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# MORPHODYNAMICS OF A GRAVEL BEACH PROTECTED BY A DETACHED LOW-CRESTED BREAKWATER. THE CASE OF LEVANTO (EASTERN LIGURIAN SEA, ITALY)

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**EXTENTED ABSTRACT**

Nel presente studio viene analizzata la pocket beach in ghiaia di Levanto (La Spezia, Italia) e la sua evoluzione morfologica in relazione alla presenza di una barriera sommersa posta a protezione del tratto di costa.

E' noto che la presenza di barriere sommerse determina accumuli di sedimenti nella zona protetta e la conseguente formazione di morfologie cuspidate, la cui evoluzione, posta in relazione con l'intensità del moto ondoso, permette di fornire una valutazione relativa all'efficacia della struttura stessa. Numerosi sono gli studi relativi a tali interazioni in spiagge in sabbia, ma ancora ridotte sono le esperienze riportate in spiagge in ghiaia.

La spiaggia analizzata in questo studio è protetta da due strutture trasversali (pennelli) che suddividono il litorale in tre celle. Unicamente nella cella centrale è stata installata una barriera sommersa. La spiaggia è stata oggetto di un intervento di ripascimento che ha previsto l'immissione di circa 16.000 $m^3$ di materiale di cava opportunamente frantumato e trattato. Lo studio ha interessato le due celle di ponente, che risentono maggiormente dei fenomeni erosivi.

Il programma di monitoraggio della spiaggia è stato condotto con l'uso di una webcam. L'utilizzo di sensori remoti per il monitoraggio delle coste è una delle tecniche ad oggi più all'avanguardia in quanto permette di ottenere in modo continuativo ed in tempo reale serie di immagini dei litorale con qualsiasi condizione meteorologica. Questa tecnica è adatta non solo alla definizione della posizione della linea di riva ed alle sue variazioni nel tempo, ma, più in generale, è atta a definire l'assetto morfo-dinamico delle spiagge e comprenderne la loro tendenza evolutiva.

In particolare, lo studio ha previsto l'acquisizione di immagini 1280x960 pixels, per circa un anno.

Il sistema acquisiva fotografie della spiaggia per tre volte al giorno, alle ore 8, alle ore 12 ed alle ore 16 con una frequenza di 1 minuto per 8 minuti consecutivi. Tutte le fotografie acquisite sono quindi state georeferenziate, rettificate ed elaborate usando il software Beachkeeper plus (Brignone *et alii*, 2008; Brignone *et alii*, 2012). Le immagini Timex e Variance derivanti dall'elaborazione delle fotografie scattate, hanno permesso di visualizzare in modo più accurato e con maggior precisione la posizione assunta dalla linea di riva permettendo anche di calcolare i valori di Run up in corrispondenza dei 3 transetti che sono stati considerati a suddivisione di ogni cella.

Le informazioni ottenute attraverso le immagini, sono state poste in relazione con i dati meteomarini registrati dalla boa R.O.N. di La Spezia, allo scopo di valutare l'evoluzione della morfologia costiera in relazione alle agitazioni ondose. I dati relativi alle giornate in cui si sono verificate le principali mareggiate, hanno permesso di ricostruire l'evoluzione della morfologia cuspidata presente sulla spiaggia a ridosso della barriera sommersa e di valutare l'efficacia della struttura. In particolare, si assiste a tre fasi evolutive della spiaggia, relazionabili con l'intensità dell'agitazione ondosa:

- $H_0 < 0.5$ m: l'opera di difesa interagisce con il moto ondoso determinando fenomeni di diffrazione che favoriscono l'accumulo di sedimento e la formazione della cuspide. Si assiste ad una sostanziale stabilità della linea di riva;
- 0.5 m $< H_0 <$ 1 m: si iniziano a registrare fenomeni di asportazione del sedimento costituente la cuspide;
- $H_0 > 1$ m: la cuspide viene completamente distrutta in quanto la barriera sommersa non è più in grado di contrastare l'azione delle onde ed il sedimento precedentemente accumulato è disperso nella spiaggia sottomarina ad opera di rip currents.

