STUDY OF CLIFF SHORELINE EROSION

G. Gómez-Pina[1], J.J. Muñoz-Pérez[1], M. Figueres[2], J.M. Garrido[2], D. Ponce de León[2], A. Pérez[2] M. Velasco[2] and S. Lizondo[2]

In this paper the cliff shoreline erosion on the coastline between Punta Montijo and the Chipiona Port (Cadiz, Spain) is studied. The reasons which cause this erosive phenomenon and the future erosive tendency of these cliffs are estimated, obtaining magnitudes of recession and the rate at which it will occur. Analysis of the current situation has been carried out by determining its plan shape, the study of the theoretical erosion profile of the cliffs and the verification of their failure. The future evolution of the cliffs shoreline has been analysed through the simulation of its recession and the study of the profile response to storm wave action. Finally, is presented a model to estimate the recession of the cliff shoreline.

Keywords: shoreline erosion; beach; cliff; slope stability

INTRODUCCION

Different studies carried out on the coastline between Punta Montijo and the Chipiona Port (Cadiz, Spain) have revealed the high vulnerability to erosion of its cliffs composed of clay, with an estimated shoreline recession of between 0.5 and 3 metres per year (Muñoz-Perez et al. 2001 and Gomez-Pina et al., 2006).

This area of study is part of the physiographic unit delimited by the Guadalquivir estuary (Sanlúcar de Barrameda) and the port of Chipiona (Fig. 1).

This physiographic unit presents two different sections: (1) Shoreline between Sanlucar and Punta de Montijo, with a lying and straight beach, (except the cliff of the *Espíritu Santo*) and (2) shoreline between *Punta de Montijo* and the Port of Chipiona, which has a low-rise cliff with a narrow sand beach at the bottom. The seabed presents waves carved terraces with upper Pliocene cemented, Plio-Quaternary and Quaternary materials, which are revealed as a shallow at low tide.

Within this shoreline, there are two subsections: the subsection 1, corresponding to Micaela beach that is protected from wave action by the Port of Chipiona and *Facies Ostionera* materials terrace, and the subsection 2, to Punta Montijo, with a more intense erosion level and higher cliffs.

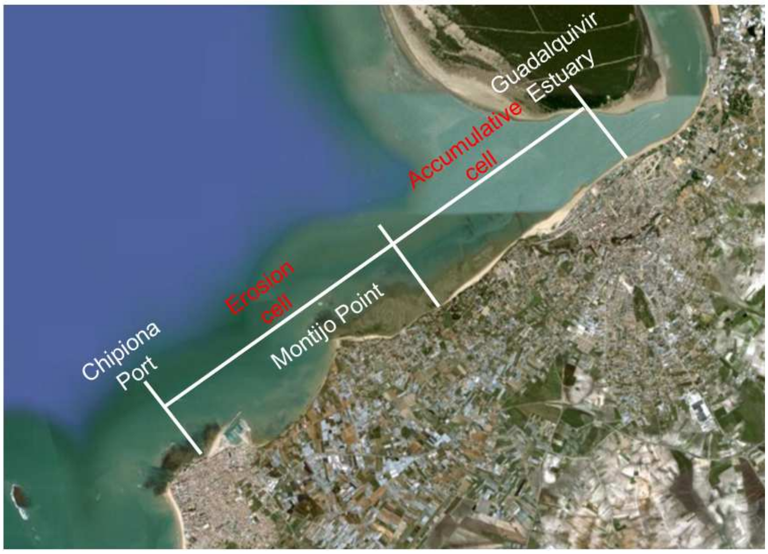


Figure 1 - Physiographic units between Port of Chipiona and Guadalquivir estuary.

The geomorphology, lithology and seabed confirm the presence of clay with some sand layers (D_{50}<0.08mm), sand beach (D_{50}=0.2mm) and a sandstone rock terrace (Ostionera) (Fig. 2) around -2m

[1] Demarcación de Costas Andalucía Atlántico, Dirección General de Costas, Ministerio de Medio Ambiente, c/Marianista Cubillo 7, 11071 Cádiz, SPAIN ggomez@mma.es
[2] Iberport Consulting S.A., C/Botiguers Nº 3. Planta 3 Puertas AB. Parque Empresarial Táctica, 46980 Paterna (Valencia), SPAIN. jgarrido@iberport.com

level. The existence of this rock platform plays a key role in the dynamics of currents and transport in the area because it causes wave breaking.

