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Modelling Shoreline Impacts of Detached Breakwaters: LTC and GENESIS Comparison

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Abstract: The possibility to model detached breakwaters was recently added to the shoreline evolution numerical model LTC. This LTC new function was tested and its performance compared to one of the most widely used numerical models for medium to long-term shoreline evolution analysis, GENESIS. In spite of the differences, both models showed an overall similar behavior to model the shoreline evolution in the presence of a detached breakwater. The LTC was calibrated in order to approximate the obtained results with GENESIS. This calibration showed that LTC has a higher morphological evolution rate, recording higher accretion and erosion rates over a smaller time interval. The LTC beach configuration showed a positive area evolution balance, with the accretion area being superior to the erosion area, while GENESIS recorded an almost null area balance. Morphological behavior of the shoreline, due to the LTC detached breakwater presence, agrees with other observed models, such as DELFT3D, and even empirical formulations. The LTC model new function was considered valid to perform the simulation of the detached breakwaters impacts on the shoreline evolution.

Keywords: shoreline evolution, numerical calibration, transmission coefficient, tombolo/salient, erosion/accretion

1 Introduction

The use of shoreline evolution numerical models for the design, optimization, and comparative evaluation of competing coastal project alternatives has many advantages over the analytical and physical approaches. These numerical models allow the analysis of multiple coastal intervention scenarios in a small time frame, with reduced associated cost, such as the effects of renourishment cycles, the effects of different coastal structures, the effects of different wave condition scenarios, and to predict the adjacent beaches impacts (USACE, 2008).

GENESIS and LTC (Long-Term Configuration) are one-line numerical models, usually applied to provide a realistic estimate of the shoreline evolution under different coastal intervention scenarios. They present several similar characteristics and behaviors and are mainly used for long-term previsions, where high resolution and detail are not that relevant. Both models assume that the longshore sediment transport volumes gradients are the main process responsible for spatial and temporal shoreline position changes, which are determined by the morphological characteristics of the coast and the wave climate conditions.

This work aimed to compare the detached breakwater modelling ability between GENESIS and LTC, in order to validate its impacts in the shoreline evolution, from short to medium-term perspectives (time period required to form a tombolo). Detached breakwaters' transmission impact on wave propagation and consequent sediment transport effects was incorporated in the numerical model LTC. A performance comparison with the GENESIS numerical model was conducted by attempting to calibrate LTC to obtain the closest possible results between models. Firstly, GENESIS model was assigned with the same sediment transport characteristics and active cross-shore profile width of the ones adopted in the LTC. To obtain similar shoreline configurations between both models, the detached breakwater wave height transmission coefficient, K_T, was altered in LTC and this calibration process is shown and discussed. In this paper, both shoreline evolution numerical models are presented, and then, detached breakwaters definition and principles in LTC and a reference scenario are shown. Later, LTC and GENESIS performance is compared, allowing calibrating the LTC. Finally, discussion and major conclusions are presented.

2 Shoreline Evolution Numerical Models

The theoretical work of Pelnard-Considère (1956) is the basis for many numerical models that have been successfully applied to simulate shoreline response to wave and current actions (Hoan, 2010). In this theory, the beach profile is assumed to maintain a constant shape. Consequently, under this assumption, it is sufficient to consider the movement of one single contour line while studying the shoreline change and that line is conveniently taken to be the shoreline (Larson et al., 1987). One-line models used to estimate longshore sand transport rates and long-term shoreline changes generally assume that the profile is displaced parallel to itself in the cross-shore direction. These models are formulated based on the conservation equation of sediments in a control cell and on an alongshore sand transport equation (Rosati et al., 2002).

Using the mass balance equation, the shoreline position is calculated in each coastal cell. The sediment transport gradients are distributed uniformly over the full extension of the active width of the cross-shore profile. Thus, volumetric changes in each cell represent a parallel retreat or advance of the profile in the case of erosion or accretion, respectively. Cross-shore transport rate is, in average, null, for medium to long-term. Therefore, one-line models do not account for cross-shore profile's evolution, due to the difficulty to reproduce a realistic evolution for this time scale (Hanson et al., 2003), and are only influenced by the longshore sediment transport gradients. Cross-shore distribution of the longshore sediment transport is also not taken into consideration.