Secondo le formule proposte per le spiagge sabbiose da Ahrens & Cox (1990) e Pope & Dean (1986), con le caratteristiche strutturali della barriera sommersa della spiaggia di Levanto, si sarebbe dovuta formare una cuspide permanente o un tombolo. Tale osservazione mette in evidenza la diversa risposta tra spiagge in ghiaia ed in sabbia alla presenza di tali strutture. Infatti, a seguito delle caratteristiche idrodinamiche del sedimento ghiaioso, nella spiaggia di Levanto si ha unicamente la formazione di una cuspide non permanente.

## ABSTRACT

During the last decades many researches were carried out to highlight interactions between detached low-crested breakwaters and beach morphodynamics. However, up to now, the influence of grain size on beach morphodynamic response to a breakwater has been scantily considered. This study focused on Levanto gravel beach, partially protected by a low-crested breakwater: the beach was observed through a video monitoring system, with the aim of underlining its morphological variations in connection to wave characteristics.

According to collected Run up values, Levanto breakwater effectively protects the beach during mild wave perturbations (Hs < 0.5).

As to the beach's morphological response to the barrier, according to Ahrens & Cox (1990) and Pope & Dean (1986) formulae, a periodic tombolo or a permanent salient should form. Conversely, obtained results highlighted the formation of a periodic salient whose evolutionary phases were strictly dependent on wave height.


***Keywords***: *low-crested breakwater, gravel beach, webcam, salient, Ligurian sea*

## INTRODUCTION

Detached low-crested breakwaters, usually named low-crested structures (LCSs), are commonly used in shoreline protection practice to shelter the coast from incoming waves, alone or in combination with nourishment. In the last three decades such coastal defenses have been widely used in different parts of the world, like USA (Dally & Pope, 1986; Dean *et alii*, 1997), Japan (Ranasinghe & Turner, 2006; Thomalla & Vincent, 2003) and along the Mediterranean coasts (Iskander *et alii*, 2006; Lamberti & Zanuttigh, 2005). The main function of breakwaters is to mitigate incoming wave energy thus protecting the beach. The beach's morphological response to the placement of a breakwater has to be considered during the planning process and in particular, the possible modifications concerning the beach face should be highlighted. Many models and experiments were suggested to explain the relation between submerged breakwaters and waves (Buccino & Calabrese, 2007; Hur & Mizutami, 2003; Jeng *et alii*, 2001; Losada *et alii*, 2005; Ranasinghe & Turner, 2006) and to identify and analyze the beach's morphological response to these barriers (Browder *et alii*, 1996; Dean *et alii*. 1997; Hanson & Kraus, 1991; Hsu & Silvester, 1990; Turner *et alii*, 2000; Zyserman & Johnson, 2002). Interactions between incoming waves and beach hydrodynamic processes can give rise to a tombolo extending from the shore to the structure or a salient extending towards the structure. In some cases a null response reaction is obtained (Wamsley *et alii*, 2003).

Thanks to these studies, conceptual models and numerical predictive expertise for the design of LCSs were created. In particular, many authors identified a few parameters controlling beach response, i.e. the length of the breakwater, the gap distance between adjacent structures, the distance of the structure from the original shoreline and the depth at breakwater structure below mean water level (Ahrens & Cox, 1990; Pope & Dean, 1986). Besides these studies, the influence of grain size on salient or tombolo formation has been scantily considered and no studies have focused yet their attention on gravel beache responses to submerged breakwaters. Higher hydraulic characteristics of gravel, significant infiltration during swash causing uprush and backwash asymmetric motions with a perceptible reduction of backwash transport capacity (Buscombe & Masselink, 2006; Clarke *et alii*, 2004; Kulkarni *et alii*, 2004; Lee *et alii*, 2007; Nolan *et alii*, 1999; Osborne, 2005; Pedrozo-Acuña *et alii*, 2006; Pedrozo-Acuña *et alii*, 2007), offshore sediment movement very limited due to the low efficiency of backwash flow and the predominance of longshore sediment transport are all hydraulic and morphodynamic differences that could be responsible for and influence a gravel beach response to a LCS.

In this paper a gravel beach partially protected by a LCS was studied. The aim is to outline the interactions between the barrier and the beachface under different wave conditions and to highlight differences in beach behavior between protected and unprotected sectors of the same beach.

## STUDY AREA

Levanto beach is located in eastern Liguria region (north-western Mediterranean sea). The beach, oriented NNW-SSE, is originated by the alluvional flat of the Ghiararo stream. It is located in a small bay geographically delimited by two promontories, Punta Gone to the West and Punta Picetto to the East. Therefore it can be defined as a pocket beach (Silvester *et alii*, 1980) (Fig. 1).

