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SIMULATING CROSS-SHORE EVOLUTION TOWARDS EQUILIBRIUM OF DIFFERENT BEACH NOURISHMENT SCHEMES

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Abstract

Beach fill design typically involves nourishing one or several of the following coastal features with sand: the dune, the beach berm, the active profile, and nearshore bars. The impact of varying the location, volume, and frequency of placing sand on an open beach is here explored by investigating the redistribution of the nourished sediment towards equilibrium in the two-dimensional vertical plane. Simulations of hypothetical nourishment scenarios are performed with a numerical cross-shore sand transport and profile evolution model (the CS-model) designed to describe the evolution of the beach-dune system at decadal scale (Larson *et al.*, 2016). This model, which has been successfully validated by Palalane *et al.* (2016) for several coastal areas (in Portugal, Mozambique, and Sweden), is here applied to a study case to demonstrate its applicability in predicting the temporal and spatial variation of artificial nourishments. The case derives from a field experiment at Silver Strand, California, where dredged material resulting from harbor maintenance activities was placed nearshore (on top of an existing bar) at a downdrift beach. Overall, model predictions showed good agreement with the observations collected over more than a year after the nearshore placement project has been completed. The onshore sand movement and berm advance that has been documented between Dec-88 to Feb-90 could be satisfactory reproduced, although some longshore perturbations affecting the model performance were identified. Although the CS-model has proved to be a useful tool to simulate long-term coastal evolution, further work should be directed towards improving the transport of material in shallower depths as well as the theoretical procedures to describe fill placement at different water depths (so far restricted to the bar location).

1. Introduction

Beach nourishment projects (also referred to as artificial nourishment, beach fill, or beach replenishment) are usually considered a sustainable protection solution, in which borrowed sediments (coming from an external source) are brought onto a beach to replace native sand that have been lost through erosion.

Typically, the beach fill design involves re-building one or several of the following beach profile features with sand: the dune, beach berm, active profile, and nearshore bars. The first technique usually involves the reinforcement of an existing natural dune by adding elevation and/or cross-sectional area, or building an artificial barrier where none existed beforehand. As the natural dune recovery process occurs at a much slower rate than storm-induced changes, these interventions are commonly required after extreme storm events to replace dune sediments that have been transported seaward by the power of high-energy waves. Also, artificial dunes are designed to naturally function as a protective barrier of the upland property, helping to prevent overtopping and flooding events. Nourishing the beach berm focuses on the primary feature included in most beach fill projects, which usually focus on the widening of the beach (*i.e.* a seaward translation of the shoreline), with a higher or lower elevation of the crest, for dissipating storm wave energy. The nourished sand is concentrated on the visible portion of the beach; this method is sometimes referred to as the overbuilding method, since a decrease of the beach width is expected during the initial fill adjustments. The third construction method is the profile nourishment, where in principal, sediments are placed along the entire active profile covering wet and dry portions of the cross-section. In

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this type of method, the use of distinct moving-equipment (terrestrial and maritime) to assess different discharge points usually increase the total cost of the fill operations. The final technique, nearshore placement, is usually undertaken in connection with dredging operations (*e.g.*, maintenance activities in navigation channels) because large volumes of material can be made available at low costs through the economic use of standard dredge equipment for distribution of the fill (*e.g.*, hopper dredger or split-haul barges). The sand is placed nearshore of the beach by creating an artificial bar along a finite length, often with a shore-parallel alignment. With a proper design (shallower than the depth of closure), the nourished sand will be set in motion by waves and migrate onshore (under certain wave conditions) until eventually it becomes a part of the beach berm and beach face system (Mark *et al*., 2003).

Although, a range of different fill construction methods can be used, techniques for fill placement should be optimized to best serve the specific requirements and primary objectives of the project. In this light, monitoring is of major importance. An adequate monitoring plan is particularly valuable to document and assess the project performance, allowing to define how well the project fulfills the requirements for which it was designed. Monitoring campaigns involving systematic data collection over time will enable the establishment and interpretation of the temporal and spatial redistribution of the fill material, and consequently provide new insights to the governing process, formulate model requirements, and define specific modelling task for beach nourishments, especially in a long-term perspective.

Distinct coastal maintenance approaches have been implemented as a way to explore the nourishing benefits in different contexts (as the mega-nourishment approach, *e.g.*, pioneering project "Sand Engine"; Schipper *et al.*, 2016). However, many projects have still been poorly recorded, contributing to a significant lack of knowledge about the performance of sand nourishment. At the same time, the understanding of the short- and long-term responses of beach fills to the forcing conditions becomes extremely important in terms of design and performance evaluation. While the short-term responses is usually taken as the first fill adjustments during severe storms (redistribution of the fill material), the long-term responses are intrinsically related to its evolution towards a new equilibrium state. Although, the effects of gradients in the longshore sediment transport may play a role in determining the long-term response of beach fills towards equilibrium, the larger modifications of the fills are typically induced by cross-shore processes, which will vary in response to the characteristics of the fill approach (sediment grain size, volumes, placement, etc.).

Due to the lack of comprehensive monitoring data, various types of models have been applied to predict the short-term response of fills (hours to days), *e.g.,* SBEACH and XBEACH, but very few models can be applied to estimate long-term cross-shore responses of fills, where the beach moves towards a new equilibrium state (years to decades). In fact, the models that have been more successfully applied for longer time scales often involve the assumption that for given conditions the beach profile will tend to an equilibrium shape without reproducing the realistic seasonal variation of the profile response (Karasu *et al.*, 2008). Also, in more comprehensive coastal evolution models, cross-shore processes are typically represented in a schematized manner through source or sink terms (Larson *et al.*, 2013).

The present study focuses on the impact of location, volume, and frequency of placing sand on an open beach by investigating the redistribution of the nourished sediment in the two-dimensional vertical plane. The potential evolution of distinct nourishment scenarios is simulated with a numerical cross-shore sand transport and profile evolution model (the CS-model) designed to describe the evolution of the beach-dune system at decadal scale (Larson *et al.*, 2016). The model takes into account transport processes that act over compatible time and space scales, *e.g.*, cliff erosion and dune recovery, but also short-term processes such as the impact of individual storms, since their effects may be long-term, causing abrupt changes with long-lasting consequences for the beach morphology. In order to model such processes, main morphological features of the profile are schematized and described through a limited set of morphological parameters, where changes in the profile shape are geometrically prescribed by the time evolution of those key parameters. In the present study, the model is also calibrated to simulate the evolution of a nourishment placed nearshore, at the top of an existing bar, in Silver Strand, California. Model results are compared against field observations recorded over the 12 months after the fill placement.

