ASSESSMENT OF COASTAL PROTECTION PROVIDED BY SEAGRASS BEACH CAST DEPOSITS: LABORATORY EXPERIMENTS

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In coastal areas where seagrass meadows exist, seagrass debris may accumulate forming beach casts called banquettes. There is qualitative evidence that these banquettes may play a role in protecting the beach from erosion and flooding. Nevertheless, there is a lack of studies quantifying this protective role. In this work, large scale laboratory experiments are used to assess the morphodynamic interaction between the beach profile and such banquettes. Results show that if the banquettes are large enough, the part of the beach behind the banquettes is not affected by wave action and remains unchanged. On the contrary, at the toe of the banquettes a greater erosion is observed. The rest of the beach profile behaves similarly to the benchmark (profile without banquette). Smaller banquettes do not show the same protective role and behave more similarly to the benchmark, although they also reduce erosion in the backshore zone.

Keywords: Seagrass wrack, coastal erosion, flume experiments, beach profile, seagrass banquette

INTRODUCTION

Beach cast deposits are usual in coastal areas where seagrass meadows exist. Such seagrass wrack is majorly composed of rhizomes, stems and leaves (Vacchi et al., 2017; Pal and Hohland, 2022). In many areas, particularly in sandy beaches with gentle slopes, extensive deposits of seagrass debris can be found covering vast areas of coast (Figure 1), from a few centimetres in the water to several meters inshore (Hyndes et al., 2022; Menicagli et al., 2022), being commonly referred to as "banquettes".

Figure 1. Image of a seagrass beach cast on a beach in Catalonia (Spain).

Some authors (e.g. Simeone and De Falco, 2012, Passarella et al., 2020) pointed out that banquettes play a protection role on beaches from winter storms and favor foredune development by providing nutrients for vegetation growth (Joyce et al., 2022; Menicagli et al., 2024). Despite this, the perception of these plant accumulations by users is often negative and banquettes are removed (Figure 2) to allow beach exploitation for tourist activities (Duarte, 2004).

Although the depositional patterns of seagrass and the sequence of formation and destruction of the banquettes have been well described (Simeone et al., 2013) and some studies have addressed the parametrization of seagrass wrack for predicting patterns of transport and deposition of such wrack or assessed morphological changes due to the presence of such structures (Corbi et al., 2018; Cucco et al., 2020), there are no studies quantifying their protective role. In particular, there is a lack of studies relating beach morphodynamic response and meteo-oceanographic conditions, when seagrass banquettes are present.

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The aim of this work is to quantify the protection role of seagrass accumulation at the shoreline and analyze the interactions between such morphologies and beach evolution (erosion), through laboratory experiments.

METHODOLOGY

A set of experiments were carried out in the CIEM large scale wave flume (100 m long, 3 m wide, 5 m deep), located at the UPC premises in Barcelona (Spain).

Before describing the experiments, it is necessary to emphasize the experimental constraints found during the planning process of the experiments.

The first one was the use of surrogate seagrass instead of real leaves. The material used was PVC based on previous experiments in the flume (Astudillo et al., 2022).

Figure 2. Image of seagrass wrack being removed from a beach.

On the other hand, the leaves should be placed within a plastic mesh, as shown in Figure 3, for several reasons: i) to prevent potential interference of loose leaves with sensors; ii) to protect the wave generation system; iii) to facilitate changes of configuration; and iv) to reduce cleaning cost and time.

Figure 3. Image of a banquette being prepared for the experiments.

The methodology applied closely follows that of Astudillo et al. (2022), which analysed changes in the evolution of a beach profile due to the presence of seagrass beds in a large scale wave flume.

However, in this study, seagrass banquettes were placed around the shoreline instead of seagrass meadows.

Banquettes were made with PVC leaves 40 and 60 cm long, 8 mm wide and 0.5 mm thick, mimicking the real morphologies that can be found in Mediterranean beaches. The wave flume had a mobile bed, with an initial flat concrete section 30 m long and a sand beach with an initial slope 1:15, while water depth was 2 m, as shown in Figure 4. The sand had a median diameter d50 = 0.25 mm.

Five different configurations of banquette were used, all of them with the same beach profile and the same water depth:

i. Beach without seagrass banquette, that was considered the benchmark.
ii. Beach with a long emerged banquette 2.25 m long and 0.30 m high, placed at a level of 0.00 m, i.e., on the shoreline.
iii. Beach with a short emerged banquette 0.75 m long and 0.15 m high, located at a level of 4 cm, i.e., at a distance of about 60 cm from the shoreline.
iv. Beach with a banquette similar to the previous case, but in this case it was buried in the sand.
v. Beach with a long emerged banquette 2.25 m long and 0.20 m high, placed at a level of 4 cm.

Table 1 summarizes the five configurations analysed.

