheme.

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doi:10.1016/j.coastaleng.2005.09.010

On the basis of the field observations described here, LCSs seem to work effectively under different environmental conditions, providing the opportunity to protect beaches in the context of Integrated Coastal Management.

Keywords: Low crested structures; Coastal management; Case studies; Pellestrina; Lido di Dante; Altafulla; Lønstrup; Elmer

1. Introduction

Coastal defence structures are often constructed with a low crest, hence the name "low crested structures" (LCSs), and are characterised by frequent overtopping and high wave transmission. Their construction is often combined with beach nourishment schemes.

Field observations are very useful to understand the efficiency of defence solutions in beach protection, to plan future designs and to assess the opportunity to choose LCSs instead of more traditional solutions such as conventional parallel breakwaters, groin systems and seawalls.

The objectives of this paper are to describe typical LCS geometries in Europe, to summarize the perceived effectiveness of the chosen LCS schemes in their main role, i.e., protecting beaches and coastlines from erosion, and to assess their environmental impact through direct prototype observations.

To achieve these objectives, in the framework of the DELOS Project (*Environmental Design of Low Crested Coastal Defence Structures*) an inventory of existing LCSs in Europe was performed and 6 sites were selected on which continuous and multidisciplinary monitoring was carried out. A map of the study sites is shown in Fig. 1.

The sites were chosen as representative of variable conditions of European coasts and different defence schemes. Elmer, UK and Lønstrup, DK, are both characterised by cold climate, strong waves and emergent detached structures; Elmer is a high tidal excursion site. Lido di Dante, IT, Pellestrina, IT, Ostia, IT, Altafulla, ES, are Mediterranean sites characterised by

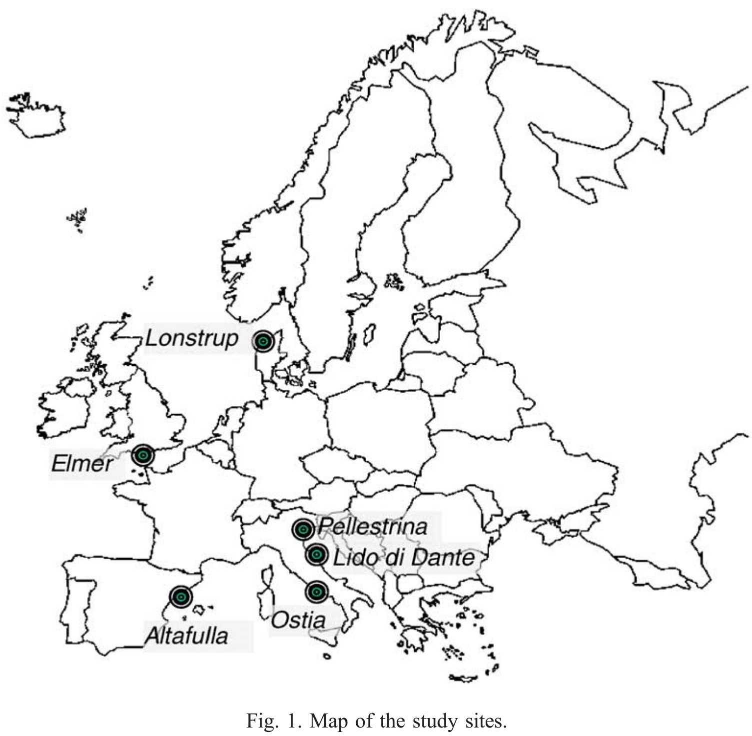

Fig. 1. Map of the study sites.

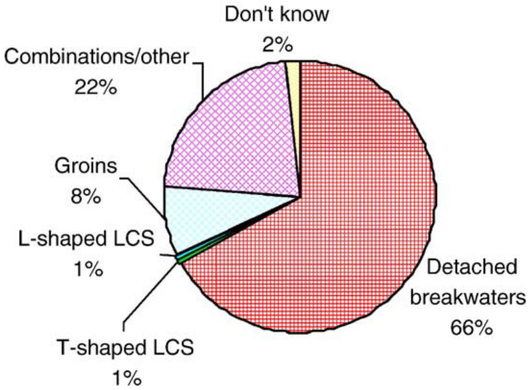

Fig. 2. Types of low crested structures in Europe.

low tidal excursion and moderate waves. Lido di Dante and Pellestrina are examples of composite interventions with groins and zero-freeboard/submerged barriers, respectively, whereas Ostia is defended by a submerged barrier and Altafulla by an isolated emergent LCS.

The information the reader will find on these sites may be also regarded as an introduction to more specific analyses of the sites described in other papers of this Special Issue which focus on morphodynamics (Sumer et al., 2005—this issue; Zyserman et al., 2005—this issue), socio-economy (Polomè et al., 2005—this issue), ecology (Airoldi et al., 2005—this issue; Moschella et al., 2005—this issue).

2. DELOS LCS inventory

The geometry and layout of existing LCSs are investigated with the aim of describing characteristics of European LCSs in a worldwide scenario. An interesting statistical study for such structures in Japan can be found in Takaaki (1988) and parameters for structures in the USA can be found in Chasten et al. (1993) and McIntosh and Anglin (1988). For European structures no literature containing statistical information exists, but within DELOS an inventory on the physical engineering properties of LCSs has been established.

The data in the European inventory was collected from seven EU countries in an attempt to represent a broad range of structural layouts. The inventory data were organized in a data bank assembled from 150 completed questionnaires. Each completed questionnaire contained a scheme including several structures often of varying types, e.g., a system of segmented offshore breakwaters with groins closing the scheme at each end. The main purpose of most schemes containing low crested structures in the inventory is beach and land protection against erosion. A few structures in the inventory are built mainly for coastal protection for ecological reasons or for protection of harbors, inlets, outlets, channels etc.

The typical type of coastal protection scheme with LCSs consists of detached breakwaters (66% of the schemes, see Fig. 2). In 22% of the schemes a combination of detached breakwaters and groins is used.

The following parameters, as defined in Fig. 3, were examined:

- D: Distance between the shore line pre-project and the centre line of the LCS;
- L: Typical length of the segments at crest level ($L_{segments}$ in Table 1);
- G: Length of the gaps between the structures at crest level (Gap in Table 1);
- B: Width of LCS at crest level;
- F: Freeboard, the distance from crest level to mean water level (MWL) (negative if submerged);
- h: Water depth at MWL.

The height of the structure is: $H=h+F$.

The total number of investigated breakwaters in the EU was about 1200 and in Japan 1550, giving about the same statistical uncertainty in Fig. 4. The data from the USA comes from only 24 schemes containing 235 breakwaters giving large statistical uncertainties in the figures.

Fig. 3. Description of structural parameters.

Table 1
Summary of geometry (detailed parameters are given in Fig. 3)

	$L_{segment}$ [m]	Gap [m]	Dist. [m]	Freeboard [m]	Width [m]	Depth [m]	Foreshore beach slope
Lido di Ostia	2800	–	100	−2.0	15	4	1:250
Pellestrina	9000	–	300	−1.5	14	4.5	1:100
Lido di Dante	800	30	180	0	12	3.5	1:160
Altafulla	116	–	180	+1.0	5	4.0	1:70
Lønstrup	45	45	40	+1.3	2	1	1:150
Elmer	80–140	60–140	40–90	+1.0 from HWS	4	3.5–4	1:130

In Fig. 4 the same trends can be seen for the EU, US and Japanese structures. However, in the USA no long structures (>100 m) exist and some systems are built with large gaps (>50 m). Structures with submerged crests seem to be more common in Europe than in Japan and in the USA. It can be seen from Fig. 4 that the variations in the parameters are wide. However typical values exist, e.g., the length of the segments at crest level is about 60–100 m with a mean value of about 80 m. In some of the histograms two peaks are present. This indicates that two very different cross-sections exist; a narrow crested emergent structure and a wide crested submerged type. The typical sets of parameters are shown in Fig. 5.

3. Study cases

From the total number of breakwaters investigated in Europe, six cases were selected for detailed study and monitoring. The study sites were chosen in an attempt to cover different and representative geometries (most of all the freeboard or submergence) and environmental conditions. The list of the sites and the main geometric characteristics are summarised in Tables 1 and 2; in Table 3, the main climate conditions for each site are reported.

Table 3 contains the low water storm surge and high water storm surge for design conditions in the second and third columns, the design wave height at the structure in the fourth, the wave height typical for morphological changes in the fifth, and typical waves and current directions at the site, respectively, in the sixth and seventh columns. The first 5 cases listed in Table 3 refer to areas characterised by micro- and meso-tidal ranges. In macro-tidal areas (tidal range >4 m), such as the UK, the use of LCS is still uncommon and the observations are very interesting. The depth of the LCSs ranges from 1 to 4 m, so the wave conditions are always depth limited by breaking.

Several ecologic impact observations were performed during the project in Lido di Dante, Lønstrup and Elmer and studies on the socio-economic impact of LCSs were carried out in Ostia, Pellestrina, Lido di Dante. The results are briefly summarized.

4. Prototype observations

4.1. Ostia (Rome)

4.1.1. Description of the site, environmental conditions and response to its construction

The sandy beaches of Lido di Ostia stretch along the southern delta cusp of the river Tiber, some 25 km from Rome on the Tyrrhenian Sea, and have long represented a very popular holiday resort for the Roman community.

The cuspated delta was formed by alluvial sediments carried by the river, producing a progressive coastline advance of more than 4 km from the Roman age until the last century. Then, particularly over the last 35 years, a severe erosion process has progressively taken place reverting the evolution trend to a recession rate of 1.7 m/year. The main cause has been the strong reduction of river sediment supply (due to upstream dams and extraction of building material from the river bed) with a consequent deficit in the coastal budget and a trend towards the cusp straightening and smoothing out. Coastal protection works, such as the system of detached breakwaters constructed near the river mouth, have shifted erosion down drift, mainly affecting the southern beach between the Vittoria Pier and the Pescatori Canal, causing damage to the beach clubs and even to the littoral road during storm events. An innovative beach nourishment project was then designed in 1988 by the competent Authority, the Office of Civil Engineers (Genio Civile) for Maritime Works – Rome of the Italian Ministry of Public Works.

The aim of the project was to re-create a wide protective beach with an efficient technical defence solution complying with the economical, managemental, political and environmental requirements. In fact any sort of traditional emerging coastal structure was rejected by the local community for the sake of tourism, aesthetics and ecology. Indeed the project represented a new approach of the Administration toward a global view in coastal defence, also taking account the environmental aspects. Given the existing high deficit of the littoral sand budget, the proposed beach nourishment needed to be protected by a coastal structure able to dissipate part of the wave energy and reduce the littoral transport, and to retain the new fill material. The most suitable solution therefore included an offshore underwater rock barrier fixing the natural dynamics sandy bar, such as a perched beach scheme.

The submerged bar would need to hold the artificial beach at a shallower slope, reducing both offshore sand losses and long-shore transport, enhancing the development of marine fauna, without endangering bathing and leisure navigation.