2. Model description

In this section, the cross-shore numerical model (CS-model) will only be briefly reviewed since a detailed description about the theoretical developments is given in Larson *et al.* (2013, 2016). This model was developed to simulate the cross-shore exchange of sand and the resulting profile response at a decadal scale by taking into account the main relevant cross-shore processes in a long-term perspective: dune erosion and overwash, wind-blown sand transport, and bar-berm material exchange. Each one of these processes corresponds to an individual module integrated in the CS-model, which contain physically based algorithms that have been validated against laboratory and field data (Larson *et al.*, 2016). In order to model the long-term profile response, a set of sand volume conservation equations are employed and solved together with cross-shore transport equations to describe the evolution of key morphological features. These limited morphological parameters are assumed representative of the cross-shore profile and include dune height (s), the locations of the landward and seaward dune feet (y_L and y_s respectively), the berm crest location (y_B), and the longshore bar volume (V_B) - see Fig. 1. It is assumed that the cross-shore sediment transport, causing changes in the profile shape, is induced by the power of waves, winds, and sea water levels. These changes, detailing the profile response, are geometrically prescribed so the schematization of the profile type is safeguarded, but the key parameters are changing with time. In the following a short description about each module integrating the model computations is provided.

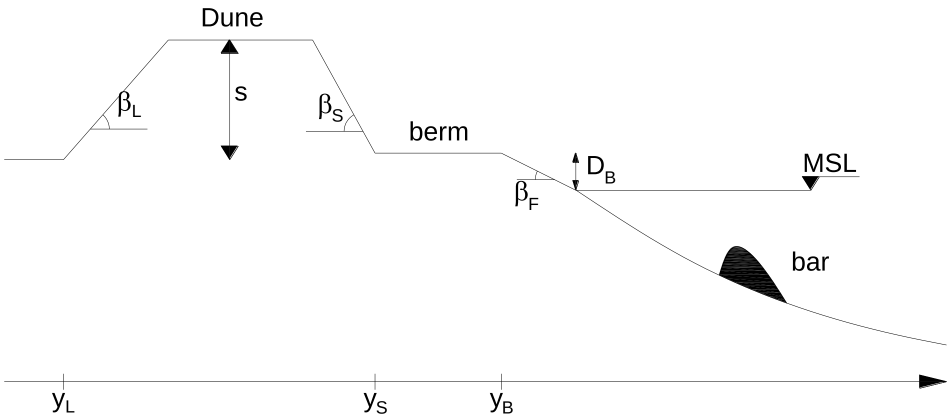


Figure 1. Scheme of the profile given by the model. The angles β_L and β_S correspond to the landward and seaward dune face slope, respectively, and β_F to the foreshore slope (constant parameters). D_B represents the berm height (related to MSL).

2.1. *Dune erosion and overwash*

Dune erosion is computed using an analytical model proposed by Larson *et al.* (2004). This model was developed based on the studies by Fisher *et al.* (1986) and Nishi and Kraus (1996) for dune erosion, where the eroded volume from the dune is taken to be proportional to the impact force from the waves hitting the dune face.

As an example of how the profile may evolve, the impact of a storm is hypothesized. If the combined waves with the water level produces sufficient runup height (R), *i.e.*, if the runup height exceeds the dune foot level, the dune will lose volume (ΔV_D) and supply the beach berm with sand (Eq.1). As a result of this erosion, the dune foot moves shoreward and y_s decreases, assuming that the same seaward dune slope is maintained.

$$\Delta V_D = 4C_S(R - z_D)^2 \frac{\Delta t}{T} \tag{1}$$

Δt is the time step of the simulation, z_D the vertical distance between the dune foot level and the water level, T the wave period and C_S the empirical impact coefficient. The smaller z_D, the greater the risk of dune erosion (Fig. 1). Also, a smaller z_D increases the probability that waves will attack high up in the profile leading to overwash ($R > z_D + s$). In this case, the wave impact is considered lower because of the additional momentum flux over the dune (Eq. 2).

$$\Delta V_D = 4C_S(R - z_D)s\frac{\Delta t}{T} \tag{2}$$

During overwash, a part of the sediment mobilized by the waves (ΔV_D) will be transported over the dune crest to the shoreward side of the dune (ΔV_L), implying a decrease in y_L (landward movement). In this case, the landward dune face slope, β_L, is also assumed constant. The remaining material will be moved seaward (ΔV_S). The partitioning of ΔV_D between ΔV_L and ΔV_s (*i.e.*, how much of the eroded dune volume goes onshore and offshore, respectively) is given as a function of the ratio α: yielding $\Delta V_L = \Delta V_D \alpha/(1+\alpha)$ and $\Delta V_s = \Delta V_D/(1+\alpha)$.

$$\alpha = \frac{\frac{R - z_D}{s} - 1}{A} \tag{3}$$

where A is an empirical coefficient determined to be about 3 by Larson *et al.* (2009) through comparison with field data. When $\Delta V_D > V_D$ it is considered that the dune is eroded away (Larson *et al.*, 2009).