2.1 GENESIS Model

The numerical model GENESIS (GENEralized model for SImulating Shoreline change) is an example of a one-line shoreline change model and covers a group of programs developed for simulating wave-induced longshore sand transport and shoreline movement (Hanson, 1989 and Gravens et al., 1991). GENESIS can be applied to a diverse variety of situations involving almost arbitrary number, location, and combination of groins, jetties, detached breakwaters, seawalls and beach fills (Hanson, 1989). This model calculates shoreline change due to spatial and temporal differences in longshore transport as produced by breaking waves and it is suitable for longshore extent in the range of 1 to 100 km and the time frame of a simulation can be in the range 1 to 100 months (Hanson and Kraus, 1989).

According to Hanson (1989), Hanson and Kraus (1989) and Gravens et al. (1991), the main assumptions of GENESIS are: 1) bottom profile does not change in time and thus, only longshore sand transport is taken into account and the cross-shore profile is considered always in equilibrium; 2) sand actively moves over the active profile to a certain limiting depth, beyond which the bottom does not move (depth of closure); 3) for the wave and sand transport calculations, the bottom profile is assumed to follow the shape of the equilibrium beach profile. One implication of this is that the depth increases monotonically. Thus, a particular point on the beach profile can be determined uniquely from the water depth, and a location at a greater water depth is always seaward of one at a lesser depth (Coelho et al., 2013).

2.2 LTC Model

LTC is a numerical model, developed at the University of Aveiro (Coelho, 2005) for sandy beaches that combines one-line theory with bathymetric updates. LTC could be seen as a combination between a one-line model (Hanson and Kraus, 1989) and a cross-shore profile evolution model, considering only the geometrical characteristics of the profile. It allows the modelling of natural and anthropogenic scenarios, from medium to long-term, being used in the design and choice of engineering solutions to mitigate coastal erosion problems. LTC is currently prepared to model a coastal extension with a maximum value around 30km over a time window of 10, 20 or 50 years (medium to long-term). LTC main difference from GENESIS is that LTC updates the bathymetric data after each wave action (Coelho et al., 2007; 2013). Each wave acts individually being transformed from offshore during propagation (Coelho, 2005). The accreted or eroded sediments are uniformly and vertically summed or subtracted, respectively, over the active width of each cross-shore profile after each computational time step. LTC also proceeds with the correction of the upper and bottom limits of the active profile, after sediment accretion or erosion, based on the intern friction angle of the wet sediments, defined by the user (Coelho, 2005). Still, no cross-shore sediment transport processes are accounted in the model.

Wave propagation simplified methods to determine refraction, shoaling, and diffraction near coastal structures are considered to compensate the computational requirements due to bathymetric updates in each computational time step. Linear wave theory is used (Dean and Darlymple, 1994) and an assumption that offshore conditions are the same over the total longshore extension of the coastal stretch is made. Refraction effect on breaking wave direction is calculated through the Snell law, assuming that wave propagation occurs over regular and parallel bathymetric lines. Breaking wave height is obtained by considering the refraction, shoaling, and, when needed, diffraction coefficients (see Coelho, 2005 and Coelho et al., 2013 for more details on the chosen approaches).

3 Detached Breakwaters

GENESIS is able to model detached breakwaters, but the LTC former version was not able to simulate this type of structure. This work includes the programming and incorporation of this function in the newer version of the LTC model. In this section, the assumptions adopted to simulate the detached breakwaters effects on the shoreline evolution modelled by LTC are presented and then, a reference scenario is described, allowing the evaluation of the numerical modelling performance, before calibration.

