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Monitoring the Nourishment of Santo Amaro Estuarine Beach (Portugal)

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ABSTRACT

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Santo Amaro is a low-energy estuarine beach that has been artificially filled to improve its recreational value. Some 136,000m^3 of sand were emplaced there in 2002 and this paper describes results from the fill performance. The fill lost 25% of the initial volume one year after the placement, especially from the upper portion of the beach. Part of this material accumulated beyond the limiting depth of significant wave action and its redelivery to the beach by wave driven cross-shore mechanisms is hardly probable. The western and eastern portions of the upper beach exhibit contrasting behaviors in both the seasonal and annual changes; the berm in the west compartment is virtually invariant in height, while the eastern one loss elevation. The whole beachfront showed significant retreat of the foreshore soon after the completion of fill works. The ultimate fate of sediment stored in the nearshore is unclear; it may be slowly lost via the ebb-dominated estuarine channel, or driven upstream by tidal eddies in combination with wave-driven oscillatory currents. The estuarine character of Santo Amaro makes it different from oceanic beaches in what respects the significance of a closure depth. The total sediment lost from the coastal system during the first year following replenishment is smaller than the net loss from the placement and is also small when compared with other beach nourishments. Assuming an exponential decay of the sediment loss, one may anticipate that this nourishment will be a successful venture.

ADDITIONAL INDEX WORDS: *Beach fill performance, beach profiles, sediment movement, closure depth.*

INTRODUCTION

The occupation pattern of the Portuguese mainland coast changed in the last decades due to fast development, economic growth and different political constraints, making the coast a powerful attractor. As the coast became more intensely utilized management difficulties grew in terms of mitigation of adverse impacts, and from the 1980's onwards a number of Coastal Management Plans have been implemented to contain or reverse uncontrolled development, regulate uses and define occupation criteria in the littoral fringe.

Santo Amaro is one of the pocket beaches lying along the northern margin of the outer Tagus estuary and adjacent coast (Fig. 1) that felt in full the impact of urban development and growing population in the city of Lisbon. The coast extending to Estoril and Cascais is a high reputation seaside resort since at least the 19th century, due to aesthetic values and climate amenity, and this attracted a progressively increasing number of visitors, which maintain a wealthy industry of tourism. More recently, and especially after the 1970's, the growth of population living and working in the Lisbon area encouraged the consolidation and expansion of former fishing villages or rural communities located in, or at a short distance from, this coast, which are at present coalescing along the shore and expanding further north, changing the patterns of land-use and increasing the pressure on the littoral fringe. In 1998 the Port Authority of Lisbon and the Municipality of Oeiras prepared a management plan of the littoral ribbon under ward of both authorities, which specifies sites requiring restoration or beneficiation, and Santo Amaro is the first case where an integrated project moved from the drawing board into practice. The works started early in 2002, were completed in that summer and included beach nourishment. This paper provides results on morphologic and volumetric changes after the infill and comments on the morphodynamic behavior of the beach during the first year following the replenishment works.

STUDY AREA

General Setting

The Santo Amaro beach sits 20 km west of Lisbon, encased in a low-cliffed coast cut in Mesozoic limestones that limits the northern margin of the Tagus outer estuary and is bordered to the north by a seawall, constructed to protect a marginal motorway (Figure 1). The native beach was sandy and extended for some 700 m between the rocky shoals and stacks margining the Forte das Maias point, to the east, and the outlet of Ribeira da Lage, to the west (Figure 1B). This outlet separated the beach from a starved, steep-sloped shore platform, which extended further west until it merged with the cliff-toe. The western section of the subaereal beach, elongated NE-SW for 400 m retained the majority of sediment, with a summer berm reaching a maximum width of 50 m (Figure 1B,C). Eastward, the beach was thinner, frequently overwashed and aligned with the dominant ENE-WSW trend of the seawall, a berm developing only in prolonged fair weather conditions and not exceeding 20 m in width. Between the eastward end of the sand beach and Forte das Maias point the coast is rocky and non-depositional for some 100 m, in association with high-turbulence at the head of a rip current, which persists throughout the year and secondarily feeds an ebb-dominated eddy.

The sea floor margining the beachfront slopes 3 - 4% between the 0 m (ZH Hydrographic datum, lying 2.08 m below mean sea level - msl) and 5 m contours and, further away from the shore, increases to 8 - 16% between the 10 and 18 m contours, where the bottom merges with the northern margin of one tidal channel.

