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Journal of Coastal Research	SI 64	35 - 39	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

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ABSTRACT

Bellido, C., Anfuso, G., Plomaritis, T.A. and Rangel-Buitrago, N., 2011. Morphodynamic behaviour, disturbance depth and longshore transport at Camposoto Beach (Cadiz, SW Spain). Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), pg – pg. Szczecin, Poland, ISSN 0749-0208.

The investigated mesotidal beach is located in Cadiz Province (SW Spain). A field experiment on beach recovery including microtopographic changes, disturbance depth, hydrodynamic measurements and sediment transport was carried out during a single tidal cycle on the 8th May 2009. Beach topography was surveyed by means of a RTK-GPS and waves and currents were monitored respectively by a pressure transducer and an electromagnetic current meter. Fluorescent tracers were used to investigate transport and disturbance depth. Tracers were injected at low tide in lower foreshore and sediment cores were gathered at the following low tide. In laboratory, the cores were divided into slices of 2 centimetres and marked grains in each slice were counted under a U.V. lamp. Rods with a loose-fitting washer were also deployed to investigate disturbance depth and microtopographic changes. Longshore transport was calculated for each one of the 2 cm depth intervals as well as considering all the seven investigated layers. The beach showed a well developed berm composed by medium sands which gave rise to an almost reflective foreshore slope (tan β=0.08). Swell waves were observed with mean and significant wave height values respectively of 16 and 20 cm. Shore parallel currents, with north-west directions, were due to the combine effect of waves and flooding tides, and presented mean values of 5.6 cms^{-1}. Accretion processes produced beach profile pivoting, with erosion in the lower and accumulation in the upper foreshore and landward berm migration. Dealing with the disturbance depth, values calculated by means of cores, and loose-fitting washers, respectively recorded average values of 3.3 and 4.3 cm. At Camposoto beach, plunging-surging breakers prevailed in the foreshore and greatly affected bottom sediments which recorded maximum disturbance values of 10 cm. Northwest sediment transport was calculated and evident in the different cores, especially for depth intervals of 0-2 cm and 2-4 cm and the average position of the centroid was about 40 m. The average velocity of the centroid was 0.0012 ms^{-1} that multiplied by the area of the active sand layer (1.4 m^2) gave a volume of 0.002 m^3s^{-1}, these values being in the same order of magnitude of the ones observed in reflective beaches by other authors.

ADITIONAL INDEX WORDS: *recovery, tracer, breaking wave, berm.*

INTRODUCTION

Coastal areas present a great variability in time and space as a response to single or multiple factors. Over time-intervals lower than one year, the principal reason for coastal variation is seasonal variability in wave energy (Masselink and Pattiaratchi, 2001) which can produces erosion during the winter storm events and beach recovery when fair weather conditions prevail (May-September in Cadiz littoral, Anfuso and Gracia (2005).

Daily beach changes and beach morphodynamic behaviour are linked to the interaction of pre-existing beach morphology and incident wave energy and associated currents. Characterization of microtopographic changes during a single tidal cycle are usually investigated by the determination of disturbance depth and longshore transport (Williams, 1971; Sunamura and Kraus, 1985; Anfuso, 2005). Disturbance depth represents the thickness of bottom sediment layer affected by hydrodynamic processes, i.e., waves and currents, during a time span varying from few minutes or hours to a tidal cycle (King, 1951; Otvos, 1965; Greenwood and Hale, 1980; Sunamura and Kraus, 1985; Ciavola *et al.,* 1997).

Determination of the "river of sand" moving upon an unaffected substratum, is important for calculation of longshore sediment transport (Komar and Inman, 1970; Sherman *et al.*, 1990) and for measuring sediment fluxes during a tidal cycle (Anfuso *et al.,* 2000; Phillips and England, 2001). All this information is very useful for properly design engineering structures or nourishment works, i.e., deciding the amount of artificial fill and re-fill volumes, the cross-shore shape of nourished profiles, the timing of nourishment works, etc. (Fucella and Dolan, 1996), or even assessing the importance of beach as a substrate for egg-laying by marine fauna and determining potential vertical borrow of contaminants, for example in case of beach oiling.