2.2. *Wind build-up*

Recovery of the dunes depends on the conditions for wind-blown sand. Therefore, dune growth can take substantial time and irreversible changes in the coastal system may occur. It is assumed that the aeolian transport rate increases along the foreshore zone, reaching its equilibrium value (potential) after some distance between the shoreline (berm crest) and the dune foot. This equilibrium transport rate (q_{WE}) is computed by using the formula proposed by Lettau and Lettau (1977) which includes the shear velocity and a critical value of the shear velocity that needs to be exceed in order for transport to occur. Also, as the wind blows from the shoreline towards the dune barrier, the equilibrium distance should depend on the local conditions, such as, the dimension and humidity of the sediments and the wind velocity (Hotta, 1984; Davidson-Arnott and Law, 1990). According to field measurements, Hotta (1984) indicated that a distance of 5-10 m would be sufficient to reach the equilibrium state, whereas David-Arnott and Law (1990) reported that 20-30 m (or more) may be required. Here, a heuristic version of the model developed by Sauermann *et al.* (2001) is applied to describe the initial spatial growth of the transport rate (q_W), allowing $q_W = 0$ at y=0 (Eq.4):

$$q_{wS} = q_{WE}\left(1 - \exp\left(-\delta(y_B - y_S)\right)\right), \qquad \delta(y_B - y_S) < 20 \tag{4}$$

where δ is a spatial growth coefficient for the transport rate. Although the model allows for time-dependent wind transport rate calculation, a constant aeolian transport rate defining the speed of the dune growth process can also be specified. This can be useful in the cases that there is no consistent data series on wind velocity and direction.

2.3. *Berm and bar material exchange*

The exchange of material between the bar and the berm is based on the mass conservative principle, which means that no material is lost offshore. The formulations that describe the sediment transfer between the berm and the bar region of the profile is based on the model presented by Larson *et al.* (2013). According to this model, the volume eroded from the berm is stored in an offshore bar that will evolve to a certain equilibrium volume (V_{BE}, Eq. 5) depending on the wave conditions and the sediment characteristics. This equilibrium bar volume is computed using an empirical based expression proposed by Larson and Kraus (1989), when employing large wave tank (LTW) data (monochromatic waves):

$$\frac{V_{BE}}{L_0^2}=C_B\left(\frac{H_0}{wT}\right)^{4/3}\frac{H_0}{L_0} \tag{5}$$

where L_0 is the deepwater wavelength, H_0 the deepwater wave height, w the dimensionless fall speed, and C_B a dimensionless empirical coefficient (0.028 or 0.08, for erosional cases of LWT experiments and field data, respectively).

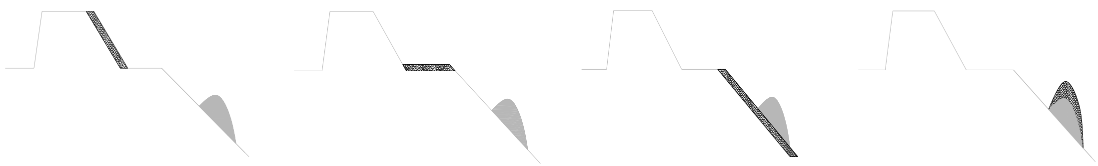
The model assumes that a growth in the bar will cause a corresponding decrease in the berm volume (or a shoreward movement of y_B) and vice-versa. The change in bar volume (ΔV_B) is taken to be proportional to the deviation from its equilibrium condition, implying that if the equilibrium bar volume (V_{BE}) at any given time is smaller than the bar volume (V_B), then the bar will decay, whereas$V_{BE}>V_B$ causes a bar growth. For realistic wave inputs, the evolution of the bar volume is computed using the analytical solution proposed by Larson *et al.* (2013):

$$\Delta V_B=(V_{BE}-V_B)(1-e^{-\lambda\Delta t}) \tag{6}$$

in which λ is a coefficient quantifying the rate at which equilibrium is approached, depending on the grain size (or fall speed, w), wave height, and two coefficients, λ_0 and m, with values to be calibrated against data (0.56×10^{-6} and -0.5 as a first estimates).

3. Methodology

The potential evolution of hypothetical sand nourishment interventions on an open sandy beach was investigated through numerical simulations of distinct design fill schemes (CS-model). All the simulations were based on the same reference profile (unnourished profile) and subjected to the same wave conditions until a new equilibrium state (implying a complete cross-shore redistribution of the fill material) could be achieved. The first simulation cases focused on the optimal location for placing sediment, specifying four key cross-shore locations for the fill (see Fig. 2): high up on the subaerial portion of the beach (on the seaward dune face), along the berm/beach, along the profile (between the shoreline and the depth of closure), and at the bar system. The nourished reference volume considered in the simulations was 0.1Mm^3 applied in 2000 m alongshore, yielding to a cross-sectional volume of 50 m^3/m.



a) Dune b) Berm c) Profile d) Bar

Figure 2. Different types of nourishment schemes investigated (varying the placement location).

Subsequently, the bar nourishment scheme was selected and six other hypothetical nourishment scenarios were simulated to focus on the frequency and the magnitude of the intervention. From these six hypothetical schemes, three were set by varying the fill placement schedule: first adding the total fill volume to the bar at the beginning of the simulation period (hereafter referred as concentrated fill or mega-nourishment approach) and then dividing equally the total fill volume in two or four distinct occasions during the simulation period (t=0; t=0 and t=6112; t=0, t=3058; t=6112 and t=9174). For the last three study cases, different sectional fill volumes (0.1Mm^3 – reference volume, 0.2Mm^3, 0.5Mm^3 and 1Mm^3) were tested following a mega-nourishment approach. All these sectional volumes were also applied for an alongshore extent of the nourishment of about 2 km.

The CS-model was not designed to handle different sediment grain sizes and thus, the fill material was assumed similar to the native sand. Realistic waves and water levels inputs derived from a case study presented by Palalane *et al.* (2016) on the northwest Portuguese coast were selected and used for the simulations. Wave heights collected by the Portuguese Hydrographic Institute (during 2009-2013), were adjusted for oblique wave angles before employed in cross-shore calculations of dune erosion using the formulation by Hanson and Larson (2008),

$$H_0' = H_0\sqrt{\cos\theta} \tag{7}$$

Where H_0' is the modified wave height used in the calculations and θ the offshore incident wave angle. The longshore sediment transport gradient was included in the simulations through a continuous sink term in order to describe a coastal stretch hypothetically affected by shoreline recession. For the dune build-up by wind-blown sand, only a constant transport rate was assumed for the seaward side of the dune, whereas for the shoreward dune face slope no wind-blown transport was considered. The idealized cross-section was set according to the typical beach profile shape, describing a flat berm (implying the berm crest at the same level as the dune foot) and a dune (or barrier) with a trapezoidal shape (which can eventually become triangular if significant dune erosion occur). The time step of the simulation was set to 3 hours according to the frequency of the wave records acquisition. The model results were interpreted and compared by taking into account specific design aspects (*e.g.*, methods, fill types, objectives, performance).