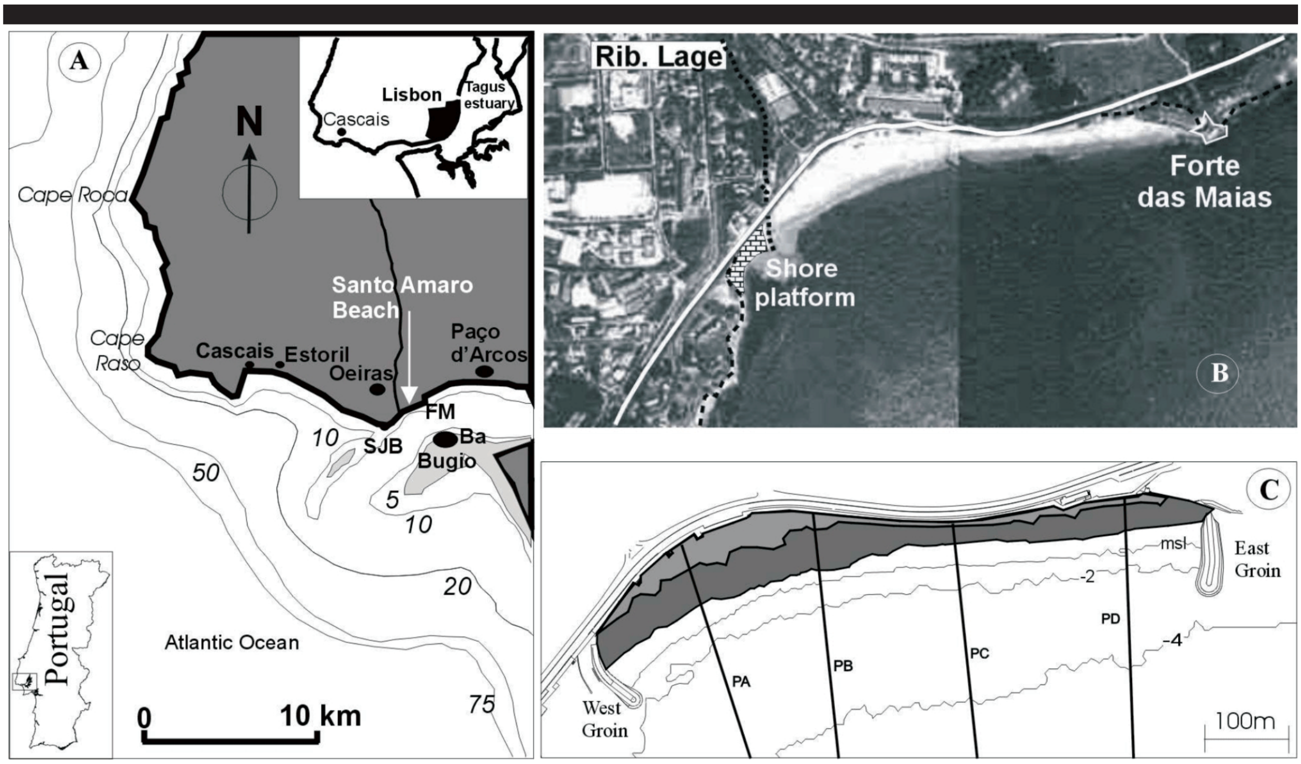

Figure 1. A Location map and study area; SJB S. Julião da Barra; FM Forte das Maias; Ba borrow area. B Aerial photography of Santo Amaro beach in natural (pre-fill) condition. C The beach in pre-fill (2001 light grey) and post-fill (June 2002 dark grey) situations, PA to PD control profiles.

Sediment

The sole source of sediment for the Santo Amaro beach is the Ribeira da Lage stream (Fig. 1), which drains a 38 km^2 basin, mostly incised in Cretaceous carbonate and Eocene volcanic rocks, implying poor textural compatibility between sediment eroded from the watershed and beach sand. The total area drained with potential to supply sand to the shore has been further reduced by urban consolidation and expansion, and represented less than 1/3 of the watershed in 1993, a figure that continued to diminish until present. The report of APL (2002a) indicates $1x10^4$ m^3 yr^{-1} as a reasonable estimate of the long-term average rate of sediment supply associated with this stream in natural conditions. However, works aiming to control stream flow and flash floods accompanied urban expansion and created sediment traps along the stream; thus, at present, its transport capacity is significantly reduced. The comparison of texture of stream sediment and soil of the drainage basin with beach material (Fig. 2) suggests that less then 1/3 of stream-sourced solid load is actually able to mix and remain in equilibrium with beach sediment.

Tides and Waves

The Santo Amaro coast is high-mesotidal acording to Hayes (1979) (Table 1). Spring tides almost reach 4 m in both elevation and amplitude, thus providing considerable vertical exposure to waves, which, in this place, contrast in energy with the west coast. Tidal currents are intense in the vicinity of the beach: circa 0.5 m s^{-1} close to the beach face and 0.75 and 1.5 m s^{-1} between the 10 and 15 m contours, during flood and ebb, respectively (APL, 2002a). The ebb currents dominate this area of the outer estuary and the eddies generated within the Santo Amaro embayment reflect this dominancy, producing a residual current field which whirls clockwise, sweeping the nearshore upriver and then flushing away from Forte das Maias, perpendicular to the shoreline, into the main current stream.

The wave regime offshore the western coast is high-energy, characterized by modal WNW to NW swell, with mean annual significant height and period of 2.2 m and 7 s, the peak period averaging 9-12 s (PIRES, 1985; BARATA *et al*., 1996; COSTA *et al.*, 2001). Storms are frequent during winter, emanating primarily from NW and W, and secondarily from SW. Storms typically persist between two and eight days, raising 5 to 8 m waves. In the vicinity of the Tagus' outer estuary this wave climate is strongly disturbed and energy levels are reduced. One relevant disturbance relates with the pronounced coastal offset north of the estuary, which provides sheltering regarding waves approaching from NW; another disturbance associates with the drowned sand bulge that includes the river's paleodelta forming most of the outer estuary, which is at present crowned by the large intertidal swash-bar complex of Bugio.

These disturbances affect the incoming oceanic waves inducing early breaking, refraction, diffraction and dissipation and changing the directional properties of the wave spectrum that eventually may find their way through the sand banks and ultimately reach the sheltered estuarine beaches. In this respect, the S. Julião da Barra (SJB) point is an important boundary, separating the western domain of the estuarine coast from the more exposed ribbon until Cape Raso. Sheltering is relevant east of SJB and grows further upstream.