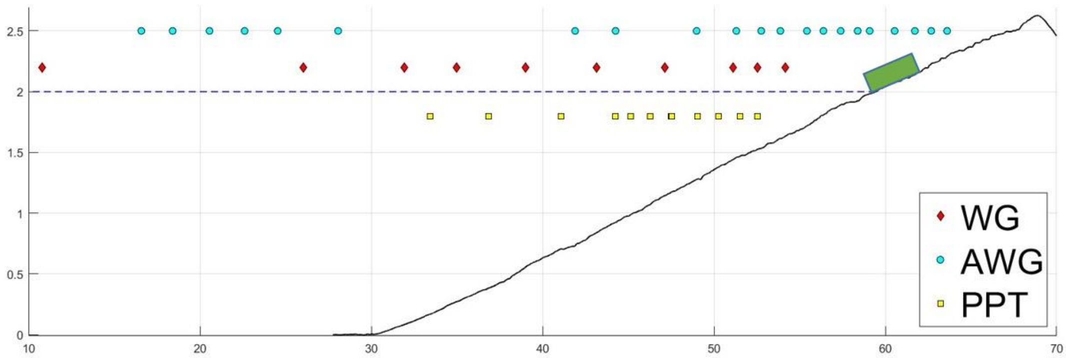

Figure 4. Sketch of the experiments' lay-out. The green rectangle indicates the banquette location, while the colour symbols refer to wave gauges of different types used.

Table 1. Summary of the experiments carried out.

Case	Code	Description	Length (m)	Height (m)	Position (m)
1	BM	Benchmark (without banquette)	-	-	-
2	LB	Long high emerged banquette	2.25	0.30	0.00
3	SB	Short emerged banquette	0.75	0.15	0.04
4	BB	Short buried banquette	0.75	0.15	0.04
4	BLB	Long lower emerged banquette	2.25	0.20	0.04

In addition, a number of different wave sensors were used to measure wave parameters. These wave sensors were resistive gauges (WG), acoustic gauges (AMG) and pressure transducers (PPT). Their deployment is also shown in Figure 4.

Each configuration was subjected to 12 series of 30 min each of irregular waves with Hs = 0.60 m, Tp = 3.71 s and a Jonswap spectrum with $\gamma = 3.3$. After each time series, the experiment was stopped and the beach profile was measured using a mechanical profiler. This allowed a comparison of the response of the beach profile in each experiment, measuring the differences in elevation from the initial profile. In addition, to evaluate the variations in volume (per unit width) between the initial and the final profile of each experiment, the area between the two profiles was calculated.

RESULTS

In Figure 5, the evolution of the beach profile after each test, for the benchmark case, is shown. The lower part of the profile does not show significant morphodynamic changes during the tests. In contrast, in the upper part of the beach, noticeable changes in the beach profile can be detected. Therefore, the study of the evolution of the profile will focus on this upper part, where the morphodynamic activity is concentrated.

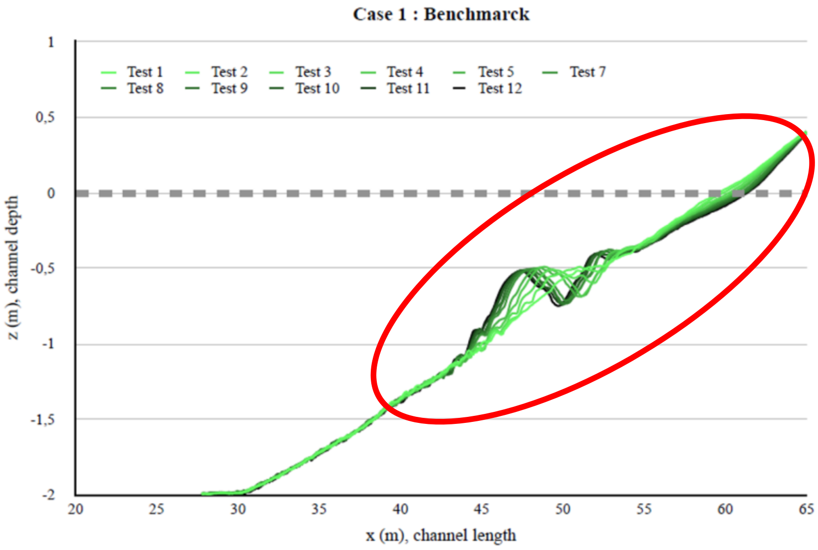

Figure 5. Evolution of the beach profile in the benchmark case. The area marked in red is where the significant morphodynamic changes take place.

Figure 6 shows the upper part of the beach profiles in the benchmark case after the tests. To facilitate the visualisation of the results, only 5 of the 12 tests have been plotted. It can be seen that the profile is erosive, with progressive loss of sand around the shoreline, sand that is used to feed two bars, one rather small and one larger located further offshore. These bars are moving offshore with time, as the erosion around the shoreline increases.