The coastline extends for approximately 800 m and it is divided into three sectors by two groins; the western sector (later described as "unprotected sector") (150 m long, 35 m wide) and the central sector (later described as "protected sector") (240 m long, 35 m wide) underwent a slight erosion, while the eastern one (400 m long, 43 m wide) was stable. The western and eastern groins are respectively 40 m and 45 m long. Implemented engineering projects include not only groins but also a detached low-crested structure (LCS). The breakwater, built in the central sector, is approximately 65 m far from the shore and it extends for almost 100 m alongshore. The structure crest is 7 m wide with an elevation of almost 2 m below the low tide. There are two 75 m wide gaps between the breakwater and the lateral groins.

Together with these structures, beach nourishments began to be carried out more than forty years ago. The last replenishment was completed in this site during Spring 2005: the distribution of 16.000 m$^3$ of gravel with grain size of 5 Φ (about 30 mm) was undertaken. The sediment was distributed in the unprotected and protected sectors that had retreated most in the past.

According to Jennings & Shulmeister' scheme (2002) these two sectors can be classified as gravel beach due to their sediment characteristics and their morphology. The unprotected and protected sectors have a shore face steep of 18% and 20% respectively. Here there is almost 30% of sand fraction and 70% of gravel fraction. The range of mean sediment grain size in the swash zone is 1.5÷-3.5 Φ (0.35÷11.31 mm) decreasing from the West to the East and towards offshore up to 3.5 Φ (0.08 mm) (Brignone *et alii*, 2008; Brignone *et alii*, 2012). In particular, a salient formed by a gravel percentage higher than 70% is often found along the protected sector.

Unlike other sectors, the eastern one is very wide, it has a shore face steep of 10% and a percentage of sand and gravel sediments denoting a trend that is opposite respect to the other two sectors. This study focused only on the unstable sectors, both protected and unprotected, in order to study their response to hard structures and storm events.

## MATERIALS AND METHODS

### *Wave data*

From June 2005 to June 2006, wave data were recorded by the buoy installed by the Hydro-Marine National Service in La Spezia (43° 55' 41.99''N; 09° 49' 36.01''E) at a water depth of 90 m. Wave parameters collected every 30 minutes included significant wave height Hs, spectral wave peak period Tp and mean wave direction (www.idromare.it).

As the buoy lies 32 km to the SE of the study area, wave parameters were transposed to the Levanto coast.

In order to depict sea state in Levanto beach, buoy data were entered with a one-hour intervals in a graphic chart, where wave height variations were related to wave direction in order to single out the most important storm events in the analyzed period.

Furthermore, wave height and wave period were analyzed daily to correlate beach morphological variation to sea conditions. During this stage, duration of wave conditions was also considered, in order to highlight a possible correlation between timing in wave variation and beach morphological changes.

### *Image database*

In this study, the morphological behavior of the beach face was analyzed through a video monitoring system (Aarninkhof *et alii*, 2005; Holland *et alii*, 1997; Jimenez *et alii*, 2007; Turner *et alii,* 2004). The image management software used is Beachkeeper, a user-friendly program downloadable from the site http://www.beachmed.eu (Brignone *et alii*, 2008).

The webcam was installed in June 2005 at the top of a building near the eastern part of the beach approximately 16 m above sea level. The camera was pointed toward the western part of the beach and afforded detailed images of unprotected and protected sectors.

From June 2005 to June 2006, images were collected three times a day at 8 a.m., at 12 a.m. and at 4 p.m., every two minutes during a period of eight minutes.

All collected images were elaborated daily through image processing techniques (Aarninkhof & Roelvink, 1999; Alexander & Holman, 2004; Davidson *et alii*, 2004; Holman *et alii*, 1993; Holman *et alii*, 2003). Acquired images were georeferenced and rectified by a Beachkeeper tool converting XYZ real world coordinates in UV image coordinates (Abdel-Aziz & Karara, 1971; Holland *et alii*, 1997; Monti *et alii*, 1999).