STUDY AREA

The study area, Camposoto Beach, is situated in Cadiz Province (SW Spain) and faces the Atlantic Ocean (Figure 1). In detail, the

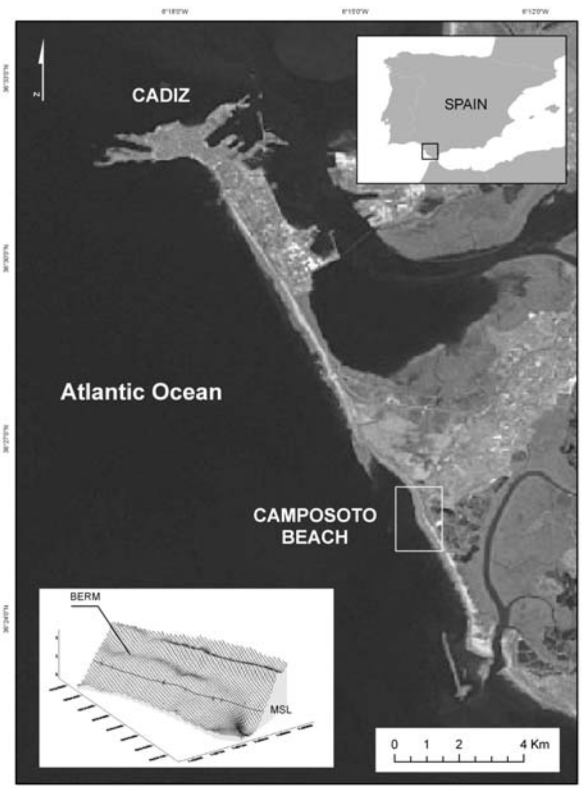

Figure 1. Location map of the investigated area and beach morphology at Camposoto.

investigated beach is located in a littoral spit which consists of quartz rich sand beaches, dune ridges (locally showing washover fans) and salt marshes. The area is mesotidal environment with 3.2 m and 1.1 m of respectively spring and neap tidal ranges.

Western winds are generally related to Atlantic low pressure systems and blow with a mean annual velocity of 16 km/h and a frequency of 13%. East and South East winds have an annual frequency of 20% and mean velocity of 28 km/h, are originally formed in the Mediterranean Sea and greatly increase their velocity due to channeling through the Gibraltar Strait. Due to coastline orientation, western winds give rise to both sea-type and swell waves and eastern winds have no important fetch giving principally rise to sea waves; Significant wave height is usually lower than 1m and, during storms, is about 2.5 m, which classifies the area as a low energy coast. Main longshore drift flows south-eastward.

METHODOLOGY

Camposoto Beach morphodynamic and recovery after winter erosion, was investigated by means of a field experiment that included the monitoring of microtopographic changes, disturbance depth, hydrodynamic measurements and sediment transport during a single tidal cycle on the 8th May 2009, when the beach showed a well developed berm and an important foreshore slope (Figure 1). Beach topography was surveyed by means of a RTK-GPS and waves and currents were monitored during the field assessment respectively by a pressure transducer and an electromagnetic current meter deployed in the surf zone.

Microtopographic changes and disturbance depth, they were measured by inserting in the foreshore beach surface, during low tide conditions, 25 rods with a loose-fitting washer that freely moved along the rods (Figure 2).

Changes in beach surface were related to the top of rods and washers permitted the determination of bed surface scouring or

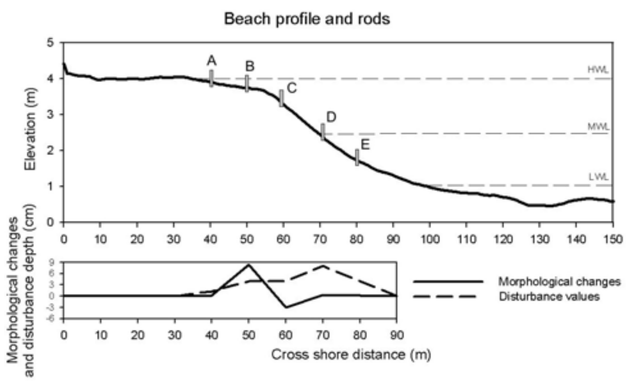

Figure 2. Beach profile with location of rods at Camposoto Beach. Average values of morphological changes and disturbance depth recorded in correspondence with the rods are also presented.

accretion (Jackson and Nordstrom, 1993; Sherman *et al.,* 1994). Rods were distributed in the foreshore on the seaward side and on the berm top, along five profiles 50 m spaced, each profile showing five rods about 10 m spaced (Figure 3).

