Journal of Coastal Research	SI 50	263 - 267	ICS2007 (Proceedings)	Australia	ISSN 0749.0208

Dynamic Numerical Simulation of Medium-term Coastal Evolution of the West Coast of Portugal

R. Silva†, C. Coelho‡, F. Veloso-Gomes† and F. Taveira-Pinto†

† Faculty of Engineering – University
of Porto, Porto, 4200 – 465, Portugal
rcsilva@fe.up.pt, vgomes@fe.up.pt,
fpinto@fe.up.pt

‡ Civil Engineering Department –
University of Aveiro, Aveiro, 3810-193,
Portugal
ccoelho@civil.ua.pt

ABSTRACT

SILVA, R., COELHO, C., VELOSO-GOMES, F. AND TAVEIRA-PINTO, F., 2007. Dynamic numerical simulation of medium term coastal evolution of the West Coast of Portugal. Journal of Coastal Research, SI 50 (Proceedings of the 9th International Coastal Symposium), 263 – 267. Gold Coast, Australia, ISSN 0749.0208

Coastal erosion is a common problem within Europe. The main causes of this phenomenon are the generalised sea-level rise, the coastal interventions (defence and harbour structures), which cause serious perturbations in the littoral drift system, the littoral occupation and the river sediment supply reduction caused by dams, dredging and fluvial regularisation. Numerical models are helpful tools in future planning and management of coastal policies, by allowing the projection and analysis of different scenarios of medium term coastal evolution. A numerical coastline evolution model (LTC – Long Term Configuration) is being developed to support coastal zone planning and management in relation to erosion problems. The model simulates the dynamic variability of sandy beaches, where the alongshore sediment transport is controlled by waves, currents, wind, water level, sediments' sources and sinks and sediments' properties. The model also simulates different coastal interventions (groins and breakwaters, longitudinal revetments, artificial nourishments, river sediments supply). It may be applied to extensive coastal areas up to one hundred years time scale. In this paper, LTC will be used in the evaluation of the relative importance of each of the identified causes of coastal erosion at the Northwest Portuguese coast at a medium term horizon. Special attention will be given to the discussion of common coastal defence interventions influence in the littoral drift system and impact in what concerns erosion.

ADDITIONAL INDEX WORDS: *Coastal erosion, Coastline model, Scenarios evaluation*

INTRODUCTION

Coastal erosion is a problem affecting coastal regions all around the world and the Portuguese West coast is not an exception. Measures to solve the problem must be incorporated in coastal zone future planning and management of coastal policies, at least at a medium term horizon. Numerical models may be helpful tools in the analysis and projection of different anthropogenic and natural scenarios

The causes of coastal erosion and their relative importance are site specific, changing from place to place. In the case of the northern part of the Portuguese West coast (Figure 1), namely between Douro river and Nazaré, where one of the largest submarine canyons of the world lies, coastal erosion is mainly due to: 1) the generalised sea-level rise; 2) the misruled littoral occupation and use, sometimes with natural defences destruction; 3) the external works in harbours which result in perturbations to the littoral system; 4) the reduction of sediments supply from natural sources with a cessation tendency. Moreover the sediment supply reduction is considered as the main cause of the erosion problem felt in this coastal stretch.

The Northwest Portuguese coast is essentially a sandy coast approximately N21ºE oriented. It is a highly energetic coastal stretch with a wave regime typically from Northwest, characterised by a mean significant wave height of 2 m and a mean period of 12 s. Storms, occurring especially in the winter, come predominantly from Northwest with offshore significant wave heights that may reach 8 m persisting for up to 5 days. The tide regime is semi-diurnal with a tidal range between 2 m and 4 m in spring tides. The potential alongshore transport mainly due

Figure 1. Portuguese Northwest Coast (Coastal classification adapted from VELOSO-GOMES *et al.* (2006a).

