Storm Events of Nice Bay: A Numerical Modeling of the Interactions Between Wave, Current, and Solid Transport

Rémi Dumasdelage, Olivier Delestre, Didier Clamond and Gourbesville Philippe

1 Introduction

Nice is located in the South–East of France on the French Riviera (Fig. 1). It is the fifth most populous city in France with nearly 1 million inhabitants. Moreover, tourism is one of the main economical activities in this region. Thus, the 4.5-km-long beach is a key element for this sector.

The erosion of neighboring pebble zones and the sediment transport by various rivers (Var, Paillon, Magnan) are at the origin of this gravel beach [5]. The main river, the Var, can carry away between 1 and 20 million tons of sediments per year. Most of these sediments are silty clays, and only 100,000 m^3 are gravels [11]. Some Var pebbles have been identified in the west part of the bay and are characterized by their lamellar shape. This shape explains their transport and their storage on the backshore, for more details see [10].

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Fig. 1 Geographical orientation of Nice bay, with its two neighboring rivers the Papillon and the Var

Globally, the upper layer of the beach is dominated by very coarse gravels and small cobbles (5–10 cm in diameter). Coarse sand composes the lower level of the beach and can be observed after a storm on the intertidal zone [1]. Below the depth of 0 m, the clast size of the sea bed is decreasing progressively, and sand can be found between −5 and −10 m. A protected seaweed called *Cymodocee nodosa* grows at about 50 m off the shore (Fig. 2). This last parameter is a major limitation to the construction of coastal structures, because this seaweed must not be impacted by any human activities.

Regarding the climate, the South-East of France experiences intense autumn and winter storms [12]. They are defined by important wave heights (up to 4 m for a 10-year return period) and intense rainfalls implying big discharges in the neighboring rivers. Thus, high quantities of sediments are evacuated during floods [2]. This special configuration stresses the variability of the sediment transfers in terms of space and time in the studied area. The more frequent wave propagation directions are South–South–West and East–South–East [8]. The French Riviera is not subjected to substantial tide (<0.5 m for spring tides) and the surge level has been evaluated to 0.7 m NGF for a 10-year return period [8]. All these observations will help us later on to understand the beach dynamics and were primordial in order to build up an accurate numerical model.

The special configuration described above, as well as the urban development of the city, can be linked to explain the significant erosion phenomena observed in the studied area. Two main sediment transports exist along the shore and across the shore. These transports are the physical results of the natural setting of the bay. However, human activities increase their effects and their impacts, modifying the environment and the morphological nature of the beach.