ANDRADE and BARATA (2001) computed wave energy in near-breaking conditions just west of SJB point and estimated that the mean yearly wave power density is here one order of magnitude lower than in the offshore; the reduction in energy grows eastward and results in lower height of modal waves (<1 m); notwithstanding the accentuated sheltering this mild wave regime is disturbed by short lived winter storms, consisting of waves approaching the estuary from a limited directional range, which find their way through the main channel and finally break almost parallel to the shoreline with 2-3 m maximum height. The study of nearshore wave climate (APL, 2002a,b) is limited in information and suggests that the plan shape of the Santo Amaro beach is in a quasi-equilibrium condition with the prevailing waves, notwithstanding the possible existence of a net, small magnitude, westward drift.

Table 1. *Tidal data for Santo Amaro beach (IH, 1987).*

Elevation (m) above vertical datum (ZH)						
High water			Mean sea level (msl)	Low water		
Max	Mean			Mean		Min
	Spring	Neap		Spring	Neap	
3.9	3.4	2.7	2.1	1.5	0.8	0.3

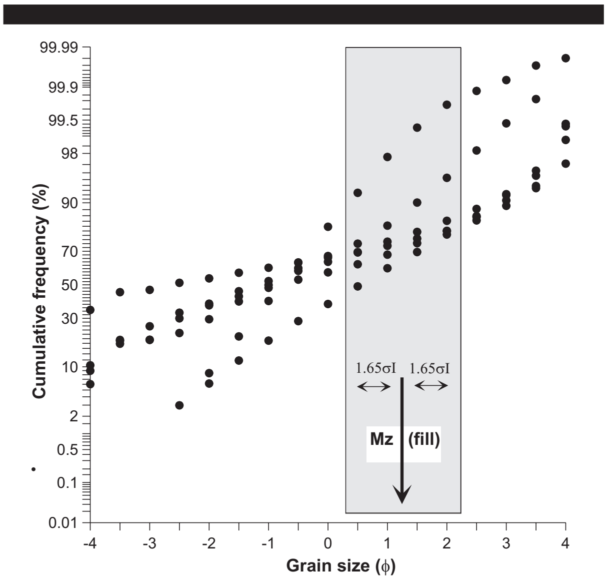

Figure 2. Comparison of texture of watershed (solid dots) and fill sediment; shaded area represents 90% (Mz±1.65σI) of the size distribution of the average fill sand centered in the mean diameter (Mz).

The Project

The beneficiation project was undertaken to improve recreational use and consisted in the construction of a 5 m-wide promenade along the backbeach (seaward of the motorway), relocation and amelioration of existing facilities and widening of the beach berm. The latter was primarily required to increase the accommodation capacity of the beach, estimated in 5,400 users in 2001 (APL, 20002a); to comply with this objective, the surface and width of the post-fill beach at mean sea level were required to grow a minimum of $2.3x10^4$ m^2 and 30 m, respectively (i.e., 54% and 35% of the pre-fill area and width) (APL, 2002a,b). Secondarily, this would replace the surface loss resulting from the construction of the promenade and counteract a slight erosional trend, established in this beach - such as in all pocket beaches of the Oeiras-Cascais reach - throughout the last 30 years and probably related with the decreasing intensity of stream sources. In addition, two groins were projected and constructed, to contain laterally the beach fill and to minimize longshore leakage of sediment, thus aiming to maximize the life expectancy of the placement. The eastern groin is 80 m long, its head sitting 4 m below msl; the western groin was initially designed and constructed 115 m-long, its tip resting 2 m below msl; a late reformulation of the project lead to a cut of its extremity in 35 m and thus it has been reduced to 80 m, with the head resting slightly below msl. The projected fill consisted in 152,000 m^3 of sand, which has been dredged from the shoals of the outer estuary (Fig. 1A) offloaded and placed in the back-berm of the native beach following the "berm-only" design (SMITH and JACKSON, 1990) and using the rainbow method. The sand has been further redistributed with bulldozers to comply with the design of an overfilled prism, topped by a surface with mean elevation of 6 m above ZH, slightly tilted eastward to counteract the anticipated counterclockwise net drift of sediment, the elevation dropping from 6.40 m to 4.60 m (ZH) between groins in all cases exceeding the maximum predicted High Water Spring elevation by more than 0.4 m. The crest of the artificial berm projected seaward with average and maximum design widths of 100 and 120 m, respectively. Seaward of the fill crest an oversteeped beach face was designed and constructed, with an initial slope of 1:5 (Fig. 1C).

The project assumed similar size range between native and borrow sediment and recommended the latter to be slightly coarser than the former; it anticipated a phase of intensive erosion of the placement in the months immediately after replenishment, followed by a pronounced decline in the rate of sediment loss, which was expected to diminish asymptotically after one or two years; eventually, it would merge with the long-term erosion rate or establish a new condition of steady state equilibrium; this was predicted to occur after redistribution of eroded material in the nearshore, leading to a seaward translation of the submarine profile, with slopes remaining invariant down to a closure depth of 5 m (ZH) (APL, 2002a,b).