Important constraints also resulted from the scarcity of marine sand for nourishment. The native beach sediments at a depth of MSL-10 m (on a 1% slope) have a too fine grain size with $D_{50}=0.1$ mm. Fill material needed to be quarried inland on the alluvial Tiber delta at a distance of 20 km from the beach: the available material is a poorly sorted mix of well rounded sands and gravels. The protection scheme covers a beach length of 2.7 Km and basically consists of:

- a sill consisting of a submerged rubble mound parallel to the shoreline at a distance of some 150 m, with toe level at MSL $-4.0/5.0$ m, a 15 m wide crest berm at -1.5 m, seaward slope of 1 : 5, a multi-layer rock mound (maximum stone weight of 1 t) placed above a geotextile and a 5 m wide rock toe protection in a 1 m deep trench. About 300,000 m^3 of rock (basalt and limestone from different quarries) was needed;
- a fill with a double layer of quarry material: a lower layer of mixed sand with grading of 0.08 – 120 mm, and a 1 m thick upper layer of sand with grading 0.3 – 1.3 mm; the underlayer also acts as a 5 m thick filter between the sand and the rock bar; the beach equilibrium slope is 2.5% and the berm crest located at MSL+1.0 m. The average design shoreline advance is about 60 m. The material quantities were about 1,360,000 m^3 of sand and selected mixed sandy-gravel.

The work started in 1990 when the submerged breakwater was built and beach nourishment (1,300,000 m^3) was made up from Vittoria Pier to the Pescatori Canal (2700 m). In 1998 a 235,000 m^3 beach nourishment was made from the Repubbliche Marinare Way to Lido (1.220 m), in 2000 a 70,000 m^3 beach nourishment was made from Magellano Square to Belsito (680 m). Maintenance work was also carried out supplying material to the structure (2001 and 2003) and to the beach (366,000 m^3 beach nourishment from Vittoria Pier to Belsito in 2003) and maintenance works have been made by 1–3 t rock recharging over the barrier along partial stretches (2001 and 2003–4) raising the crest up to -1.0 and -0.5 m MSL.

Given the innovation of this technical solution and the unusual length of nourished beach without groins, the Supreme Council of the Ministry of Public Works attributed an experimental character to the works and imposed the setting up of a monitoring program from the start of construction in 1990. The periodic acquisition of field data includes: aerial photographs, beach profile surveys, sediment sample analysis and direction wave recordings (Franco et al., 2004).

4.1.2. Observations and research results

Historical "geo-referred" shorelines were diachronically analysed to derive the aerial variations of the emerged beach compared to the "natural" 1944 situation. Before the 1990 works the 2.8 km long dry beach had lost nearly 60,000 m^2 as compared to the 1944 condition. After the works of 1990 an erosion rate of some 16 m^2/m can be observed in the following 8 years. The analysis of the topographical beach surveys showed a marked rotation of the shoreline with shoreline advance (at the southern end) and retreat (at the northern end), due to the southbound littoral drift. In 2003, after the last fill, the emerged beach area was almost equal to that of 1944.

Historical beach profiles were compared for 6 representative sections at 500 m spacing (Fig. 6),

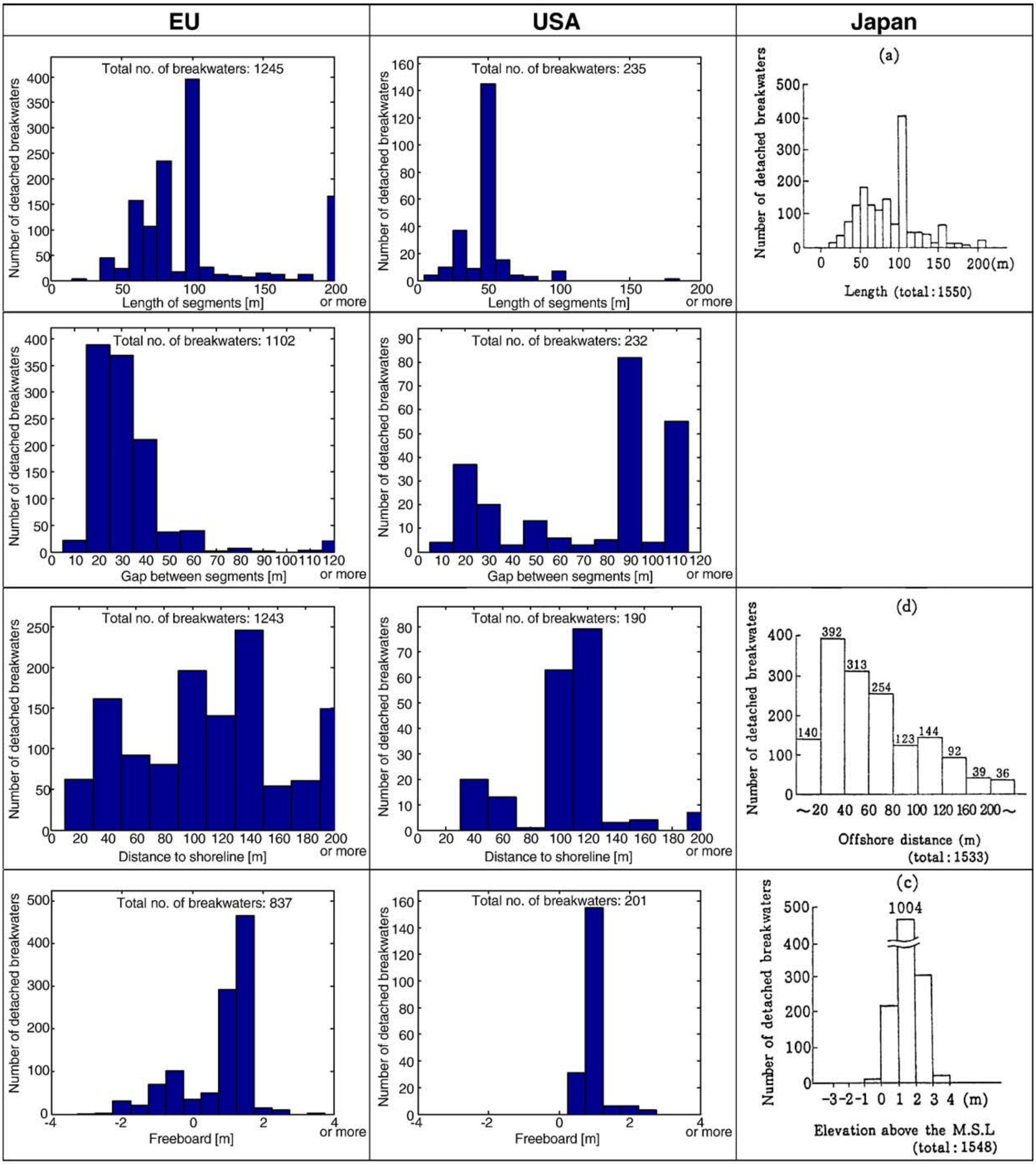

Fig. 4. Part I. Histograms showing the distribution of LCSs for each investigated parameter. Part II. Histograms showing the distribution of LCSs for each investigated parameter.

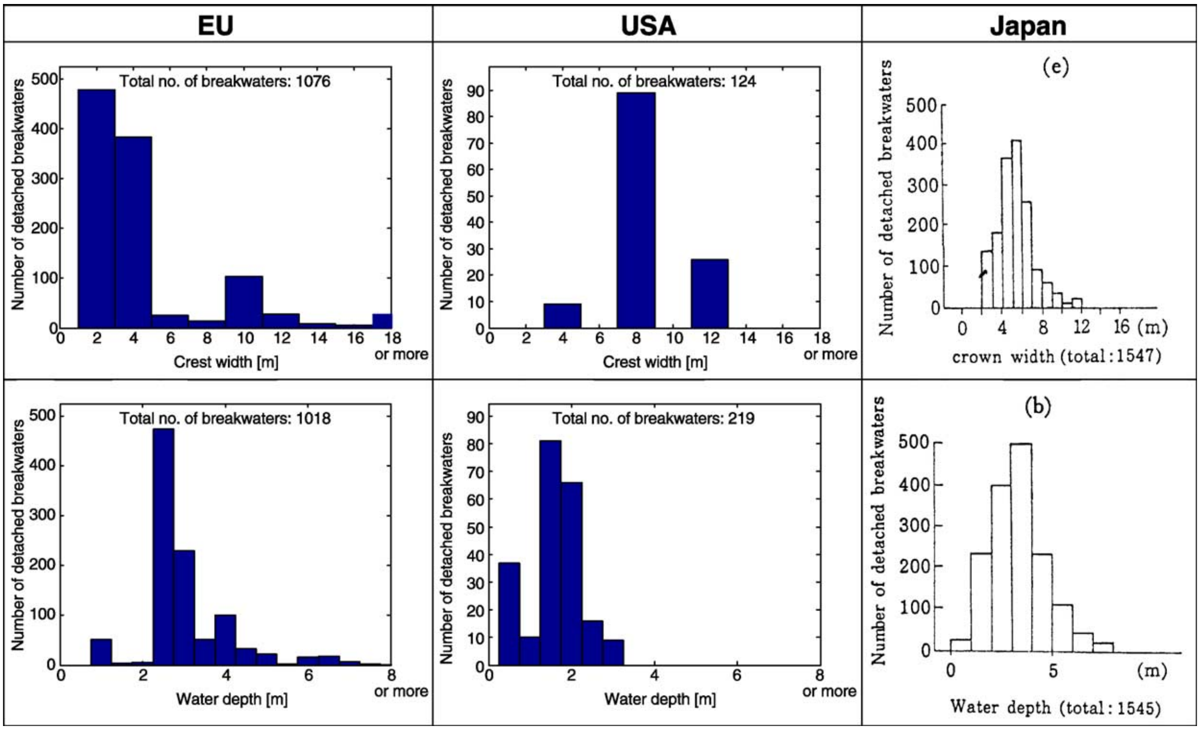

Fig. 4 (*continued*).

where the rock barrier position is also indicated. The disappearance of the offshore bar is noted. Volumetric computations carried out with BMAP (CERC) show the beach reduction in the first period 1992–96 with an erosion peak of 234 m^3/m at Section11, while accretion obviously occurs after additional recent fills, particularly at the downdrift sections (due to the expected deposit against the Canal groin) and at the most updrift section (due to the LCS raising at −0.5 m MSL).

Grain size analysis confirms the migration of sands both offshore and downdrift, only reduced after the rock recharges of the submerged barrier. The LCS has been reshaped over time by both settlements and wave action, with an average crest lowering of 0.5 m in a decade. A computation of the actual "damage" was made by comparing negative differences (eroded areas) of barrier cross-sections with the "as built" geometry of 1992 survey. The average damage for the 6 representative sections shows an obvious ten-

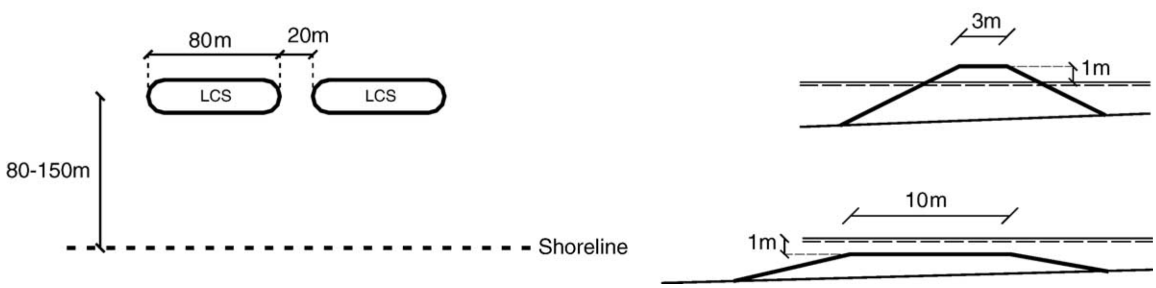

Fig. 5. Typical structural layout and cross-sections.