Figure 2 – Erosion of cliffs in Chipiona shoreline

After analyzing the available information, the type profile in Chipiona shoreline is shown in Fig. 3.

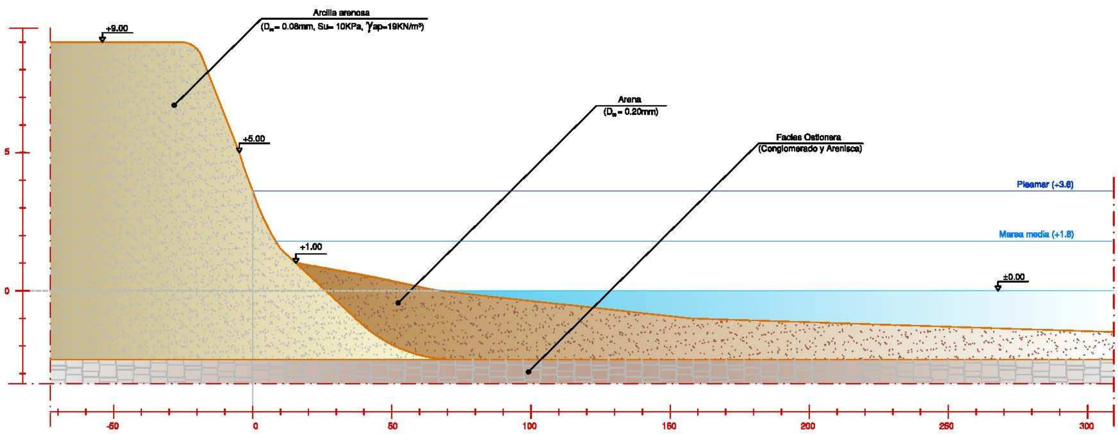
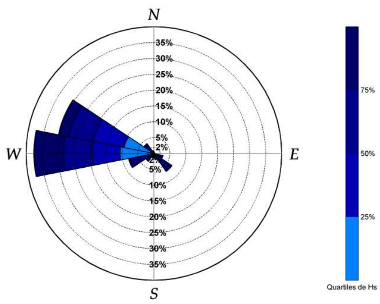


Figure 3- Profile type in Chipiona shoreline

The waves arrive mainly from sectors W, WNW and WSW, in more than 75% of the total record, and are associated with larger fetch distances. The higher waves arrive from sector W.



The goal of this work is to study the causes and rate of the erosion of the coast. In order to achive this objective, this work is structured as follows: firstly, the historic evolution of shoreline is described; the next section deals diagnosis of the current state of the coast, the erosion process is studied from different points of view and, finally, a future scenario of the erosion rate is proposed.

EVOLUTION OF SHORELINE

The study of historic evolution of shoreline is based on information of nautical charts, restored pictures and field measurements. The evolution of the coastline has been studied from 1868 to present (2010). To do this, the different shorelines in different years have been restored and compared in order to show the shoreline retreat in fixed sections perpendicular to the coast.
Due to the high tidal range (3.6 m) the shoreline historic evolution study has considered situations of high tide and low tide.

By comparing initial and curent position of the shoreline, it can be concluded that, between the chipiona Marina and Punta Montijo, a maximum shoreline retreat of 239 in 142 years can be observed (Figure 4). The most eroded section corresponds to the north-eastern Punta Montijo boundary, while in the center of the stretch (section B) the shoreline has retreated 190m, and in the south-western zone close to the Chipiona marina, the shoreline has retreated 120m.

