COASTAL DYNAMICS 2005

PROCEEDINGS OF THE 5TH INTERNATIONAL CONFERENCE

April 4–8, 2005
Barcelona, Spain

SPONSORED BY
Laboratori d'Enginyeria Marítima
Universitat Politècnica de Catalunya

WITH THE SUPPORT OF
International Centre for Coastal Resources Research (CIIRC)
E.T.S. d'Enginyers de Camins, Canals i Ports de Barcelona
D.G. de Investigación, Ministerio de Educación y Ciencia
D.G. de Costas, Ministerio de Medio Ambiente
Dursi, Generalitat de Catalunya
Universitat Politècnica de Catalunya

WITH THE COOPERATION OF
The Coasts, Oceans, Ports, and Rivers Institute (COPRI)
of the American Society of Civil Engineers

EDITED BY
Agustín Sánchez-Arcilla

Published by the American Society of Civil Engineers

Notices

ISBN 0-7844-0855-6

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document.

ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefore. This information should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing this information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

Copyright © 2006 by the American Society of Civil Engineers.
All Rights Reserved.
ISBN 0-7844-0855-6
Manufactured in the United States of America.

American Society of Civil Engineers
ASCE International Headquarters
1801 Alexander Bell Drive
Reston, VA 20191-4400 USA

Call Toll-Free in the U.S.: 1-800-548-2723 (ASCE)
Call from anywhere in the world: 1-703-295-6300
Internet: http://www/pubs.asce.org

Sponsors

ORGANIZED BY

LIM UPC

Laboratori d'Enginyeria Marítima
UNIVERSITAT POLITÈCNICA DE CATALUNYA

WITH THE SUPPORT OF

International Centre for Coastal Resources Research

CIIRC
International Centre
for Coastal Resources
Research

E.T.S. d'Enginyers de Camins, Canals i Ports de Barcelona

UPC
Escola Tècnica Superior d'Enginyers
de Camins, Canals i Ports de Barcelona
UNIVERSITAT POLITÈCNICA DE CATALUNYA

D.G. De Investigación, Ministerio De Educación Y Ciencia
(Ref. Ctm2004-21603-E)

D.G. de Costas, Ministerio de Medio Ambiente

Dursi, Generalitat de Catalunya (Ref. 2005 Arcs1 00243)

Universitat Politècnica De Catalunya

WITH THE COOPERATION OF

The Coasts, Oceans, Ports, and Rivers Institute (COPRI)
of the American Society of Civil Engineers

DEPTH OF SAND ACTIVATION ON PROTECTED AND NON-PROTECTED NOURISHED BEACHES: A LABORATORY STUDY IN A LARGE-SCALE WAVE FLUME

Paolo Ciavola[1], Fabio Nadalini[2], Viviana Ardone[3]

[1] Dipartimento di Scienze della Terra, Università di Ferrara, Via Saragat 1, 44100 Ferrara, Italy. cvp@unife.it
[2] Protecno S.r.l., via Risorgimento 9, Noventa Padovana, 35027 Padova, Italy. fnadalini@protecno.it
[3] Consorzio Venezia Nuova, San Marco 280330124 Venezia, Italy.
Viviana.Ardone@consorziovenezianuova.com

Abstract: The depth of sand activation on a beach under the action of waves is a key parameter for many scientific and applied projects in coastal engineering. Although there is a good literature on field studies, the work presented here represents the first laboratory study of its kind. Two nourished beaches from the Venice barrier-island system (Pellestrina and Cavallino) were reconstructed in a large wave flume and sediment activation was studies using trenches filled with colored sand. The results confirm the control by Significative Wave Height (H_s) and Peak Wave Period (T_s). The spatially averaged Sediment Mixing Depth (Z_m) resulted to be respectively 20% of H_s and 8% of $T_{p.}$ In the case of the beach protected by a breakwater (Pellestrina) wave steepness resulted to be an additional indicator, possibly because of variable transmission rates over the structure.

INTRODUCTION

The depth of sand activation on a beach indicates the thickness of the sedimentary column that experiences remobilization under currents and wave action. The concept has several important engineering applications: the estimation of the mobile layer where artificial sand tracers can be introduced, the design of beach replenishment projects, the estimation of the depth of scour at the base of coastal structures. The topic has been widely studied in the field using several methods, namely trenches filled with marked sands together with pins inserted into the sediment (King, 1951; Williams 1971; Jackson and Nordstrom 1993; Anfuso et al. 2000; Gonzales et al. 2004) or the distribution of tracer grains (Kraus 1985; Ciavola et al. 1997). The experiments usually involved the simultaneous measurement of wave characteristics: all authors agree that the main control parameter is the wave height, with a secondary influence of the wave period. However, field experiments cannot be undertaken under controlled forcing parameters. There is often lateral variability in beach profile characteristics (see Ferreira et al. 2000 for quantification of the beach slope influence), manpower requirements are very demanding if many points of measurements are introduced, the presence of grain size variability may locally produce artifacts, due to armoring of small particles by larger ones. Finally, there are logistical constraints if the study takes place in tideless settings, as the access to the swash zone is controlled by the wave climate. A novel approach was recently introduced by Jackson and Malvarez (2002), who built an autonomous self-logging platform for taking measurements in the surf-zone. Unfortunately this approach is feasible only on a few points of measurement and it is limited to mild wave conditions.