Table 2
Summary of materials

	Armour layer rock type	Armour layer stone size D_{n50} m	Beach material grain size [mm]
Ostia	Quarry rock Basalt and limestone	0.7	0.08 – 1.20 (lower layer) 0.3 – 1.3 (upper layer)
Pellestrina	Quarry rock	0.56 – 0.90	0.20
Lido di Dante	Quarry rock	0.8	0.08 – 0.23
Altafulla	Rubble Mound	≈1.5	0.12 – 0.2
Lønstrup	Quarry rock	0.80 (Toe: 0.55)	0.2
Elmer	Norwegian syenite (igneous rock)	1.50 (Toe: 0.35)	Sand: 0.115 Shingle: 20

All the projects foresee a nourishment maintenance, made with sand or shingle as in Elmer.

dency to equilibrium with a maximum mean damage of 12.5%. The most damaged section is Section 1 with 25%, while Section11 and Section16 only show a 4% damage. This damage is well predicted by Van der Meer formulae, assuming $D_{50}=0.5$ m ($W_{50}=0.35$ t) and depth-limited breaking waves.

The progressive barrier siltation from both shoreward and offshore transport reduces the rock barrier porosity and efficiency, and increases its reflectivity.

In conclusion the original rock LCS has a weak protection effect due to its low crest elevation, (average of −2.3 m MSL) after settlement (despite geotextile) and erosion due to direct wave action and scour; the size of the rock also appears to be underdesigned. The old barrier only provides a transmission coefficient of about 0.6 under typical storm conditions.

The strong wave obliquity still produces a significant drift, which is now being slowed down by a few semi-submerged "construction" groins.

4.1.3. Socioeconomic aspects

In order to perform a statistical field investigation on the contingency evaluation of Ostia beach a detailed questionnaire (with approx. 40 questions including photos and figures) was prepared. A few "technical" questions related to the preference about coastal protection works and sediment type have been added with the aim to obtain an idea of the users' taste and needs.

Around 100 interviews were made at Ostia beach in summer 2002 with good responses: in general the residents showed more concern about the overall sea defence issue, while the summer visitors from Rome paid more attention to visual impacts and water quality. With regards to the preferred type of beach protection scheme nearly 50% favored the inclusion of some kind of "rigid" structure (14% emergent detached breakwaters, 22% submerged barriers, 6% groins, 5% a mixed "box"-type system) since they believe they last longer and are more effective for the beach defence. However the remaining 50% prefers a pure "soft" sand nourishment, especially for aesthetical reasons, but also to favor recreation activities.

With regards to the preference about sediment characteristics it is notable that nearly 80% of users prefer fine light-colored sands and just 14% like the dark sand which was the original color of the Ostia beaches. Some 10% prefers coarse sand and no one likes a gravel beach. These quite obvious responses can be useful for nourishment projects. With regards to the fundamental question about the amount of money users would spend for one day at the replen-

Table 3
Summary of hydrodynamics

	Spring tidal range (m)	Low water storm surge (m)	High water storm surge (m)	Design wave height (m)	Typical significant wave height (m)	Wave direction	Current direction (from-to)
Ostia	0.4	−0.30	+0.30	2.5	1.0	SW	–
Pellestrina	1.0	−0.90	+1.20	3.7	0.70	ESE	N to S
Lido di Dante	0.8	−0.84	+0.97	2.4	0.60	NE SE	N to S
Altafulla	0.3	−0.41	0.45	6.3	0.80	E S	E toW
Lønstrup	0.3	−1.0	+1.5	2.0	0.60	W	S to N
Elmer	5.3			5.5	1.10	SSW	W to E

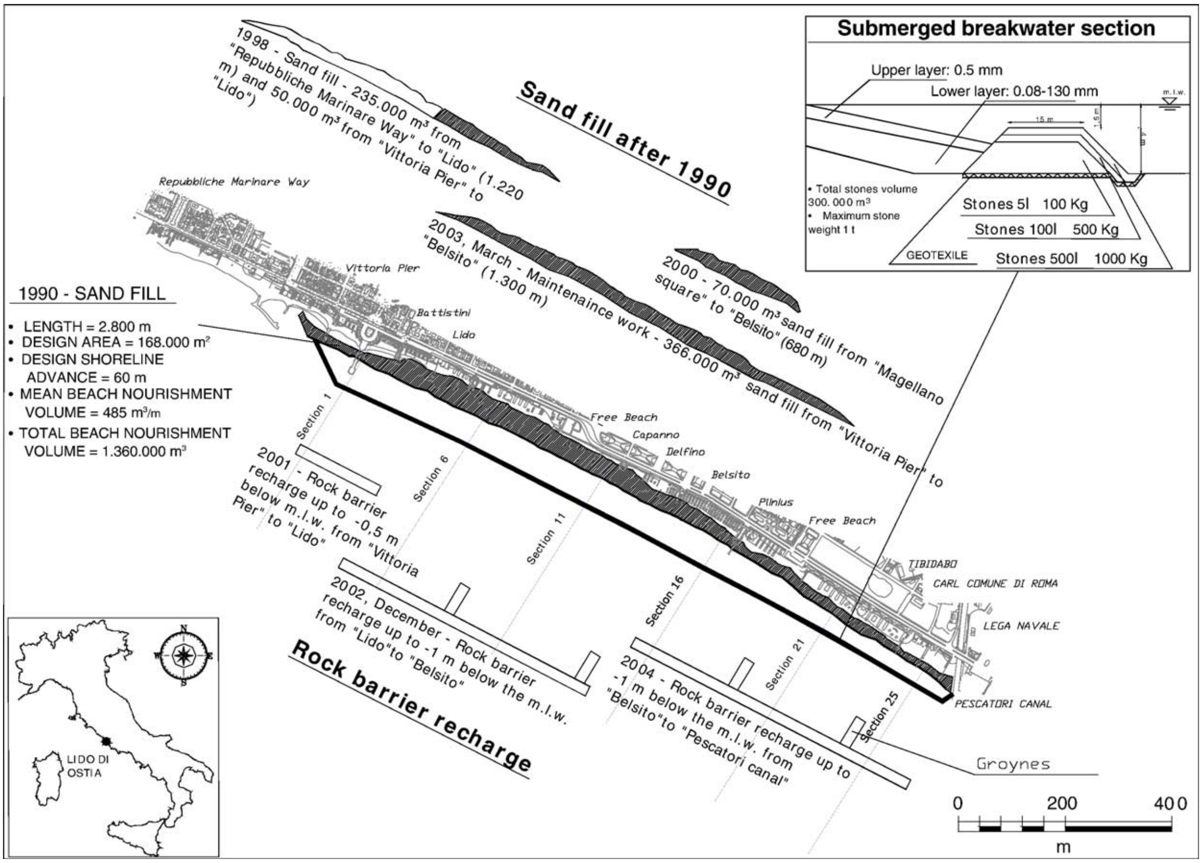

Fig. 6. Plan view and submerged breakwater section scheme.

ished beach, the average value was around 23 euros in developed areas and just over 6 euros within free undeveloped areas, but this would drop to only 1–2 euros in the case of a severely eroded beach. This analysis allows us to quantify the loss of enjoyment due to erosion problems and can thus be used to quantify the benefits of coastal protection works.

4.1.4. Ecologic impacts

As far as ecological considerations are concerned no specific biological studies were performed at Ostia beach. Only various diving inspections and a video film (November 2003) were carried out by Leo Franco and supplied to the ecologist partners for analysis. Observations show that the rock barrier is mostly filled with sand and well naturalized with the seabed, resembling a natural reef with active marine life (fishes, octopuses, vegetation, mussels, etc). However, the existing sandy beach did not experience hard bottom structures before. In general the water quality at Ostia beach has improved in the last years and the general attitude towards the rock barrier is positive.

4.2. Pellestrina (Venice)

4.2.1. Description of the site, environmental conditions and response to its construction

Pellestrina, stretching for 9 km in the Northern Adriatic Sea from Chioggia (Southern limit) to Malamocco (Northern limit), is one of the three islands protecting the Venice lagoon (Fig. 7). In the past the construction of the groins of Malamocco (North) and of Chioggia (South) led to a strong reduction of sediment supply. The Pellestrina beach disappeared and the defence of the village (and of the Venice lagoon) was left to a rigid wall (i.e., Murazzi, built

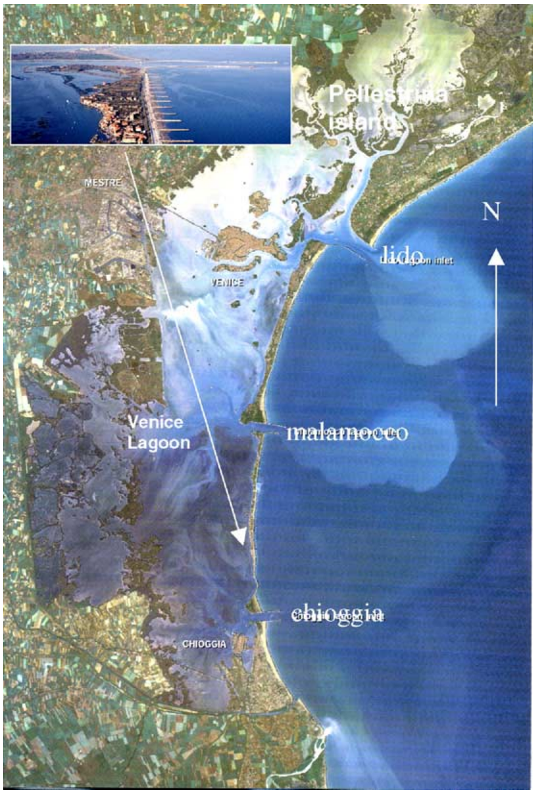

Fig. 7. View of the Venice Lagoon.

in the 18th century). The beach slope at the shoreline increased and storms became more dangerous for the buildings of the island (e.g., the. 1966 flood).

The major winds to which Pellestrina is exposed are the Bora (NE), the strongest in frequency and magnitude during winter and autumn with a typical velocity of 70 knots; and the Scirocco (SE), which predominates during spring and summer with a maximum velocity of 55 knots. Continuous directional wave records are collected at the *Acqua Alta* oceanographic tower, managed by the Italian Research Council (CNR), located in the Adriatic Sea some 20 km offshore Venice (Cavaleri, 2000). Wind and wave statistics derived from these data and elaborated by MODIMAR and Consorzio Venezia Nuova (CVN) are reported in Fig. 8.

Main wave attacks come from 80° (*Bora*) and 130° (*Scirocco*); the significant wave height with a return period of 10 years is 3.70 m (Consorzio Venezia Nuova, 1990).