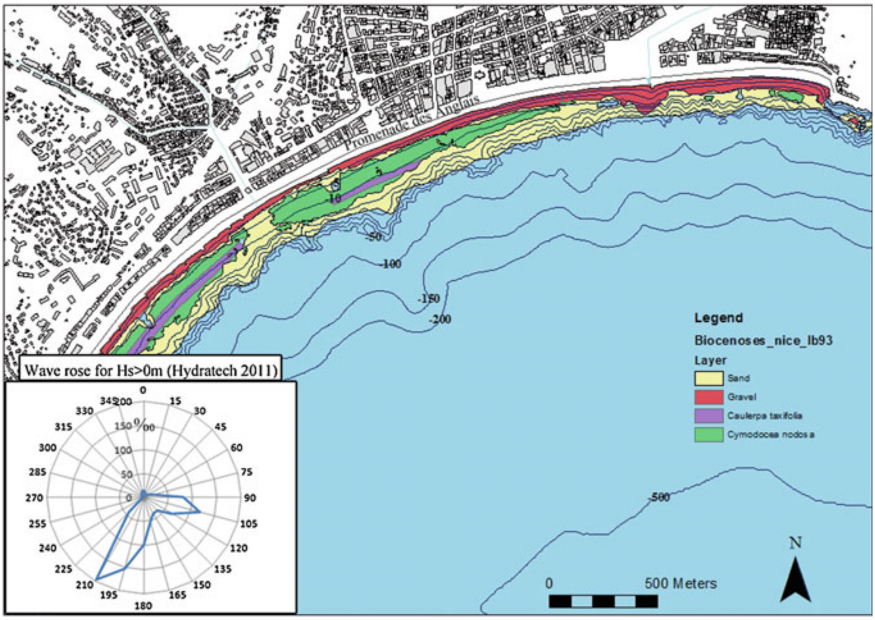


Fig. 2 Bathymetry of Nice Bay, sea *bottom* coverage and wave rose

Nice is defined by a steep continental margin and high value of the shoreface slope (Fig. 2). In fact between depths of 0 and −20 m the mean slope is around 10 % (with a beach step at the inner shoreface). At the depth of −20 m, the bathymetry is decreasing quickly until −100 m because of an abruptness (slopes are between 20 and 80 %) [12]. Thus, waves can propagate longer inshore before breaking. Combined with the low tide range, plunging waves are concentrated over a narrow and constant region of the beach. So, the high pressure and the important energy dissipation constitute the driving forces of the cross-shore gravel transport.

This downslope loss of materials is amplified by the wave reflection on the beach step [1]. In fact, this step forces waves to break at the base of the beach and so prevents the formation of a surf zone [3].

A second effect of the abrupt bathymetry is that the wave refraction is often incomplete. Thus, waves arrive at the beachface with a significant angle, creating a longshore current [4]. This current and the nearshore waves regime are at the origin of the longshore gravel transport.

Most of the time, these two sediment transports (cross and along the shore) have to be taken into account in order to understand the changes on the coastline.

During exceptional events, the extreme power of high plunging waves makes the cross-shore transport the major actor of the sediment mobility (Fig. 3).

However, it is important to stress that these transports do not fully explain the significant erosion phenomena faced by Nice's beach each year. Studies have shown that the total beach sediment losses is around 15,000 m^3/year and that the

Fig. 3 Example of the 2010 storm event in Nice

sediment budget of some part of the beach is around −5,000 m^3/year [12]. The anthropological action that experiences the French Riviera is at the origin of this erosion. Structures have been built on the neighboring streams. For instance, in the lower part of the Var, ten weirs have been constructed in order to raise up the river bed (previously lowered by extraction and urbanization of the flood plain). Thus, the bed load transport has almost completely stopped [7], implying a drastic decrease of the main gravel supply for Nice's beach. In addition, the modification of the Var delta which followed the building of Nice-Riviera airport in the 1940s can be compared to a huge groin that deviates the sediments towards the nearby bay (Fig. 1).

Urban development has also impacted directly the morphology of Nice beach. Between 1929 and 1958, the *Promenade des Anglais* has moved from a simple coastal pathway to a main 4 ways road indispensable to Nice traffic. Thus, a 3-m high seawall has been built at about 4 m from the coastline in order to protect the roads and to create a walkway along the sea. As a result, Nice backshore faced an important decrease and an amplification of the reflection phenomena during storms. This seawall stops some morphological process such as the roll-over of Nice beach and cuts off the storage of sediment capacity of the backshore [10].

The municipality has decided to artificially nourish the beach in order to stabilize its width. Since 1969, around 580,000 m^3 have been brought. According to Anthony and Cohen [1], the efficiency of this process is analyzed, so we will not discuss it further. Before 2006, the recharged material was provided by the construction sites and the gravelly bed of the Papillon river. So, the price of the artificial nourishments was only due to the transport of sediments. Since 2010, the municipality has to buy the gravels from a quarry around 100 km away, at the rate of 130 \$/m^3. Therefore, the cost of these operations has increased, which forces the decision makers to find new solutions to the beach erosion.

In this context, we started a modeling approach to represent the natural phenomena that participate to erosion, such as the longshore current and the wave propagation. Finally, it enables us to study the interaction between them and the artificial structures.

2 Study Method

The numerical model has been built with TELEMAC, a free and open source system developed by EDF R&D's Laboratoire National d'Hydraulique et Environnement (LNHE). It is a powerful integrated modeling tool, composed of different simulation modules, such as TOMAWAC and TELEMAC2D.

TOMAWAC (TELEMAC-based Operational Model Addressing Wave Action Computation) aims at representing the sea states by solving the balance equation of the action density directional spectrum, for more details see [6, 9]. The code attempts to reproduce the evolution of this spectrum at each point of a spatial computational grid.

Concerning TELEMAC2D, it solves the Saint-Venant/shallow water equations in two space horizontal dimensions so as to provide mainly, values of the water height and mean horizontal velocity (averaged vertically) at each point of the grid. Our results are based on a resolution of the system with the finite element method.