METHODS

The monitoring plan of Santo Amaro´s beach departed from an existing topohydrographic survey characterizing the native beach shortly before the initiation of works and a second survey of the subaereal and submarine beach performed by the contractor just after completion of the works, in June 2002. Between June 2002 and February 2003 only qualitative inspection of beach changes was performed. Two additional hydrographical surveys have been undertaken by the Port authority in March and June 2003, using the *Guarda-Rios* launch, a vessel equipped with a high-performance Trimble DSM 212 DGPS receiver for positioning, a Simrad EA-400 echo sounder for depth measurements and a portable computer with Trimble HydroPro Software to collect and integrate all data. The Hydropro software was also used for data processing and editing and to export the resulting data to Autodesk Land Desktop and Surfer v.8, to calculate, produce, view and plot hydrographic maps. During hydrographic surveying the tidal level was monitored at Paço d'Arcos tidal gauge. Synoptic topographic surveys of the suabaereal beach have been undertaken in March and June 2003 using a Sokkia 72B total station and the resulting data have been blended with the hydrographic information to produce composite topohydrographic maps.

In addition, from February until July 2003, four cross-shore control profiles spaced 200 m apart in the subaereal beach have been repeatedly surveyed in low tide, each profile starting at the seawall and extending down to ZH. Profiles were taken using a Zeiss Elta R55 total station, on a periodic basis and immediately after storms (Profiles PA to PD, Fig. 1C). Profile A samples the western section of the beach with the widest berm and higher backshore; profile B represents the central beach area where the general trend of the berm crest changes; profiles C and D represent the eastern beach area, where the berm is smaller in length.

Sediment from the upper layer at the mid-tide point of the beach face was collected at each profile, yielding a total of 29 samples, and the slope of the beach face measured with a Brunton compass; additional samples of the berm (5) and low-tide platform (3) have been occasionally taken. Sediments have been processed for grain size using conventional sieving methods. The contractor supplied grain size data on one single sample of the native beach and on a second one of the dredged sediment. These were considered insufficient for textural characterization and thus, four additional samples of the native sand have been retrieved after completion of the filling works using an Edelman auger, which was driven below the pre-fill surface; five other sand samples, previously collected during the works of reshaping of the placement, were also processed for textural characterization of the fill.

RESULTS AND DISCUSSON

Textural Readjustment and Slopes

Among the stability and performance criteria for beach filling forwarded by several authors (e.g. SPM, 1984; CERC, 1995; DEAN, 2002 and references therein) the adjusted overfill ratio (R_A) and the renourishment factor (R_J) introduced by JAMES (1975) and discussed in SPM (1984) and CERC (1995) are perhaps the most widely used to evaluate the effects of textural mismatch between fill and native materials. The use of these parameters is based upon the assumptions that the native sediment was in equilibrium with the local environment and that sorting of borrow material will change with time by wave reworking until it eventually matches the size dispersion of the native sediment (assuming both follow log-normal grain size

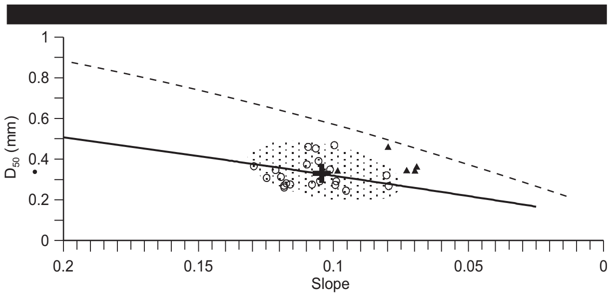

Figure 3. Plot of median grain size *versus* slope of the foreshore at Santo Amaro (post-fill, 2002/03) and comparison with average equilibrium conditions of low-energy (solid line) and high-energy beaches (dashed line) (KOMAR, 1976). Solid cross - centroid of plot; solid triangles - post-storm situation; shaded elipse boundary of plots corresponding to fair-weather.

distributions). In this study these factors were applied to assess the extent of fit between assumptions on texture underlying the project design and the nature of the sediment fill used.

The textural analyses of the native beach material revealed that it consisted essentially of moderately well sorted medium sand, virtually free of silt and clay. The mean grain size ranged between 0.85 and 1.46ϕ (average 1.16ϕ) and sorting values ranged between 0.59 and 0.70ϕ (average 0.66 ϕ). Fill material was found to consist also of moderately well sorted clean medium sand but slightly finer and better sorted on average: the mean grain size ranged between 1.08 and 1.47ϕ (average 1.25ϕ) and sorting values ranged between 0.37 and 0.82ϕ (average 0.59ϕ). The average figures of mean grain size and sorting were taken as descriptive statistics of composite samples of both native and fill materials and applied to the formulae given in CERC (1995) for calculation of R_A and R_J factors. The fill factor R_A was determined as 1.4 m^3 of fill material required to produce 1 m^3 of beach material in equilibrium with the natural beach; the plot of R_A value falls in quadrant 4 of the SPM (1984) nomogram, yet close to the origin of co-ordinate axis, suggesting that instability exists but not to a great extent. A value of 1.25 was obtained for the renourishment factor R_J, indicating that refill should not be required soon after emplacement. In fact, the figures obtained for both factors differ substantially from the values of $R_A>5$ and $R_J>7$ quoted as limits of impracticability of beach replenishment (CARTER, 1988).