To the knowledge of the authors there are no previously published laboratory studies on the topic, based on wave flume modeling. For the study of beach processes laboratory model has many advantages compared to a field experiment (Trim et al. 2002). If the model is bi-dimensional like a classical wave flume, the observed mixing depths will not be affected by lateral migration of rhythmic forms like beach cusps, a process that has often made interpretation of field results difficult (Ferreira et al. 2000). While the number of points measured in the field is generally small, and not well extend along the submerged beach, in the laboratory a large number of measurements can undertaken. Also, the frequency of measurements can be higher and frequent profiling of the seabed can be easily done. The other advantage is the control on the forcing parameters: wave generators can simulate regular and irregular wave climates and it is possible to simulate cumulative effects due to raising wave energies, like during a storm. Finally, the possible control by grain size, although never found by previous authors, can be minimized by using well-sorted sands. On the other hand, grain size is the most difficult parameter in laboratory based downscaling (Bruno, 2005).

The work presented here is part of an extensive modeling effort undertaken by the Consorzio Venezia Nuova on behalf of the Magistrato alle Acque (Venice Water Authority) at the Voltabarozzo Hydraulic Model Experimental Centre, near Padua (Italy). The experiments were carried out in support of beach replenishment activities undertaken by the authorities on the Pellestrina and Cavallino beaches. These two beaches are located along the Lidi Veneziani barrier-island systems and their presence controls the safety of many settlements and structures located in the back-shore, to the extent that the first works were undertaken by the *Serenissima Venetian Republic* as early as the 18th century, building one of the first sea-walls (the *murazzi*) in Italy. The Magistrato alle Acque replenished 11 km of beach at Cavallino with 4 million cubic meters of marine sands, while at Pellestrina the replenishment was of 5 million cubic meters, along 9 km of coastline. The main difference between the interventions in the two sites is the presence of a submerged breakwater that protects the replenishment at Pellestrina.

The main aims of the flume modeling were the following:

- To assess the behavior of the beach profile after the replenishment, simulating a set of representative wave events and their joint occurrence with storm surges.
- To evaluate the role of the submerged breakwater.
- To evaluate the maximum sand remobilization during these wave events.

The last issue may seem trivial and in turn related to the overall behavior of the beach profile. However, it has a considerable importance for coastal managers. One should remember that the offshore sand used to rebuild the beach has a gray color, while the local sand is yellow-brown. It is therefore not feasible to use the offshore sand just dumping it on the beach, as the aesthetic value of the beach would diminish. Therefore, coastal managers normally dig a trench alongshore, place the replenishment sand in it and finally cover it with the local one. Therefore the capability of being able to predict the maximum depth of sand activation has practical implications.

METHODS

The flume and the wave events

The flume at Voltabarozzo is built with concrete and is 140 m long, 2 m wide and 2.5 m deep (Figure 1a). It is equipped with a piston-type wave generator (Figure 1b) that can simulate Jonswap spectra computed from measured wave events, as it is software controlled. Wave measurements are provided by a series of resistance wave gauges (one is visible in Figure 1a). Two laser sensors are located on a movable platform that runs on a rail system for bed profiling at the end of each simulation. An interesting feature is the presence of glass windows in the terminal part of the flume (Figure 1a), which allows the operator to make observations of bed changes as the simulations are undergoing.

Fig. 1. (a) View of the flume looking towards the prototype beach; (b) view of the piston type generator.

Table 1. Wave climate simulated during the experiments

Event number	Significative Wave Height (m)	Peak Period (s)	Duration of the event (hours)	Spectral Bandwidth
1	2.5	6.5	20	3.3
2	3.0	8.0	20	3.3
3	4.0	9.0	20	3.3

For the study presented here three wave events were simulated and are presented in Table 1. To notice that the Jonswap spectrum that was reproduced had a width (γ) of 3.3. For both simulations a storm surge set-up of + 1 m above MSL (IGM Datum) was introduced, as this is phenomenon which is common in the Venice area, generating under storm conditions the infamous *acqua alta* (Canestrelli et al. 2001). To notice that wave event n. 3 corresponds to a return period of 30 years.

Depth of sand activation

For the simulations the trench method was adopted (King 1951; Williams 1971), it consists of filling up a trench or plug-hole with colored sand and measure at regular time intervals the erosion of the colored layer or the deposition of new sand above it. In the field the observations are usually carried out at the end of each tidal cycle, when the beach is dry (Figure 2). In the laboratory we carried out the observation at regular hourly intervals, as we could see through the glass window of the flume (Figure 3).

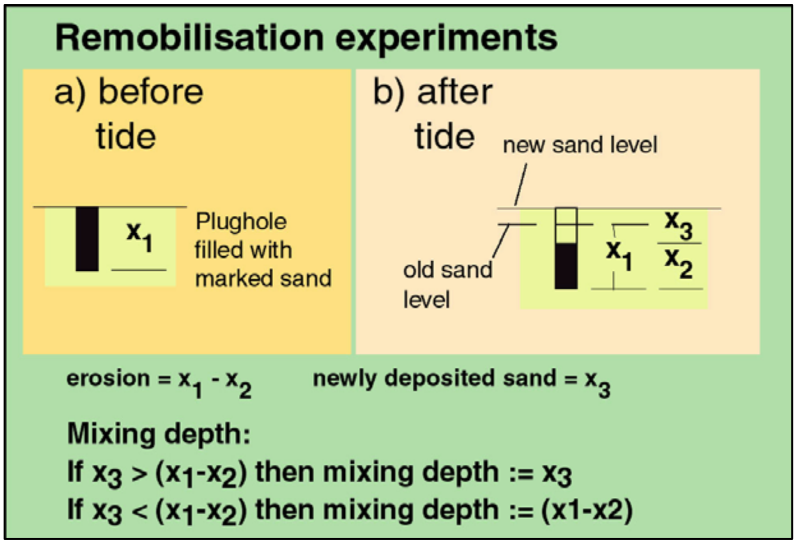

Fig. 2. Summary of the method of the plughole or trench filled with marked sand (drawing by R. Gonzales).