3.1 LTC Detached Breakwater Assumptions

The detached breakwater acts over the wave height (wave energy) and this effect is assigned by a transmission coefficient, whose value depends on the incident wave height and on the detached breakwater properties/characteristics, such as the width of the breakwater crest, its depth and the type and size of the breakwater top layer (Debski and Loveless, 1997, Taveira-Pinto, 2001, Nunes, 2012 and Fernandes, 2017). The choice of the transmission coefficient value is left for the user to make. The user should previously evaluate different formulations (Goda et al., 1967, van der Meer and Daemen, 1994, D'Angremond et al., 1996, Ahrens, 2001, Taveira-Pinto, 2001 and Mariano and Mario, 2007) to define the adequate wave transmission coefficient to represent the situation to simulate. It is assumed that the wave transmission does not affect the wave direction.

To evaluate the impact of the detached breakwater in the wave height, it is necessary to define the shadow area of the detached breakwater, which is defined by the angle of the incident wave at the detached breakwater location, as Fig. 1 shows. If the location of the detached breakwater is not affected by the presence of another coastal structure, the incident wave height (H_{in}) is calculated considering only refraction and shoaling phenomena when waves propagate to the detached breakwater location. Afterwards, the transmission coefficient (K_T), given by the user, is applied to the incident wave height (H_{in}) and the transmitted wave height value (H_{bw}) is computed. The new wave characteristics are then used to determine the sediment transport, considering the shoaling and refraction effects of the transmitted wave propagation between the detached breakwater and the wave breaking position. The breaking depth (d_b) is obtained from the transmitted wave breaking height. If the waves break before reaching the detached breakwater there is no impact in the wave breaking height and consequently there is also no impact on the longshore sediment transport.

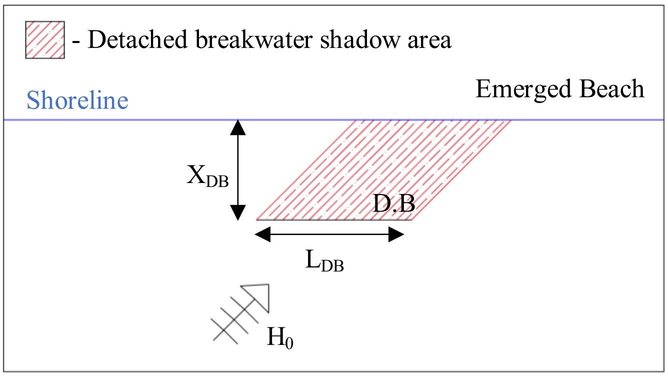

Fig. 1. Detached breakwater shadow area scheme.

Directly applying the transmission coefficient to the wave height only over the detached breakwater shadow area leads to gradients in the wave height and consequently in the longshore sediment transport along the whole domain. Thus, accretion and erosion rates will be registered at the shadow area limits, inducing a morphological impact on the shoreline evolution. To avoid an abrupt sediment transport gradient at the detached breakwater limits, which would cause nonrealistic morphological structures to appear at those limits, and in an attempt to simulate the diffraction effects of the detached breakwater in its surroundings, a transition curve was set at the near limits of the detached breakwater. This curve is composed by parabola shaped curves and its extension depends on the breakwater extension, as the larger the detached breakwater is, the larger the transition extension will be. These curves are responsible to perform the transition from a transmission coefficient of 1 (not affected), towards the transmission coefficient of the breakwater. According to Figure 1, sediment's deposition will occur at the updrift limit of the shadow area of the detached breakwater, where the wave heights are smaller, and erosion is registered in the downdrift limit of the shadow area. Due to sediment accumulation between the ends of the breakwater, a tombolo tends to be formed. In this case, further evolution of the shoreline with LTC model assumes that the effect of the completed formed tombolo is similar to a groin when evaluating the longshore sediments transport blocked/bypassing the coastal structure.