Almost 4300 photos were checked and a selection was analyzed to assess the evolution of the gravel beach. Shoreline detection from images was carried out according to the approach suggested by Aarninkhof *et alii* (2003), Plant & Holman (1997), Ojeda & Guillén (2006) and Lippmann & Holman (1989). This technique identifies shoreline as the contact area between still water level and beach face. Furthermore, with the aim of minimizing errors in shoreline detection due to sea level variations, timex averaged images, and not single images (snapshots), were analyzed. Wave run up was also measured on averaged images in order to eliminate variability caused by single waves (Bogle *et alii*, 2001; Bryan & Swales, 2003; Coco *et alii*, 2005).

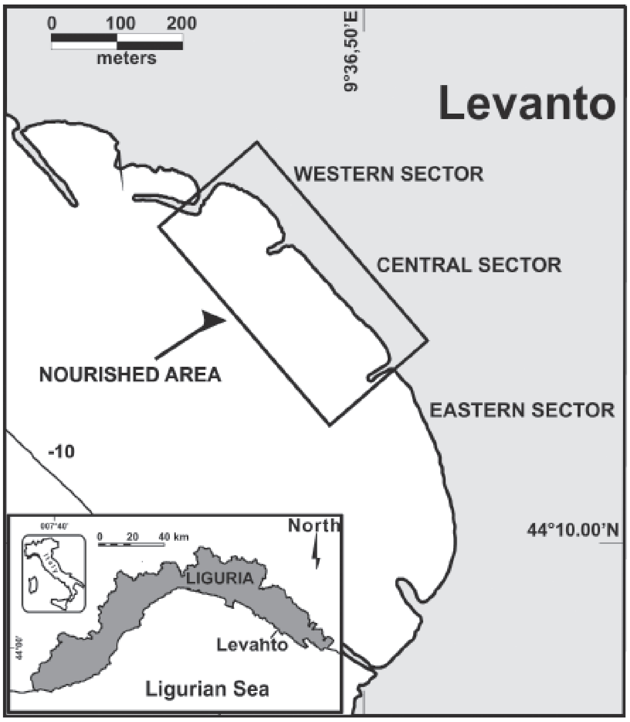


*Fig. 1 - Study area*

### *Data processing*

Unprotected and protected sectors video derived data were complemented with wave conditions in order to interrelate beach variations with wave height, wave period and direction, and also to juxtapose morphological modifications underlying differences or similarities between the response to storm surges of protected and unprotected sectors.

Levanto beach evolution was observed during the most significant storm events through run up analysis and short time shoreline migration. A transect partitioning of the two different sectors, was performed to analyze shoreline displacements in detail. Sectors were divided by means of transepts evenly spaced out by 5 meters and perpendicular to the shoreline. In this study three especially representative transects are analyzed (the 3rd, 7th and 11th transects), lying respectively in the western, central and eastern part of the sectors.

Shorelines were manually digitized on Timex rectified images and their intersection with fixed transects was measured.

Run up was estimated during storm cycle events. The parameter was calculated along the 3 transects in order to assess the functionality of the LCS in dissipating incoming wave energy and its influence on beach morphodynamics. An analysis of detected shorelines morphology was also performed to study its variation in relation to wave height.

In this study tidal correction was deemed unnecessary: in fact Levanto is a micro-tidal area with a maximum tidal excursion of about 30-40 cm (Istituto Idrografico della Marina, 2005).

## RESULTS

### *Wave data*

Collected La Spezia Buoy RON data related to annual wave condition are showed in Fig. 2 Upon a total of 380 days of observation, the frequency of waves coming from SW was 66,5%. In particular, the most frequent wave direction was 240° (23.6%).

The most frequent wave condition, with a 50% rate, is calm water (Hs < 0.5 m). Wave height measures between 0.5 m and 1 m with a 17% rate with a minimum period of 1 sec and a maximum period of 6.5 sec.

Significant wave height higher than 1 m appears on 33% of all cases with a minimum period value of 1.5 sec and a maximum value of 7.5 sec.

Between June 2005 and June 2006, a total of 37 storm events was identified. 18 storms occurred in autumn and winter while 19 in spring and summer. Among recorded events, this study considered the most representative storms for the three main wave directions, namely August 15, 2005, December 3, 2005 and May 9, 2006. In particular, during the August 2005 sea storm, main wave direction was WSW with a significant maximum wave height of 2.2 m, a period of 4.7 sec and a duration of 22.5 hours. December 2005 storm had SSW wave direction with an Hs of 4 m, a period of 6.5 sec and a duration of 144 hours. As for May 2006, the storm had SW wave direction, significant wave height of 2.5 m, a period of 5 sec and it lasted for 22 hours.