The textural results also indicate that equilibrium slopes of the artificial beach will be smaller than projected, given the empirical relations between fall velocity of grains (an indirect measure of grain size) and slope of the foreshore (KOMAR, 1976). The plot of grain size versus foreshore slope agrees with the equilibrium curve of low-energy beaches depicted in KOMAR (1976) (Fig. 3). The plot is elongated parallel to the abscises axis, indicating that seasonal variation of the profile in response to higher energy events is essentially absorbed by readjustment of slope, rather than by changing grain size characteristics. The equilibrium slope of the nourished beach ranges between 0.125 and 0.08, averaging 0.10.

During storm events, the beach face is less steep, reaching a minimum of 4º; during swell conditions, its slope increases to a maximum of 7º. It is worth to note that the equilibrium thresholds found in both the intertidal and subtidal zones of the foreshore (beach face and low tide platform) plot in continuity in Fig. 3, suggesting that the afore-mentioned relations stand in the submarine section of the active beach, which is in agreement with reasoning forwarded in MARTINEZ (1987). Using the relationships depicted in figure 3, the equilibrium slopes in the native beach (D50 ≈ 0.45 mm) may be computed as averaging 0.14 - 0.17 and thus were steeper than in the nourished beach. The equilibrium slopes of the filled beach are also smaller than the slope of the bottom away from the shore: this suggests that any sediment lost from the fill during high energy events and eventually transported beyond the depth of seasonal bottom disturbance by wave action will hardly return to the shore, given that critical equilibrium conditions are exceeded there.

Morphologic and Volumetric Changes

Field observations indicate that the nourished beach maintained the pre-fill predominant reflective morphodynamic setting throughout the first year following replenishment, similar to the "fully-reflective" condition of SHORT (1999), which is in agreement with modal waves less than 1 m and medium sand. The surf zone is virtually inexistent and waves break by surging at the beach face or over a plunging step at its toe. Short-lived excursions to the "Low-tide terrace" stage (SHORT, 1999) have been observed during storms with waves exceeding 1.5-2 m; storm waves eroded and scarped the beach face and berm at an elevation dependent on tidal stage and wave height; sediment washed from the berm and beach face was redeposited in a bar running parallel to its toe, from where sand returned quickly to the upper foreshore, shortly after the storm fade away. This sand was first modeled in the form of a single cusp system, which welded to the highest location of the foreshore affected by erosion and later the cusp's troughs slowly filled to smooth the upper foreshore's morphology. During moderate to high energy conditions, westward drift has been observed at the beach face, indicated by obliquity of swash and in cases by rotation of the cusp horns downdrift, which, in this case generated a saw-tooth rhythmic morphology. During storms, cusps were obliterated and waves were seen to spill or plunge at some distance from the beach, beyond the tip of the western groin and regardless the tidal elevation, indicating that storm-induced longshore drift bypasses this structure. On the contrary, the eastern groin was observed to extend seaward of breaking waves in all conditions.

The expression of seasonal changes in beach profiles is summarized in figure 4. In general, all profiles show a seasonal envelope of change contained within the pre- and post-fill boundaries and the eastern section of the beach shows larger seasonal variation. In all profiles, the portion extending landward of the 4 to 5 m depth Contour retains most of the morphological changes, which are more apparent landward of the ZH, in contrast with their deeper portion, where variations are subtle. Thus, the depth of 5 m (ZH) may be taken as a first estimate of significant disturbance of the nearshore by wave action, i.e. as a closure depth of the beach at a seasonal time-scale of observation.

Profiles PA and PB exhibit virtually no seasonal changes in the elevation of the berm. The beach face changed in slope in response to varying energy conditions and the concomitant formation and vanishing of a low-tide bar was more neatly observed in PA. In both cases, the berm edge experienced persistent retreat during the first year following replenishment.

Profiles PC and PD show identical responses of the beachface slope to fair weather and storm conditions but differ from the former profiles in the larger dimension of seasonal changes and landward extension of storm influence; actually, the earlier storms, which were unable to flood the western section of berm, extensively overwashed its eastern portion, removing sediment from the fill and lowering the back beach up to the seawall. In consequence, the elevation of the eastern berm diminished and it became subject to flood during spring tides, even with small to moderate waves. Given the presence of the promenade and seawall, the upper beach in PC and PD could not retreat or adjust to wave forcing and overwash lead frequently to the obliteration of the berm, the whole profile reducing to a low-gradient slope.

During fair weather, an ephemeral yet narrow and cuspate berm reformed, but failed to further accrete vertically; thus, a step has formed between the western (higher) and eastern (lower) surface of the berm, whose limiting boundary was observed to have slowly migrated west, until midsummer 2003. From this time onwards profile PD showed pronounced widening of the berm close to the eastern groin. This is interpreted as representing limited eastward drift at the eastern extreme of the beach following slow landward migration of sediment from the shallow nearshore, in water depth less than *circa* 5 m.