Spring tide in Venice is 1.00 m and high tide coupled with *Scirocco* winds can cause very high water levels, often called *acqua alta*, up to 1.5 m. The closed and narrow shape of the Adriatic basin allows the rising of seiches that are usually characterized by a period of 22 h. In the studied area the predominant sediment transport direction is from North to South; before the defence system was built the transport rate was around 130,000 – 150,000 m^3/year (Cecconi and Maretto, 1996).

The average steepness of the beach is about 1:60 with lower values Southwards (1:90) caused by the natural nourishment due to the maritime dike of Chioggia. The Pellestrina littoral is characterized by a closure depth of 5 m.

To defend the Lido of Pellestrina, a system of partially submerged groins and a submerged breakwater was built in 1995 with beach nourishment (about 4,600,000 m^3 of sand dredged from offshore and pumped onto the new beach with $D_{n50}=0.20$ mm). The groins are joined to the submerged longitudinal breakwater. The result is a system of 18 partially closed cells.

The groins are about 150÷210 m long with the crest at about +2.2÷2.7 m above the MWL and for their first 100 m they are on the beach. These groins are joined to the submerged breakwater through a submerged part with the crest at about −1.5 m below the MWL. The barriers are made of 50–500 Kg stone material at the leeside and of bigger stones of 500–2000 Kg at the seaside, lying on a geotextile. The width is about 14 m and its position is about 300 m from the shoreline (Fig. 8).

4.2.2. Observations and research results

Given the importance of such a beach defending the Venice Lagoon, the CVN (Consorzio Venezia Nuova) performed regular surveys of sections and shoreline twice a year, in order to observe changes of the bottom and of the shorelines. In every cell three sections were monitored. Field data analysis, based on six beach profile surveys (from October 1997 to December 2000) showed that the system structures defence built at the Lido of Pellestrina is effective because the sand quantities were trapped in efficient manner: for the first cells (the Southermost ones) the relative volumes percentage variations normalized with the cell nourishment volume was about 2% in three years, whilst for the last ones (the most recent) the variation was greater due to the

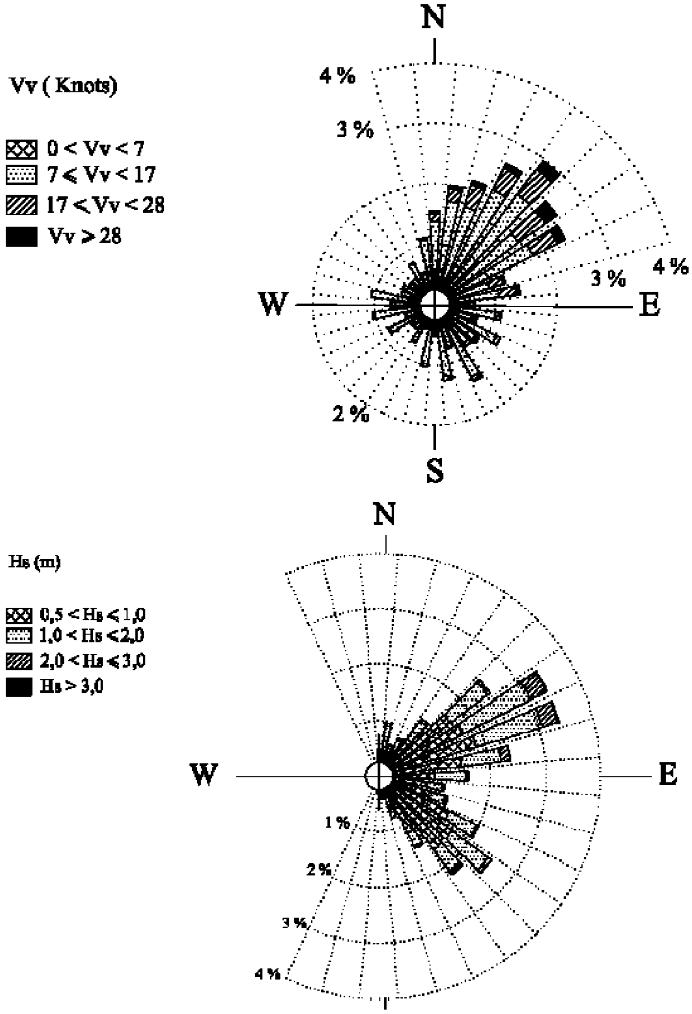

Fig. 8. Wind rose (up) and wave rose (down) at CNR (National Research Council) tower (Venice). Period: October 1987– December 2002.

reshaping phenomena where sand is moved toward the submerged structure (Fig. 9). The project foresees a loss of about 10% in ten years, so the results are acceptable.

During DELOS, a detailed bathymetry (multi-beam system) of a representative cell (the 9th) and of the southern roundhead was made in October 2002.

A significant erosion at the Southern roundhead due to waves and current interaction has occurred and is presented in Zyserman et al. (2005—this issue). Landward the same roundhead, it is noticeable also a scour hole due to the action of plunging breakers is also notable (Sumer et al., 2005—this issue). Extensive erosion has taken place inside the protected cell and at the submerged connectors as discussed in Zyserman et al. (2005—this issue).

Comparison between LCS profiles performed by CVN in 1997 (after the construction) and in 2002 shows that the barrier submergence has increased to 1.80–2.00 m, due to sinking and settlement.

A field campaign aimed at measuring waves and currents in the central cell (the 9th) chosen as representative of the Pellestrina littoral was performed between 5th–15th November 2002. During this field campaign an Acoustic Doppler Current Profiler

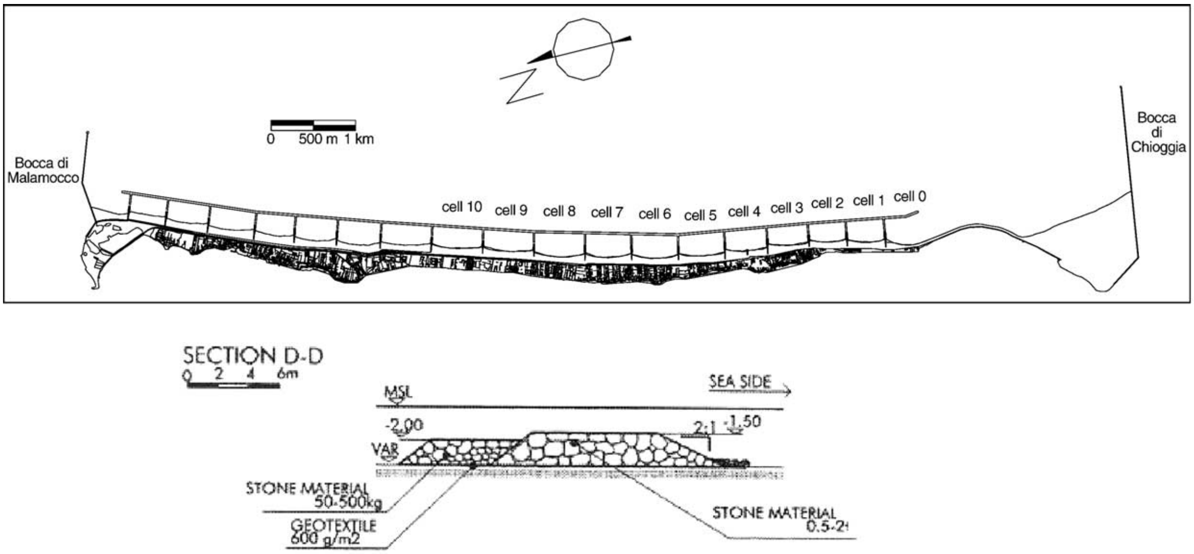

Fig. 9. Plan view of Lido of Pellestrina and LCS section.

(ADCP) and three current-meters were installed in the area of interest. During this period, several storm events were generated by strong winds from N-NE (Bora): measured waves height reached 3 m (storm return period approximately of 10 years) outside and 1.6 m inside the protected area. The collected data were used to calibrate numerical models.

With the final aim of evaluating the efficiency of the defence system in preventing beach erosion, a series of numerical simulations aimed at understanding the basic hydrodynamics phenomena induced by the interaction between the waves and the structures have been carried out using two different models (Di Risio et al., 2003; Zanuttigh et al., in press).

The set-up difference between seaward and landward of the structures can be seen as the main cause of the current generation far from the surf-zone.

Currents at the swash zone, at LCS and at the groins roundheads can reach up to 1.5–2 m/s during severe conditions, but for frequent conditions are of the order of 0.5 m/s; clockwise vortexes are generated at the groin roundheads.

Sediment transport reflects the hydrodynamics: the most energetic situations come from N-NE and cause critical conditions for transport (erosive trend); also S-SE waves are critical for transport given their frequency. Dominant long-shore transport direction is from North to the South.

In a typical cell an equilibrium trend of the sediment budget, with a small annual erosion of about 2.9% of the nourished sand was simulated (Zanuttigh et al., in press). This result is coherent with observation performed by CVN (1990). The new defence system seems to be able to solve erosion problems.

4.2.3. Socioeconomic analysis

A socio-economic analysis was performed in order to evaluate the new benefits derived from the new existing beach in Pellestrina (Marzetti and Lamberti, 2003): the enjoyment value for the use of the Pellestrina beach was estimated by applying a Contingent Valuation Method (CVM), and a second analysis aimed to find out the preferences about different kinds of coastal defence structures and some flooding and salt corrosion costs. Results show that more than 70% of respondents are willing to pay something for the project for the defence of Venice, and that the great majority of residents and day-visitors elicited positive values for the daily use of the artificial beach of Pellestrina island. Finally, amongst possible defence structures, interviewees prefer a composite intervention consisting of nourishment, groins and submerged breakwaters (as done). Details can be found in Polomè et al. (2005—this issue).

4.3. Lido di Dante (Italy)

4.3.1. Description of the site, environmental conditions and response to its construction

Lido di Dante is a seaside resort located on the Adriatic coast 7 km far from the city of Ravenna. It is located between the mouths of the Fiumi Uniti river in the North and of the Bevano river in the South. The Lido di Dante beach is characterised by a significant development of tourism facilities.

The beach is about 1300 m long and it has a surface of about 70,000 square meters. It is classified as a dissipative beach characterized by a flat, sandy beach with a wide surf zone, and presents a concave shape of the cross-shore profile with orientation NW–SE. It is still possible to find some dunes at the rear of the beach. Nowadays, however, this system is quite narrow due to the development of tourist facilities and erosion problems.

Lido di Dante is part of a wide coastal area undergoing erosion problems whose causes started around the 1950s. The erosion has both natural and anthropogenic origins. Land subsidence is one of the main causes: the young age (geologically speaking) of the sediments which characterize the Pianura Padana area together with underground water and gas drilling have exacerbated this process.

Low rates of sediment transport associated with the location of Lido di Dante, close to the estuarine river mouth of the Fiumi Uniti, which has long ceased to transport significant amount of sediment, do not allow the natural support of sand to preserve a constant beach width. Furthermore, the tourist development has modified the natural dynamics of the beach.