Only these storms were considered because of their wave direction and because they supply a complete view of beach response to storm events.

### *Shoreline evolution*

Observing shoreline displacements recorded during the three aforementioned storm events (Tab. 1), the maximum shoreline displacement associated with run up values clearly varied between 2.5 m in the unprotected sector and 3 m in the protected sector when the strongest storm coming from SSW reached its peaks.

Generally, in the unprotected sector, with WSW and SW storm wave directions, Rup values obtained from graphical image treatment are uniform for the whole sector and are similar to calculated values. On the contrary, graphic Run up values for the sector protected by a LCS were higher than calculated values. Furthermore, Run up was higher in the protected sector than in the unprotected sector.

In particular, considering the events of August 2005 and May 2006, with null or very low wave angle of incidence, Run up values were uniform in the unprotected sector. During the same events, in the protected sector graphic Run up was higher than calculated values and than unprotected sector values, reaching its maximum values in the central and eastern part of the sector.

During the December 2005 storm, Run up values trend was slightly different. In particular, in the unprotected sector Run up increased westward and it was clearly higher than during the other events, due to greater wave height. This occurred also for the sector protected by the LCS, where graphic Run up was higher than theoretical run up and increased westward as well, concordant with wave direction.

| Date | $H_{s\ max}$ (m) | Wave direction (°) | Sector | Transect | $R_{up\ min}$- $R_{up\ max}$ (m) | $R_{up\ calculated}$ (m) |
|---|---|---|---|---|---|---|
| August 14, 2005 | 2.2 | WSW | Unprotected | 3rd | 1.3 – 1.6 | |
| | | | | 7th | 1.2 – 1.4 | 1.9 |
| | | | | 11th | 1.4 – 2.0 | |
| | | | Protected | 3rd | 1.0 – 1.3 | |
| | | | | 7th | 1.5 – 1.8 | 1.4 |
| | | | | 11th | 1.5 – 1.7 | |
| December 2, 2005 | 4 | SSW | Unprotected | 3rd | 1.6-2.5 | |
| | | | | 7th | 1.5-2.0 | 3.1 |
| | | | | 11th | 0.7-1.0 | |
| | | | Protected | 3rd | 2.0 – 2.9 | |
| | | | | 7th | 2.8 – 3.0 | 2.3 |
| | | | | 11th | 1.8 – 2.1 | |
| May 9, 2006 | 2.5 | SW | Unprotected | 3rd | 1.6 – 1.7 | |
| | | | | 7th | 1.3– 1.6 | 1.6 |
| | | | | 11th | 1.4 – 1.5 | |
| | | | Protected | 3rd | 1.3 – 1.7 | |
| | | | | 7th | 2.0 – 2.7 | 1.9 |
| | | | | 11th | 2.6 – 2.8 | |

*Tab. 1 - Shoreline displacements for protected and unprotected sectors. $H_{s\ max}$ is the maximum significant wave height measured during considered intervals, $R_{up\ min}$ and $R_{up\ max}$ correspond to the minimum and maximum Run up obtained from images; $Ru_{p\ calculated}$ is obtained from the formula proposed by Mase (1989)*