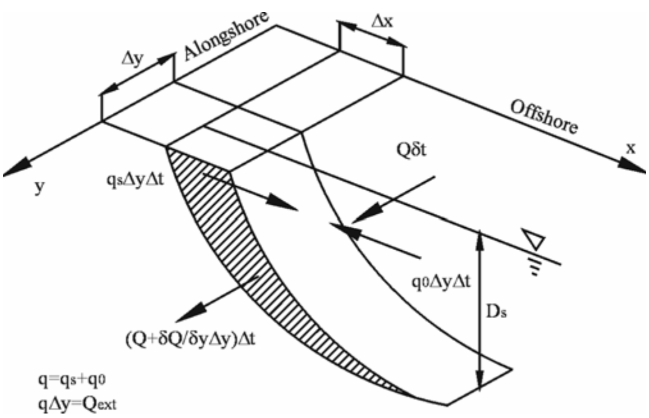

Figure 2. One-line model definition scheme (adapted from HORIKAWA (2005)).

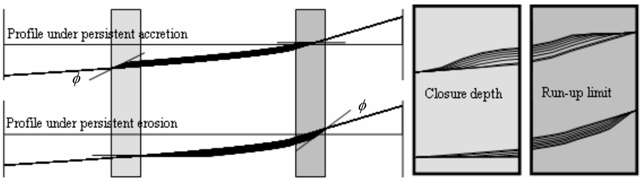

Figure 3. Sediment distribution along cross-shore profile definition scheme.

to the wave action is approximately 1-2 million m^3/year. The most contributive sediment sources for this coastal stretch are the Douro River and coastal erosion. In its natural regime the Douro River would supply about 1.8 million m^3/year, but this value has been decreasing, showing presently a cessation tendency (OLIVEIRA, 1997). This reduction is only balanced by coastal erosion.

The felt preferable solution to the erosion problem would be artificial sand nourishment. However, this solution is not feasible due to the high amount of sediments in deficit. A solution may be achieved through the construction of coastal defence structures to protect urban fronts and the passive acceptance of erosion in intermediate stretches (OLIVEIRA, 1997).

In this context, it is crucial to make available to decision makers tools to support the evaluation of scenarios. With this purpose a numerical model (Long Term Configuration) for coastal evolution at medium to long term is being developed (COELHO, 2005). The model combines a classical one-line model with a rule based model. The volume of sediments in transport alongshore, given through the continuity equation, are distributed along the active profile, according to predetermined rules.

METHOD

In this paper the LTC numerical model will be used to help illustrating the discussion of the relative importance of the coastal erosion causes in the Northwest Portuguese coast. Special attention will be given to transversal defences, since their construction is being widely used as a coastal defence technique to solve the erosion problem. In particular, their influence and impact down-drift will be discussed.

This model was especially designed for sandy beaches, where the main cause of shoreline evolution is the alongshore sediment transport, dependent on the wave climate, water levels, sediment sources and sinks, sediment characteristics and boundary conditions. The model inputs are the changing water level and the topography of the landward adjacent zones which is changed during calculation. Extensive areas can be analysed up to 50 years. The volumes transported are estimated through the application of formulae which depend on the shoreline to wave breaking angle and the wave breaking height, or the beach slope and the sediment grain size. The model assumes that each wave acts during a certain period of time (computational time step). The wave transformation by refraction, diffraction and shoaling is modelled in a simplified manner, or, wave conditions may be imported from more complex wave models.

The shoreline's changes are due to transport gradients between sediment cells, just like in the case of a classical one-line model, Figure 2. The balance of the volumes of sand is done through the continuity equation, Eq.1.

$$\frac{\partial V}{\partial y} = \left(\frac{\partial Q}{\partial y} - q\right)dt \quad (1)$$

The variation of the volume of sand, *V*, along an infinitesimal length of the shoreline is the same as the variation of sediments in transport, *Q*, in that length added or subtracted of eventual external sediments, Eq.2.