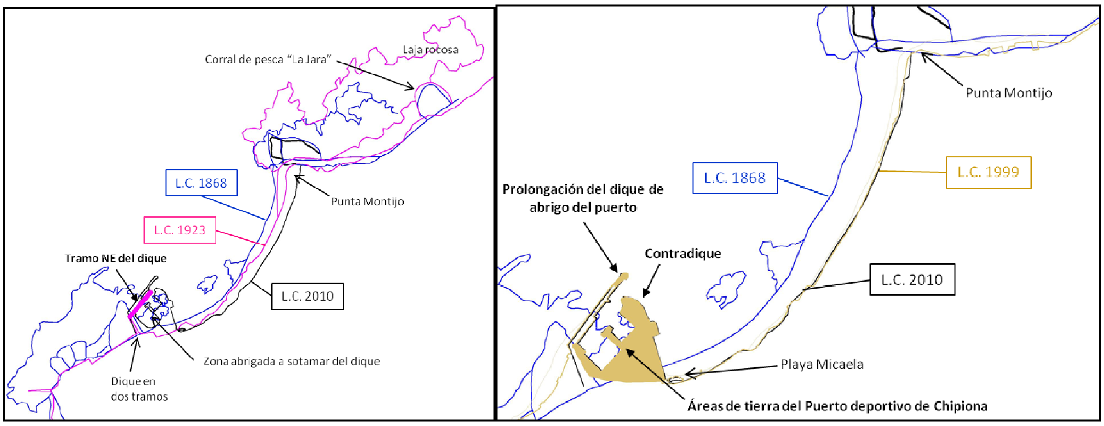


Figure 4 – Evolution of the shoreline between 1868 and 2010

In Fig. 4 the changes produced in the central section (Section B) can be observed. It can be confirmed that the shoreline evolution was affected by the construction of the marina breakwater first alignement (1868), and the construction of the marina breakwater second alignment (before 1923).

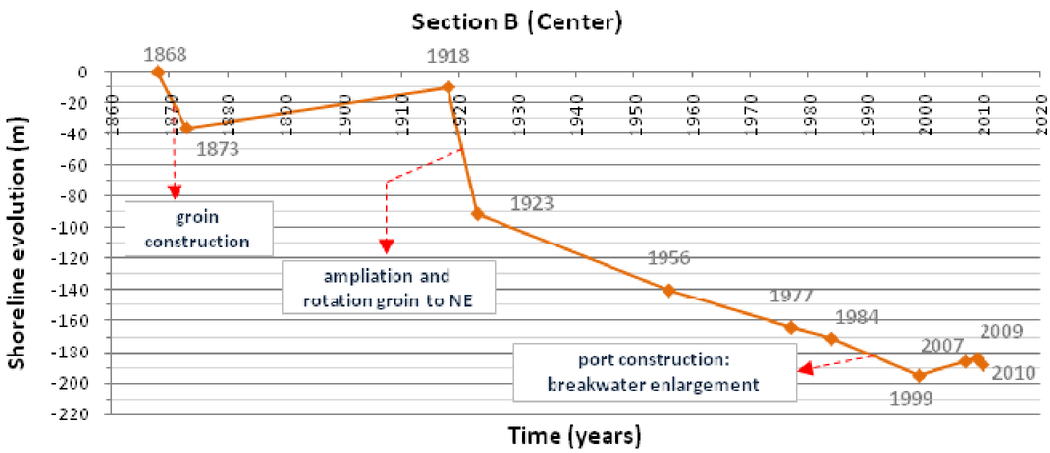


Figure 5 - Shoreline evolution (section B)

DIAGNOSIS OF THE CURRENT STATE

Plan equilibrium shape

The equilibrium shape of the shoreline has been analysed by means of three different procedures: (1) obtaining the average energy flow at several points near the coastline (levels -3 and -1 m); (2) from the Hsu and Evans (1989) theoretical model; and (3) from results obtained with the numerical evolution model of the shoreline GENESIS (Hanson and Kraus, 1989). It is concluded that the current plan shape is similar to the equilibrium plan shape (Fig. 6). It can therefore be assumed that the main cause of cliff erosion is not the longitudinal sediment transport.