Fluorescent tracers were used to investigate longshore and cross-shore transport and disturbance depth (Komar and Inman, 1970). Dealing with tracer preparation, during the week before the experiment, a composite sand sample of 20 kg was collected at Camposoto Beach. The sample was washed with freshwater to remove salt content and dried in the open air. Sediment was subsequently marked according to Ciavola *et al.* (1997) using a fluorescent orange paint with no resin to avoid aggregate formation. The sand was then dried on the open air and later sieved using a 2-mm mesh to eliminate aggregates. A subsample of marked sand was sieved and statistical parameters (Folk and Ward, 1957) were obtained in order to compare them with the ones corresponding to natural, no marked, beach sand. At morning low tide, marked sand was injected into a trench in beach foreshore surface after lubricating it with a mixture of water and liquid detergent to avoid grain aggregation and transport as floating sand. During the following low tide, 65 cores of beach sediments were gathered using PVC pipes 20 cm long and 5 cm in diameter (Figure 3). In the laboratory, the cores were split and cut into 2 cm slices. Sub-samples were dried in the open air and weighted using a balance with a precision of 0.01 gr. Marked fluorescent grains in each one of the 2 cm slice were manually counted under a U.V. lamp and results were analysed using the Spatial Integration Method (SIM, Komar and Inman, 1970) for each one of the 2 cm depth intervals as well as considering all the seven investigated layers. The longshore position of the tracer-cloud centroid was obtained by applying the relationship:

$$Y = \frac{\sum M_i d_i}{\sum M_i} \qquad (1)$$

Where *Mi* is the mass of tracer recovered at a distance *di* from the injection point, and *i* is the number of samples. The velocity of the centroid is obtained dividing the distance between the centroid and the injection point by the time between the moment in which water started to disperse tracers and sample collection.

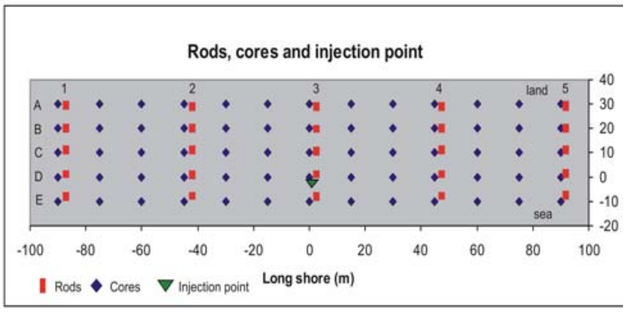

Figure 3. Beach plan view with location of rods, cores and injection point.

Tracers were also used to calculate the disturbance depth which was identified as the interval within beach cores where 80% of the tracer was recovered (Kraus, 1985).

RESULTS

Concerning hydrodynamic parameters, the field assessment was carried out during fair weather conditions characterised by swell waves with mean (H_{bm}) and significant (H_{bs}) breaking wave height values respectively of 0.16 and 0.20 m and 7 and 9 s associated periods. Waves were approaching from SSW directions (5º angle respective to beach) and, breaking with plunging and surging types on the beach face. Shore parallel currents, with north-westward direction, were due to the combine effect of waves and flooding tides, and presented mean values of 5.6 cms^{-1}. No wind conditions at all were recorded during the field assessment.

Beach sediment mean grain size was 1.38 phi (0.38 mm, i.e. medium sand) and marked sand was slightly coarser (1.27 phi, 0.41 mm); nevertheless, comparison of absolute frequency curves for natural and marked sands shows that modal classes are very similar.

Beach morphology, during the field assessment presented in this study, showed a well developed berm composed by medium sands. The berm gave rise to an almost reflective foreshore slope (tan β=0.08) which did not record important changes at the end of the field assessment (Figure 2). Surf Scaling (Guza and Inman, 1975), which predicts the morphodynamic beach state, and Surf Similarity (Battjes, 1974), which predicts the breaking wave type, were calculated taking into account wave parameters and beach slope recorded during the field assessment. Surf Scaling (ε) presented a value of 5 which corresponds to the lower portion of the "intermediate" beach state, it being very close to the "reflective" state - limits according to Guza and Inman (1975): $\varepsilon < 2.5$ (reflective), $2.5<\varepsilon<30$ (intermediate) and $\varepsilon>30$ (dissipative surf zones). Surf Similarity (ξ) presented a value of 1.6 which is characteristic of the upper portion of the plunging breakers interval, it being very close to the surging breakers interval - limits according to Fredsoe and Deigaard (1992): $\xi> 2$ (surging), $0.4 < \xi < 2$ (plunging) and $\xi< 0.4$ (spilling).

Regarding morphological changes, accretion processes, related to swell waves, produced a beach profile pivoting around mean sea level, with erosion in the lower foreshore and accumulation in the upper foreshore. Greater accretion values (about 12 cm) were recorded on the seaward side of the berm and lower values on the berm top and seaward side (about 2 cm, Table 1, Figure 2). At the end of the field assessment the berm migrated about 50 cm landward.