$$\Delta V = \left(\Delta Q - Q_{ext}\right)\Delta t \qquad (2)$$

The variation of the volume of sand in an infinitesimal length along the beach represents a variation in the depth level of the points in the same profile. Erosion/accretion is distributed along the active cross-shore profile, between the closure depth and wave run-up limit, Figure 3. Near the closure depth, in an accretion situation, the angle of repose, ϕ, controls the sediment distribution and in an erosion situation, the control is made by the minimum underwater bottom slope. Near the wave run-up limit, the controlling parameters are the angle of repose and minimum beach face slope, respectively for erosion and accretion. An important improvement is achieved through this model: different profile evolution slopes may be tested under different erosion or accretion situations, reducing the limitations of not knowing the profile shape evolution over time.

Due to the importance of the boundary conditions in the model simulations, several options can be made: constant sediment volumes going in or out; constant volume variations in the border sections; extrapolation from nearby conditions.

Moreover, different coastal protection works combinations may be considered with almost no limitation for the number of groins, breakwaters and seawalls, the number of sediment sources/sinks sites or artificial nourishments.

RESULTS AND ANALYSIS

Relative Importance of Coastal Erosion Causes in the Portuguese Northwest Coast

1) Generalised Sea-level Rise

The sea-level has been rising with the last century tendency of 1.5 mm/year (DIAS AND TABORDA, 1992). Due to climate change this rate is expected to accelerate, with significant values only in 50 to 100 years. An estimate of these values may be achieved considering a beach in equilibrium. If the sea-level raises *s*, the material needed to restore equilibrium will be *sl*, being *l* the width of the active profile. This amount of sediments will come from the beach erosion. If *e* is the beach berm height above mean sea-level, the eroded amount will be *er*. This results in the BRUUN (1962) rule, for coastline retreat, *r*:

$$r = \frac{sl}{e + d_c} \quad (3)$$

In the above equation d_c is the depth of closure, i.e., the seaward limit of the beach active profile, along which significant sand movements occur by wave action. The method recommended by HALLERMEIER (1981) for depth of closure calculation in the case of erosion due to sea-level rise over long periods of time is:

$$d_c = \left(\overline{H_s} - 0.3\sigma_{H_s}\right)\overline{T_s}\left(\frac{g}{5000\, d_{50}}\right)^{0.5} \quad (4)$$

In the previous equation, the bars denote mean values, H_s is the mean significant wave height, σ_{Hs} is the standard deviation, T_s is the mean wave period, and d_{50} is the median sediment grain size.

An example from the Portuguese Northwest coast is ‘Costa Nova do Prado, a beach located south from Aveiro harbour. This beach has a regular dissipative profile with some concavity and a small slope of about 0.7 %, and a berm height above mean sea-level of about 7 m, Figure 4. We will assume that the bathymetry is regular and shoreline parallel, oriented N15ºE, defining a bottom essentially composed with fine sand of 0.7 mm. Based on a three year data series registered near that beach, the wave conditions may be characterised by an annual mean significant wave height of 1.41 m with a standard deviation of 1.00 m and a mean period of 11 s. Using the above expressions, Eq.3 and Eq.4, and considering the last century sea-level rise tendency, the estimated shoreline retreat due to sea-level rise is 0.16 m/year, which is very small when compared with 5.5 m/year rate felt between 1978 and 1996 in this coastal stretch, far from groins (VELSO GOMES *et al*, 2006a). Considering the worst case scenario for sea-level rise due to climate change of 0.88 m in 2100 (IPCC, 2001), the mean estimated shoreline retreat is 0.84 m/year, 15 % of the referred rate. This way, the sea-level rising does not justify the present verified erosion.

On the other hand, the sediment supply reduction, due to increase of the settling capacity in estuaries, also does not justify the verified erosion. In the case of the Douro river assuming that the river estuary is 32 km long, with a mean width of 250 m, and that the bottom rises as the free surface, the settling capacity would increase of 12 000 m^3/year, less than 5 % of the present river supply. This way, the generalised sea-level rise is not a very significant cause of the erosion problem felt in the Northwest Portuguese coast.