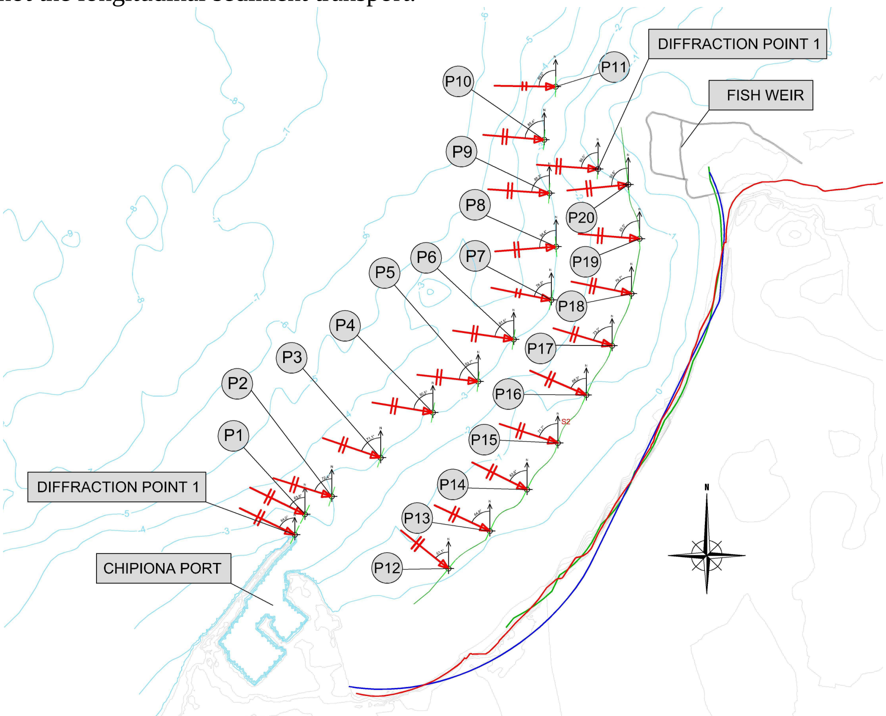


Figure 6 - Superposition of the current plan shape (red line), Hsu and Evans (blue line) and average flow (green line)

Equilibrium profile

The geotechnical characteristics of the materials, the orientation of the shoreline related to the wave incidence and the length of the rock terrace in front of the cliff determine their stability.

The study of the equilibrium profile has been analyzed with three approaches: (1) theoretical equilibrium profile assuming that the eroded material contributes to the formation of the slope, (2) overall stability of the slope, which configures the current profile, with no wave action and taking into account the wave action, using numerical model of slope stability (SLIDE), and (3) the stability against the erosion caused by the scour at the foot of the slope, by application of criteria critical speed of movement of particles.

Theoretical equilibrium profile

In a first diagnostic hypothesis, the possible formation of a theoretical equilibrium profile is simulated with the Dean profile (D_{50} = 0.08 mm). It is shown in Figure 7.

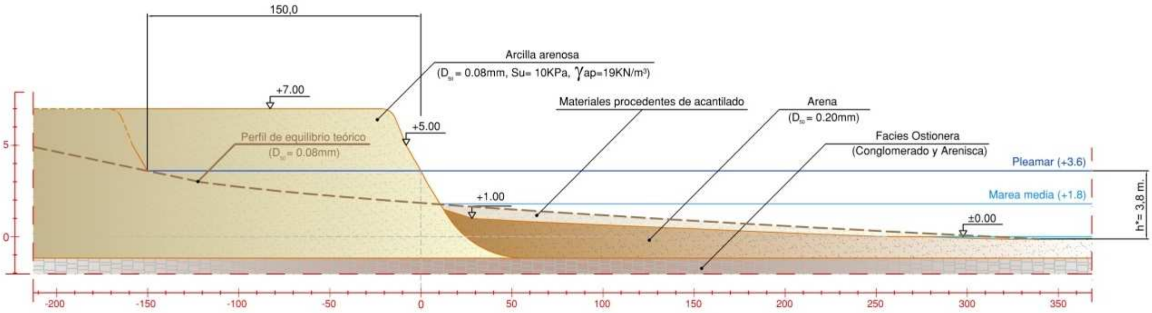
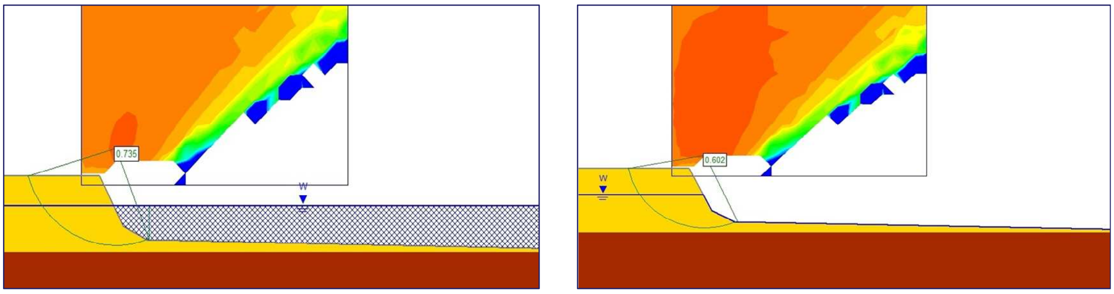


Figure 7 - Equilibrium profile versus Dean profile

Assuming that the cohesive material is lost by suspension, it is concluded that the theoretical Dean's equilibrium profile, that would produce a retreat of 150 m, can not be reached.