Fig. 3. View of the plugholes under the action of breaking waves. The orange line marks the initial profile.

As an alternative to this method, there is the introduction of tracers within the sand body and the use of a cut-off concentration in the vertical distribution for the estimation of the mixing depth (Kraus 1985; Ciavola et al. 1997). The concept of sediment mixing implies displacement of particles as cross-shore and/or longshore transport. It seemed inappropriate to use this method in what it is essentially a one-line model, as by definition only cross-shore transport can be reproduced in a bi-dimensional flume. Besides, the concepts of sediment mixing and depth of activation do not coincide, as outlined in previous papers (Ciavola et al. 1997; Ferreira et al. 2000). It is indeed possible to have remobilization of the sand without having net sediment transport, by assuming that the seabed at that point reached equilibrium conditions.

Initially the “rod-and-washer” method of Greenwood and Hale (1980) was also tested. In this case the position of the seabed is referred to the top of a rod inserted in the sediment, to measure net accretion/erosion. The maximum value of sediment activation is quantified by inserting a washer at the base of the metal pin at the beginning of the experiment and by measuring its position at the end of it, referred to the top of the rod. Notice that erosion of the seabed implies a sliding down of the washer along the rod. If then accretion takes place, the washer rests buried, thus recording the maximum seabed lowering that took place. A return of the bed level at the same position of the beginning of the experiment may imply that the distance from the rod’s top will be the same before/after the experiment, but the washer will have recorded the event. The method has been widely used in the field, with a variable degree of success, often because of the loss of the rods, which are removed by the breakers. On the other hand, the method could be suitable to a laboratory study and it was indeed tested on this occasion. Unfortunately, it was noted that under scouring was conspicuous at the base of the rod, which in any case it is not a scaled-down element like the rest of the model. Therefore the method was abandoned.

The trenches were extended laterally from the glass side of the flume for 30 cm, were 5 cm wide and had a depth of 20 cm. The initial bed profile was marked on the glass window with colored tape (Figure 3). The sediment used to build the mobile was a well-sorted quartzitic fine sand with a d_{50} of 0.21 mm. It was painted with standard synthetic green and blue paints. To assess the impact of the painting on the grain size distribution, sieving of sub-samples was undertaken using a battery of ASTM sieves, with spacing of 0.25 phi. From the comparison in Figure 4 it is evident that the cumulative curve of the natural sand was comparable with that of the painted one.

The Cavallino Beach Model

The mobile bed model was built at a 1:7.5 scale (Figure 5). It is essentially divided into three significative segments with variable beach slope. The emerged beach (elevation between +2.70 m and +1.00 m) had a slope of 0.04. A second segment, corresponding to the innermost submerged beach, between –1.00 m and –2.00 m had a slope of 0.02, while the nearshore seabed had an average slope of 0.01. To notice in the figure that the last part of the profile has a slope 0.05, between the water depths of 5.5 m and 11.00 m. This is an artifact introduced in order to establish intermediate water conditions at the depth of the generator. To notice that the model is based on the design profile chosen for the replenishment.

In this case 23 trenches for observation of sand removal were located between an elevation of + 2.65 m and -1.40 m. (Figure 6), therefore on the beach face under the action of the innermost breaker.

The Pellestrina Beach Model

The model's scale was slightly smaller than the previous one, being 1:8.5. In this case the model is based on the surveys carried out by local authorities immediately after the end of the replenishment operations. The replenishment was initially confined between the base of a sea-wall (+ 2.00 m) and the inland edge of a submerged breakwater, at a water depth of –4.5 m (Figure 7). The replenished profile was again reproduced from the outer edge of the breakwater, down to a depth of –7.5 m. In order to reach intermediate depth conditions for the generated waves, a fixed bed platform was built down to a depth of –12.75 m.

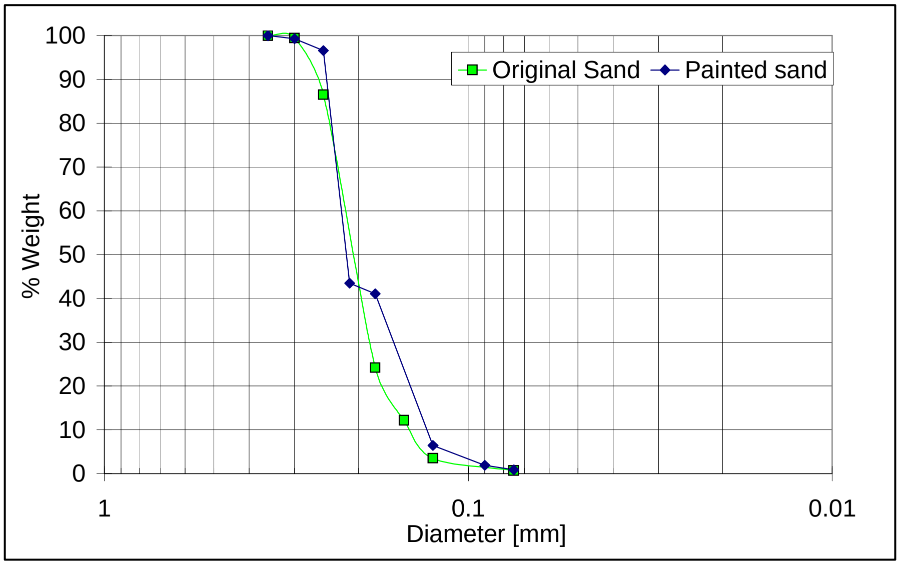

Fig. 4. Comparison between particle size distribution before and after marking.