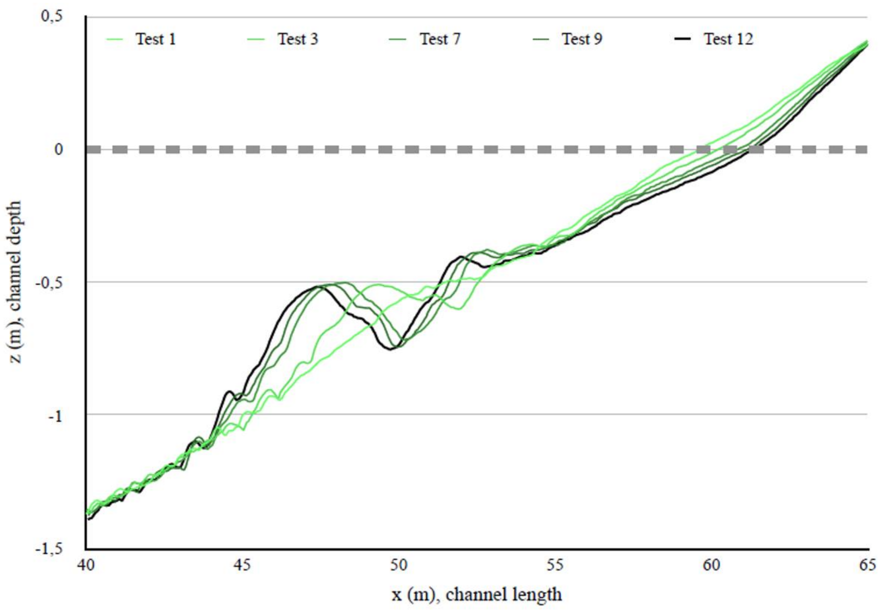

Figure 6. Evolution of the upper part of the beach profile in the benchmark case.

The maximum erosion reached around the shoreline is -26 cm and occurs (in the last test) just before the shoreline, where the breaking waves have their maximum erosive power. From this point and in offshore direction, the magnitude of the erosion decreases, although the profile of the beach remains below the initial one, until the first bar, which reaches a maximum level of 10 cm above the initial profile. Between this bar and the one located further offshore there is a trough with a minimum of up to -8 cm below the initial profile, while the large bar reaches a level 33 cm above it.

In Figure 7 the profile evolution for the case LB is presented. This corresponds to a long and high emerged banquette (2.25 x 0.30 m) placed on the shoreline. In this case, the profile behaves differently from the previous case. In the backshore, behind the banquette, the beach profile does not change, showing the protective role of the banquette. In front of the banquette, there is a pronounced and progressive erosion, similar to the scouring at the toe of a seawall-type hard structure. The minimum value measured in this trough with respect to the initial profile is -36 cm, and occurs after test 12. From this scour area extending offshore, the beach profile remains lower than the initial one, with maximum differences of up to -10 cm, particularly after test 12. The sand removed in this area feeds two bars similar to those of the previous case, with maximum heights of 10 cm and 32 cm respectively and with a trough of up to -4cm between them.

Lastly, changes in the banquette shape are also very remarkable. Waves push the leaves which tend to accumulate in a narrower and therefore higher space, as they are constrained by the plastic mesh.

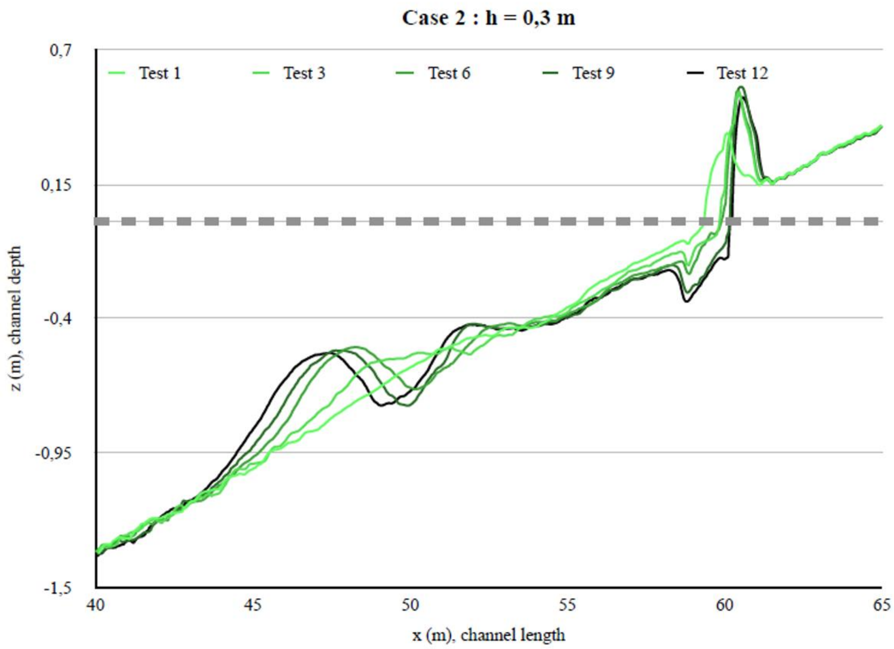

Figure 7. Evolution of the upper part of the beach profile in case 2 (long and high emerged banquette).