The strongest winds occur during winter (more than 24 knots) from NW-N-NE; summer, on the other hand, is characterized by a high frequency of southern winds. As a consequence the wave climate is characterized by most frequent storms from *Scirocco* (60–120°) but the strongest come from N-NE (*Bora*). Offshore waves reach an average height of 3.5 m every year and around 6 m every 100 years.

There are two principal aspects causing variation in water level: astronomical tide, which contributes with a range equal to 80 cm at spring tide and 30 cm at neap tide, and the storm surge that becomes significant when the *Scirocco* wind blows. Currents generated by these processes are estimated to be ~ 0.05 m/s, one order lower than wave-generated currents.

The submerged breakwater (770 m long placed at 180 m from the coast at a 3.5 m depth, interrupted by a surface opening 30 m wide) is part of a more complex project made in 1995 mainly to solve the problem of the extensive erosion. The original submergence was 0.5 m, which was reduced to 0 in 2001 (Fig. 10).

Beside the LCS, the lay-out includes three groins (the first built in 1978 at the northern site and the others placed 300 m and 600 m south of the first in year 1983) and 2 submerged groins linking the groin head to the barrier (the northern built in 1995 and the southern in 2001). The peculiarity of this breakwater was that its crest is emergent during low tide and submerged during high tide. Recently (June 2003) due to some maintenance works, the freeboard of the LCS and of the two boundary groins was increased up to approx. 20 cm above the mean sea

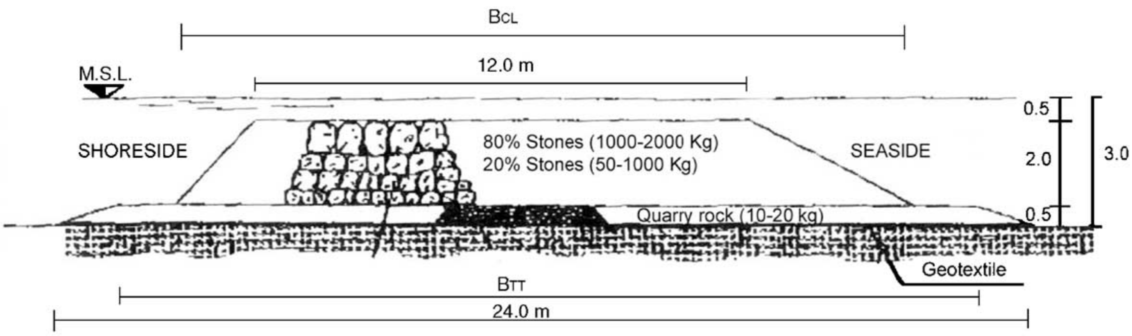

Fig. 10. Typical cross-section of LCS in Lido di Dante (before 2001).

water level. Beach nourishments using sand with $D_{n50}=0.23$ mm were performed: 60,000 m^3 in 1993 and 74,400 m^3 in 1996. A view of the beach is shown in Fig. 11. A detailed description of the site and the design of the structures can be found in Lamberti et al. (2002) and Archetti et al. (2004).

A monitoring program (topography, bathymetry and hydrodynamics) began immediately after the construction of the semi-submerged breakwater.

Short-term studies were directed to determine the efficiency of the nourishment, while medium-term studies focused on determining the development of currents around the structure. Storms from both the north and south hit the area, and the unbalanced wave set-up, a result of the wave breaking inside and outside the protected area, drives the generation of a particular current system recently responsible for severe erosion of the southern littoral.

Analysis of beach cross-sections shows that the shoreline at the north of the study area is affected by an intense erosive process and retreated between 12 and 17 m. Inside the protected area, behaviour in the northern cell seems to be in equilibrium whereas the southern cell is still eroded, particularly during winter storms.

Fig. 11. Perspective view of the shore-protection system defending Lido di Dante beach.

4.3.2. Observations and research results

During DELOS, currents were monitored using one or two ADCP, which gives a measurement of waves and currents at the instrument position, and by dropping floating drifters at the edge of the study area and following their patterns with various techniques. Both methodologies appeared to be essential to obtain a reliable representation of velocity fields and for calibration of numerical models (Drei et al., 2000, 2001; Archetti et al., 2003a,b).

The current system is mainly driven by wind–wave pattern, so wind coming from NE (*Bora*) leads to a south-going current whereas wind coming from SE (*Scirocco*) leads to a north-going current. Interaction between the main current system and the LCS and groin system of the area leads to the formation of eddy circulation at both heads of the LCS, and rip-current towards the gap in the middle of the LCS. Due to this current's pattern several changes in the bottom morphology have occurred since the LCS was built, as well as erosion at both heads of the structure caused by the eddy circulation. During the surveys with drifters it was observed that currents strongly increase from the northern cell to the southern cell for waves coming from NE. Some results were found through numerical simulations: representative points were identified at the northern and southern roundheads, the central gap and two points located leeward and seaward the barrier close to the position of the ADCP. Current intensity reaches the maximum values at the roundheads, where intensities as high as 1.8 m/s were simulated, and at the central gap, whereas it is less intense along the barrier where it reached an intensity of 1.0 m/s offshore but only 0.4 m/s leeward, where, the submerged connectors produce a calm area. Wave intensity is obviously higher seaward than leeward the barrier. These currents are responsible for strong erosion at the southern roundhead of the LCS.

Hydrodynamic simulation at the site before and after the construction of the southern submerged groin confirmed that the currents during the Bora event are strongly reduced by this intervention (Lamberti and Zanuttigh, 2005).

Waves and currents were measured inside and outside the protected area: inside the area 20 m from the central gap during several field campaigns, wave height reached 0.9 m during intense storms from N.

Outside the protected area 50 m offshore the northern LCS during two fields campaign, these data were used as boundary conditions for numerical simulations. Velocities through the gap are due to tide oscillation and during severe storms to wind and waves. Currents can reach up to 0.5 m/s (confirming the simulation results). These currents are responsible for the strong erosion at the gaps, therefore special maintenance is required at the gap and at the roundheads.

From the comparison between wave height inside and outside the LCS a wave transmission coefficient ranging from 0.35 – 0.65 was estimated. As expected, k_t increases with swl. Comparing the swl in and outside the structures we can see a strong set up during intensive storms ranging between 0 to 0.4 m, for very high wave height.

Two detailed bathymetries (multi-beam system) were made in June 2001 and in January 2004: a deep eroded area at about 70 m from the two roundheads was identified. This is due to the strong vortexes that are induced at the roundheads during strong storms from the Scirocco (at the southern roundhead) and the Bora (at the northern roundhead). In the latter one a deep erosion at the gap was observed, due to the effect of the final 'close cell lay out', where accumulated water in the protected area can flow out only through the gap, as the boundary groins are now emergent. It is also interesting to remark the sand accumulation at the seaward side of the LCS.

4.3.3. Ecological impacts

In Lido di Dante very little is known about natural macrobenthos inhabiting non impacted sediments. The macrofauna of Lido di Dante is represented by a relatively higher number of species belonging to three main phyla: Mollusca, Annelida, Arthropoda.

In particular, results from the ecologists have shown that the natural benthic assemblages inhabiting the surf zone (from 0 to 4 m depth) can be described as a typical *Lentidium mediterraneum* community. As is common on the shallow coastal environments of North Adriatic Sea, the living communities of Lido di Dante are relatively species poor. Only few species are quantitatively dominant and characterize the spatial and seasonal variation of the assemblage. In particular, the high dominance of *L. mediterraneum* determines low diversity and marked fluctuations in abundances throughout the year, with low densities during the winter and spring and a maximum in summer. This is a typical situation of physically controlled environments, where the main structuring factor is the hydrodynamics.

Two field campaigns were carried out to investigate the impact of low crested structures and the extent of the effects of the LCS on soft-bottom sediments in Lido di Dante. The aims of this study were to analyse the changes of bottom sediments related to the presence of LCS and the impact on soft-bottom assemblages surrounding the LCS. and to investigate the extent of the effect of LCS at increased distance from the structures.

Waves and currents described so far have been related to barrier colonisation.

The periodical ecological surveys in the area and on the structures show the composition of the epibiota and reveal that mussels (*Mytilus galloprovincialis*,) and green algae (*Enteromorpha intestinalis)* are present both seaward and leeward the structures but are more abundant seaward, whereas oysters (*Ostrea edulis* and *Crassostrea gigas*,) and microfilm are more abundant leeward the barrier. Oysters in particular are practically absent seaward (around 5%). Relating hydrodynamics and ecological data, some conclusions can be drawn, showing that both mean and extreme values of hydrodynamic fluxes strongly affect the barrier colonisation.

4.3.4. Socioeconomic analysis

A survey, made up of 600 face-to-face interviews on the Lido di Dante beach, was carried out in August–September 2002. During the survey the interviewed people were requested to provide monetary values representing enjoyment from recreational activities on the beach and its variation when the beach advances or retreats.

In conclusion, the value attributed to the beach in the current state together with the aesthetic preference for the composite type of intervention appear to "justify" completely, in terms of societal satisfaction, the works carried out in Lido di Dante (cost 1 MEuro) and the periodical maintenance necessary to preserve the beach in the current state: the cost of maintenance corresponds to approximately 1/10 of the total declared value of enjoyment. Details can be found in Polomè et al. (2005—this issue).

4.4. Altafulla beach (Spain)

4.4.1. Description of the site, environmental conditions and response to its construction

Altafulla is a typical Mediterranean beach, belonging to the tourist coast of Tarragona (Spanish Mediterranean), 100 Km south of Barcelona (Fig. 12).

The orientation of the coastline of the beach of Altafulla is nearly E–W i.e., facing the south-coming waves, and is located in-between two rocky salients (Els Munts and San Juan) enclosing the considered morphodynamic system.

The Altafulla beach is located in a microtidal environment, where the astronomical tidal range is no greater than 0.3 m. Wind data are available from a meteorological station located at the Tarragona harbour (about 15 Km to the SW). Wind climate shows that the most frequent winds are those from the N (18%) followed by WNW (8.4%), NW (8.1%), SW (7.5%). The strongest winds are those from W-NW, with speeds greater than 11.6 m/s. Winds from N rarely exceed 5.4 m/s. The local wave climate has been derived from forecasted data (1996 to 2003) supplied by the “Puertos del Estado” (Spanish Ministry of Public Works), obtaining the distribution of significant wave heights and directions. The analysis of the sea wave data shows a typical Mediterranean wave climate, with mild conditions most of the time. The significant wave height is lower than 1 m about 91% of the time and more than 99% of the time is lower than 2 m (including the calm periods). The prevailing wave conditions are those between E and S (more than 62% of the time). Wave periods also show typical Mediterranean values, with peak periods ranging between 3 and 7 s about 73% of the time. These data have been used for the numerical morphodynamic simulations carried out within the frame of DELOS.

The beach length is about 2300 m, with a medium grain size of 0.12–0.2 mm, an average slope of 0.016. There is a net sediment transport from E to W.

In order to prevent erosion, in 1965 a concrete seawall was built, with an initial length of 250 m. This wall was further lengthened to 450 m in 1972. In 1983, the seawall failed due to a constant scouring process, the failure area was then protected with a conventional rubble mound structure.