In this study, TOMAWAC and TELEMAC2D have been coupled so that the interaction of the current and the waves could be taken into account. This direct coupling TOMAWAC-TELEMAC2D enables an exchange of variables between the two modules. Therefore, the action of the waves on the current and the current on the waves are represented. TELEMAC2D calculates current velocities and water depths and transmits them to TOMAWAC which in turn solves the wave action density equation by using these updated variables. Then TOMAWAC sends back to TELEMAC2D the new values of the wave driving forces that interfere with the current.

The spatial computational grid has been created with Blue Kenue. This software, developed by The National Research Council of Canada, provides tools to generate a triangular unstructured mesh (Fig. 4). Thus, different grids have been tried by changing the mesh density and the area of the study, in order to have an accurate representation of the phenomena with an acceptable time of simulation. The grid represented on Fig. 4 has been used to run the TOMAWAC model and is composed of 74,000 nodes. However, the coupling with TELEMAC2D required too much computation time, so the domain has been reduced by removing zone 3. The waves do not have any impact on the bottom in deep water, that is why we deleted this part of the grid (Fig. 4). The scenarios tested with this numerical approach are based on the previous study of the observed wave propagation directions (SSO and SE) and intensities. These data allowed us to set a JONSWAP spectrum on the boundaries.

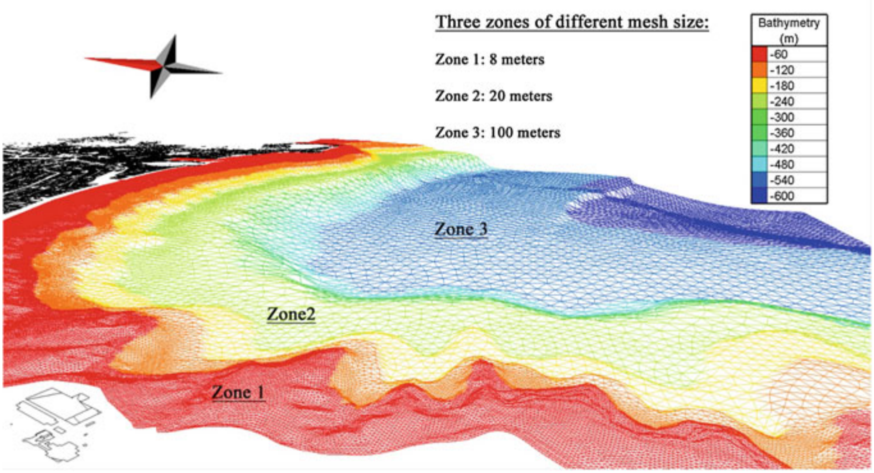


Fig. 4 TOMAWAC grid generated on Blue Kenue

3 Results and Discussion

3.1 TOMAWAC Results

Four wave directions of propagation have been tested on the model, N120, N140 (ESE-SE) and N180, N200 (S-SSW). The return period of the simulated storms is around 1 year, so the significant wave heights prescribed at the boundary of the grid are approximately 2.5 m (for ESE-SE swell) and 3.0 m (for S-SSW swell) [8]. Of course, source and dissipation terms have been configured to integrate the influence of some physical parameters, as for instance the bottom friction-induced dissipation, which occurs in shallow water. Other phenomena have been considered, like the white capping and the wave breaking dissipation.

As expected, because of its geographical orientation, a larger portion of Nice's beach is affected by the swell, when it comes from ESE-SE directions. However, the S-SSW swells are defined by more important wave heights and periods than the other swell directions. Therefore, even if the west part of the bay is protected, the east part is completely exposed to high wave heights.

A common phenomenon to all the swell directions can be observed near the coastline (around 30 m from the beach): an increase of the significant wave heights on some zones of the bay (Fig. 5). This can easily be explained by the bathymetry. Indeed, the geometrical refraction process forces the waves to propagate perpendicularly to the isobaths. Consequently, sub-marine caps create areas of high energy concentration (Fig. 5).