In Figure 8, results for the case of a short and buried banquette are presented, which contrast markedly with those of the previous case.

In this case, the behaviour is more similar to the benchmark; however, there is no erosion at the top of the backshore, and the beach profile even shows slight accretion of up to 5 cm. This indicates a degree of protection provided by the banquette. In the remaining areas of the backshore, erosion is observed, reaching a maximum of -33 cm (after test 12) behind the banquette. It is also noted that the banquette experiences some subsidence, shifting downwards due to erosion, and shows minor scouring in front of it.

Moving offshore from the banquette position, the erosion is progressively reduced, with the displaced sand forming two bars in deeper areas: the inner bar with an elevation of 10 cm and the outer bar of 35 cm, with a trough between them of -7 cm (these levels are reached in test 12, measured with respect to the initial profile).

Results for the case of the short and emerged banquette (case 3), where the set-up was the same as in the previous case with the only difference that the banquette was not buried, are not presented here because they are very similar to case 4, as shown in the discussion section. Similarly, the results of case

5 (a long banquette with lower elevation) closely resemble those of case 2 and, therefore, they are not presented.

Figure 8. Evolution of the upper part of the beach profile in case 4 (short buried banquette).

DISCUSSION

As indicated in the Results section, three types of beach profile behaviour can be distinguished depending on the banquette configuration. The first type corresponds to the benchmark (profile without banquette), which shows a typical erosive profile, with significant sand loss around the shoreline and the formation of two bars, one smaller and one larger, in the offshore direction. The second type is that of the long banquettes, which keeps the profile unchanged behind the banquettes but, on the other hand, it is experiencing severe erosion in front of them. Further offshore, in the bar area, the profile is very similar to that of the benchmark. The third type is that of the short banquettes, in which, behind them, the stretch closer to the banquette is eroded, while further away from the shoreline, the profile presents accretion. In front of the banquettes, the beach profile evolves in a very similar way to that of the benchmark.

Figure 9 summarizes these three types of beach profile evolution. In this figure, the final profiles (after test 12) of each experiment are shown, together with the initial profile (before the experiments). There, the large erosion produced in the swash zone and the upper shoreface, in the benchmark case, can be observed. This sediment loss has been estimated at 1.29 m^3 per unit width, 8% of which forms the inner bar and 81% the outer bar. This eroded zone extends over a length of approximately 12 m from the swash zone to a depth of 44 cm.

When long banquettes are placed on the dry beach (cases 2 and 5), two significantly different features are observed with respect to the benchmark. The first is that, behind the banquette, the profile of the beach is maintained without erosion. This indicates that the presence of the banquette limits wave action in the swash zone by increasing coastal roughness, although it does not completely prevent the passage of the waves, as during the experiments it was visually verified that some individual waves overtopped the banquette. However, the action and number of these individual waves were not sufficient to change the profile in this area.

The second remarkable feature of both cases is that in front of the banquette a strong erosion occurs, similar to the scouring generated by a hard coastal protection structure such as a seawall. This is probably due to the fact that, although the banquette is relatively permeable and some waves are partially transmitted through it, part of the wave energy is reflected by the banquette structure, as observed visually in the experiments. Furthermore, when analyzing the wave gauge data, higher wave heights were measured in front of these long banquettes than in the other cases, indicating that this additional wave energy comes from the reflection (see as an example Figure 10). In case 2, this most eroded section is approximately 1.75 m long and has a volume of 0.51 m^3/m. In case 5, although the height of the banquette is lower, the wave energy is also reflected in it and the scour area has similar length (1.65 m) and volume (0.51 m^3/m). The main difference is that, in case 5, as the banquette is located at some distance from the shoreline, both the final position of the banquette and the scour area are located further onshore than in case 2. From the trough extending offshore, the profile of both cases closely resemble that of the benchmark.