Figure 4. ‘Costa Nova do Prado’ in the Portuguese Northwest Coast (October 2006).

2) Misruled littoral occupation

Coastal environment preservation and valorisation is presently consensually considered of high importance. Nevertheless, in a coastal stretch under a progressive erosion process with a permanent sediment deficit, it is not a first priority.

The misruled littoral occupation and coastal erosion are connected through the weakening or even destruction of dune systems, considered as natural defences. Dune recovery is important but not very significant under the present erosion state of the Northwest Portuguese coast. If we assume that the active profile moves parallel to itself, Figure 2, and that D is the active profile height, the distance between the depth of closure bottom level and the wave run-up limit, the continuity equation, Eq.1, may be rearranged as:

$$D\frac{\partial x}{\partial t} = \left(\frac{\partial Q}{\partial y} - q\right) \quad (5)$$

For a certain alongshore transport, increasing the active profile height results in an inverse variation of the linear rate of shoreline retreat. Using typical values from the example considered in the previous point, for a active profile with a bottom level -20 m CD (Chart Datum), as calculated by Eq. 4, and a berm height of about 7 m CD, then D = 27 m. If through dune recovery an increase of 5 m in the run-up limit of the active profile is achieved, this will have the effect of reducing in about 16 % the shoreline retreat rate.

3) External Works in Harbours

The harbours are fundamental in terms of socio-economic development. The long breakwaters in the harbours have two major functions, to shelter the harbour entrance and its interior, and this is achieved by changing the wave conditions, and to fixate navigation channels and minimise retention, by changing the sedimentary dynamics. However, these long structures introduce severe perturbations in the littoral drift system: refraction, diffraction and reflection wave patterns transformation occur; currents, that push sediments offshore to depths where the waves are not able to bring them back to the beach, are induced; and the littoral drift is interrupted. Besides that, external works in some Portuguese harbours (Viana do Castelo, Leixões, Aveiro e Figueira da Foz) tend to aggravate the erosion phenomenon (e.g. sand extraction on up-drift beaches, channels dredging without reposition down-drift, and retention). For the sake of illustration, in the ‘Figueira da Foz’ harbour between 1991 and 1996 about 2.6 million m^3 of sand have been removed from the littoral system, extracted from the beach up-drift and dredged from the harbour entrance. These correspond to a mean annual value of about 0.43 million m^3/year (LNEC, 1998), with significant erosion consequences down-drift from the harbour.

4) River Sediment Supply Reduction

The river sediment supply reduction is the basic cause of the erosion process that has been affecting the Portuguese Northwest coast. The Douro River in its natural regime would supply about 1.8 million m^3/year, but this value has decreased to about 0.25 million m^3/year (OLIVEIRA, 1997) showing presently a cessation

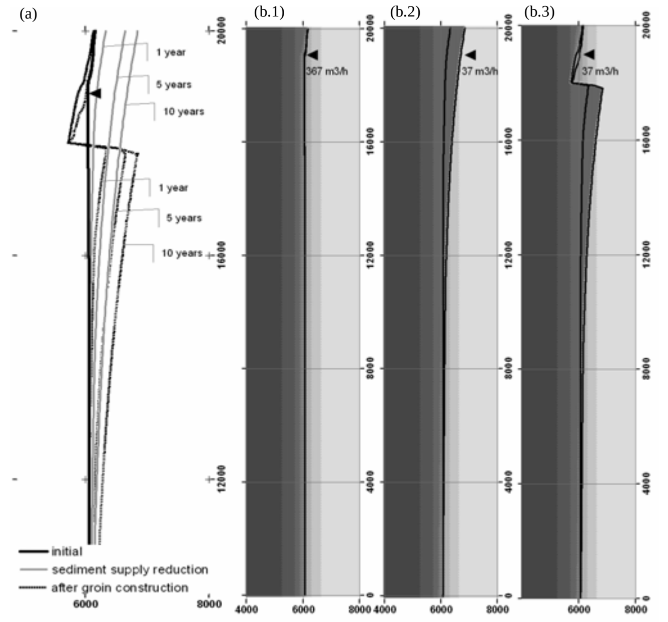

Figure 5. Plant view of (a) coastline evolution as predicted by LTC model in 10 years for each of the situations: (b.1) beach in equilibrium with a constant sediment supply in the upper part of the domain; (b.2) sediment supply reduction to 10 %; (b.3) groin construction.