Finally, the properties of the model were demonstrated by simulating the evolution of a bar nourishment project undertaken in Silver Strand Park, California. Model calibration was performed by adjusting site-specific input parameters based on previous studies and information available in documentation from reliable sources, whereas the model validation process was carried out through comparisons against field observations (bar volumes) estimated from surveys.

4. Numerical application for hypothetical nourishment scenarios

4.1. *Model set up*

A schematic cross-section, based on the input profile selected by Palalane *et al.* (2016) to represent the beach-dune system evolution of a coastal stretch located in the northwest coast of Portugal, has been taken as reference profile for the following numerical applications, corresponding to a situation with no nourishment (see Table 1). Furthermore, the parameters used to set up the model are the same values as specified by Palalane *et al.* (2016). These values were determined following an optimization process in order to obtain the best agreement between the model results and the field observations collected during 2009-2013 for the beach-dune system response. The parameter C_S (coefficient in the dune impact formula) was set to 1×10^{-3} and a friction coefficient, C_f, of 0.01 was adopted to reduce the front speed of the wave affected by the friction as it propagates over the berm towards the dune face. The constant aeolian sediment transport was set at 14 m^3/year/m. The δ coefficient was assumed to be 0.1, in accordance with the values proposed by Larson *et al.* (2016). The water temperature was set to 15°C. For the bar volume, an initial value of 100 m^3/m was specified, representing not only the offshore bar volume but also nearshore deposits. The depth of closure, d_{clos}, was calculated to be 12.4 m using Hallermeier's (1981) formula. Finally, a shoreline retreat rate representing the generalized shoreline retreat trend of the Portuguese northwestern beaches was included in the simulations through a constant change in the berm position (3.7 m/year) by adjusting the y_B parameter. For more information about the calibration process of the model previously undertaken, consult Palalane *et al.* (2016).

Distinct cross-shore locations for the fill material were set up in the model as follows. Dune nourishment was simulated by imposing an advance of the seaward dune foot position (y_S). For berm nourishment, a different elevation between the crest berm and mean sea level, z_D, (calculated through the ratio between the fill volume and beach width) was considered. In this case, the input model parameters s, y_S, and y_B had to be appropriately adjusted to ensure that the berm crest and the seaward dune foot were set at the same level, as well as applying the same sectional fill volume (see Fig. 2). The profile nourishment scheme was set through an equivalent seaward advance of the berm position (y_B), determined through the ratio between the sectional fill volume and the vertical distance between the berm crest and the depth of closure, d_{clos}. Finally, the profile nourished at the bar was simulated by adding the total fill volume to the bar volume input parameter, V_B. All nourishment schemes were configured at the beginning of the simulation period (time step: t=0).

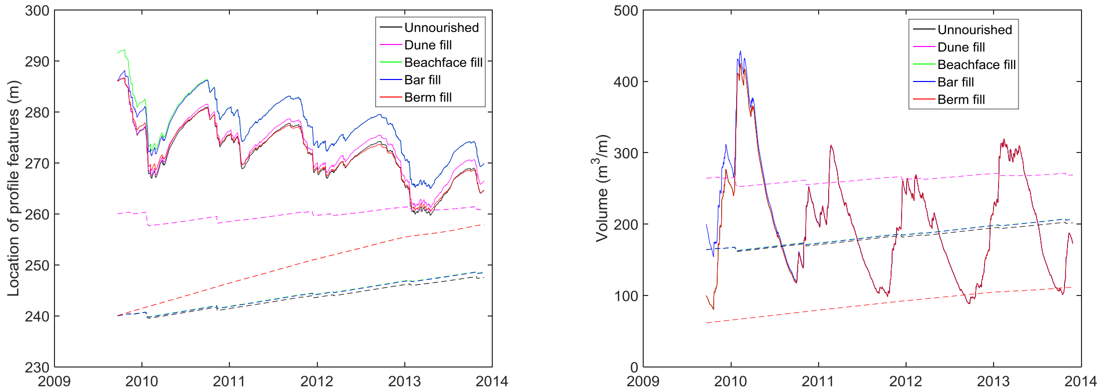
Table 1. Morphological parameters; initial values of variables for the hypothetical nourishment scenarios.

y_L [m]	y_S [m]	y_B [m]	s [m]	$s_{máx}$ [m]	D_B [m]	V_B [m^3]	β_L [rad]	β_S [rad]	β_F [rad]
181	240	286	5	5	5.9	100	0.30	0.14	0.07

4.2. *Model results*

4.2.1. *Varying* ***cross-shore location***

The purpose of changing the cross-shore location of the fill placement was to analyze how this can affect the nourished profile response, evaluating its temporal and spatial evolution towards an equilibrium state. As CS-model assumes that no material is lost offshore, the nourished profile response (or its time adjustment) was distinguished here by the time that the same cross-sectional fill volume takes to become part of the beach system when subjected to the same forcing conditions.



a) Modeled results for y_S and y_B. b) Modeled results for V_D and V_B.

Figure 3. Simulation results varying the placement of the nourishment. The continuous and dashed lines represent the modeled berm and seaward dune foot positions in a) and the dune and bar volume in b), respectively.

Fig. 3 displays the evolution of the seaward dune foot (y_S), berm position (y_B), and the dune and bar volume variation for profiles nourished with the same amount of sand at the dune, berm, along the profile, and at the offshore bar. In order to be able to compare the results obtained for each scheme, the displacement imposed to the berm and to the seaward dune foot position ($\Delta y_S = \Delta y_B$), for simulating the berm nourishment, was added to the calculated values of y_S and y_B (see Fig. 3). Due to the berm elevation resulting from the nourishment, a reduction of the dune height, and consequently of the dune volume, had to be imposed to simulate this scheme, so the same profile volume could be considered in the simulations (see Fig. 3b).