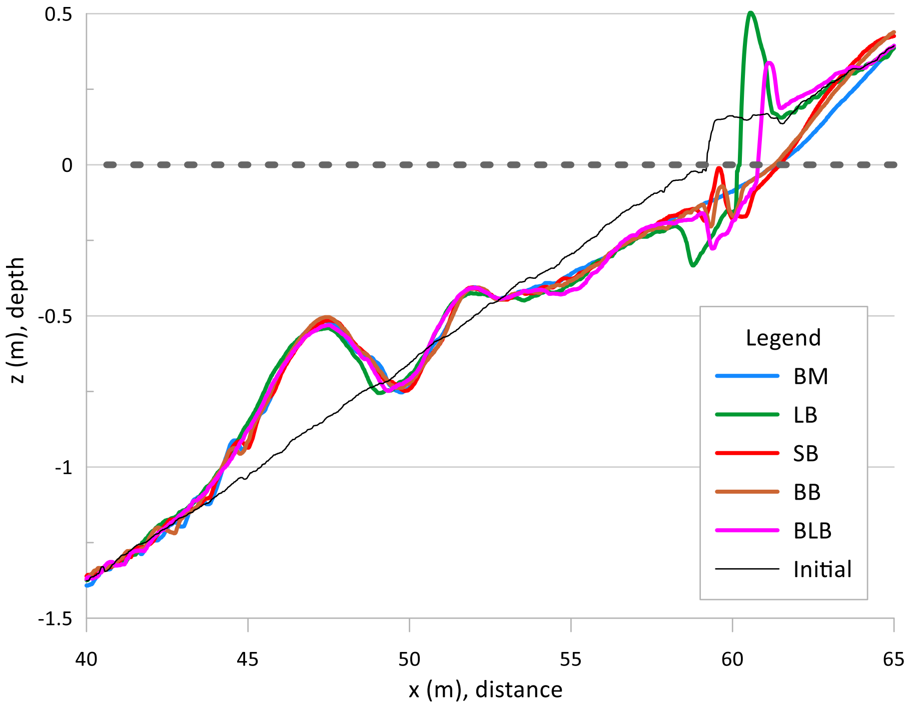

Figure 9. Initial beach profile compared with beach profiles after test 12 in the five experiments.

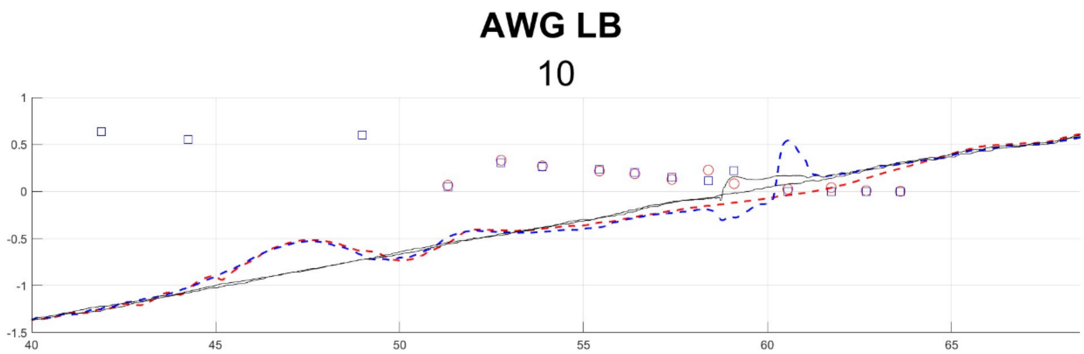

Figure 10. Wave heights recorded by the acoustic wave gauges in test 10: the red circles correspond to the BM case and the blue squares to the LB case. The black line represents the initial profile for both cases, while the red and blue lines correspond to the profile for the BM and LB cases respectively, at the end of test 10.

In the cases with short banquettes (experiments 3 and 4), the evolution of the beach profile is quite different from those with long banquettes. The main difference is that the scouring in front of the banquette is much smaller, both in length (about 30 cm) and depth (3 cm). This is because the small size of the banquette means that more energy is transmitted through or over the banquette, resulting in much less wave reflection. From this point, in the offshore direction, the beach profiles are very similar to those of the benchmark.

Another significant difference is found behind de banquette. Since more wave energy reaches this area, some erosion occurs there, although of a lesser magnitude than in the benchmark, because the banquette dissipates some energy. However, part of this eroded sediment is deposited on the upper part of the backshore, giving rise to a certain accretion with respect to the initial profile.

The response of the beach profile in the case of long banquettes is similar to that observed on natural beaches, as shown in Figure 11. This picture shows how, behind the banquette, the profile remains unchanged, while in front of the banquette there is a strong erosion, as observed in the experiments.

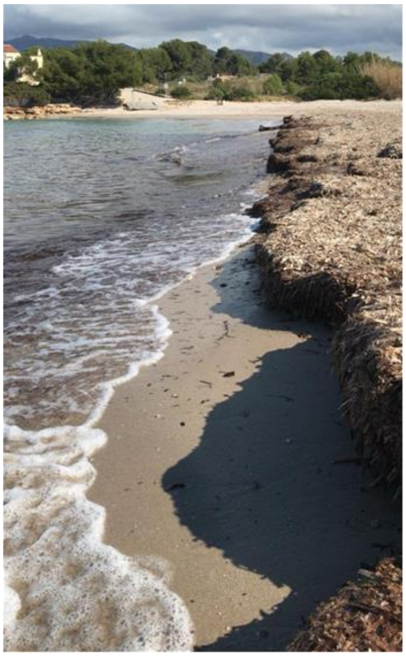

Figure 11. Picture of a large banquette showing the erosion in front of it.