3.2 Reference Scenario

A reference scenario is presented to assess the shoreline evolution under the influence of a detached breakwater. The initial beach was characterized by a regular bathymetry, with an emerged slope of 0.03 and a submerged extension characterized by Dean's profile (Dean, 1991), with an A and m parameter of 0.3337 and 2/3, respectively. To characterize the detached breakwater characteristics, it was defined a value of 0.6 for the transmission coefficient (K_T), a detached breakwater length (L_{DB}) of 300m and axis-to-shore distance (X_{DB}) of 300m (see Fig.1). The detached breakwater was kept parallel to the shoreline. A constant and regular wave climate was chosen, with a significant wave height of 2m, a peak period of 9.34s and a wave direction of 15º with the shoreline. The detached breakwater was placed in the centre of the numerical domain, which was defined with a 20km longshore extension and a total cross-shore extension of 5km. The two open boundaries were defined to supply, at updrift, the total longshore sediment transport, while the downdrift boundary was set to collect all the sediments being driven downdrift. A longshore sediment transport of around $1.2\text{x}10^6\text{m}^3$ per year was obtained in the LTC.

Preliminary numerical runs were made to estimate the time interval needed for the shoreline, initially linear, to reach the detached breakwater. A value of 3.5 years was obtained. This time interval represents the reference detached breakwater filling time. Figure 2 shows the shoreline position every 6 months for a 3.5 years run (from t0 to t7).

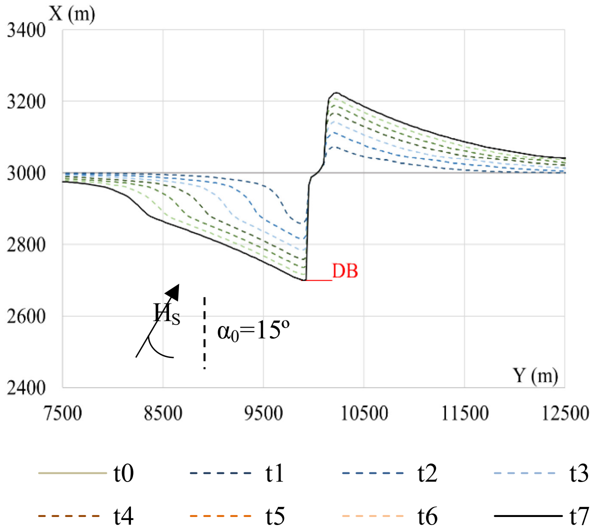

Fig. 2. Shoreline evolution for the reference scenario in LTC: t0 represents the initial shoreline and t1-t6 are evenly spaced by 6 months.

The results show there is an updrift accumulation of sediments and downdrift erosion over time. A higher accretion closer to the immediately updrift extension of the detached breakwater axis can be seen, which propagates towards updrift. The shoreline configuration transition, between the accretion and erosion areas, is quite steep. The ratio between accreted and eroded areas is positive, representing higher accretion areas then the eroded ones. This is due to the sediments' volume distribution in the cross-shore profile because the eroded area is located in the steeper part of the profile.

4 LTC and GENESIS Calibration

The first step of the performed analysis was to assign the GENESIS model with the same sediment transport characteristics and active cross-shore profile extension/length of the ones adopted in the LTC. Values of GENESIS' k1 and k2 constants (calibration parameters for the longshore sediment transport formula) were assigned to reproduce an identical longshore sediment transport as in LTC, for the same wave climate and without the presence of coastal structures/interventions. Since a constant wave climate is being used, the GENESIS sediment transport parcel influenced by the k2 coefficient is null, thus only k1 needed to be determined. To obtain the same longshore bulk sediment transport value as in the LTC ($1.2x10^6 m^3$ per year), a value for k1 of 0.17 was estimated for an equal sediment transport in GENESIS. Closure depth was manually introduced in GENESIS as 4.3m, which corresponds to the same value obtained through Hallermeier (1981) expression, considered in the LTC model calculations.