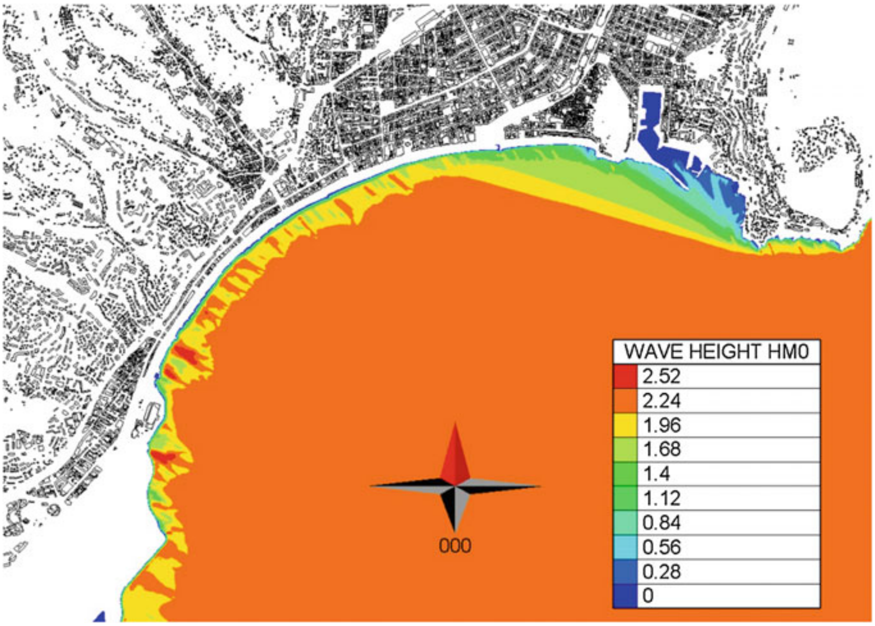


Fig. 5 TOMAWAC results for a 1-year return period event with a direction of swell N120

3.2 TELEMAC2D Results

The analysis of the current velocities results gives us more information about the potential sediment transport of a storm. Indeed, it allows us to interpret the effect of current patterns on the sediment dynamic. The event simulated in this second part is a little less important than 1-year return period events in terms of wave heights (Fig. 6). Yet, we can observe high values of the velocity with 1 m/s on some parts of the beach. They are observed in the middle of the bay, zone 1 (Fig. 6). These results are explained by the orientation of zone 1 compared to the near shore wave direction. A significant angle exists between the wave direction and the coastline of this zone. Thus, our comments in the introduction regarding the bathymetry are illustrated here. The refraction phenomena cannot be completed because of the late influence of the bathymetry on the wave direction, creating an alongshore current near the coastline.

In Zone 2, the current is coming from the East to the West with low velocity values. Two causes can be mentioned. The first one is, as seen before, the angle between the near shore wave direction of propagation and the beach orientation. In this case, the waves come nearly perpendicularly to the coast, thus the current velocity is lowered and oriented towards the East. The second one is the implanted

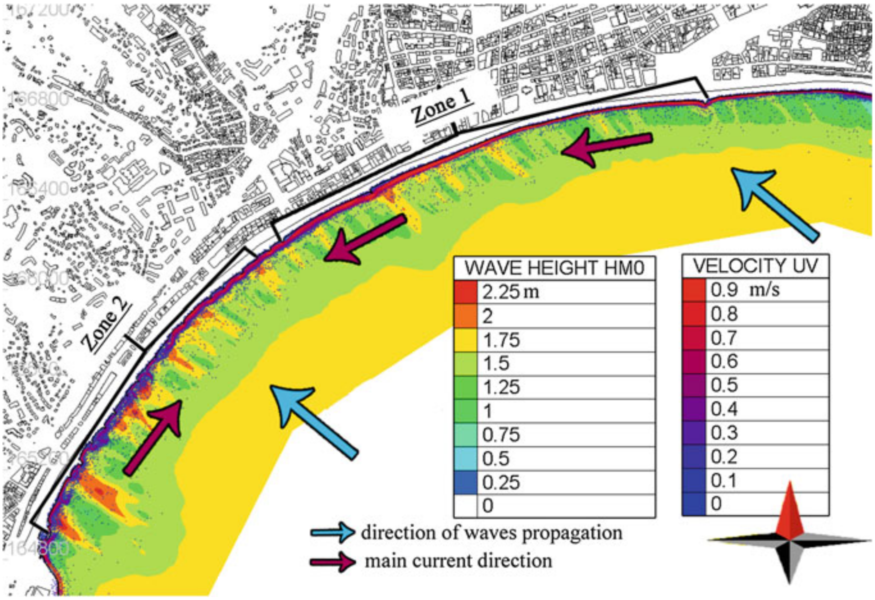
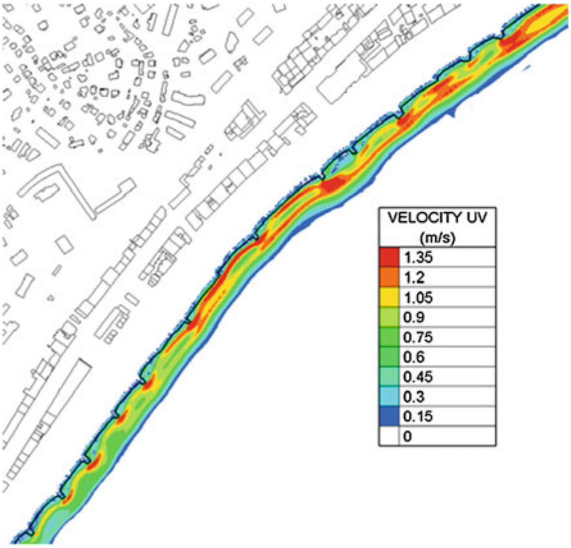