Overall, results of the cross-shore exchange of the nourished material demonstrated that most of the nourishment schemes differed mainly concerning the time evolution of profile adjustment, whereas the equilibrium states themselves were similar. The same morphological conditions were observed for the bar and profile nourishment schemes after the first winter, suggesting that a quicker fill redistribution takes place when the profile is nourished at the bar: y_B and V_B tend to the same values. The same V_B evolution trend is observed for all designed fill schemes, since its computation is taken to be proportional to the deviation from its equilibrium volume. This explains the gradual decay of the offshore bar volume observed for the bar scheme during its early development, describing the bar volume adjustment towards normal conditions.

For cases when the material is placed high up in the profile (at the dune) it was observed that the fill material takes longer to be redistributed across shore. However, a shift in the forcing conditions towards a more frequent recurrence of storm events, in the early of 2010, forced sediments to move seaward, causing a significant landward movement of the dune foot position, y_S. Since the dune is mostly exposed to waves during storms, the distribution of the nourished sand remains restricted to the occurrence of high-energy conditions, inducing offshore sediment transport to the berm. Although in the dune nourishment scenario the profile adjustment is slower, a trend to achieve the same conditions as for the profiles nourished at active profile and at bar (same values of y_S, y_B and V_D) can be observed in Fig. 3a. At equilibrium, the same beach width is observed for the three nourishments schemes (dune, beach slope, bar).

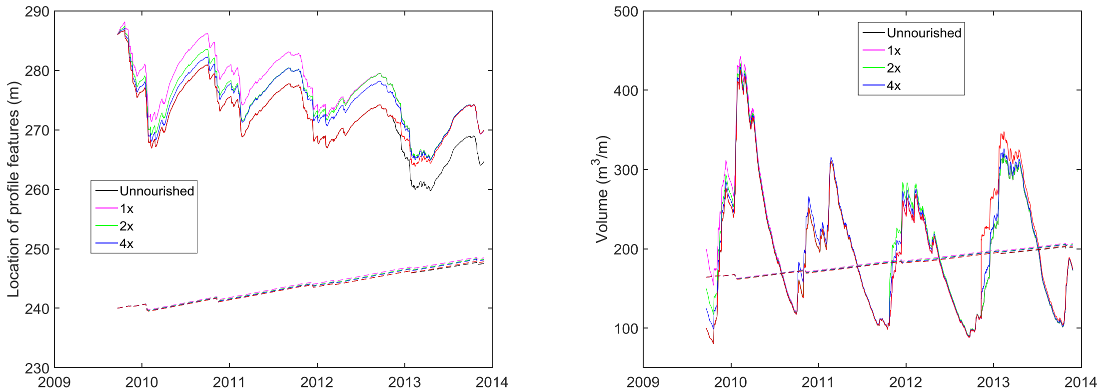
With respect to the berm nourishment, model results showed that an increase in the berm level provides improved dune protection against storms, reducing the probability of the waves attacking high up in the profile. During recovery periods, as dune erosion occurs with less frequency (preventing sediments from being transported from the dune to the berm), the profile that was not nourished presents a more advanced berm position. Still, the profile nourished at the berm and the unnourished profile showed similar values for the berm position, y_B, since the change in the shoreline position is inversely proportional to the berm height.

The simulated seaward dune foot position shows an increasing trend with time for all nourishment schemes due to the wind-blown sand transport (moving sediments from the berm to the dune). However, for the berm fill, a quicker build-up of the dune is observed as a result of the lower wave impact over the dune, implying a relatively stronger contribution from the wind.

Since no offshore losses are being taken into account in the simulations, the model results obtained for the unnourished profile can be described by a general profile translation in relation to the equilibrium states achieved for the nourished profiles. Apart from this be a quite logical response to the nourishment activity, several authors (Park *et al.*, 2009; Marinho *et al.*, 2016) have found a more active sediment exchange between the nearshore and offshore areas than expected. Also, Marinho *et al.* (2016), when analyzing the short-term responses of underwater fills through their spatial and temporal variations, detected some offshore-directed losses in which sediments were driven to deeper waters (acting as a sink for the sediments).

4.2.2. *Varying the schedule for fill placement*

The impact of changing the chronology for placing the same cross-sectional fill volume is evaluated here. Fig. 4 displays the model results for the seaward dune foot (y_S), berm position (y_B), and dune and bar volume variation for a profile with different timing of the fill placement.



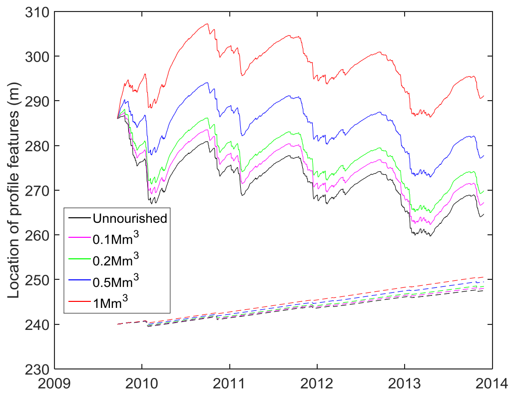
a) Modeled results for for y_S and y_B. b) Modeled results for V_D and V_B.

Figure 4. Simulation results varying the fill placement schedule. The continuous and dashed lines represent the modeled berm and seaward dune foot positions in a) and the dune and bar volume in b), respectively.

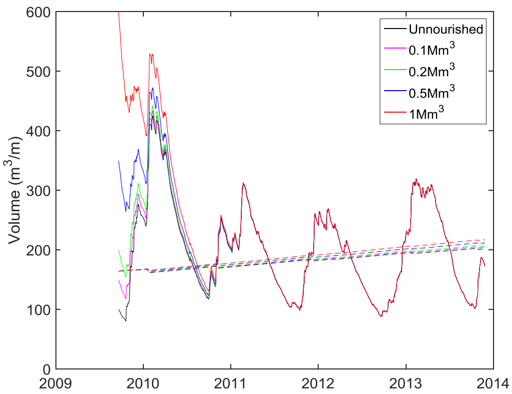
Overall, the simulation results showed that a concentrated fill placement in time provides a rapid advance of the shoreline position (y_B), although all the different schemes for fill placement tend to reach the same values of y_B after the total fill material has been placed at the bar. The concentrated fill reduces the impact force from the waves hitting the dune face since waves propagate a larger distance to reach the dune foot. Consequently, the eroded dune mass (quantity of sand transported from the dune to the berm) to balance the build-up by wind processes is lower, contributing to a pronounced dune growth. The same reason explains why the seaward dune foot ends up at a more retreated position when the fill placement is split up in different occasions. Furthermore, integrating the beach width in time, the concentrated fill presents a larger accumulated beach width at the end of the simulation, providing longer coastal protection. In terms of shoreline position, y_B, the more advanced position was obtained for the profile nourished at four occasions, whereas the beach width is narrower when a mega nourishment is employed (at t=0).