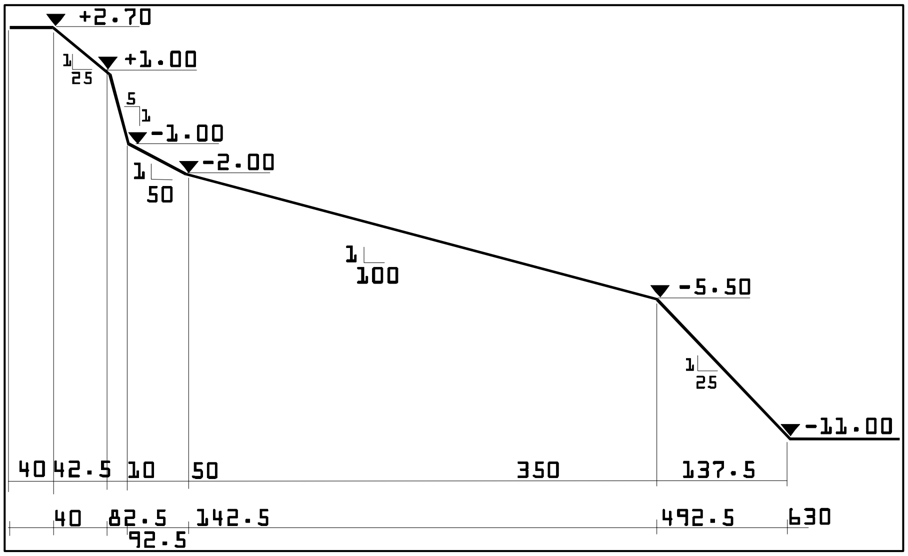

Fig. 5. Scheme of the model set-up for Cavallino Beach. Units (m) are in real-world dimensions.

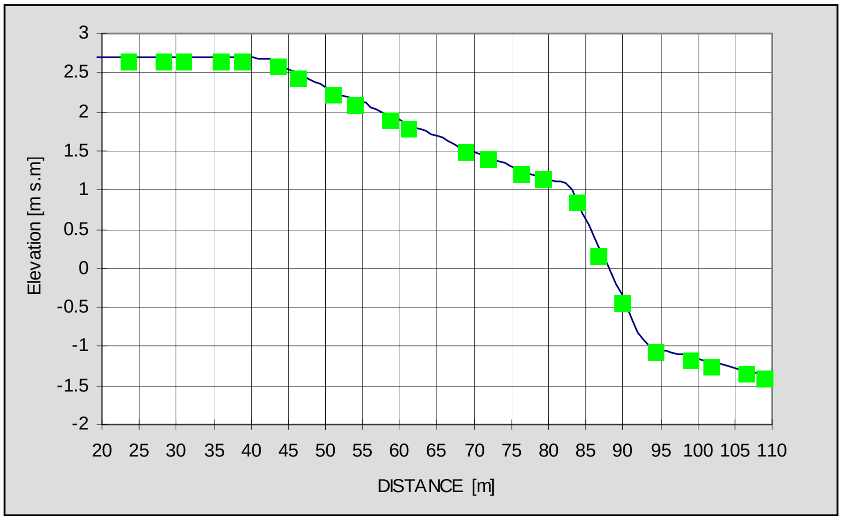

Fig. 6. Location of the trenches in the Cavallino Beach Model. Heights are referred to mean sea level.

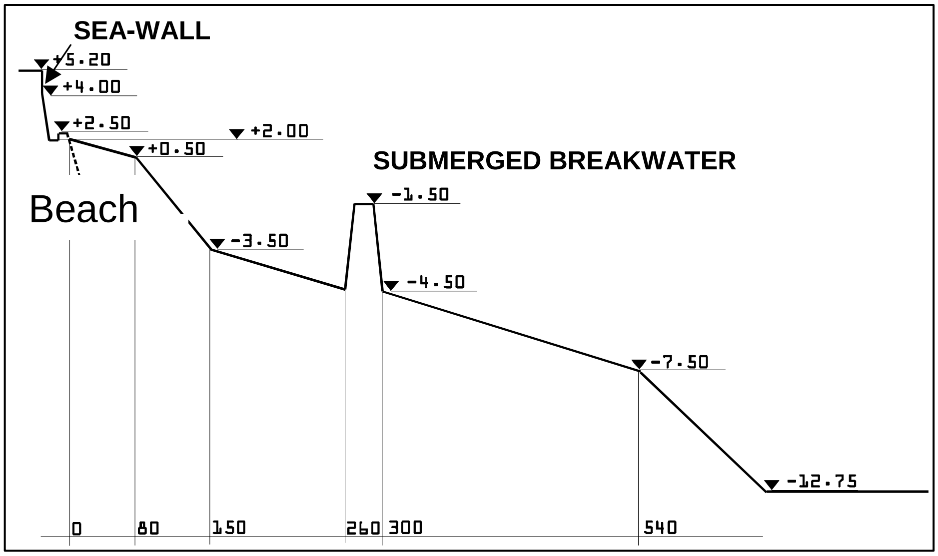

Fig. 7. Scheme of the model set-up for Pellestrina Beach. Units (m) are in real-world dimensions.

Likewise the other model, only the upper part of the profile was studied for sand remobilization. However, because of the presence of the breakwater, only a part of beach face was monitored, at elevations between –1.0 m and + 1.5 m. Along this length, twenty trenches were introduced, spaced every 5 m (Figure 8).