Overall stability failure

Global stability of the slope has been obtained by using the numerical model in three design situations: (1) high-tide level without wave action, (2) high-tide level with wave through and (3) high-tide level with wave crest and model of soil uplift pressure. In all of the above situations, the slope is unstable with slip planes causing erosion of only 4-5 m on the crest of the slope (Fig.8).



HWL without waves **HWL with waves**

Figure 8. Limit state equilibrium numerical model (SLIDE)

However, historical observations of the progressive recession of cliffs have lead to the consideration of more reliable failure mode consisting of the failure of the slope due to gradual landslides caused by scour at its toe, instead of the global stability failure.

Slope bottom erosion failure mode

In order to analyse the progressive cliff toe erosion, the critical velocity (U_{cr}) for initiation of sediment motion at the toe of the slide (h = 0.1 m) is determined by applying the formula of Soulsby (1997).

$$\overline{U}_{cr} = 0{,}19(D_{50})^{0.1}\log_{10}\left(\frac{4h}{D_{90}}\right) \qquad 0.1 \leq D_{50}(mm) \leq 0.5 \qquad (2)$$

Once this threshold velocity has been obtained (Ucr = 0.17 m/s), with D_{50} (mm) = 0.2, D_{90} (mm) = 2 and h=0.10 m, the exceedance of this value within the area of study is analysed by determining erosive currents in both the horizontal plane (near-shore currents) and the vertical plane (difference between the "run-up" and "run-down" of the wave on reaching the slope with respect to the average period). It is concluded that velocity of current is higher in the vertical plane than in the horizontal plane, being in both cases higher than the critical velocity calculated. This threshold velocity is related to a wave height with a probability of occurrence of at least 50% annually (Table 2).

Table 2. Horizontal velocity (average wave regime 50% of time)

H_s toe (m)	Tide level (m)	u_h current (m/s)
0.48	1.8	0.22

The vertical velocity for frequent wave regime (<35% of time) is shown in Table 3.

Table 3. Vertical velocity (average wave regime 35% of time)

H_s toe (m)	Tide level (m)	Tp (s)	u_v current (m/s)
1.0	3.6	5.5	0.41

As it can be seen, the flow velocity is higher in the vertical plane on the horizontal, both being greater than the critical speed of movement of the material calculated from the cliff, from which it follows that the toe may be eroded by scour, and as a result, cause progressive landslides of the cliff.

Conclusions of erosion process

From the results obtained in the initial analysis, it can be concluded that:

The shape of the shoreline of the coast between Chipiona marina and Punta Montijo fits the Hsu and Evans (1989) parabola, suggesting that longitudinal transport is not the cause of the erosion.

The main mode of failure of the cliff between Punta Montijo and the marina and fishing port of Chipiona corresponds to a gradual erosion of the toe of the slope given by the action of perpendicular waves on the clayey cliff formation.

The fine material removed from the cliff is suspended and transported offshore of the physiographic unit, outside the coastal dynamics, preventing its accumulation at the toe of the slope and the formation of a beach.

EROSION MODEL: DIAGNOSIS OF THE FUTURE STATE

In order to study the long term tendency of the cliff erosion, the resulting waves in two hypothetical future scenarios of the eroded cliffs from its current position have been studied: the first with a recession of 150 m and the second with a recession of 450 m.

In the simulation the current cliff profile position is retreated, taking as reference the equilibrium shoreline shape of the coast.