tendency. The reasons behind this reduction are mainly sand extraction in estuaries and along the river, and dam construction. The dam construction induces sediment supply reduction in two ways: retention in reservoirs and changing the hydrological regime.

Coastal Defence Interventions

The coastal defences are intended to reduce erosion in an up-drift beach extension, resulting in transitional erosion down-drift. When analysing their impact, two points of view must be considered: shoreline stabilisation and sediments retention. The longitudinal revetments do not have retention capacity while groins perform their function precisely by accumulating sediments up-drift.

Groins are the oldest and most commonly used shore-connected, beach stabilisation structure. How do groins work? Groins work as physical barriers to the alongshore transport of sand, that starts to accumulate up-drift. This accumulation reorients the shoreline and reduces the angle between the shoreline and the prevailing incident wave direction, reducing the local rate of alongshore sand transport to produce more accumulation. The amount of sand transported past the groin is greatly reduced causing erosion impact at the down-drift area. Modern coastal engineering practice is to combine beach nourishment with groin construction allowing sand to immediately begin to pass the groin, reducing transient erosion down-drift. As stated by KRAUS, HANSON, and BLOMGREN (1994), "…the literature (on groins) may appear to assign validity to certain concepts and conclusions by weight of repetition (but) not by independent confirmation." (p. 1329). A critical review of the literature shows that little previous discussion exists on how to judge success of a groin design. Laboratory investigations on this topic suffer from severe scale distortions in sediment transport, raising doubts on their results. Success should be judged on two factors: to maintain a minimum, dry beach width to guarantee protection beyond a reference baseline; and to minimise down-drift impacts (BASCO, 2006).

Consider the Northwest Portuguese coast typical situation consisting of a coastal stretch with Douro River as the major sediment source up-drift, Figure 5. Assume that the stretch is initially in equilibrium, Figure 5 (b.1) meaning that in average the river sediment supply rate equals the potential alongshore transport by wave action, and that the coastline is stable. If the sediment supply is reduced, the coastline down-drift from the source retreats and the beach is eroded. Somewhere down-drift in the coastal stretch the equilibrium is maintained by the river sediment supply plus the sediments eroded from the beach, Figure 5 (b.2). As time goes by the beach erosion propagates down-drift, Figure 5 (a). If this situation is predicted with some anticipation an intervention may take place for example, to preserve a beach or to prevent destruction of natural defences of an urban front. Let us consider the construction of a groin in the position where the eroding process is expected to start, Figure 5 (b.3). After a transient period of time, during which some volume of sediments is blocked by the groin, the coastline down-drift will evolve as if the defence wasn't there, Figure 5 (a).

The volume of sediments accumulated up-drift from the groin is a function of its dimensions, wave conditions and sediment grain size, being indicative of the erosion contention. If the limiting retention capacity of the groin is reached it stops blocking sediments, letting them pass through. The down-drift adjacent erosion is higher by the time of the works construction, decreasing in time, Figure 6. Even by the time of the construction some sediments transpose the groin, for instance under high wave conditions and low tides. The down-drift supply will increase until the groin gets saturated and sediment transposition becomes almost 100%. As the ratio of gross to net transport increases, the retention functioning decreases. Because of sand bypassing, groin permeability, and reversals in transport, the up-drift shoreline cannot reach the end of the groin only by alongshore transport processes. Onshore transport would be required for the shoreline to reach the groin tip, for the groin to be buried, or for the groin compartment to fill naturally.