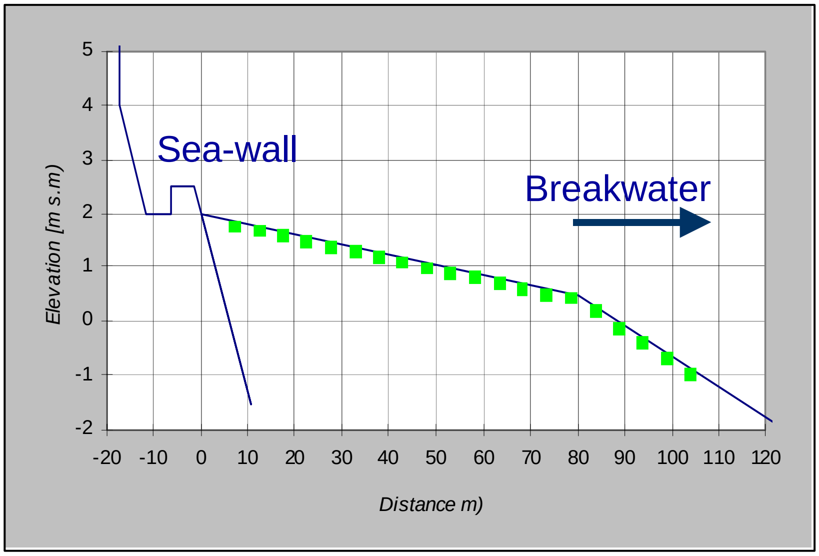

Fig. 8. Location of the trenches in the Pellestrina Beach Model. Heights are referred to mean sea level.

RESULTS AND DISCUSSION

The results presented are divided into datasets that correspond to each simulated wave event. Despite the fact that the depth of sand activation was measured at hourly intervals, it was decided to present here only the survey undertaken at the end of each run, as this represents the net result of the considered wave event. In fact, if one wants to compare the work presented in this paper with fieldwork, it should remembered that in practice only the final scenario is the one measured, as no observations can be undertaken on the sea bed under high energy conditions, because of safety reasons.

In the graphs presented, the values of remobilized sand appear in a "cumulative" format that is the value computed adding the thickness of sand deposited above the initial trench level, with that removed from the colored layer. Clearly this figures become cumulative only at the end of the simulations of events n. 2 and 3, representing the growth in energy levels across the three wave climates. The trend in remobilization is finally related with the bed profiling carried out at the end of each model's run. An important point to outline is the fact that the replenishment profile changes in response to the different wave climates.

The non-protected beach of Cavallino

Event n. 1 (H_s=2.5 m;T_p=6.5 s)

The hourly observations indicate that most of the changes occur in the first ten hours of the simulations. Maximum disturbance occurs at the position of berm on the replenished profile. Secondary peaks in remobilizations occur on the newly formed berm and bar crest (Figures 9, 10). The thickness of remobilized sand has three maxima. One at the edge of the berm (45 cm), one at around 80 m along the profile (101 cm) and a third one at the crest of the bar (71 cm). At the end of the run the flat replenishment profile gives way to a concave one, with a well-defined berm and a fully formed bar-trough system. The trenches define three zones with different morphological behavior. A first one from the upper end of the beach face up to the edge of the berm; a second one from the berm to the inner end of the trough; a third one around the bar's position. An important point to notice is that the passage from the initial profile to the final one develops by rotation of these three segments around two axis, which correspond to minimum values of remobilization (Figures 9, 10).

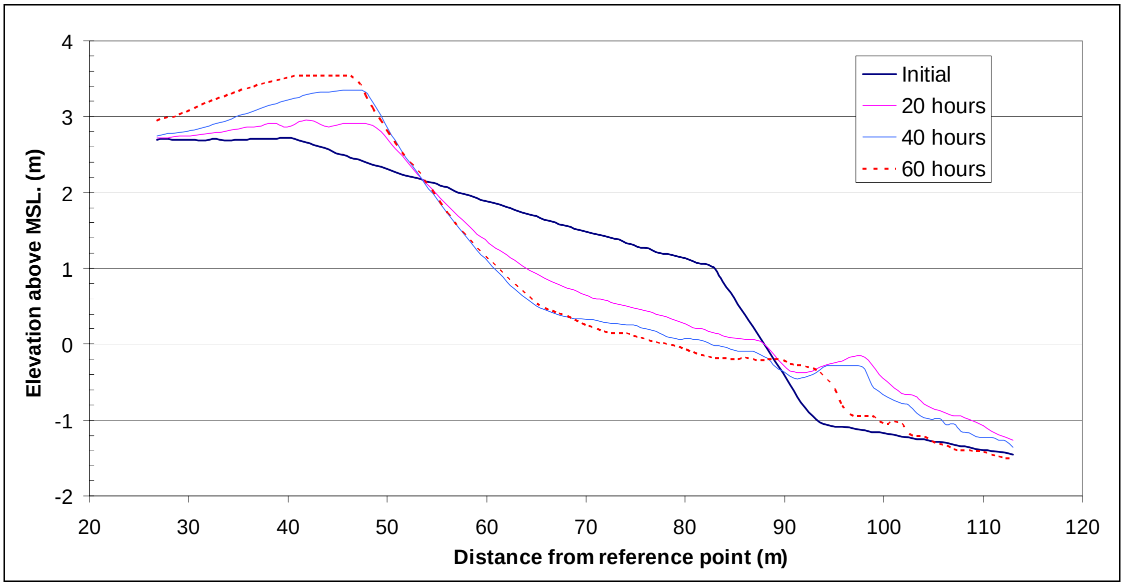

Fig. 9. Profile changes at Cavallino Beach during the simulations.