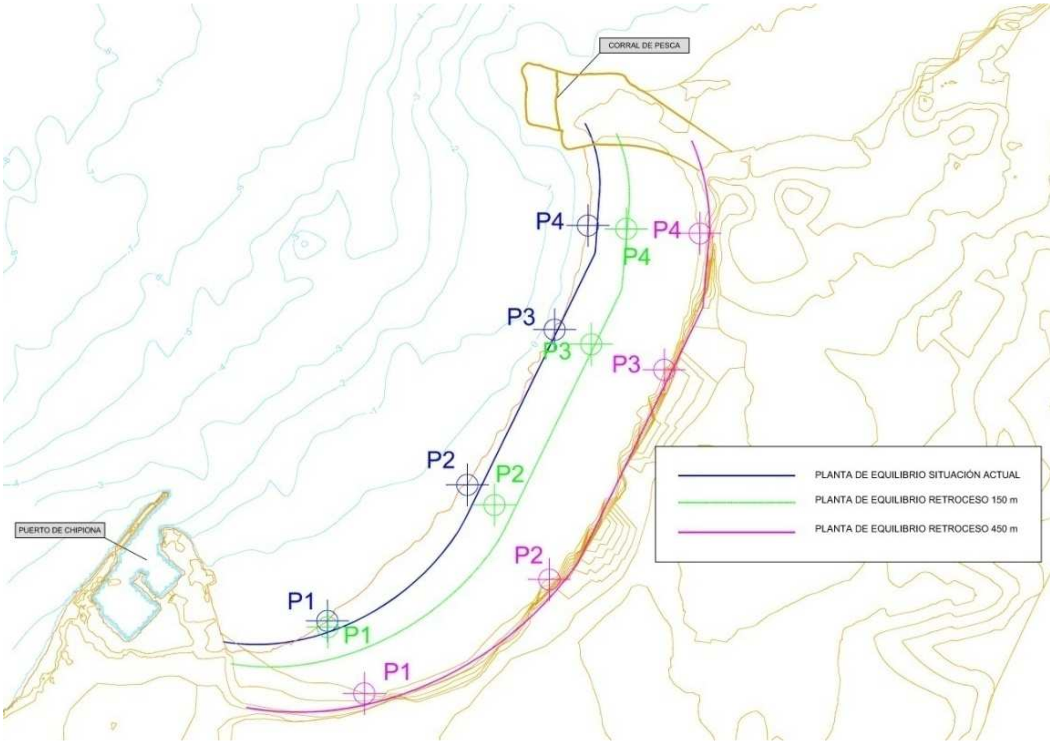


Figure 9 - Hypothetical future scenarios of the eroded cliffs

As it can be seen in the figure and as discussed above, the area of higher waves and erosion of the cliff is located at the northeast zone. Results from the propagation analysis including waves and currents will be obtained and related to the dimensionless parameters relative height (H_s/h) and steepness (H_s/L), and vertical velocity over the slope, Vv (m/s), so that a pattern of behavior can be established.

The analysis shows that the state of sea that represents the most unfavourable values of wave height and currents, are the most frequent in the area. The following cases have been taken as representative of the wave regimes: Significant wave height H_s = 1.2 m and peak wave period Tp = 5.5s for the average wave regime, and T_R= 68 years, H_s =9.3 m. and T_p=14 s for the extremal wave regime, with a tidal range of 3.6 m.

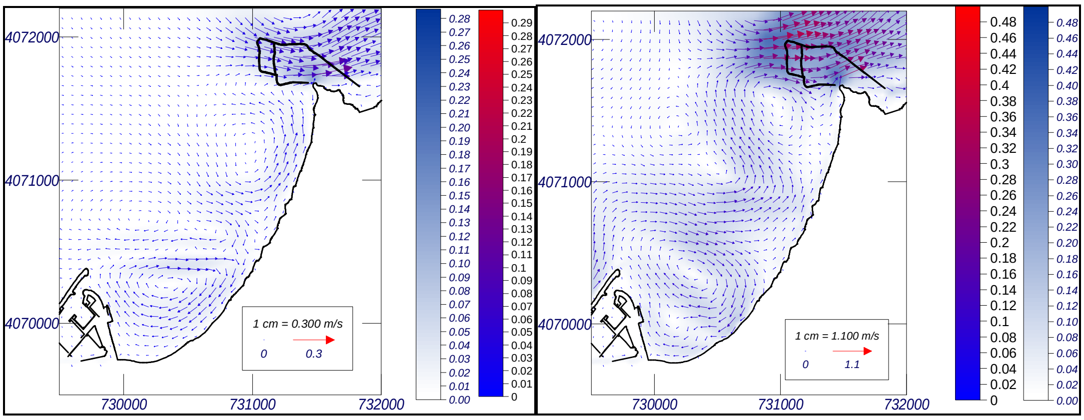


Figure 10 - Wave propagation with R=150 m: (a) Average wave regime and (b) extremal wave regime.