4.2.3. *Varying the sectional volume*

What was desired here was to evaluate the performance of the model by simulating different sectional fill volumes ($0.1Mm^3/m$, $0.2Mm^3/m$, $0.5Mm^3/m$, and $1Mm^3/m$). Fig. 5 displays the evolution of the seaward dune foot (y_S), berm position (y_B), and dune and bar volumes for a profile nourished with increasing sectional fill volumes.



a) Modeled results for y_S and y_B.



b) Modeled results for V_D and V_B.

Figure 5. Simulation results varying the sectional fill volume. The continuous and dashed lines represent the modeled berm and seaward dune foot positions in a) and the bar and dune volume in b), respectively.

In agreement with the model results obtained in 4.2.1. and 4.2.3., an increase in the fill volume resulted in an increase of the beach width (the bar goes back to its equilibrium shape, gradually releasing sediment towards the beach – see Fig. 5). The model includes a physically based approach to simulate the cross-shore sediment transport over decades, so, the larger the fill volume dumped at the bar, the longer the time will be required to redistribute the nourished material (note in Fig. 5b that the time adjustment of V_B increases with the nourished volume). Although the time to reach a new equilibrium state depends on the sectional volume applied, it was verified that the profile usually takes one seasonal cycle to redistribute the nourished sand (storms events accelerate the distribution of the fill material). Also, as offshore losses are not included, the values of y_S and y_B are proportional to the increase in the fill volume (see Fig. 5). However, due to the frictional losses over the berm, a widening of the berm implies a decrease in the wave impact force hitting the dune, meaning that after a certain sectional fill volume, the increase of fill material does not have any additional benefit on the profile. This yields an increased ability for the wind to build up the dune, which considering the sand availability will imply a general decrease of the beach width with time (wind blows sand towards the dune, increasing y_S and retreating y_B), consequently intensifying again the wave impact force hitting the dune. The maximum benefit from nourishment was shown to depend on the beach width necessary to dissipate all the incoming wave energy.

5. Numerical application: Case study of Silver Strand State Park, Coronado, California, USA

In order to test the model in an applied case study, the cross-shore evolution of an offshore nourishment project performed at Silver Strand State Park, San Diego, California, in Dec-1988, is reproduced here. The project consisted of the nearshore placement of dredged material, resulting from maintenance activities of San Diego Harbor, at the top of an existing bar, between a water depth of 3 and 9 m as a way to supply the beach and prevent further beach erosion. The placement site was located 7.5km south of the entrance to San Diego Bay. The dimensions of the artificial bar created were approximately 360 m (≈1200 ft) alongshore and 180 m (≈600 ft) across shore, with an average relief around 2 m. The estimated dredged amount was 100 000 m^3 (≈ 130 000 yd^3), divided by the longshore length of the placement site, 360 m, yielded to a cross-shore volume of 276 m^3/m of shoreline. The median grain size of the native material was approximately 0.25 mm (Juhnke *et al.*, 1990).

5.1. *Data set*

After nourishment a monitoring program was set up to survey the offshore mound. Repetitive cross-shore surveys covering the placement area were collected during about one year after the mound construction (between 9 Dec 1988 and 21 Feb 1990). In total, 9 field campaigns were carried out for 7 profile lines (P1 to P7, counting from South), in which four lines covered the initial location of the fill, and three were located southward. From the 9 observations, two of them were collected just before (9 Dec 1988) and after (29 Dec 1988) the nearshore berm construction. These data have earlier been analyzed by Larson *et al.* (2016) when evaluating the movement of the offshore mound placed at Silver Strand. According to these authors, all the survey lines located across the placement site displayed similar behavior. Since line 5 was located in the middle of the mound, where end effects caused by longshore transport should have been small (Larson and Kraus, 1992), in the present study, this line is used as input profile for model calibration. Fig. 6 shows the several surveys that were conducted for Line 5. Data collection extended from the top of the dune to a depth 15.0 m below MSL.

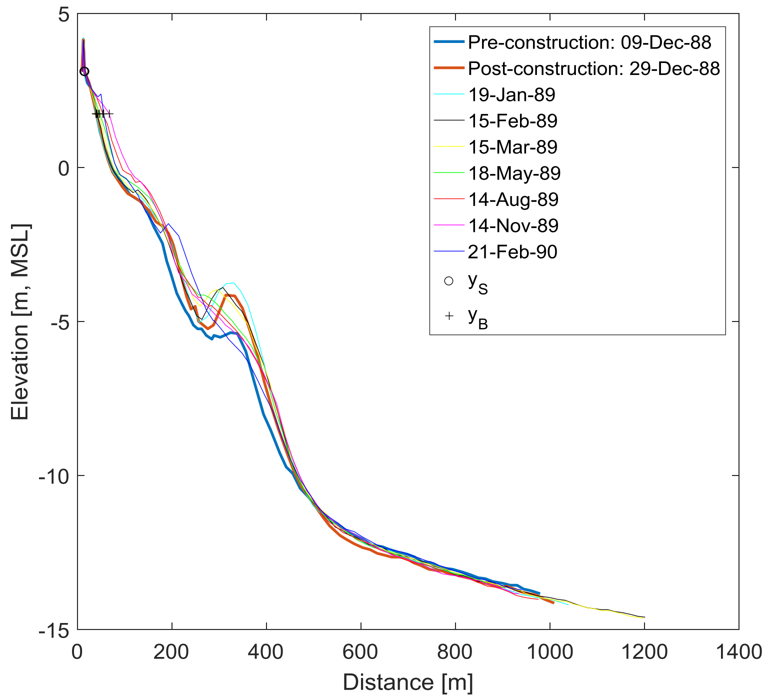


Figure 6. Surveyed profiles at Line 5 during first year after construction.