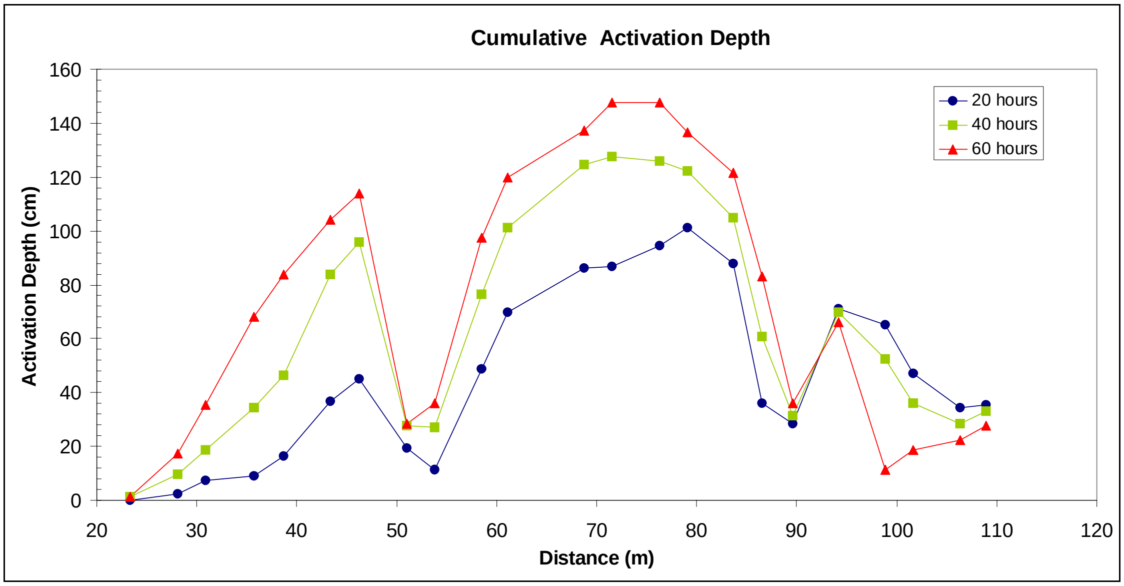

Fig. 10. Cumulative depth of sand activation on Cavallino Beach.

Event n. 2 (H_s=3 m;T_p=8 s)
The profile maintains a concave shape, becoming steeper in its intermediate portion. To notice that the berm has grown in height, generating a back-shore that has an anomalous slope towards the upper beach. The intermediate part of the beach has widespread erosion that continues even on the bar, which is now wider and flatter (Figure 9). The highest remobilization is observed on the berm (Figure 10), the maximum depth of activation is close to the value measured in the previous simulation (51 cm). To notice that the axis of profile rotation is located at the same distance as in the previous experiment. Sediment activation is small on the bar.

Event n. 3 (H_s=4 m;T_p=9 s)
The most energetic wave climate generates a completely different response of the profile. Different profile behavior: The shoreface slope remains constant ($\tan\beta$=0.15), while accretion on the berm continues and the bar is smoothed out (Figure 9). To notice that profile stability does not imply any sediment mobility, the trenches record a net depth of remobilization on the shoreface up to 20 cm. The spatial distribution of remobilization has a different pattern: one maximum on the berm and one on the bar crest. The maximum on the bar crest produces with time a “beach step”, which corresponds on reflective beaches to the point of maximum sediment remobilization under the action of plunging breakers.

The protected beach of Pellestrina

Event n. 1 (H_s=2.5 m;T_p=6.5 s)
Likewise for the non-protected profile, the hourly observations indicate that most of the changes occur in the first ten hours of the simulations, generating the profile seen in Figure 11. The trench that shows the maximum of erosion is located at about 12 m away from the base of the sea-wall (Figure 12). Moving offshore along the profile, there is a secondary maximum that corresponds to the crest of the bar that formed during the run of the model. It is also interesting to notice the formation of bedforms in the area at a distance between 47 and 70 m from the reference point, with height of 7 cm.

Event n. 2 (H_s=3 m;T_p=8 s)
Regarding profile variability, the upper and intermediate part of the beach is not as active as in the previous simulation (Figure 11). Accretion at the base of the sea-wall is still on-going. The bedforms formed in the previous run have shifted at greater water depths, more than 60 m from the baseline, becoming higher (15 cm) but maintaining the same wave-length (3.4 m). No bar is present in the part of the profile with trenches.

Event n. 3 (H_s=4 m;T_p=9 s)
The accumulation of sand at the base of the sea-wall continues. There is a point of equilibrium in profile variability located at 25 m from the baseline, past this point profile erosion becomes widespread. Moreover, while the profile is slightly concave in the first 42 m ($\tan\beta$=0.05), there is a flat area between 50 and 65 m away from the base of the sea-wall (Figure 11), at around the MSL position. This is what in normally described in the field as *low-tide terrace*.

Further offshore the profile becomes convex up to a successive break in slope which gives way to flat bed below the –1 m contour. Bedforms are no longer existent. The maximum values of remobilization are observed at the base of the sea-wall, with a maximum around the axis of rotation of the profile segments (Figure 12). To notice how the trenches between 63 and 88 m from the baseline only show weak removal of sand, mainly related to erosion of the bedforms.