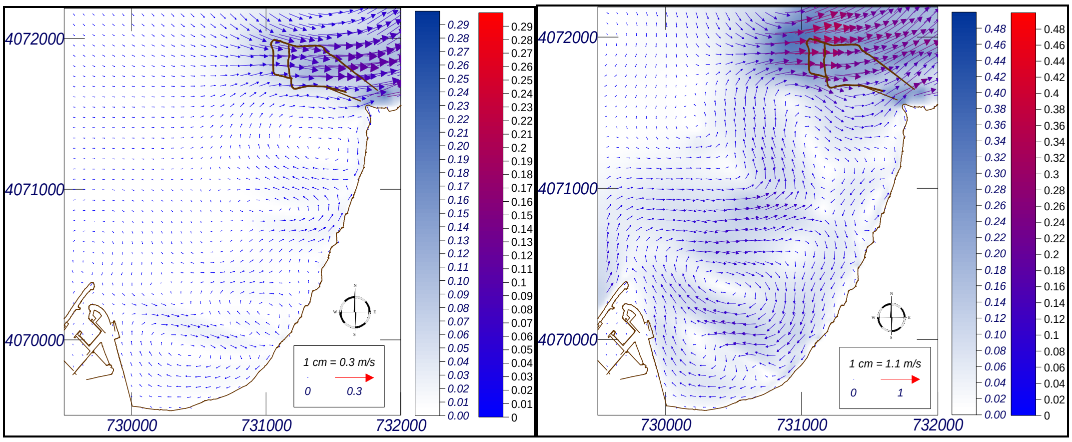


Figure 11 - Wave propagation with R=450 m: (a) Average wave regime and (b) extremal wave regime.

An exponential function of vertical velocity of currents (Vv) depending on the retreat of cliffs shoreline (R) is fitted. With this function, the value of the cliff shoreline retreat that predicts the stable behaviour of the slope for a critical velocity (U_{cr}) can be estimated. The fitted expression of the new cliff shoreline recession model is shown in [2].

$$V_v = 0{,}32e^{-3 10^{-4} R} \qquad (2)$$

As stated earlier in this document, the critical velocity necessary to move the material forming the cliffs between Punta Montijo and Chipiona Port is 0.17 m/s. Therefore, the cliff shoreline will not be stable while there are currents exceeding this value. Stabilisation will occur when the recession of the cliffs shoreline is 2100 m (Fig. 12) approximately.

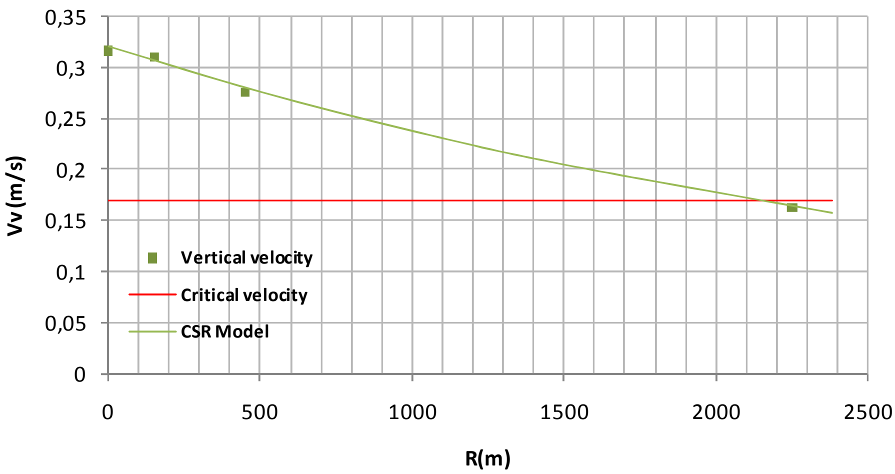


Figure 12. Fitting CSR model of Vv(m/s) vs. R(m)

Slope erosion temporal evolution

Finally, in order to provide an order of magnitude of the time necessary to reach the previously mentioned recession, the response of the profile to storm waves was determined by PETRA model (Gonzalez et al., 2007) (Fig. 13).