Table 1. Microtopographyc changes/disturbance depth values recorded at rods.

Rods	Long shore profiles				
	Prof. 1	Prof. 2	Prof. 3	Prof. 4	Prof. 5
A	-1 / 3.5	0 / 0	0 / 0	0 / 1	0 / 2
B	12 / 10	5 / 9	8 / 11	12 / 12	5 / 6
C	-2 / 3	-5 / 3	-6.5 / 3	-3 / 3	1.5 / 5.5
D	0 / 8	4 / 9	0 / 10	0 / 7	-1 / 6
E	0 / 1.5	1 / 5	-1.5 / 4	0.5 / 6	-1 / 3.5

Disturbance depth, calculated by means of cores and loose-fitting washer respectively recorded average values of 3.3 and 4.3 cm. In detail, considering values obtained at rods, the thickness of mobilised sediments increased from the low foreshore to the upper foreshore (i.e., the seaward side of the berm) and decreased on the berm top and its landward side (Figure 2). The area of the active sand layer calculated according to disturbance values recorded with rods and loose-fitting washers was 1.7 m^2 (Figure 2). North-west sediment transport was calculated and evident especially in the first and second investigated layers (i.e. for depth intervals of 0-2 cm and 2-4 cm, Figure 4).

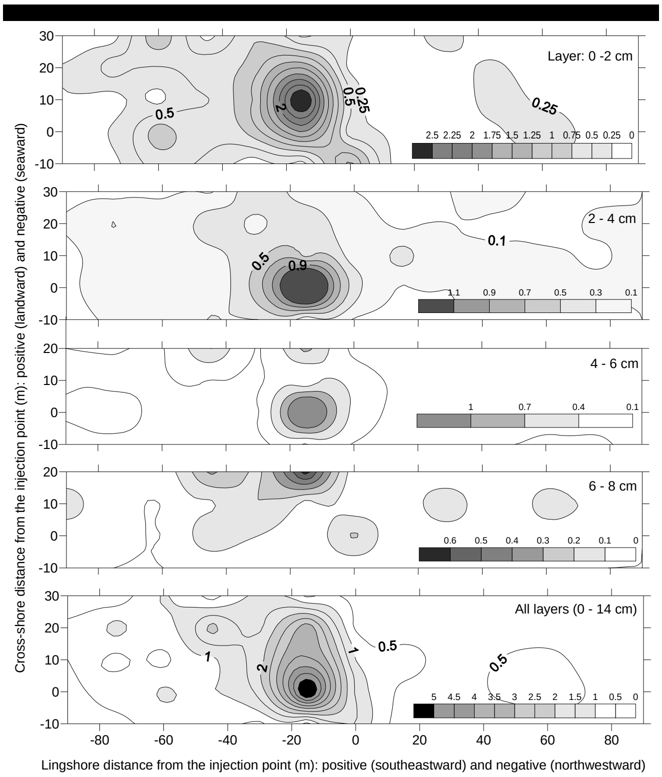

Figure 4. Number of marked grains in 100 grams of samples. Axis refer to the distances from the injection point (0,0).

The average position of the mass (centroid) was calculated as about 40 m, with values ranging from 35 to 52 m.

The average velocity of the centroid was calculated as 0.0012 ms^{-1} that multiplied by the area of the active sand layer (1.7 m^2) gave a volume (Q) of 0.002 m^3s^{-1}.

DISCUSSION

Surf Scaling and Surf Similarity parameters reflected observed beach morphodynamic state and breaking wave conditions. During the field assessment the beach experienced small erosion in low foreshore and accretion in the upper foreshore according to the beach pivoting (at mean sea level) mechanism described by Nordstrom and Jackson (1992). In detail, the field assessment was carried out during a period of beach recovery following the winter storm related erosive period and associated diminution of beach slope from 0.05 (October 2008) to 0.03 (January 2009).

Two main groups of empirical equations relating disturbance depth and breaking wave height exist in literature. By one hand, the one proposed for disturbance and mixing depths for gentle beaches by King (1951), Sunamura and Kraus (1985) and Anfuso *et al.* (2000), in which disturbance depth is about 1-4% of significant breaking wave height; by the other hand, the relation proposed by Otvos (1965), Williams (1971), Jackson and Nordstrom (1993) and Ciavola *et al.* (1997) for steep beaches, with values of disturbance ranging from 20 to 40% of significant breaking wave height. It is interesting to notice as disturbance depth presented at Camposoto Beach great variations according to beach morphology and slope. In fact, as observed by several authors, vertical distribution of disturbance depth depends on various factors like breaking wave height and period, beach grain size and slope and morphodynamic beach state (Anfuso, 2005). Even if these aspects are commonly mentioned in previous studies, usually, obtained empirical relationships only relate mean disturbance depth and breaking wave height. Exceptions to this statement are the works of Ferreira *et al.* (2000) and Anfuso *et al.* (2000). The former related disturbance depth with wave height and beach face slope, while the latter related disturbance with beach slope, grain size and surf similarity index. At Camposoto beach, plunging breakers prevailed in the foreshore and greatly affected bottom sediments which recorded maximum disturbance values of 10 cm.