However, and because of the huge importance of the tourist industry for the economic development of this location, in 1991, both, the construction of a Low Crested Structure (LCS) as well as a sand nourishment of 160,000 m^3 were carried out in order to increase the width of the beach.

This LCS was placed in the middle of the beach, in front of the “Roca de Gaià” which splits the beach (Fig. 12) in two parts. The 110 m length and 5 m wide structure was located between -4 and -5 m water depth with a still-water freeboard less than 1 m. The nourishment took place in the East where there was a lower amount of sand due to the E–W net sediment transport pattern. Due to the lack of precise knowledge on the actual oceanographic conditions, the nourish-

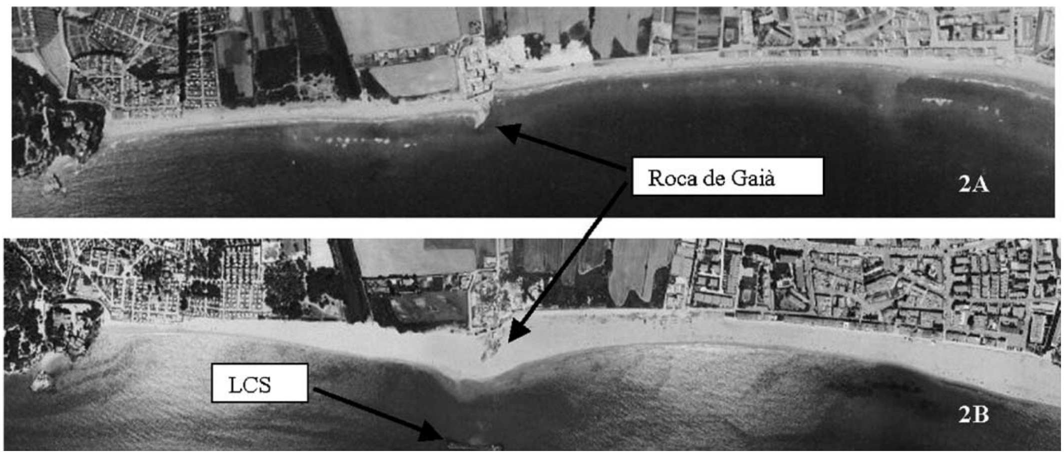

Fig. 12. Aerial view of the Altafulla beach in 1983 (above) and 2001 (below).

ment did not behave as expected and two years later (in 1993), 250,000 m^3 of sand were placed at the East side of the beach, in order to keep the sub-aerial beach surface.

From the original bathymetry of 1989, obtained from previous surveys to the construction of the LCS, there was a nearly rectilinear beach with isobaths almost parallel to the shoreline. The rocky outcrop "Roca de Gaià" located near the middle of the beach interrupted this shoreline. The LCS was constructed at 180 m from the head of the "Roca de Gaià", and the initial distance from the LCS to the shoreline was about 230 m.

4.4.2. Observations and research results

In Altafulla no survey was made during the project, however there is a lot of bathymetric information available from previous studies provided by Toponort (1999) and the Ministry of the Spanish Environment.

In July 1991 (3 months after the first nourishment) significant bathymetric changes and a fast redistribution of sediment near the structure were observed. The presence of the LCS leads to significant bathymetry changes and shoreline response in the "sheltered" area, decreasing water depths and acting as a sediment trap. The distance between the LCS and the shoreline reached an averaged value of 162 m. The outcrop had been by then completely buried.

In December 1993, before the second nourishment, the fast movement of sand (placed in the first nourishment) observed in the first bathymetry after the LCS construction was evolving more slowly: the isodepth of −5 m close to the place where the LCS was constructed in 1991 had moved seaward 88 m while the one of −2.5 m had been softened by the better distribution of the sediment coming from the nourishment in these elapsed years.

The second recharge (1994) introduced an important reserve of sand in the East part of the beach. The 250,000 m^3 of sand introduced in the system helped the beach to avoid scour near the water front, while the sediment movement has continued to move from East to West.

In February 1999 the shoreline was located at 130 m from the LCS, while the beach and bathymetry changes were smoothly shaped behind the structure. The depth at the leeside of the LCS had been dramatically reduced from −3 m in 1991 to less than −1 m in 1999.

In Fig. 13, the first and last available bathymetries are shown. It can be observed how the greatest changes have occurred in the lee side of the structure. The irregularities observed on the right side of the 1991 bathymetry can be attributed to the nourishment made 3 months before the measurements.

Similarly, no wave and currents measurements were performed during the DELOS Project, but several simulations were performed: simulations on idealized bathymetries to evaluate the effect of different wave conditions H_s and θ on the water fluxes and simulations on the real bathymetries of 1992 and 1999 (Politecnical University of Catalunia, 2004). The importance of both parameters in the observed fluxes at the leeside of a LCS has been verified and they seem to be important enough to be considered in the functional design of such structures. Thus, the water circulation in the study area is strongly conditioned by

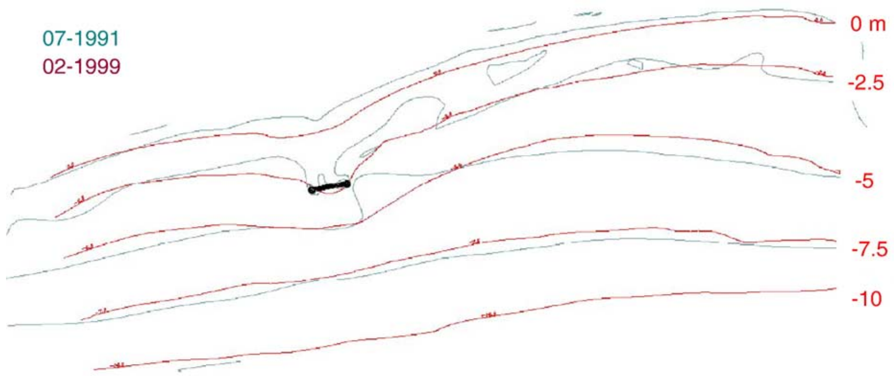

Fig. 13. Comparison between 07-1991 and 02-1999 Altafulla bathymetries.

the angle of wave incidence. For normal incidence there are two eddies at both sides of the structure controlling the circulation while for oblique incidence these eddies are modified due to the presence of longshore currents generated by this oblique incidence. Moreover, if the water mass fluxes are considered, there is an enhancement of the longshore current component close to the coast. If oblique incidence coincides with an increase of wave height then the longshore current cancels both eddies transforming them in a meandering current.

Finally numerical simulations have been carried out with the actual bathymetries of 1992 and 1999 obtaining the circulation pattern around the structure. The bathymetric changes (increase of tombolo dimensions and decrease of depth in the sheltered area) that had occurred between both dates gave rise to a different circulation pattern. The observed changes consisted of different eddies intensities and the displacement of the upper eddy to the sheltered area.

From available observations and simulations we can conclude that the construction of a LCS in the Altafulla beach introduced significant changes in its littoral dynamics, especially immediately after beach nourishments when great amounts of sand were available. A salient has been formed in the leeside of the structure evolving to a situation of dynamic equilibrium at the present.

4.5. Lønstrup (Denmark)

4.5.1. Description of the site, environmental conditions and response to its construction

The map in Fig. 14 shows the location of Lønstrup and a picture of the breakwater is given in Fig. 15. A system of breakwaters is placed both north and south of this site. The breakwaters were built to protect the small village Lønstrup located near the sea and the adjacent beaches from the ongoing coastal erosion caused by the North Sea waves. The most frequent wind direction is from West and South West where the strongest winds also occur. Due to the large fetch in Western direction the waves and the storm set-up is large during autumn storms. If unprotected the coast at Lønstrup will erode 1.5 m/year. In fact during a storm back in 1981 some places were eroded up to 15 m. This event induced the construction of the protection scheme in 1982/1983.

The difference between the water level at mean low and mean high tide is 0.3 m. Storm surge can be around 1.5 m above MSL in the case of storms from West. During storms from the east the water

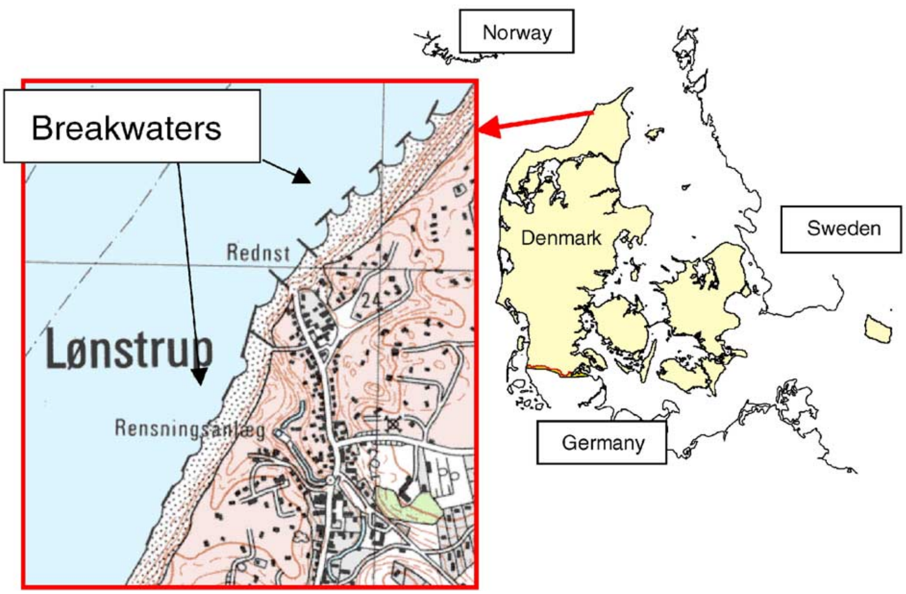

Fig. 14. Position of Lønstrup study site.

Fig. 15. Pictures of the study site at Lønstrup.

depth can be 1.0 m below MSL. The most typical wind is from the West and is very infrequent from the East. The waves are depth limited during storms due to the low water depths at the LCS locations.

The area of interest is being nourished with 20,000–30,000 m^3/y sand between the coast and the breakwaters. The area is a popular tourist and nature spot in Denmark and many summerhouses are located here. The system of breakwaters at Lønstrup is 1100 m long. Each breakwater is 45 m long and is in turn separated by 45 m. All breakwaters have circular roundheads and are aligned parallel to the coast. The system of breakwaters found along the coastline is located sufficiently close to the beach so that tombolo formations are generated. The water depth on the offshore side of the breakwaters is approximately 1 m and the steepness of the bottom slope is approx. 1 : 150. All breakwaters are rubble mound breakwaters. A sketch of a typical cross-section is shown in Fig. 16 (from Laustrup and Madsen, 1994). The level of the crest is seen to be 1.3 m above MSL.

On the West coast of Northern Jutland the current and sediment transport is generally in a Northern direction (indicated by arrows on Fig. 17, left). The coast is eroded and much material is transported from the southwest due to littoral drift on both sides of the spit. More than 1 million m^3 is deposited on the coast in the northern area of the spit every year. At Lønstrup the sediment transport within 10 m water depth is great (approx. 600,000 m^3/year).

Since the construction of the breakwaters the annual nourishment volume has been decided by the needs to maintain the beach. The breakwaters and the nourishment have stopped the ongoing erosion of the cliff at the site securing the village and leaving the beach for recreational activities.