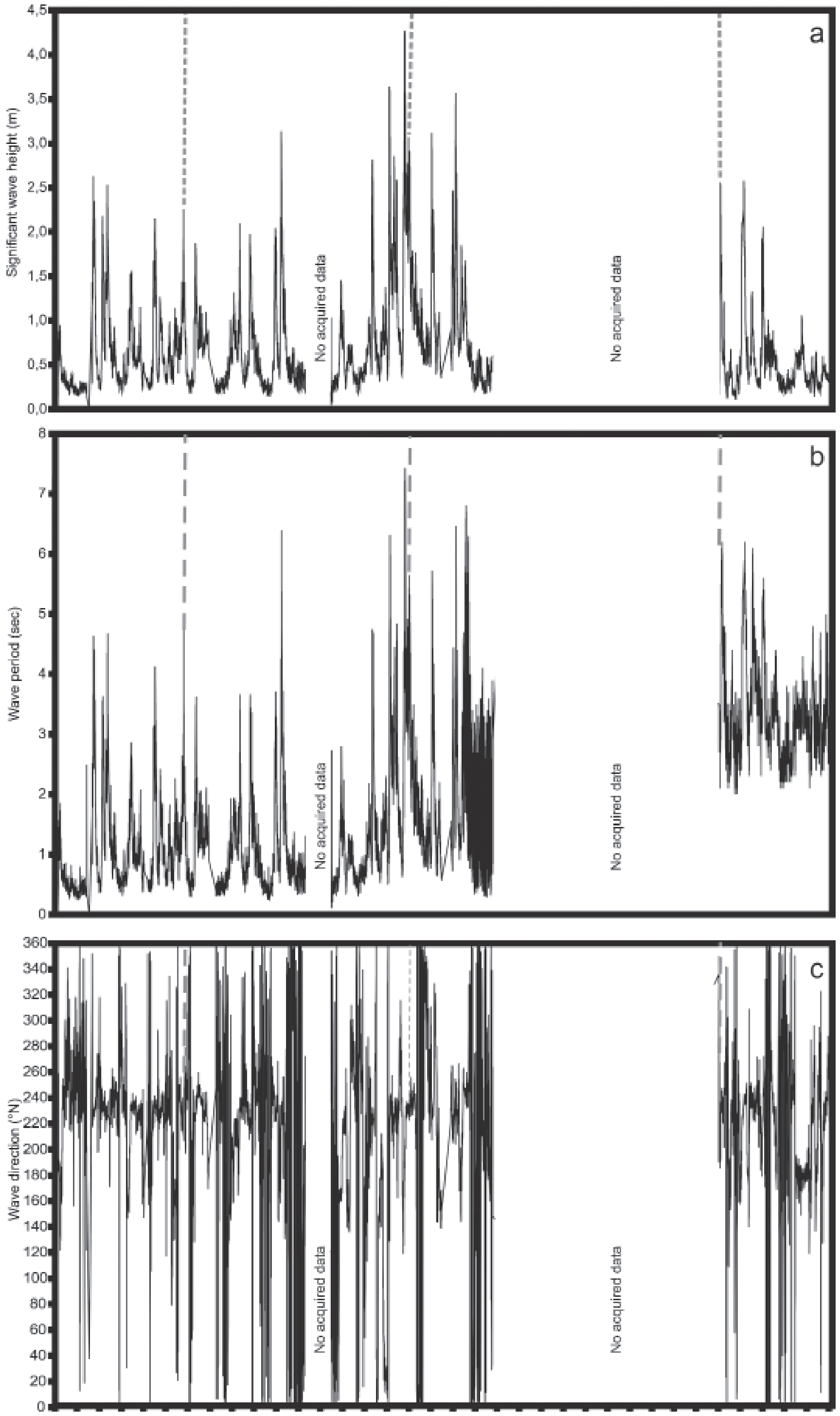


*Fig. 2 - Time series of a) offshore significant wave height Hs, b) peak wave period and c) wave direction during the study period. Observed storm events and cusp appearance considered are indicated by the dotted vertical lines*

Finally, morphological beach face variations were analyzed for the sector protected by the LCS. Images analysis revealed a salient, whose presence and form seem closely tied to wave height values.

In particular, the salient appears in 82% of calm sea conditions (Hs < 0.5 m). When wave height is greater than 0.5 m the structure evolves and its sediments are partially removed; when Hs is among 0.5 and 1 m, the salient can indeed be seen in 17% of observations. When Hs > 1 the salient never appears. Its maximum recorded width is 19 m with NW wave direction, Hs 0.05 m and Ts 3.5 seconds.

In general, a relation between wave direction and salient formation was not evident. The only recorded connection between salient and wave direction concerns longshore displacement. The salient undergoes a longshore transfer eastward with WSW wave direction. In particular, during the August storm (Fig. 3a), the greatest recorded transfer was 25 m. Lesser transfers take place for SW direction. During the May 2006 storm, a transfer of about 14 m was registered (Fig. 3b). As for SSW storms, no transfer takes place as can be seen for the December storm. (Fig. 3c).

Recorded data also highlight beach rotation taking place during sea storms. In the unprotected sector the rotation remains clockwise and is comparatively high during May and August storms, reaching its peak with WSW waves (almost 15°). With SSW wave direction, rotation is instead minimal (almost 3°) and anticlockwise. On the other hand, in the sector protected by a LCS, mild clockwise rotations (almost 3°) occur with WSW and SW wave direction, while, with SSW perturbations, rotation is anticlockwise and greater (around 5°).