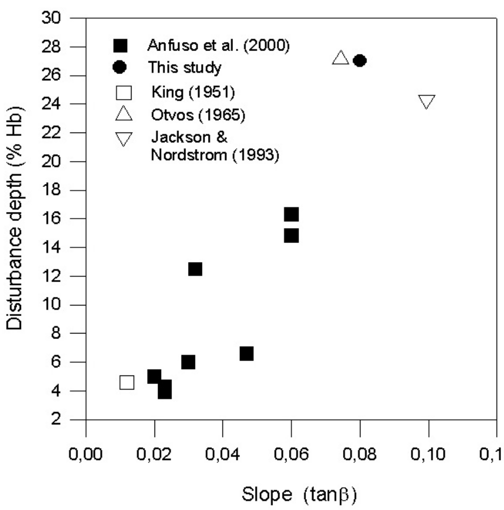

Figure 5. Relationship between disturbance depth (expressed as percentage of breaking wave height) and beach slope.

These results (Figure 5) confirmed observations of previous authors on steep beach faces with plunging breakers (Otvos, 1965; Williams, 1971; Jackson and Nordstrom, 1993; Ciavola *et al.,* 1977; Ferreira *et al.,* 2000).

The obtained longshore transport rate (Q = 0.002 m^3s^{-1}) is broadly similar to the one observed in reflective beaches by Ciavola *et al.* (1998), differences due to the average energetic conditions recorded by previous authors. It is interesting to compare experimental results on sand transport with theoretical formulations, in this sense the volumetric transport rate was used to calculate the immersed weight transport rate (I) in N/s, using the formulation of Inman and Bagnold (1963):

$$I = (\rho_s - \rho)(1 - p)Q \quad (2)$$

Where ρ_s and ρ are respectively sand and seawater density, p is sand porosity and Q the volume of transported sand. Application of previous formulation (eq. 2) to the investigated beaches gave a transport of about 19 N/s, much smaller than the value obtained in similar beaches by Ciavola *et al.* (1998) under average energetic conditions.

Last, obtained information allow stating that beach recovery and berm formation and landward migration at Camposoto Beach is relatively rapid when compared with other beaches of Cadiz littoral. Wave conditions during spring time favoured natural beach recovery; according to this it is possible to state that spring time is the most appropriate period for beach nourishment works in order to enhance beach width before summer, i.e., the tourism season, and favour natural sand mixing processes in order to achieve good, natural sand compaction of nourished sediments.

CONCLUSIONS

A field assessment on disturbance depth and longshore transport was carried out at Camposoto Beach. Investigated area belongs to a natural sand spit and has a great importance from a tourism point of view. In detail the beach suffered huge erosion during winter storms and field assessment was carried out during fair weather conditions to observe and quantify beach recovery.

Camposoto Beach presented an almost reflective profile with a well developed berm. Low energetic conditions recorded during the field assessment favoured sand movement from lower to upper foreshore zone (beach pivoting mechanism), with special accretion at the berm (with maximum values of 12 cm), and landward migration of the berm (with average values of 50 cm).

Disturbance depth was quite important taking into account the observed low energy conditions and it was essentially related to breaking wave type (plunging-surging) and high beach slope values. Longshore transport was calculated by means of fluorescent tracers at seven, 2 cm-thick, layers. A north-western directed transport resulted in all investigated layers, recorded values being similar to the ones observed in reflective beaches by other authors. Last, information obtained during the field assessment permit to state that beach recovery and berm landward migration is quite rapid when compared with other beaches of Cadiz area.

ACKNOLEDGEMENTS

This work is a contribution to the RESISTE Research Project (CGL2008-00458/BTE, Spanish Ministry of Science &

Technology and F.E.D.E.R.) and the MICORE (EU grant FP7-ENV-2007-1-202798) and to the Andalusia Research Group no. RNM-328. This investigation has been partially developed at the Centro Andaluz de Ciencia y Tecnología Marinas (CACYTMAR, Junta de Andalucia-UCA), Puerto Real (Cadiz, Spain).

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