4.1 GENESIS

In this section, the GENESIS simulation, with the same sediment transport and detached breakwater characteristics of the reference scenario is presented. As observed in Fig. 3, the GENESIS shoreline does not reach the detached breakwater after 3.5 years (filing time for the reference scenario in the LTC). The obtained shorelines over time are also different from the ones obtained from the LTC, describing lower accretion and erosion values, updrift and downdrift of the detached breakwater, respectively. A smoother morphological gradient is presented over the shadow area, where the separation between accretion and erosion occurs, while the LTC shoreline presents a rough transition in the shoreline configuration for that same zone. The accretion area resulting from the detached breakwater impact matches the erosion area, thus there is an almost null area balance in the detached breakwater influence region.

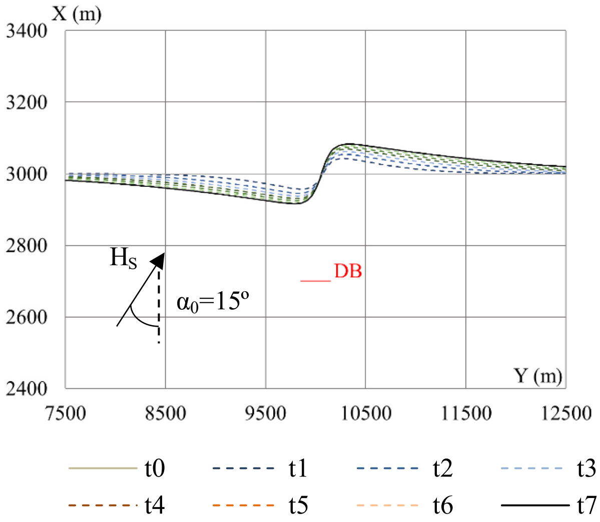

Fig. 3. Shoreline evolution for the reference scenario in GENESIS.

4.2 LTC Calibration

As referred, a steeper shoreline configuration of the tombolo/salient is present in the LTC model and a smoother configuration is observed in GENESIS' shoreline after 3.5 years of simulation. The accretion area is similar to the erosion area in GENESIS, with values of around 222700m^2, describing an almost neutral balance, while for the LTC, these values are 401500m^2 and 326000m^2, respectively, describing a global area gain in the influence region of the detached breakwater. These values represent about 80% more accretion and 46% more erosion than in GENESIS (Fig. 4a).
The most efficient way to obtain similar shoreline configurations between both models was achieved by changing the detached breakwater wave height transmission coefficient. Maintaining the properties of the reference scenario in GENESIS (K_T=0.6), a value of K_T=0.73 for LTC was obtained in order to reproduce a similar shoreline configuration after 3.5 years. A transmission coefficient of approximately 0.73 led to a difference of 9% of the accretion areas and 10% of the erosion areas, with the LTC having a larger accretion area (Fig. 4b).