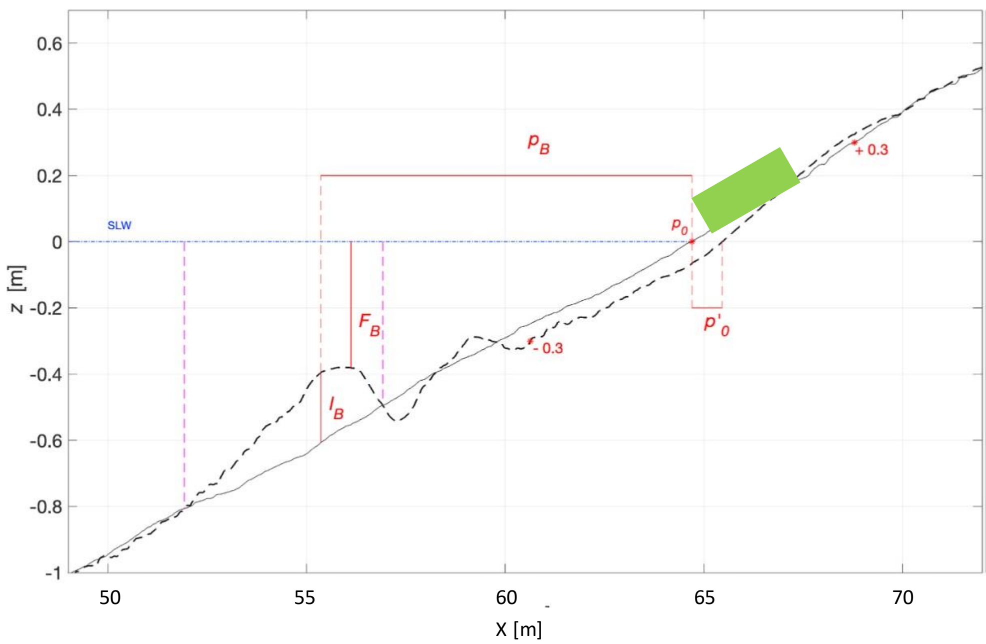

Figure 12. Morphodynamic parameters considered to assess beach profile evolution.

Another way to analyze the response of the beach to different banquette configurations is to study the evolution of some parameters during the tests. The parameters of interest are shown in Figure 12. These parameters are: bar freeboard (F_B), bar height (l_B), bar crest distance to the shoreline (p_B), initial shoreline position (p_0), shoreline retreat/advance of p_0 (p'_0), which is computed at the levels z = 0 m and z = 0.3 m.

The shoreline evolution at levels z = 0 m and z = 0.3 m in the 12 tests of each of the 5 experiments is presented in Figure 13, where the horizontal distance to the initial profile is measured.

At level z = 0 m, the results show that in the benchmark case, the erosion is progressive and almost constant, reaching 2 m after the 12th test. On the contrary, in the case of the long high banquette, the beach retreat is faster in the first tests, reaching 1 m after the 4th, compared to 0.8 m in the benchmark in the same test. After this, the erosion rate is significantly reduced and after the 8th test the profile position at this level remains almost constant, with a value of about 1.35 m, being the experiment with the lowest final erosion at the z = 0 m level.

The short emerged banquette features the strongest shoreline erosion of all cases. Such erosion is very accelerated in the first two tests, slowing down in the following ones, although it continues to make progress up to 2.6 m. The short buried banquette, on the other hand, erodes quite a lot in the first 4 tests, but then the beach retreat remains constant at this level until test 9, when it starts to increase again, until it ends up with a value similar to the benchmark.

Finally, the long lower banquette shows a strong erosion in the first test and then, the shoreline progressively recedes more slowly, until it reaches a final value of 2.2 m, the second worst configuration in terms of response at level z = 0 m.