## DISCUSSION

This study analyzed morphological and sedimentary behavior of a gravel beach partially protected by a LCS.

In Levanto protected sector, a periodic salient formation is observed. On the basis of defense work features and wave conditions, according to Ahrens & Cox (1990) and Pope & Dean (1986) formulae for sand beaches, a permanent salient or periodic tombolo should form. This therefore highlights a substantial difference between gravel and sand beaches response to the setting up of a LCS. Moreover, in this beach salient presence and/or absence is noteworthy closely related to Hs wave values, and it does not depend on wave direction as assumed by Ranasinghe & Turner (2006). Wave direction determines instead salient position: in fact, the higher the wave angle of incidence, the greater is its transfer. In particular, with WSW or SW wave directions, the salient moves towards ESE or SE.

Obtained data were compared with literature data (Calabrese *et alii*, 2008; Ruol *et alii*, 2003), and a few similarities with sand beaches were noticed.

In Levanto gravel beach a pilling up can be observed during sea storms in the sector protected by a LCS, and it is caused by the structure itself (Calabrese *et alii*, 2008). In its turn, this triggers a rise in run up, which is high not only by the structure, as indicated by Calabrese *et alii* (2008) and Ruol *et alii* (2003), but also and primarily in the beach section near its side openings. This phenomenon is clearly tied to wave conditions, as when wave height increases, Rup increases as well.

Run up values higher than calculated values can also be noticed in the eastern part of the unprotected sector, especially when there are waves with a lower angle of incidence. Therefore, this phenomenon could be correlated to grain size as well as to breakwaters. The predominance of longshore sediment transport and a reduction in cross-shore movements are determined by the following factors: a steeper beach slope, determining more oblique wave breaking points (Austin & Masselink, 2006); higher sediment permeability, causing less return transport (Pedrozo-Acuña *et alii*, 2006); lower gravel mobility due to its size (Wilcock & Kenworthy, 2002).

The presence of longshore movements is confirmed by high rotations recorded for the unprotected sector's shoreline. Such rotations are observed in the sector protected by the LCS only during the strongest storms, while during milder storms lesser rotations take place. As a matter of facts, in these cases a LCS partially interferes with waves, reducing wave energy and altering wave direction. This mitigates longshore currents, the main cause of gravel sediment transport, and thus minimizes shoreline rotation.

Longshore movements also trigger cusp dismantling during high-intensity events, i.e. when the structure makes very little contact with waves. Moreover, during the most frequent wave movements from WSW and SW, water collecting in the eastward sector area generates overwash, a consequent rise in run up and thus sediment loss. The sediment is displaced beyond the groin upstream the foot of the structure, nourishing the eastern sector, that is indeed stable.

On the contrary, when storms are ceasing (1 m < Hs < 0.5 m), favorable conditions for salient formation are created, such as higher wave energy dissipation and diffraction phenomena near the structure. Salient size recorded for this beach is moderate when compared to similar formations arisen on sand beaches (Ahrens & Cox, 1990; Pope & Dean, 1986), due to a higher sediment permeability reducing cross-shore transport.

When the sea is calm, waves cannot transport gravel sediment, and therefore the salient is stable: it cannot increase in size but it cannot be destroyed either.

## CONCLUSION

In order to evaluate the morphodynamic reaction of a gravel beach partially protected by a LCS, 13 months of littoral images were acquired from a coastal video-monitoring webcam. The beach's morphological and sedimentary evolution was analyzed