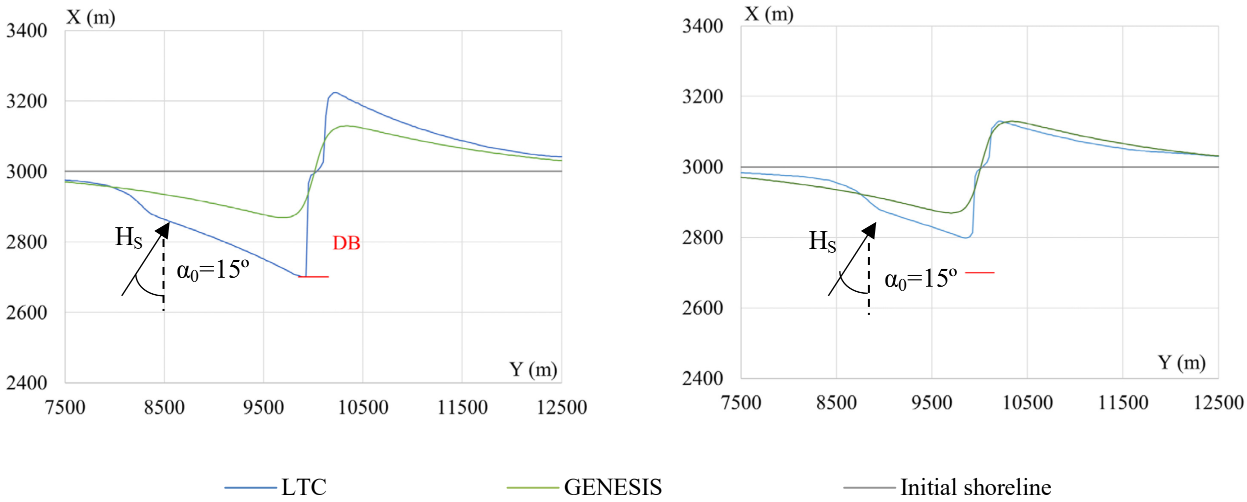

Fig. 4. Shoreline configuration before (left) and after calibration (right) at the filling time.

To determine the relationship between both model's transmission coefficient that ensures the same total area (balance between accretion and erosion) after a simulation period of 3.5 years, several wave height transmission coefficients, between 0.6 and 1, were considered in the LTC, and between 0.55 and 0.85 for GENESIS K_T (Fig. 5). Considering accretion, erosion or global balances, three transmission coefficients in the LTC ($K_{T\ LTC}$) were estimated for each coefficient value defined for GENESIS ($K_{T\ GEN}$): one value that reproduces the accretion area (K_T accr) more accurately; another one but for the erosion area (K_T eros); and an average value that could simulate both areas with maximum accuracy comparing with GENESIS (K_T avrg).

The average transmission coefficient relationship obtained is described by a third-degree polynomial equation, applicable over the K_T GEN interval of 0.55 to 0.85. The determined standard deviation is low for both accretion and erosion K_T values (0.0234 and 0.0237, respectively), associated to a maximum absolute relative difference of 4.76%. Note that the determined transmission coefficient relationship is only applicable for the presented scenario characteristics.

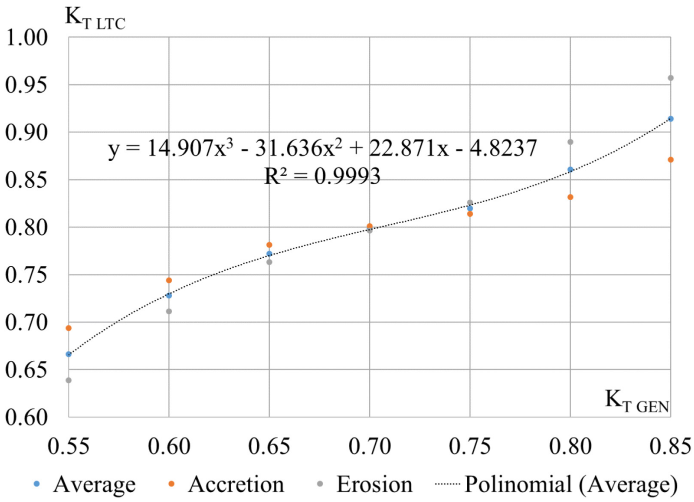

Fig. 5. Transmission coefficient relationship between LTC and GENESIS values.

For a 3.5 years simulation in the reference scenario, it is observed that the transmission coefficient in LTC needs to be higher to result in similar shoreline configurations. This similar behaviour is obtained for $K_{T\ GEN}$=0.7, resulting in $K_{T\ LTC}$=0.8. Increasing or decreasing the K_T coefficient in relation to this values, will increase the difference between LTC and GENESIS performance. By using a transmission coefficient of 0.4 in GENESIS (higher sediment transport gradient), after a 3.5 years run, a tombolo is observed, which corresponds to a shoreline advance of 300m, as shown in Fig. 6. This scenario is similar to the reference scenario in LTC. GENESIS scenario for K_T=0.4 accretion and erosion areas are superior to the ones obtained in the LTC for K_T=0.6 in 51% and 92%, respectively.