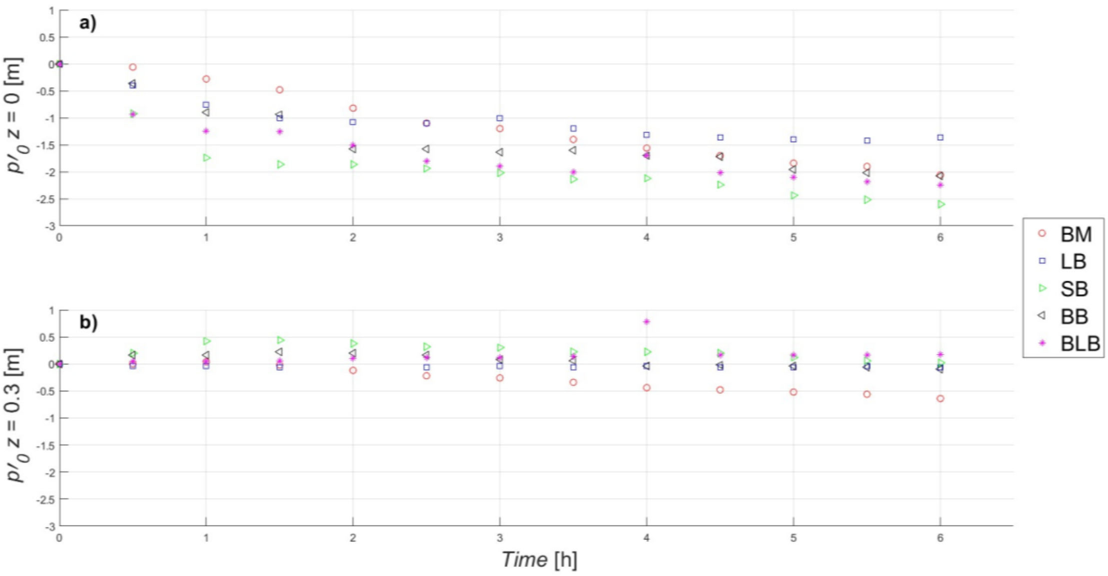

Figure 13. Shoreline evolution at *z* = 0 m and *z* = 0.3 m in each test for the 5 experiments.

Analyzing the results at level z = 0.3 m, it can be seen that the benchmark configuration exhibits the highest final erosion, reaching approximately 0.6 m. On the contrary, in both configurations with long banquettes, the shoreline does not change at this level in any of the tests. Lastly, the configurations with short banquette show some accretion in the first tests, but then undergo a slight erosion to end up in the initial position in both cases.

Ultimately, Figure 14 shows the evolution, during the 12 tests, of some of the bar parameters.

With respect to the distance of the bar crest to the shoreline (p_B), although some discrepancies can be observed in the first tests (Figure 14a), from test 5 onwards the values are very similar and this distance differs by only a few decimeters between the configurations.

Regarding the height of the main bar (l_B), in Figure 14b it can be seen that the bar grows progressively during the first 6 tests, while thereafter the height remains almost constant. In the first tests the benchmark shows the lowest bar height, but from the fourth test onwards it is the long high banquette that shows the lowest bar height. After the 12th test the buried banquette presents the highest bar, although the differences between the 5 configurations are only a few centimeters.

Finally, concerning the bar freeboard (F_B), some differences can be seen in the first tests, especially in the benchmark case, which has the lowest freeboard. However, from the 7th test onwards, the F_B values are similar and practically identical after the last test.

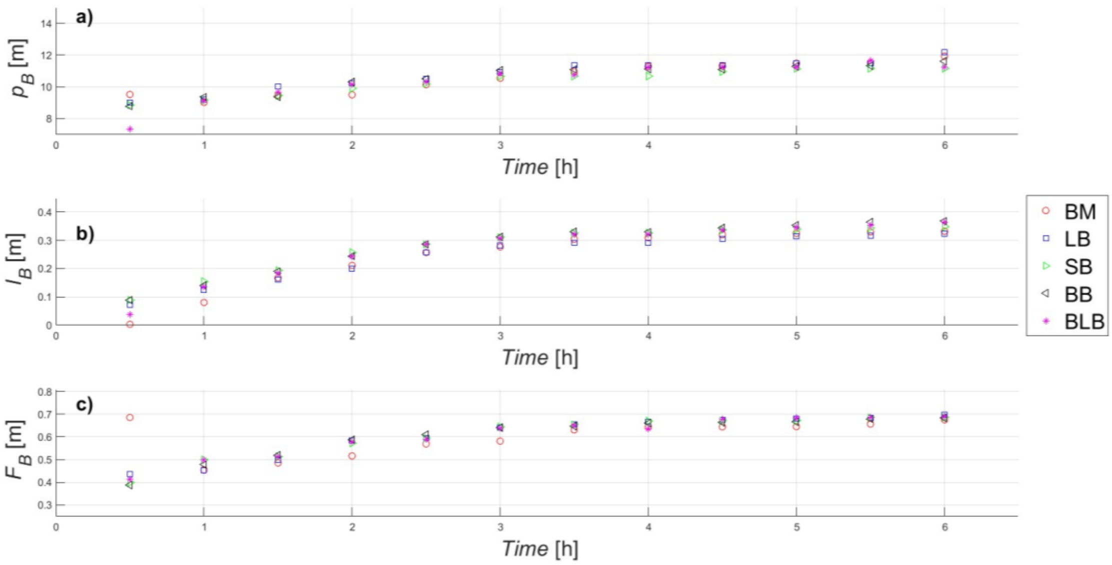

Figure 14. Evolution of bar parameters in each test for the 5 experiments.