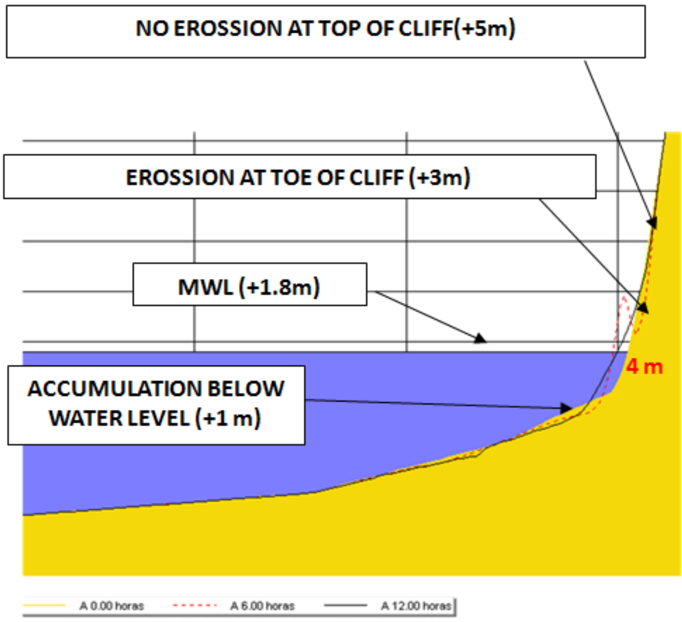


Figure 13. Slope erosion temporal evolution

The cases analysed and the results obtained are shown in the Table 3.

Table 3. Results of recessions and eroded volumes

Return Period T_R (years)	Tide Level (m)	Duration (h)	Recession (m)	Eroded Volume (m^3/ml)
68	1.8	1	-	2.4
68	3.6	1	2	8
68	3.6	6	3.2	15
5	1.8	1	-	1.6
5	3.6	1	2	6.5
68	variable	12	4	10

CONCLUSION

The following conclusions can be drawn:

- The studied coast region shows continuos erosion since beginning of XX century.
- The cause of the shoreline retreat is the progressive erosion at toe of the cliff
- Average wave regime causes erosion with MWL
- Future state shows that erosion continues even with a retreat of 450 m
- Transversal profile erosion numerical model shows good agreement with retreat of shoreline rate
- A rubble mound protection of the bottom of the cliff is necessary.

ACKNOWLEDGMENTS

This study has been realized as part of project "*Proyecto de sendero y tratamiento del borde litoral entre Arroyo Reyerta y el Puerto Pesquero-Deportivo de Chipiona, (Cádiz)*" financed by Directorate General for the Sustainability of the Coast and the Sea of the Government of Spain.

REFERENCES

Gomez-Pina, G., Fages, L., Ramirez, J.L., Muñoz-Perez, J.J., Enriquez, J., (2006). "A critical review of beach restoration projects in the northern coast of Cadiz (Spain) after thirteen years". Proc. of ICCE 2006, pp. 4167-4178.

Gonzalez M., Medina, R., Gonzalez-Ondina, A., Osorio, A., Méndez, F.J., and García, E., (2007). “An integrated coastal modeling system for analyzing beach processes and beach restoration projects, SMC”. Computers & Geosciences, 33, pp. 916–931.

Hsu, J. R. C. and C. Evans, (1989). “Parabolic Bay Shapes and Applications”. Proc., Institution of Civil Engineers, London, England, vol. 87 (Part 2), pp. 556-570.

Hanson, H., Kraus, N.C., (1989). “GENESIS: Generalized Model for Simulating Shoreline Change”. US Army Corps of Engineers, DC 20314-1000.

Muñoz-Perez, J.J., López de San Román-Blanco, B.,Gutierrez-Mas, J.M., Moreno, L., Cuena, G.J. (2001). “Cost of beach maintenance in the Gulf of Cadiz (SW Spain)”Coastal Engineering, 42, pp. 143-153.

Soulsby, D.H. (1997). "Dynamics of marine sands. A manual for practical applications," Thomas Telford Publications, London, England, 249 p.