How long does it take for the groin to get saturated? The answer to this question is not simple, the time elapsed to fill a groin depends on several factors, like wave conditions at the groin location, beach morphology, tide regime and even current pattern in the surrounding area. A first approximation is to assume that during the filling time there is no transposition and once the groin is filled; all the incoming sediments are transmitted, Figure 6. Under these assumptions the filling time would be given by the ratio between the accumulated volume and the alongshore transport rate. This apparent simple way of answering to the

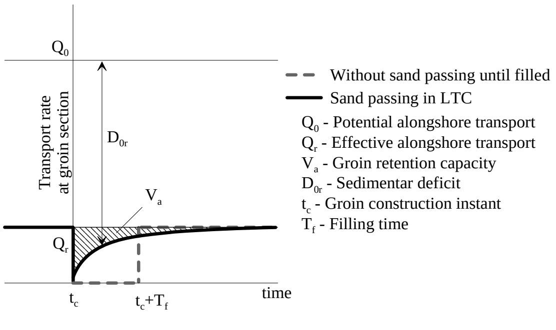

Figure 6. Groin filling process scheme (adapted from OLIVEIRA (1997).

question is in fact very complicated, since both accumulated volume and alongshore transport are difficult to evaluate. Besides that, the question could only be answered by the time the groin would already be filled.

A very negative impact that would result from these works, if they had the capacity of inducing rip currents, would be the irreversible loss of sediments dragged to offshore. However, the only currents thought to exist result from the inflection imposed by the structure to the alongshore currents. They run, with typical velocities of tens of cm/s, within a straight strip parallel to the groin, losing strength immediately after the groin head, because they disperse over higher depths. Observation shows that the sediment plume that, sometimes denote their presence only reaches small distances. Groins erode the beach by rip current jetting of sand far offshore? Short groins cannot jet material far offshore and permeable groins reduce the rip current effect. However, long impermeable jetties might produce large rips and jet material beyond the average surf zone width. Affirming that groins erode the offshore profile is questionable and doubtful.

Groins are now being re-evaluated as sand-retention structures (KRAUS, HANSON AND BLOMGREN 1994; KRAUS AND BOCAMAZO 2000) by now asking the question “how much sand can be allowed to pass?” while still maintaining a minimum width of beach at the groin for some level of shore protection. Under this perspective, groins should be permeable, allowing water and sand to move alongshore, and reduce rip current formation and cell circulation.

In LTC the groins are considered impermeable, the sediments only pass the groin offshore from its head. Besides, the groin is admitted to function as schematised in Figure 6. The amount of sand that passes the groin is calculated admitting that it is proportional to the ratio of the up-drift adjacent active profile at a lower depth than the groin head. This way not all of the sand that reaches the groin passes it, being retained and accumulated up-drift. The deficit of sand down-drift results in erosion. The sand that passes the groin is redistributed down-drift along the whole active profile. In front of the groin the sand is distributed between the depth of closure limit and the groin head limit.

CONCLUSIONS

The Portuguese Northwest Coast suffers from a continued high sedimentary deficit that is primarily due to Douro River sediment supply reduction, with a cessation tendency. Due to the present critical state, the generalised sea-level rise, due to climate change, will have significant importance only in 50 to 100 years. The measures to recover and preserve dunes and natural defences are also important, but more severe measures are needed to face the problem.

The felt preferable solution to the erosion problem would be artificial sand nourishment. However, this solution is not feasible due to the high amounts of sediments in deficit and the costs involved. A solution may be achieved through the construction of coastal defence structures to protect urban sea fronts and the passive acceptance of erosion in intermediate stretches. Modern coastal engineering practice is to combine beach nourishment with groin construction allowing sand to immediately begin to pass the groin, reducing transient erosion down-drift. This kind of technique is planned for ‘Costa da Caparica’. The beach nourishment plan predicts a 3 million m^3 of sand nourishment (VELOSO-GOMES *et al.*, 2006b). Groin design should be carefully done and success should be judged on two factors: to maintain a minimum, dry beach width to guarantee protection beyond a reference baseline; and to minimise down-drift impacts.