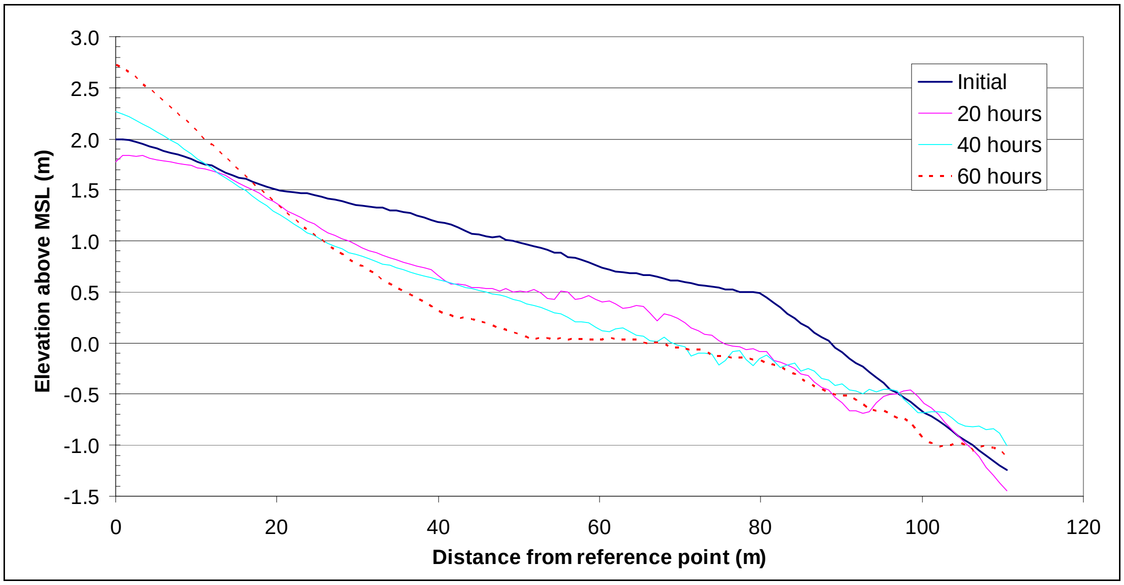

Fig. 11. Profile changes at Pellestrina Beach during the simulations.

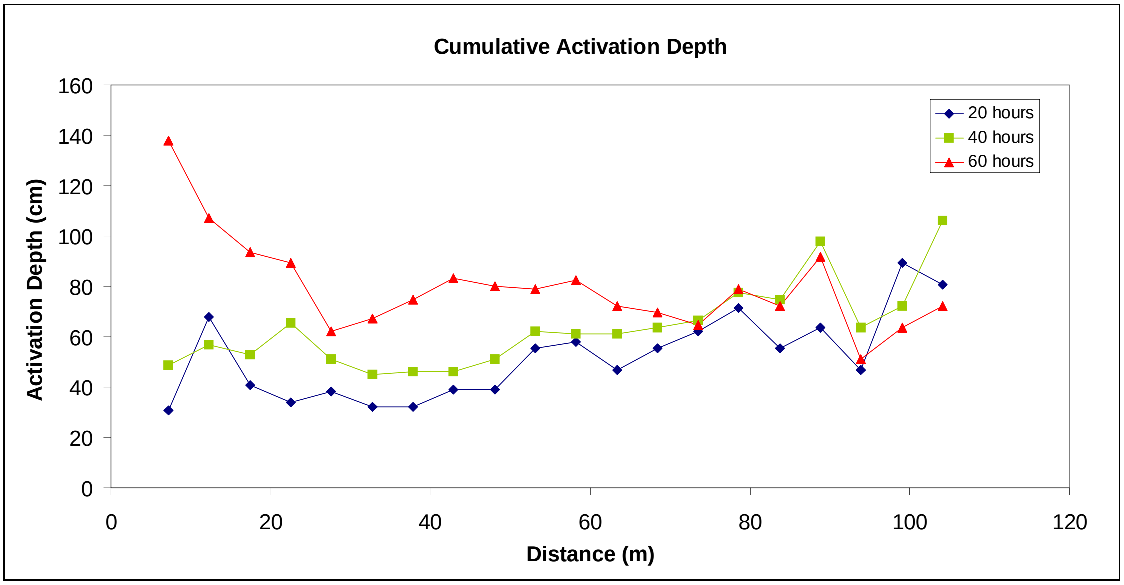

Fig. 12. Cumulative depth of sand activation on Pellestrina Beach.

Control on remobilization by the incident waves

Previous work has clearly stated a linear relationship with breaking wave height and period (Jackson and Nordstrom 1993; Ciavola et al. 1997; Ferreira et al. 2000) measured at the breaking point. Here no measurements were made at breaking and the characteristics of the waves offshore were preferred for the analysis, as full control on spectral characteristics was possible, through the software of the wave generator. The advantage of simulating increasing energy level can efficiently test the presence of a linearity in any numerical solution to relate sediment remobilization with wave parameters. For what regards the value to relate with the wave climate, the thickness of remobilization measured by the trenches was spatially-averaged for each dataset and related to the Significative Wave Height (H_s) and the Peak Spectral Period (T_p).

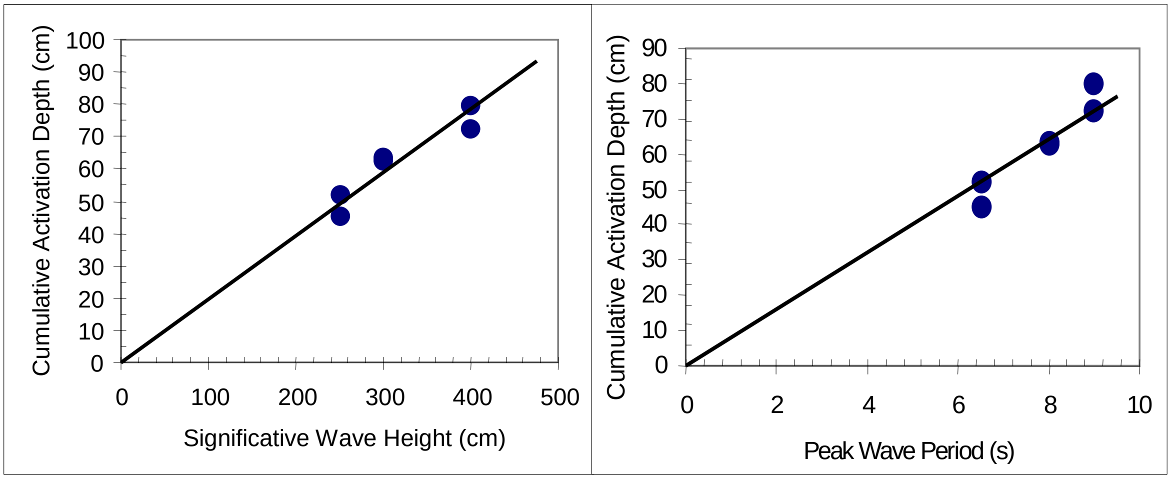

Fig. 13. Relationships between Activation Depth (Z_m) and wave parameters (H_s, T_p). The lines in the graphs indicate a Z_m/H_s of 20% and a Z_m/T_p of 8%.