CONCLUSIONS

The main conclusions of this work are the following:

- In all configurations of banquette, erosion in the backshore is reduced with respect to the benchmark due to the increase of coastal roughness and less swash.
- Longer banquettes provide more protection of the backshore (area located behind them), while shorter ones have stretches of erosion and accretion in this area.
- The main morphodynamic changes take place around the shoreline: erosion in the benchmark and configurations with short banquette and scouring plus erosion in the cases with long banquette.
- Long banquettes behave as a seawall, in particular the highest, producing scouring at the toe and no erosion in the backshore.
- Bar features show certain differences at the initial stages (tests) but tend to converge with time being very similar in the last tests for all cases.

This work could be continued testing more banquette configurations, trying to define which is the best, i.e., that providing more coastal protection. In addition, it would be interesting to make tests under accretive conditions, to assess which is the response of the beach and the banquette.

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REFERENCES

Battjes, J.A., and J.P.F.M. Janssen. 1978. Energy loss and set-up due to breaking of random waves, *Proceedings of 14th International Conference on Coastal Engineering*, ASCE, 466-480.

De Vriend, H.J., J. Zyserman, J. Nicholson, J.A. Roelvink, P. Pechon, and H.N. Southgate. 1993. Medium-term 2DH coastal area modeling, *Coastal Engineering*, 21, 193-224.

Wiegel, R.L. 1965. *Oceanographical Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey, 531 pp.

Astudillo, C., Gracia, V., Cáceres, I., Sierra, J.P., and Sánchez-Arcilla, A. 2022. Beach profile changes induced by surrogate Posidonia oceánica: Laboratory experiments. *Coastal Engineering*, 175, 104144.

Corbi, H., Riquelme, A., Megías-Baños, C., and Abellan, A. 2018. 3D morphological change analysis of a beach with seagrass berm using a terrestrial laser scanner. *ISPRS International Journal of Geo-Information*, 7, 234.

Cucco, A., Quattrocchi, G., Brambilla, W., Navone, A., Panzalis, P., and Simeone, S., 2020. The management of the beach-cast seagrass-wracks – A numerical modelling approach. *Journal of Marine Science and Engineering*, 8, 873.

Duarte, C.M. 2004. How can beaches be managed with respect to seagrass litter? In Borum, J., Duarte, C.M., Krause-Jansen, D., Greeve, T.M. (Eds.) *European seagrasses: an introduction to monitoring and management*. The M&MS roject publisher, pp. 83-84.

Joyce, M.A., Crotty, S.M., Angelini, C., Cordero, O., Ortals, C., de Battisti, D., and Griffin, J.N. 2022. Wrack enhancement of post-hurricane vegetation and geomorphological recovery in a coastal dune. *PloS One*, 17, e0273258.

Menicagli, V., Balestri, E., Bernardini, G., Barsotti, F., Fulignati, S., Raspolli Galleti, A.M., and Lardicci, C. 2024. Beach-cast seagrass wrack: A natural marine resource improving the establishment of dune plant communities under a changing climate. *Marine Pollution Bulletin*, 201, 116270.

Menicagli, V., De Battisti, D., Balestri, E., Federigi, I., Maltagliati, F., Verani, M., Castelli, A., Carducci, A., and Lardicci, C. 2022. Impact of storms and proximity to entry points on marine litter and wrack accumulation along Mediterranean beaches: management implications. *Science of the Total Environment*, 824, 153914.

Hyndes, G.A., Berdan, E.L., Duarte, C., Dugan, J.E., Emery, K.A., Hamb¨ack, P.A., Henderson, C.J., Hubbard, D.M., Lastra, M., Mateo, M.A., Olds, A., and Schlacher, T.A. 2022. The role of inputs of marine wrack and carrion in sandy-beach ecosystems: a global review. *Biological Reviews*, 97, 2127–2161.

Pal, D., and Hohland, W. 2022. An overview and assessment of the existing technological options for management and resource recovery from beach wrack and dredged sediments: An environmental and economic perspective. *Journal of Environmental Management*, 302, 113971.

Passarella, M., Ruju, A., De Muro, S., and Coco, G. 2020. Horizontal runup and seagrass beach cast-litters: modelling and observations. *Journal of Coastal Research*, SI95, 143–147.

Simeone, S., and De Falco, G. 2012. Morphology and composition of beach-cast Posidonia oceanica litter on beaches with different exposures. *Geomorphology*, 151-152, 224-233.

Simeone, S., De Muro, S., and De Falco, G. 2013. Seagrass berm deposition on a Mediterranean embayed beach. *Estuarine, Coastal and Shelf Science*, 135, 171–181.

Vacchi, M., de Falco, G., Simeone, S., Montefalcone, M., Morr, I.C., Ferrari, M., and Bianchi, C.N. 2017. Biogeomorphology of the Mediterranean Posidonia oceanica meadows. *Earth Surface Processes and Landforms*, 42, 42-54.