The artificial nearshore bar is recognized in Fig. 6 just after the placement (Dec 1988). Overall, the survey data demonstrates a gradual shoreward migration and dispersion of the mound after construction. A notable shift of the berm crest towards shallower contours as well as a direct transfer of material from the mound area to the inshore portion of the profile can be observed in each survey. Simultaneously, a significant reduction of the berm relief is observed during the first 4-5 months after construction. Thereafter, the berm crest decreases more slowly. Overall, the berm movement resembled a cross-shore diffusion process with a shoreward-directed advection.

5.1. *Model calibration*

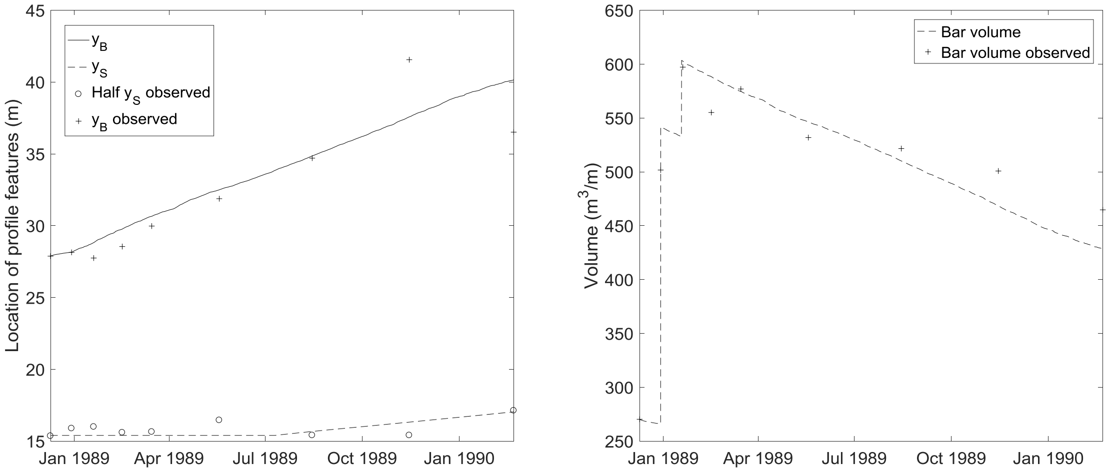
The profile was schematized based on the surveyed profile in 9-Dec-1988 (see Table 2). The beach in Silver Strand differs from the schematized model profile shape, as there is no pronounced berm and the slope is approximately constant from the dune foot (specified at 3.1 m above MSL) to 1.7 m depth contour. In the calibration exercise, the berm width was set as haft of the measured beach width in 9 Dec 1988, so that the berm volume is correctly represented. The potential aeolian transport rate, q_{wS}, was calibrated to account for the observed dune evolution ($1.1\times10^{-7} m^3/s/m$). Although some surveyed profiles were extended to the back region of the dune, allowing the authors to obtain a rough idea about the shoreward characteristics of the dune shape (y_L, β_L, s), most of campaigns did not properly cover this area, preventing high-quality data to be selected for calibration. Consequently, although it is included in the simulations, the dune volume variation was not evaluated. Instantaneous additions of sediment (representative of the cross-sectional fill volume) were introduced to the bar volume to simulate the effect of nourishment operations. According to Andrassy (1991) clean-up dredging and disposal operations were still conducted between 29 Dec 1988 and 19 Jan 1989 surveys, so this was added in the simulations as an extra representative volume of 71 m^3/m. Since wave measurements in connection with the profile surveying were only available for a short time period (between 20 Jan 1989 and 18 May 1989), numerical hindcasts were employed in the simulations. The time step was set up based on the wave information studies (WIS) available for every 3 hours. Sea water level data were available for the same period as the wave measurements. Thus, a simple harmonic model based on the method of least squares was employed to fit the tidal components to the available data. With the harmonic constants, tidal predictions for the remaining monitored period (9-Dec-88 to 21-Feb-1990) were used in the simulations. Although, the fill material was estimated to be somewhat finer than the native sand, a value of 0.25 mm was adopted for d_{50}. Based on the surveyed profiles available the seaward limit of the active profile, d_{clos}, was estimated at 12 m below MSL. The water temperature was specified to be 15ºC. Remaining site-specific parameters were set according to the following input specifications: m=-0.5, C_B=0.08, λ_0=0.002h^{-1}. A multiplier of 0.025 was applied to adjust the bar response rate, so that a smother response of the offshore mound resulting from the cross-shore diffusion process could be reproduced.

Table 2. Morphological parameters; input values of variables for the Silver Strand case study.

y_L [m]	y_S [m]	y_B [m]	s [m]	$s_{máx}$ [m]	D_B [m]	V_B [m^3]	β_L [rad]	β_S [rad]	β_F [rad]
10	15.4	27.9	1.1	1.1	3.1	270.3	0.36	0.38	0.06

5.2. *Model validation*

The model results in terms of locations of the seaward dune foot, y_S, and the berm crest position, y_B, are presented in Fig. 7a, whereas the simulated bar volume (representative of the subaqueous profile response) are displayed in Fig. 7b. As mentioned before, although the dune volume has been included in the simulations, the results are not displayed here. The model results for y_B are compared with half the measured berm width. Measured values for the bar volume were calculated through comparison of the surveyed profiles to a derived equilibrium profile (Larson and Kraus, 1992).



a) Modeled and observed values for y_S and y_B. b) Modeled and observed values for V_B.

Figure 7. Silver Strand case study: profile evolution after nourishment.

During the simulation period there was no change in the landward dune foot position, y_L, therefore it is not displayed in Fig. 7. Overall the model prediction was satisfactory. The simulated seaward dune foot position showed good agreement with the observations, presenting a maximum deviation to the measurements lower than 1 m, in May 1989. Small changes in the dune volume were estimated during the first period of simulation (reason why y_s is constant until Jun 1989), which suggest a delicate balance between the wind-blown sand transport (rebuilding the dune) and the wave impact force (promoting erosion). In terms of bar volume variation, the agreement between the measured and computed values is judged to be good. The computed bar volume decays during the simulation period, indicating a gradual distribution of the fill material towards the beach. In spite of this, an increasing deviation from the measured values can be observed. This is attributed to the fact that a fixed coefficient to quantify the bar rate response is used in the simulation, whereas the surveyed profiles have shown a deceleration of the offshore mound deflation, indicating a slower diffusion process for the mound approximately 5 months after the construction.