Considering both tests the following relationships (Figure 13) can be obtained:

$$Z_m=0.20\ H_s \tag{1}$$

$$Z_m=0.08\ T_p \tag{2}$$

This linearity in the relationship between average activation depth and wave parameters is comparable with previous work, based on measurement of breaking wave heights (H_s). For example Ciavola et al. (1997) found Z_m=0.27 H_b; Jackson and Malvarez (2002) found Z_m=0.24 H_b. Regarding the relationship with wave period, the previous authors found lower linearity.

It was decided to combine wave parameters by computing the wave steepness for the three events, at the generation point. Event n. 1 had steepest waves (0.038), compared to event n. 2 and 3 (0.030). No clear relationships were found with the cumulative activation depth, while for what regards the net activation depth, this increased linearly as a function of wave steepness for the protected beach of Cavallino, but not for the unprotected one of Pellestrina. This may be caused by the presence of the breakwater, as steeper waves would overtop more easily the structure with a higher transmission rate.

CONCLUSIONS

The work presented in this paper described a unique dataset on sediment mixing depths obtained under controlled wave conditions. The results confirm field observation, concluding that wave characteristics are the main control parameter on the process. The behavior of the reconstructed beaches was similar, despite the presence of structures in one case. Clearly the presence of the submerged breakwater is a factor which may have introduced a notable control on the wave parameters for the simulations. However, the part of the profile that was studied is far enough from the structure to exclude a direct impact on the morphology. The work confirms that the relationships available in the literature con be used for predictive purpose with a reasonable degree of confidence. Clearly the role of grain size was unexplored and remains one of the main questions to address.

ACKNOWLEDGEMENTS

The authors are grateful to the Magistrato alle Acque for permission to publish the paper. The experiments were financed within the *Studio C.2.1.4-Modelli matematici, fisici e rilievi ondametrici per il sistema di gestione delle sabbie di ripascimento*. P. Ciavola is grateful to Ramon Gonzales (formerly University of Algarve) for preparing Figure 2 and for the helpful discussions on sediment activation.

REFERENCES

Anfuso, G., Gracía, F.J., Andrés, J., Sánchez, F., Del Río, L. and López-Aguayo, F. (2000). “Depth of disturbance in mesotidal beaches during a single tidal cycle.” *Journal of Coastal Research*, 16(2), 446–457.

Bruno, M.S. (2005). “Physical Models”. In: *Encyclopedia of Coastal Sciences*. M. Schwartz (ed.) Published by Kluwer Academic Publishers, Dordrecht, The Netherlands, 1253-1258.

Canestrelli, P., Mandich, M., Pirazzoli, P.A., Tomasin, A. (2001). “*Wind, depression and seiches: tidal perturbations in Venice (1951-2000).*” Venice, Italy: Comune di Venezia, Centro Previsioni e Segnalazioni Maree, 105 p.

Ciavola, P., Ferreira, Ó., Taborda, R., and Dias, A. (1997). “Field observations of sand-mixing depths on steep beaches.” *Marine Geology*, 141, 147-156.

Ferreira, Ó.; Ciavola, P.; Taborda, R.; Bairros, M., and Dias, J.A. (2000). “Sediment mixing depth determination for steep and gentle foreshores.” *Journal of Coastal Research*, 16 (3), 830-839.

Greenwood, B. and Hale, P.B. (1980). “Depth of activity, sediment flux and morphological change in a barred nearshore environment.” In: McCann, S.B. (Ed.): *The Coastline of Canada*, Pap. 80-10, Geological Survey Canada, Halifax, 89-109.

Gonzales, R., Ciavola, P., Corbau, C., Falati, S. and Ferreira Ó. (2004). “Mixing depth experiments on an estuarine dissipative beach: St. George Beach, Gironde (France).” *Journal of Coastal Research*, SI 41, 43-52.

Jackson, D.W.T. and Malvarez G. (2002). “A new, high resolution ‘depth of disturbance’ instrument (SAM) for use in the surf zone.” *Journal of Coastal Research*., SI 36, 406-413.

Jackson, N.L. and Nordstrom, K.F. (1993). “Depth of activation of sediment by plunging breakers on a steep sandy beach.” *Marine Geology*, 115, 143-151.

King, C.A.M. (1951). “Depth of disturbance of sand on sea beaches by waves.” *Journal of Sedimentary Petrology*, 21, 131-140.

Kraus, N.C. (1985). “Field experiments on vertical mixing of sand in the surf zone.” *Journal of*

Sedimentary Petrology, 55, 3-14.

Trim, L. K., She, K. and Pope, D. J (2002). "Tidal effects on cross-shore sediment transport on a shingle beach." *Journal of Coastal Research*., SI 36, 708-715.

Williams, A.T. (1971). "An analysis of some factors involved in the depth of disturbance of beach sand by waves." *Marine Geology*, 11, 145-158.