At present, the average elevation of the eastern berm

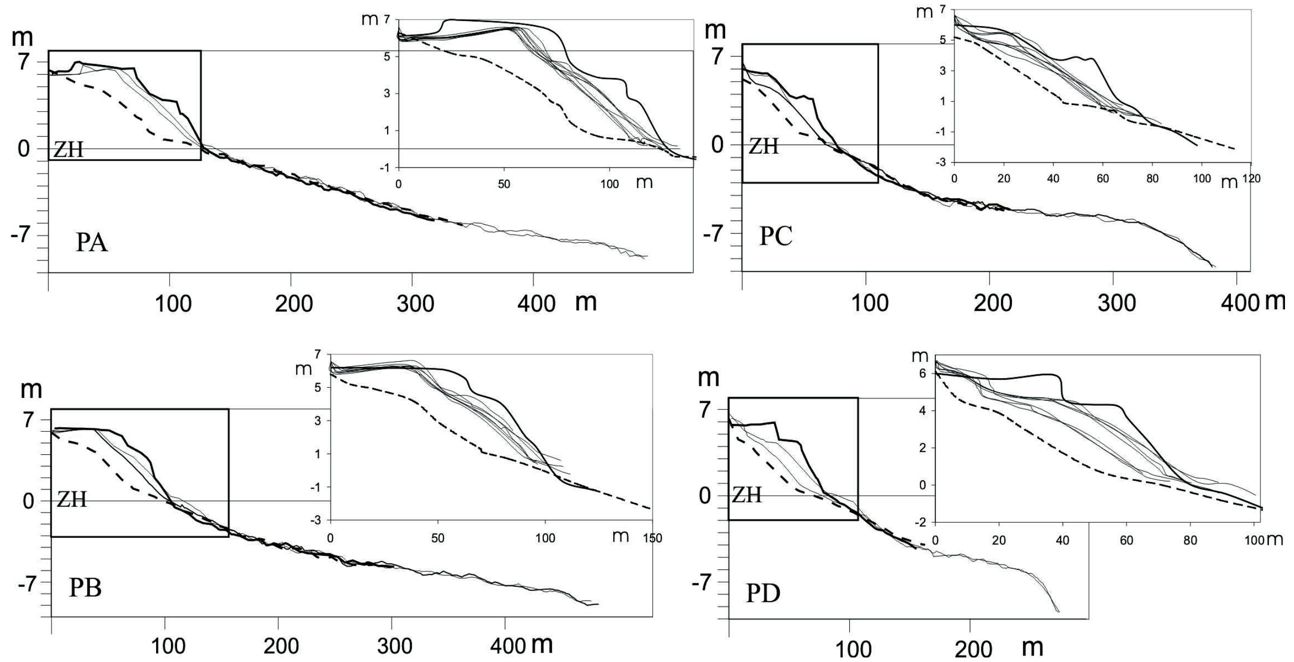

Figure 4. Profiles PA to PD extracted from topohydrographic surveys. Boxes - detail of seasonal changes in beach morphology resulting from periodic surveying of the subaereal beach profile; dashed line - pre-fill situation; solid line - post fill situation.

matches the pre-fill situation in this region, and this appears to be in equilibrium with prevailing sea and tidal dynamics.

For the purposes of quantification the surface under study has been divided in a number of polygonal cells according to contrasts in morphodynamic behavior (Fig. 5): one polygon extends from the ZH contour up to the landward border of the dry beach and this has been further split into one western (c1) and one eastern (c2) cell with a boundary located at the afore.mentioned step in the dry beach; the nearshore region was divided in two shore-parallel cells (c3 and c4) by the 4 m (ZH) contour. Whilst the landward cells are invariant in dimensions, cell c4 shows different widths according to the seaward extent of the hydrographic surveys (Fig. 5 and Table 2).

About 136,000 m^3 of sediment were in fact emplaced at Santo Amaro beach (compared with the projected 152,000 m^3) and the changes in elevation and volume across the beach and the nearshore between pre- and post-fill situations and until June 2003 are illustrated in figures 6 to 8 and table 2. The volumetric changes were asymmetrically distributed both in time and space. Soon after the winter term the placement had lost 46,000 m^3 of material, about 34% of the initial fill (Fig. 7 and Table 2).

This loss took place mostly in the upper beach, affecting the seaward edge of the artificial berm along the entire beachfront and resulted from fast retreat and rotation of the beach face (Fig. 7). The eastern segment of the upper beach was the most affected, contributing with 33,000 m^3 (about 70%) to the total loss. Loss from c1 has been maintained by the retreat of the berm crest while in c2 this mechanism was added by lowering of the berm surface. In both nearshore cells, the data indicate a very small net fill of 2%. The remaining material was not found within the surveyed nearshore and thus it may be concluded that it was lost to depths exceeding 6m - ZH (the contour line roughly limiting the post-fill hydrographic survey) or alongshore, beyond the boundaries defined by the containing groins.

In the Spring term the changes were significantly different. Between March and June the fill continued loosing sediment (a total of circa 7,000 m^3) and yet this net change corresponds to erosion in cell c1 (-12,000 m^3) whilst c2 recaptured circa 5,000 m^3, apparently in response to accumulation against the eastern groin. Results obtained in the nearshore zone also indicate net fill: circa 7,000 m^3 in c3 and 10,500 m^3 in c4.

The topohydrographic surveys of March and June were conducted to a wider offshore distance and thus the volumetric calculations embrace a larger surface in cell c4 most of which extends beyond the 5 m (ZH) contour. Given that no information was available for the most seaward portion of this cell in both pre- and post-fill surveys, this accumulation can not be accurately dated; still, it is reasonable to assume that most of this sediment corresponds primarily to erosion of the fill shortly after the beach initiated its volumetric readjustment, during winter, added by later and less intensive contributions, with a net residue towards the offshore. This implies that the seaward boundary of the beach is permeable, allowing sand to be lost offshore during high-energy events but this sediment cannot return into the beach system during fair-weather, given the steeper slopes and the low intensity of oscillatory currents in this depth range. The available data only allow closing the sediment budget if a loss of some 36,000 m^3 from the coastal system under study is assumed. It is worth to note that the sediment budget between March and June situations yields a very small residual balance if only cells c1 to c3 are considered and this suggests that the intensity of the net losses may have decreased substantially in the second period of observation.