Profile started with a narrow berm, experiencing a continuous widening during the simulation period. The shoreline has moved seaward as a result of the incremental volumes placed on the bar during the feeding operations carried out at Silver Strand in Dec 1988 and Jan 1989 (see Fig. 7). In general the calculated and measured values are consistent, although model predictions deviate from the last two observations, producing onshore transport rates that seemed to yield excessively lower and larger accumulation of sand above MSL, in Nov 1989 and Feb 1990, respectively. This is likely a result of the limited ability of the model to simulate accumulation in the swash zone. In the simulations the fill material is transported by the waves directly to the beach (a decay in the bar implies a growth of the beach width). However, as it was earlier observed in Fig. 6, part of this material go through the surf zone before it ends up on the beach. As opposed to the bar region, which is exposed to wave breaking only during large storms, the surf zone experiences breaking waves during most of the year, so a considerable sensitivity to changes in the nearshore with indirect consequences for the berm evolution is expected. Simultaneously, it is hypothesized that one year after construction, the actual profile has experienced some changes associated with longshore transport (not included in the present simulations), which may also have contributed to the apparent deviation of the last observations for y_B from the overall trend of the remaining measurements. These longshore perturbations have also been discussed by Larson and Hanson (2015).

6. Final remarks

A numerical model with a simplified long-term description of the beach profile evolution, accounting for dune erosion and recovery, overwash/breaching, and the exchange of material between the bar and the berm (CS model; Larson *et al.*, 2016) has been implemented to investigate the potential evolution of hypothetical nourishment interventions on an open sandy beach.

Overall, the CS-model gave a satisfactory representation of the expected behavior of different types of nourishment schemes during cross-shore material exchange. Regarding the cross-shore exchange of nourished material, the analysis demonstrated that most of the nourishment schemes differed mainly concerning the time evolution of profile adjustment towards a new equilibrium state (which is dependent on the fill volume and placement), whereas the equilibrium states themselves were similar. Due to the coupling between the berm and the bar, placement along the profile and at the bar showed similar behavior, quickly reaching the same equilibrium states (typically during one seasonal cycle). On the contrary, simulation of dune nourishment indicated that the material remains high up in the profile, requiring longer periods to adjust compared to the other schemes, being highly dependent on the occurrence of energetic events to redistribute the nourished sand. An increase in the berm height acted as an additional dune protection against storms, since the probability of waves reaching the dune decreases, preventing erosion. It was verified that after a specific nourishment volume, the profile does not benefit from an increased fill volume. The schemes tested with different placement chronology tend to reach similar values for the berm position (y_B) after the same nourishment volume has been placed in the profile; however, integrating the beach width in time, the concentrated fill presented larger accumulated beach width, implying protection during a longer time period. A major conclusion from the study is that different types of nourishments serve different purposes. To strengthen the dune system over time, berm nourishment may be an appropriate solution, decreasing the probability of the waves reaching the dune foot and also promoting the build-up of the dune by wind. To protect the area around the shoreline on a short-term basis (*e.g.*, emergency operations due to storm damage is required), nourishment of the profile or at the bar may be suitable to get a faster cross-shore distribution of the fill. Finally, a long-term solution would be dune nourishment, where a storm surge will gradually distribute the fill material along the profile, increasing the berm width until new equilibrium condition prevails.

Furthermore, the model was validated towards data collected at Silver Strand, California, in connection with a field experiment, where sand has been placed as an offshore mound on top of an existing bar, producing onshore sand movement and berm advance. It has been shown in the present study that the model can be used for investigation of beach fill responses, as the evolution of the nearshore nourishment was correctly reproduced, showing a general good agreement with trends in measurements. Equally, the model has shown to be applicable for other fill design schemes in determining the time scale and movement of the nourished material placed in other forms, giving the expected beach fill response.

Apart from the simplifications introduced so that longer time scales can be addressed, the model has also some shortcomings that should be overcome in further studies. The relevance of including offshore losses in the simulations (could act as a sink or source of sediments) has been mentioned. Also, if the berm is re-built at a higher crest elevation, an undesirable scarp may form as a response to the wave power. However, the berm slope is maintained constant during the calculations. The benefits of allowing for a change in the berm slope during the simulation should be further investigated. Also, the profile nourishment was set as general distribution of the fill volume along the active profile (sum of the berm crest height, D_B and depth of closure, d_{clos}). However, this may be not realistic since for practical and economic reasons in the field, fill operations are usually concentrated at specific features of the profile (subaerial or subaqueous).

The transfer of material from offshore deposits (*e.g.* longshore bars, fill mounds) towards shallower portions might be important to incorporate, as an exchange of material continually takes place between these areas, depending on change in the nearshore wave conditions. As opposed to the deeper bars, which are exposed to wave breaking only during large storms, the surf zone experiences breaking waves during most of the year. A rapid response rate is expected for this region, *i.e.*, a considerable sensitivity to changes in the nearshore, thus affecting the shoreline movement. In fact, the present model does not resolve the necessary hydrodynamic quantities to predict cross-shore sediment transport rates in the surf zone (as the SBEACH model does for example), instead from a regional perspective the total volume corresponding to the subaqueous portion of the profiles is described as a function of the bar volume variation computed in relation to its equilibrium value. It would be fruitful to incorporate a representative morphological volume for the inshore area in the model, so that the transport of the fill material in the surf zone could be better simulated. Due to its compatible temporal scale and robustness, the coupling with a shoreline evolution model would increase the model predictability of the beach-dune system response, as the gradients in longshore transport could be included through numerical inputs of shoreline change computations. Additional model development efforts should be directed to improve the ability in distinguishing underwater nourishments with distinct water depths (so far, limited to the bar location), as the morphological responses occurring along the seaward sloping mean bed level are expected to be different as a result of changing dominant transport rates.

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