The beach is extensively used for recreational activities, especially for sun bathing and swimming during the summer. Winds and waves are often very light

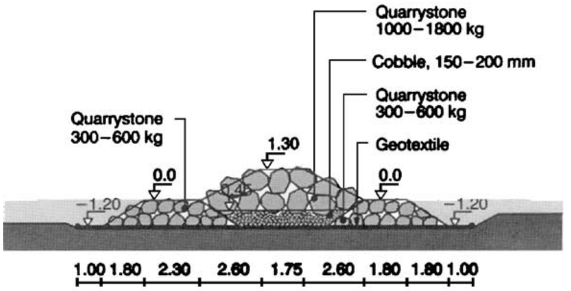

Fig. 16. Cross-section of breakwaters at Lønstrup. From Laustrup and Madsen (1994).

during the hot summer months and the water behind the breakwaters is periodically of poor quality. The limited water exchange seems to trap seaweed behind the breakwaters leaving it to putrefy and making the water smell unpleasant.

4.5.2. Ecological impacts

During the 1st year of DELOS (2001), the composition of intertidal epibiota was assessed at 3 localities (14 structures) on the coast of Northern Denmark. During 2002 the composition of both intertidal and subtidal epibiota were assessed at two of the localities (at 2 larger LCS by 10 transects at depth of 0.0, 0.5, 1.0, 1.5, and 2.0 m). Algae and invertebrates contributed equally to the biodiversity. The structures positioned lower on the shore were dominated by the red algae *Mastocarpus stellatus*, *Chondrus crispus*, and *Ceramium rubrum* as well as by the mussel *Mytilus edulis*, particularly of juveniles (SL $<$ 2 cm), barnacles, and the locally abundant bryozoan, *Electra pilosa*. The distribution of epibiota is significantly related to the vertical position of the structures. Several of the structures were situated higher on the shore, where they were scarcely fringed by the sea. These structures were either bare or sparsely colonised by *Enteromorpha* spp. and juvenile *Mytilus edulis*. The majority of the structures are positioned on sandy shores where rocky substrate is sparse. The presence of partly submerged boulders increases the biodiversity of the epifauna component (including both algae and invertebrates) on the shore. However, the biodiversity increases significantly with increasing depth of the structure.

4.6. Elmer (United Kingdom)

4.6.1. Description of the site, environmental conditions and response to its construction

Elmer is located on the southern coastline of England; it is situated approximately 5 km to the east of

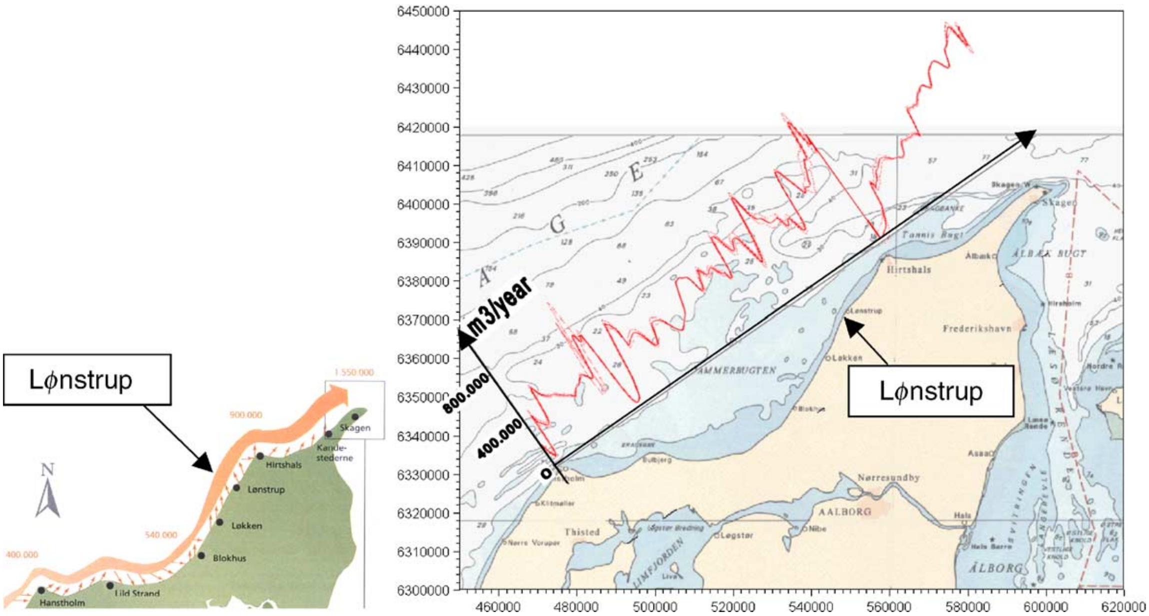

Fig. 17. Sediment transport at the West Coast in the Northern part of Denmark (Kystdirektoratet, 2001).

Bognor Regis, on the West Sussex coastline (Fig. 17) (this frontage is the joint responsibility of the Arun District Council (ADC) and the National Rivers Authority (NRA)). This particular section of coastline has been associated with increasing residential development; this, in turn, has created the need for effective flood control works through coastal protection schemes, resulting inevitably in significant environmental changes. The area is protected, at present, by a segmented offshore breakwater scheme constructed in 1992. The length of the segments range between 80 to 140 mat a distance from the shoreline between 40 – 90 m. In Fig. 18 the cross-section is sketched.

A series of field campaigns were carried out in an effort to assess the hydrodynamic and sedimentary response of the coastal system at Elmer, following construction of the low-crested offshore breakwater scheme. Towards this objective, selected processes acting in the area of immediate breakwater influence were examined (see Fig. 19).

The area is characterized by a simple bathymetric configuration, with the isobaths running almost parallel to the coastline in the nearshore area. The topography of the beach has undergone important changes in the past decades, due to the general erosion trends over the area; this is in response to the construction of a series of seawall and groins, replenishment schemes and the placement of the offshore rock island breakwaters. Following the completion of the final scheme, extensive beach surveys were undertaken, by local authorities and research organizations; this involved, mainly, beach profiling and aerial surveying, in order to investigate the morphological changes that the breakwaters imposed upon the beach. A clear pattern of deposition in the lee of the breakwaters, together with erosion in the bays adjacent to the gaps, was observed during the first 6 months following construction. Over the following 15 months the changes were not as significant, due probably to a certain equilibrium reached by the coastal system (King et al., 2000). The area associated with the first two breakwaters (1 and 2, Fig. 20) showed the most accretion, although salient development was present behind each of the breakwaters. Comparison of erosion records at Elmer beach with similar sites are extremely difficult because of the repeated nourishment taking place in the area without systematic recording of the volume or exact location of the added material (Cooper, 1997).

Elmer is located within a macrotidal environment, with a semi-diurnal tide and a tidal range which increases slightly, on a regional basis, from west to east. The mean spring tidal range is approximately 5.3 m, whereas the mean neap tidal range does not exceed 2.9 m maximum. Spring tidal ranges can reach up to 6 m. The offshore structures are exposed completely at low tide and, during high water they do not become

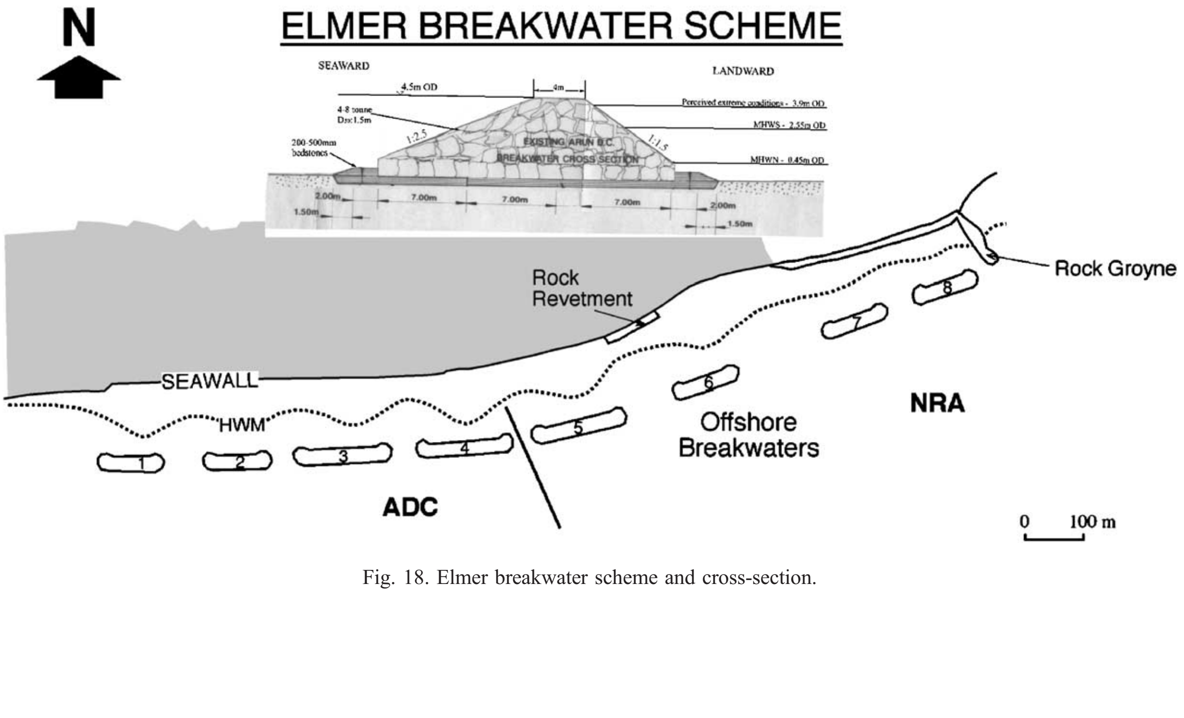

Fig. 18. Elmer breakwater scheme and cross-section.

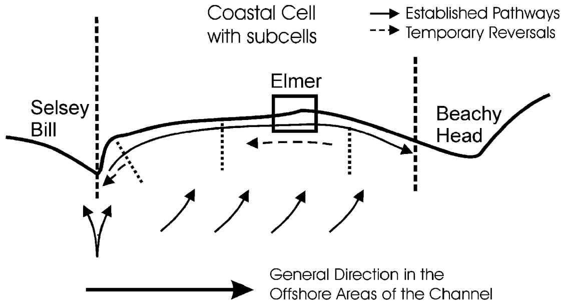

Fig. 19. Regional sediment transport direction in the West Sussex coastal cell (adapted from various sources).

completely submerged. The high tidal range over the area created difficulties in positioning the breakwaters, with respect to the coastline, since there was a need for scheme efficiency (towards protection) during the whole of the tidal cycle.

The wave climate over the study area contributes considerably to the prevailing hydrodynamics; as such, it has formed the main focus of the studies undertaken prior to the construction of the scheme. Some 65% of the waves originate from the south-southwest (segment 180° to 220°) and represent the highest predicted wave heights (up to 5.5m and a wave period of about 7.5 s) (Hydraulic Research, 1994). The waves that reach the coastline at Elmer, from westerly to southwesterly directions, are associated with somewhat smaller heights than anticipated for areas with such a fetch length (the area is open to waves coming from the Atlantic Ocean), due to the sheltering effect of the Isle of Wight.