The LTC numerical model may be used as a tool in evaluating different scenarios. The model could be used to support in the design of coastal structures, helping in the choice of best engineering solution to a particular erosion problem. Simulations and model calibration are presently being carried out using topographic data collected in a three year monitoring program established by the time of the construction of a detached breakwater, which ended to function like a groin.

LITERATURE CITED

BASCO, D.R., 2006. Shore Protection Projects. In: Donald L. Ward (editor), Coastal Engineering Manual, Part V, Coastal Project Planning And Design, Chapter V-3, Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington, DC.

BRUUN, P., 1962. Sea-level Rise as a Cause of Shore Erosion. *Journal of Waterways and Harbours Division*, American Society of Civil Engineers, 88, 117-130.

COELHO, C., 2005. Riscos de Exposição de Frentes Urbanas Para Diferentes Intervenções de Defesa Costeira (in Portuguese). Aveiro, Portugal: University of Aveiro, Ph.D. Thesis, 404 p.

DIAS, J.A. and TABORDA, R., 1992. Tidal Gauge Data in Deducing Secular Trends of Relative Sea-level and Crustal Movements in Portugal. *Journal of Coastal Research*, 8, 655-659.

HALLERMEIER, J.R., 1981. Seaward Limit of Significant Sand Transport by Waves: An Annual Zonation for Seasonal Profiles. U.S. Army Corps of Engineers, CERC, 19p.

HORIKAWA, K. and ISOBE, M., 2005. Dynamic behaviour of coastal sediment. *Proceedings of the Japan Academy (Japan)*, Series B, Vol. 81, No. 9, pp. 363-381.

IPCC, 2001. Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Watson, R.T. and the Core Writing Team (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 398 pp.

KRAUS, N.C. and BOCAMAZO, L.M., 2000. State of Understanding of Groin Functioning and Recent Promising Innovations. *Proceedings 3rd Annual Conference*, Northeast Shore and Beach Preservation Association.

KRAUS, N.C., HANSON, H. and BLOMGREN, S.H., 1994. Modern Functional Design of Groin System. *Proceedings of 24th International Conference on Coastal Engineering (*NY, ASCE), pp 1327-1342.

LNEC, 1988. Análise da Dinâmica Costeira do trecho Cabo Mondego - Estuário do Mondego. Erosões em Buarcos (in Portuguese). Lisboa, Portugal. Report 88/98 - NET, LNEC.

OLIVEIRA, I.B.M., 1997. Proteger ou Não Proteger ou Sobre a Viabilidade de Diferentes Opções Face à Erosão da Costa Oeste Portuguesa, *In*: CARVALHO, G.S. (ed.), *Colectânea de Ideias Sobre a Zona Costeira de Portugal* (in Portuguese), Associação Eurocoast-Portugal, pp. 205-227.

VELOSO-GOMES, F., TAVEIRA-PINTO, F., DAS NEVES, L. and PAIS-BARBOSA, J., 2006a. EUrosion - A European Initiative for Sustainable Coastal Erosion. Pilot Site of River Douro - Cape Mondego and Case Studies of Estela, Aveiro, Caparica, Vale do Lobo and Azores. Porto, Portugal: IHRH, 317 pp.

VELOSO-GOMES, F., TAVEIRA-PINTO, PAIS-BARBOSA, J., COSTA, J. and RODRIGUES, A., 2006b. Monitoring of Coastal Defence Works of Costa da Caparica, Portugal. *Proceedings of the 30th Conference on Coastal Engineering* (San Diego, USA, ASCE) (in print).

ACKNOWLEDGEMENT

Raquel Silva is supported by Fundação para a Ciência e a Tecnologia, Ph.D. grant ref. SFRH/BD/19090/2004.