At present, it is not clear if material lost from the system reached the tidal channels and exited the estuary, or was dispersed alongshore, in which case the tidal eddies combined with wave driven oscillatory currents, are hypothesized to have re-entrained sand previously pushed beyond the closure depth during storms. This material may be slowly migrating upstream and its ultimate fate could be shoreward deposition in the neighbor beach of Paço de Arcos, or belated rejection into the tidal channel. Both hypothesis are open at present and require further investigation, involving tracer experiments and detailed modeling of wave refraction and diffraction. Whatever the existing dispersion pattern of lost sediment, the amount of sand subtracted from the coastal system one year after replenishment works is small in comparison with the placement volume (circa 25%) and with figures reported in the literature: CARTER (1988 and references therein) quotes loss of 54-62% of the initial fill in low-energy beaches of the USA one year after completion of restoration works the time span usually required for adaptation of slopes and textural readjustment in a large number of cases, according to CERC (1995) - whilst LEONARD *et al*., 1990 indicate that most beach fill instances on the Atlantic coast of the USA have a life expectancy of less than five years, loss of sediment being initially heavy, regardless the volumes emplaced.

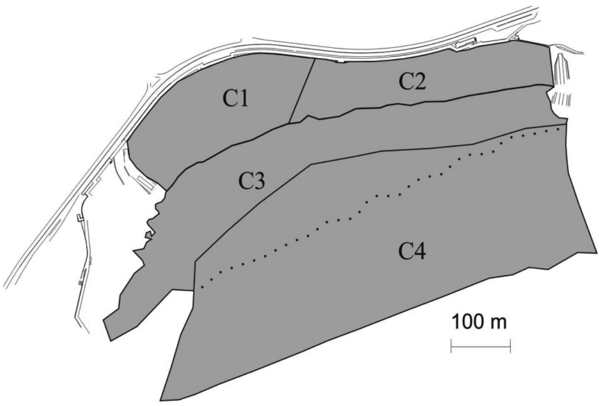

Figure 5. Location and boundaries of cells used for the calculation of volumetric changes.

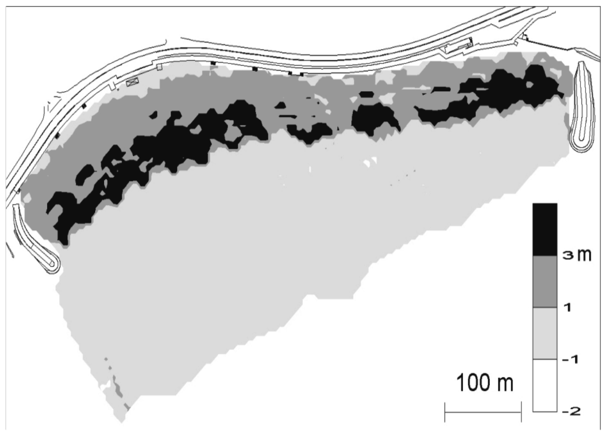

Figure 6. Elevation changes between pre and post fill situations.

The entrainment and dispersion of sand induced by current fields simultaneously driven by tides and waves is not a simple problem to address and in the case of estuarine beaches such as Santo Amaro this may be fundamental in governing the movement of sediment beyond significant bottom disturbance by waves. In this respect, the study area differs pronouncedly from an open oceanic beach given that the concept of closure depth should include synergy with tidal currents, which are negligible in wave-dominated environments.

CONCLUSIONS

Santo Amaro is an estuarine beach that shows ideal settings to favor success of an artificial replenishment venture involving exogenous sediment: it is a pocket beach affected by low-intensity erosion, apparently forming a complete coastal cell; wave energy is low and seasonal changes mostly associate with cross-shore sediment movement. The fill venture was driven primarily to increase by half the accommodation capacity and recreational value of the beach, and secondarily to counteract long-term erosion. The project followed the berm-only design and consisted in the placement of 136,000 m^3 of sand borrowed from neighbor estuarine shoals. Two groins further confined the placement and whilst the eastern one proved to block longshore drift, the western groin allowed bypassing in moderate to high-energy wave conditions.

The comparison of native with borrow sand shows that exogenous material is slightly finer and better sorted, but the performance criteria suggest that these differences are small; in spite of sediment loss that will certainly occur due to textural readjustment, the success of the venture is not in risk for this reason. The equilibrium slopes of the foreshore and nearshore diminished in comparison with the pre-fill situation; this implies a larger than anticipated sediment loss from the emplacement, required to reshape the submarine section of the beach down to the closure depth (which was tentatively placed at 5 m-ZH). The upper portion of the filled beach developed contrasting responses in its western and eastern sections, leading to the split of the subaereal beach in two coastal cells confining along a boundary with morphological expression. The western cell continuously lost sediment during the first year following replenishment and this erosion has been accomplished by persistent recession of the berm crest, accompanied by minor seasonal changes in the morphological features of the foreshore; the eastern cell showed larger seasonal variation and erosion was dominant during the winter, affecting both the foreshore and the berm up to its landward limit. The berm height in this cell rests at present close to the pre-fill situation and its width was extended during summer due to drift blocking at the eastern groin. The nearshore showed net gain of sediment, most of which accumulated beyond the limiting depth of significant wave action. Sediment redelivery to the beach by cross-shore mechanisms is improbable, given the exceeding of equilibrium slopes in this region. The coastal system is open in terms of sediment budget and a net loss of *circa* 36,000 m^3 of sediment occurred throughout the monitoring period, most of it during the first semester.