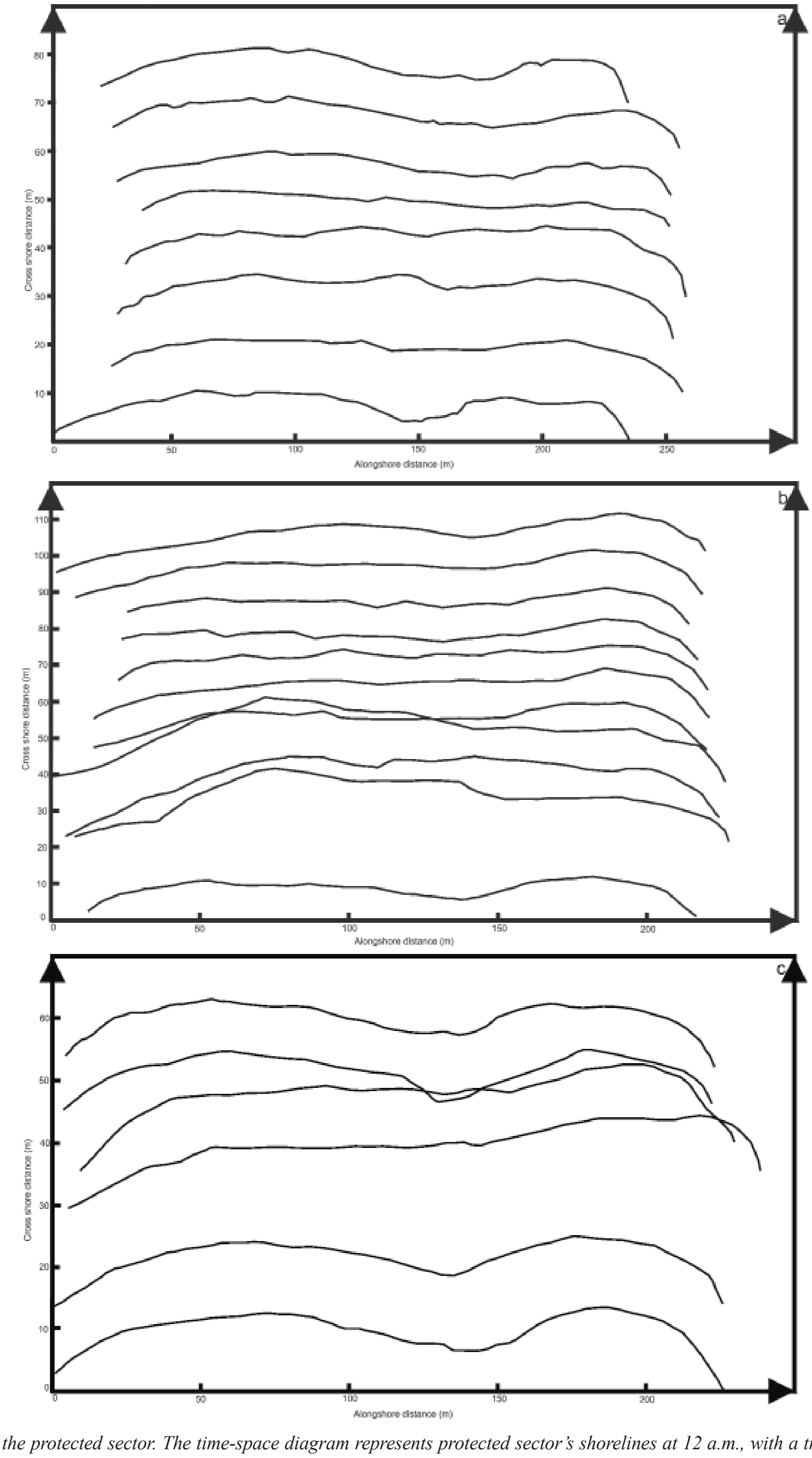


*Fig. 3 - Cusp trend in the protected sector. The time-space diagram represents protected sector's shorelines at 12 a.m., with a translation of 10 m from one another a) on August 12-19, 2005 (from bottom to top), b) on May 7-12, 2006 (from bottom to top), c) on December 2-12, 2005 (from bottom to top)*

under different weather and sea conditions.

This research highlighted morphological and sedimentary reactions of an artificial gravel beach protected by a LCS.

In accordance with literature data concerning sand beaches protected by LCSs, a pilling up is recorded in the sector protected by the breakwater, and not in the adjoining unprotected sector. The LCS also influences a periodic salient formation whose evolution is tightly related not to wave direction but to wave height. Moreover, it was observed that the salient never reaches its theoretical estimated size, therefore never becoming a permanent salient and never causing the formation of a tombolo. This feature must be related to sediment grain size (Mz < -2Φ) causing a limited cross-shore mobility.

Generally, a Low-Crested Structure effectively protects the beach during mild wave perturbations (Hs < 1 m). However, during storms it is not only useless but also detrimental, due to the fact that in such situations the rise in Rup, related also to overwash, enables sediment transport to adjacent sectors.

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