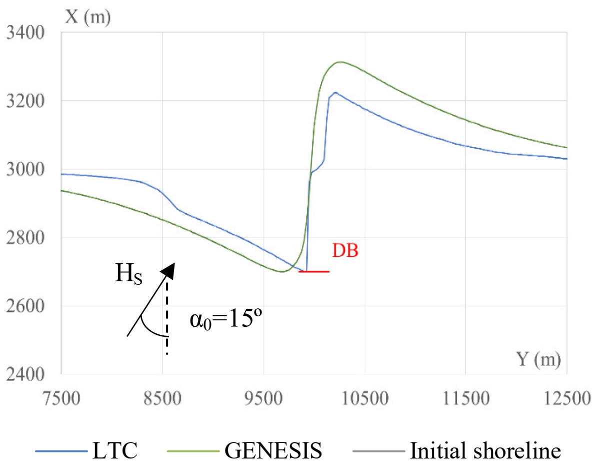

Fig. 6. Shoreline at t=3.5 year (filling time) for LTC K_T=0.6 (reference scenario) and GENESIS K_T=0.4

5 Discussion

Overall, the LTC modelling detached breakwaters presents a similar behavior to the GENESIS. Nevertheless, LTC has a faster shoreline evolution, reaching higher accretion rates than GENESIS in a smaller time frame, despite having the same initial conditions, including sediment transport and active profile width characteristics. The LTC results for all the simulations show a positive area balance while GENESIS obtained a null balance. Despite the registered differences, it is possible to adjust both models to perform similar configurations by adapting the transmission coefficient.

A comparison was performed between LTC and both DELFT3D numerical model and empirical formulations that describe the morphological configuration outcome of a beach affected by a detached breakwater. According to van Rijn (2018), using the Delft3D to model a scenario, with similar hydrodynamic conditions (irregular waves with H_s=2m and T_p=8s) and in a presence of an equal detached breakwater (L=300m and D=300m), should lead to the formation of a tombolo. As the incident waves were normal to the shore, there was accretion at the center sections of the detached breakwater position and erosion in both updrift and downdrift limits of the detached breakwater. Also, decreasing the detached breakwater capacity to block the waves (higher K_T coefficients), lead to the formation of a salient instead of a tombolo, which also happens in the LTC (by increasing the transmission coefficient of the detached breakwater). Despite the increase complexity of morphological evolution of this model, similar results were obtained with the LTC.

Several other scenarios (*e.g.* different detached breakwaters, distances to the shoreline), which are not present in this work, were tested and the obtained morphological responses were in agreement with several formulations (mainly dependent on the relationship between the detached breakwater length and axis to shore distance) present in Bos et al.(1996) work, such as: Gourlay (1981); Dally and Pope (1986); Harris and Herbich (1986); Suh and Dalrymple (1987); Hsu and Silvester (1990); and Hanson and Kraus (1990).

6 Conclusions

A new function was assigned in LTC numerical model, allowing to simulate the shoreline evolution due to detached breakwaters. This behavior was simulated by considering a K_T coefficient to affect the wave height and represent the impact on the longshore sediment transport and consequent shoreline evolution. A range of K_T values were tested and compared between both the LTC and GENESIS models in order to calibrate the LTC to obtain the most approximate results to GENESIS. The most similar behavior is obtained for K_T in GENESIS equal to 0.7, which results in a LTC K_T coefficient of 0.8. LTC presented a positive area balance for the wave climate and sediment transport characteristics initially imposed in the reference scenario, while GENESIS resulted in a null area balance (erosion and accretion areas were similar throughout the tests). The choice of the which model to use depends on the site geomorphological and hydrodynamic characteristics, since the accretion/erosion rates/areas varies from site to site.

The LTC model also agrees with the morphological behavior of the DELFT3D model, when a detached breakwater is considered. Similar shoreline configurations (morphological formations, salient and tombolo) were obtained for similar detached breakwaters and hydrodynamic conditions. Some empirical formulations, that describe which kind of morphological formation will occur as a function of the hydrodynamics and detached breakwater characteristics, were also found to behave accordingly to the obtained results in the LTC.

Overall, due to the similarities between GENESIS and LTC morphological evolution and the similarities with DELFT3D and the empirical formulations, the LTC model new function was considered valid.

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