Digital bathymetric data for the area were provided by Arun District Council. The data consisted of echo-soundings undertaken on 30th May – 3rd June 2001; they covered an area extending approximately 1 km to the west and 3.5 km to the east of the breakwater scheme. In the cross-shore direction, the survey incorporated the bathymetry 50–70 m offshore of the scheme, up to 5 km southwards into the English Channel.

The regional littoral drift in the area is from west to east, as implied by sediment accumulation on the western side of the groins. Elmer is positioned in the middle of the coastal cell that extends from Selsey Bill to the west and Beachy Head to the east, with west to east littoral transport (Fig. 19). In the sub-cell incorporating Elmer occasional reversals of the sediment transport direction have been observed. The coast is losing sand-sized material from the lower part of the beach (Bray et al., 1995). The input of sedimentary material to the macro cell is mainly by beach nourishment and wave-driven shingle and chalk supplied from offshore.

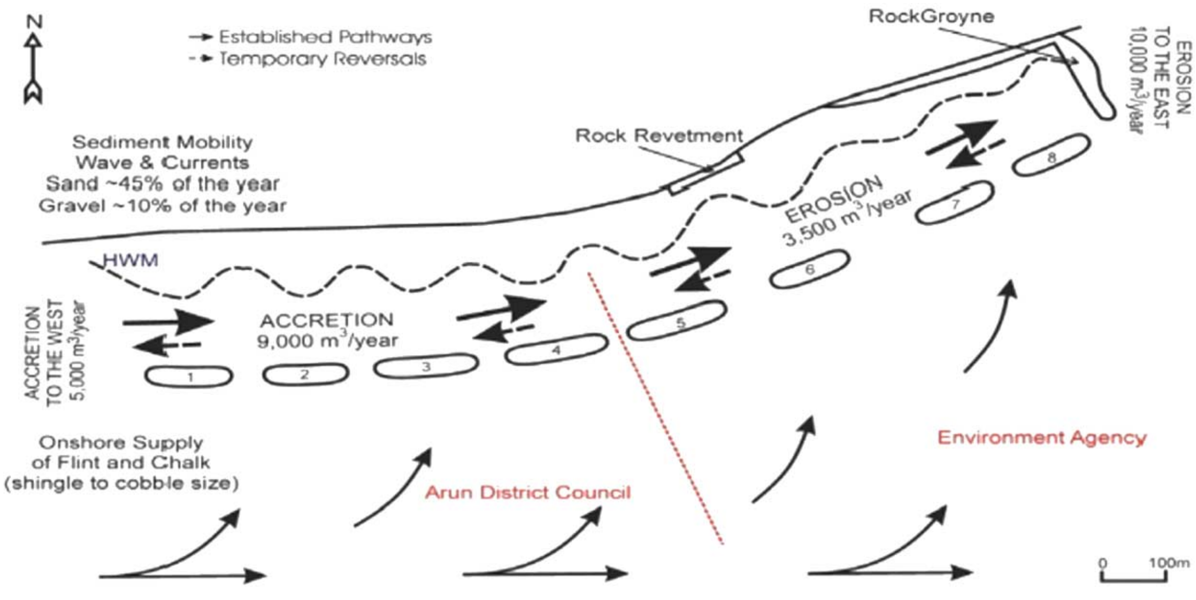

Fig. 20. Localised sediment transport in the vicinity of the Elmer (offshore breakwater) scheme (adopted from various sources).

The salient features associated with the offshore structures have become more pronounced with time; as such, they interact with the regional sediment movement behind the structures (see Fig. 20). Aluminum tracer experiments have revealed that the direction of sediment addition to the salients has varied according to the prevailing wind and, therefore, wave conditions (King, 1996; Cooper et al., 1996). Overall, with the predominant southwesterly waves, net transport directions recorded were from west to east, with recorded rates of up to 2 m^3/day, under the most typical wave conditions. The maximum rate of transport recorded in the lee of the breakwater was 57 m^3/tide (for shingle), during a storm (King et al., 2000). However, this rate of transport, as opposed to that on natural beaches under the same conditions, is an order of magnitude lower; this demonstrates the efficiency of breakwaters in reducing the wave energy that reaches the beach. Fluorescent pebble tracer studies have revealed that sediment in the immediate lee of the breakwaters remained immobile during storm conditions, highlighting the degree of protection afforded by the structures; likewise, their ability to maintain the beach (King, 1996; Cooper et al., 1996).

4.6.2. Observations and research results

Hydrodynamics models, wave models and sediment transport models were performed in order to understand the complex key processes governing the sediment transport in the area. A detail description of the models and of the performed simulations is given in Plomaritis et al. (2004). Field measurements undertaken over the area of interest were used for the calibration of the hydrodynamic model. The resultant tidal currents, in the area of the breakwater scheme, flow in an anticlockwise direction, reaching their peak magnitude during high water, with a direction of around 270° (east–west). The associated net bed-load sediment transport, over a spring-neap tidal cycle over the area, has the same direction as the peak currents. Tidal currents enter the area behind the structures, through the gaps within the eastern part of the scheme; there flow over the salient features, accelerating during high water conditions. Such accelerated flow, over an area of restricted water depth, causes the mobility of the sediment; as such it is probably a controlling factor in the salient growth. The bay area between the breakwaters has low sediment mobility, under tidal currents alone.

Wave diffraction at the gap of the breakwaters was predicted for all weather conditions, as confirmed by the field measurements. Diffraction is the main process decreasing the incident energy on the coast. Wave-induce sediment mobility, estimated using a Stokes 2nd order wave theory, shows the ability of even mild waves to transport the sediment in the direction of propagation of the diffracted wave. The presence of the salient feature provides evidence of the sediment transport pathways.

The sediment trends established for the area (Plomaritis et al., 2003) are in good agreement with the estimated wave-induced sediment transport. For the case of mild energy conditions prevailing over the bay area of the breakwaters scheme, both methods estimate the direction of sediment transport to be onshore. Sediment is directed towards the salients, in the lee of the structures. Closer to the salient features the grain size trend method was used to estimate mobility under high energy conditions; this was once again in an onshore direction, such as during an event with high energy conditions.

In conclusions in terms of hydrodynamic regime, two significantly different hydrodynamic conditions were revealed in response to differences in the incident wave energy. Under low wave energy the tidal currents are dominant; however, flow reversal appears under higher energy conditions (Pope, 1997). The wave-induced circulation pattern observed inshore of the breakwaters (Sterlini, 1997) are characteristic of surface piercing breakwaters with a clockwise pattern, with its core inshore of the gap (Pechon et al., 1997). The sediment mobility behind the structures was found to be reduced in comparison with natural unprotected beaches.

The scheme appears to be successful in protecting the low-lying areas from flooding. However the increasing gap dimensions and the decreasing length of the breakwaters to the east led to the need for further scour protection at the revetment. Further, the east part of the scheme undergoes a net loss of material of 3500 m^3/year.

Downdrift erosion is estimated to be 10,000 m^3/year significantly different from the updrift accession rate of 5000 m^3/year.

4.6.3. Ecological impacts

Effects on sediment in fauna were investigated during two studies, in summer 2001 and 2002, respectively and surveys of fish and censuses of mobile fauna were carried out over the three years of the DELOS project.

The LCS showed several effects on the surrounding environment, including changes in the composition and abundance of sediment infaunal assemblages, increase in diversity of epibiotic species of the area and enhancement of juvenile fish. These impacts, however, tend to be localised on the landward side of the structures and seem to be of reduced magnitude in comparison with other case studies such as Lido di Dante (Italy). This might be due to the high permeability of the structures and the increase in gap length, which allow a higher level of water movement and sediment transport on the landward side. The geographical location and the type of shore, however, are likely to influence the magnitude of these impacts.

The main impact of the Elmer defence scheme is probably represented by the accumulation of seaweed detritus on the landward side. This has a negative effect on the recreational value of the area but could also severely impact the sediment characteristics and the associated infaunal assemblages.

The Elmer defence scheme is apparently a success in terms of protecting flooding and coastal erosion in the area. From a socio-economic perspective, the impacts of the Elmer schemes are counter balanced by the high amenity value created in the area.

5. Discussion and conclusions

LCSs present several advantages with respect to conventional structures, not only concerning the visual impact (which, from the "beach-user's" point of view is very important), but also in that they allow more wave overtopping, enhance the water renovation rates in the sheltered area, and produce higher sediment transport rates.

Despite these advantages, there are still several important uncertainties regarding the functional design and the "foreseen" impact on the shoreline. In order to assess the beach response (tombolo, salient or minimal response) to the placement of a LCS, the various parameters conditioning the functional design of the structure must be taken into account, mainly the relative distance to the shoreline, since this will determine the diffraction pattern in the lee side of the structure and the freebord of the crest. Therefore, the inventory of LCSs, together with the summary of "geometric" features, can be seen as a very valuable tool in terms of amount of information made available for further comparisons between different LCSs and their morphodynamic impact on the shoreline.

Moreover, the database of the geometric features of the LCSs and the shoreline evolution (before and after the placement of the structures) provides interesting information for the calibration and validation of numerical morphodynamic models that simulate the shoreline evolution over a certain period.

During the project, six cases with different geometric characteristics and in wide-ranging climate conditions were monitored to assess the functionality of LCSs.

The climatic conditions of study cases range from Mediterannean with low tidal range to typical Atlantic conditions, such as Elmer, with a very significant tidal excursion.

The geometric characteristics cover 3 LCS families: deeply submerged (Ostia, Pellestrina), semi-submerged (Lido di Dante) and emergent (Altafulla, Lønstrup and Elmer).

The protection layout in Pellestrina has so far given an excellent performance. However, similar LCSs (Ostia) with strong long-shore drift have not performed so well, highlighting the importance of groins.

The semi-submerged LCS (Lido di Dante) offers a good beach protection but water level set up can be high and structure gaps and protruding heads can create strong currents with associated local seabed erosion, meaning that special care is needed and a maintenance program has to be planned.

Sinking and settlement of the LCS was observed in the 3 Italian cases.

Emergent LCSs, such as in Altafulla, favour salient formation or, as in the case of Lønstrup, tombolo formation, depending on the distances of the structure from the original shoreline, and can also create water quality problems in micro-tidal areas.

In macro-tidal beaches (e.g., Elmer) tidal currents can control the salient development and the overall performance of the scheme.

All structures were built with the sole purpose of coastal protection without ecological scope. Consequent variable bio-effects were investigated too and their presence seem to increase the biodiversity of species; the ecological dynamics is strictly correlated to hydrodynamic conditions.

In conclusion, except for the case of Ostia, where an additional intervention to build boundary groins is required (and is now under construction) LCS defence systems seem to work effectively; maintenance works and periodical nourishments are obviously required.

Considering the preference that visitors and coastal inhabitants give to LCSs with respect to different designs, also the social effect would appear to be positive.

Acknowledgement

The support of the European Commission through the DELOS project contract EVK3-CT-2001-00041 is gratefully acknowledged. The lower photo in Fig. 15 was provided by Poul Jacobsen SIC.

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