During high-energy events, sediment was either pushed deeper than 5 m or alongshore. The nearshore extending beyond significant bottom disturbance by waves is a temporary sediment reservoir, which may be leaking into the tidal channel or alongshore. In the former case, sediment will be flushed out into the sea, whilst its fate is unclear in the second situation: it is hypothesized that tidal eddies combined with incoming waves may favor upstream transport of sediment within a depth range beyond the closure depth determined by wave action solely. In this respect, Santo Amaro and other estuarine beaches differ from open oceanic equivalents in that synergy between tidal and wave currents may influence the closure depth of the coastal system.

Table 2. *Volumetric changes recorded in cells. (C) - cut; (F) - fill; (N)- net.*

Volume (m^3)		Cell 1	Cell 2	Cell 3	Cell 4
Pre- post fill	C	-401	- 187	-9 022	-2 280
	F	+ 74 141	+64 731	+5 382	+2 658
	N	+ 73 740	+64 545	-3 640	+ 378
Post fill-March	C	- 16 373	-34 957	-8 739	-2 850
	F	+ 2501	+1 707	+9 801	+2 604
	N	- 13872	-33 250	+1 062	- 247
Área (m^2)		38 037	33 057	72 269	33 882
March - June	C	- 12 628	-5 812	-4 848	-9 016
	F	+ 556	+11 050	+11781	+19 547
	N	- 12 071	+5 239	+6 933	+10 532
Área (m^2)		38 037	33 057	72 269	168 570

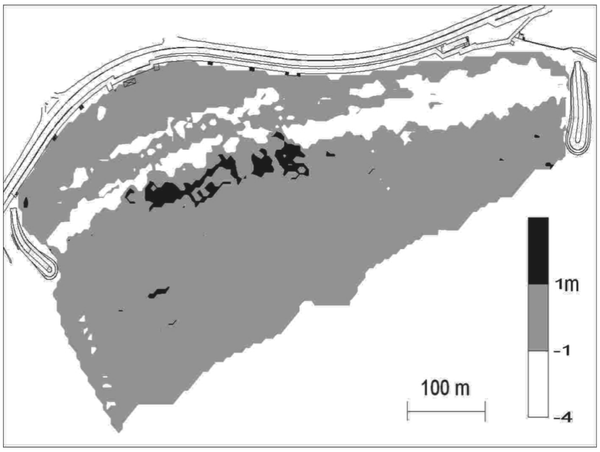

Figure 7. Elevation changes between postfill situation and March 2003.

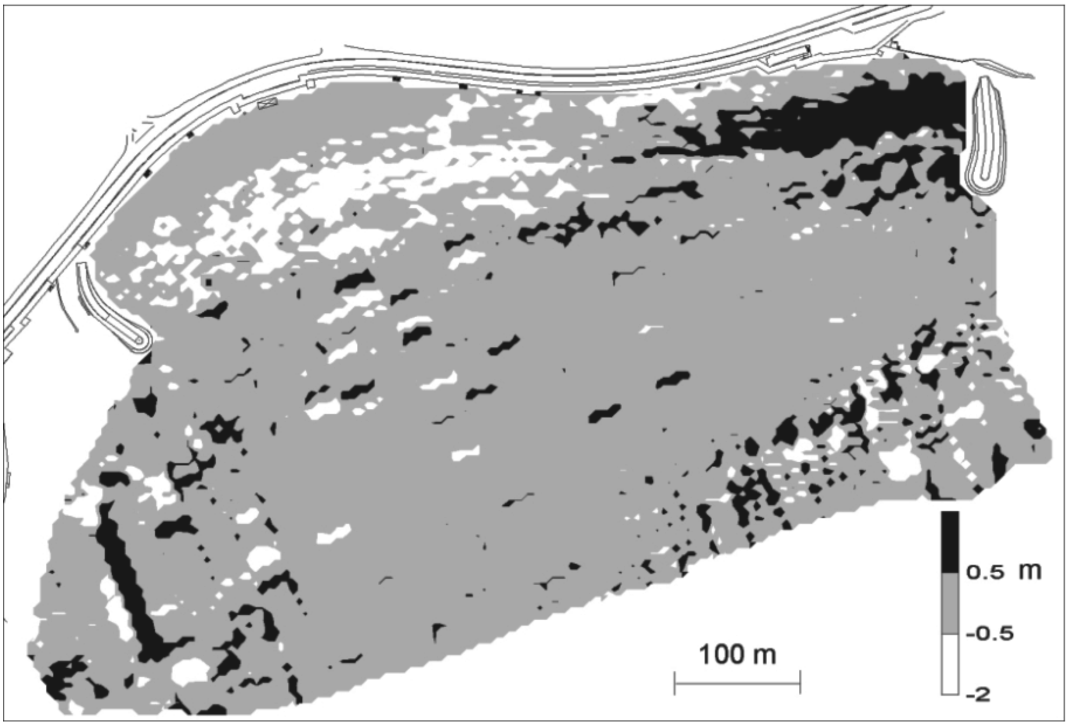

Figure 8. Elevation changes between March and June, 2003.

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