Fig. 6 Coupling TOMAWAC-TELEMAC2D results

groins in the west part of the bay. We can see that the velocity is still important in the east part of zone 2, but then it decreases progressively. This blocking action on the alongshore current is the first purpose of the groynes (Fig. 7).

Fig. 7 Interaction of the current with the groynes



3.3 Validation and Prospects

Because of the lack of data, we could not validate accurately the wave and the current modeling results. Nevertheless, our findings have been compared with different local observations (storm damages, shape of the beach) with satisfactory results. For instance, after a South–East swell event, sediments have piled up on the west side of the groins (especially in the west part of zone 2, Fig. 8).

The final goal of this study is to model the sediment transport. So, we started to work on coupling TOMAWAC and TELEMAC2D with SISYPHE, the sediment transport module of TELEMAC. Thus, the data that needed to be acquired first concern the sediment motions. That is why we focused on obtaining these data and through them we tried to validate our waves and currents model.

Some simple correlation between the simulation results and the decrease of the beach width could be used to demonstrate the accuracy of the approach. In fact since 1950, Nice municipality has been measuring the beach width nearly 3 times a year. But this set of data is not well adapted to our modeling work.

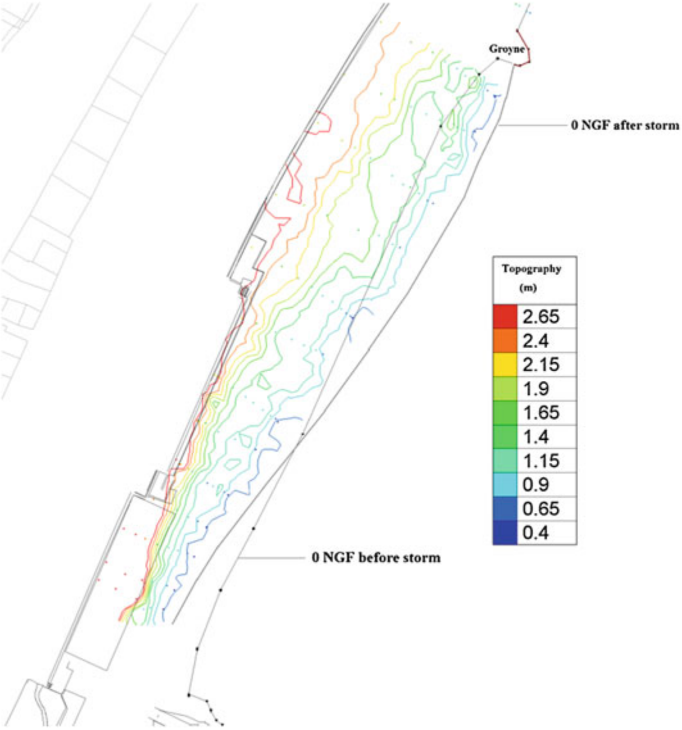


Fig. 8 Example of beach shape modifications after a South–East storm

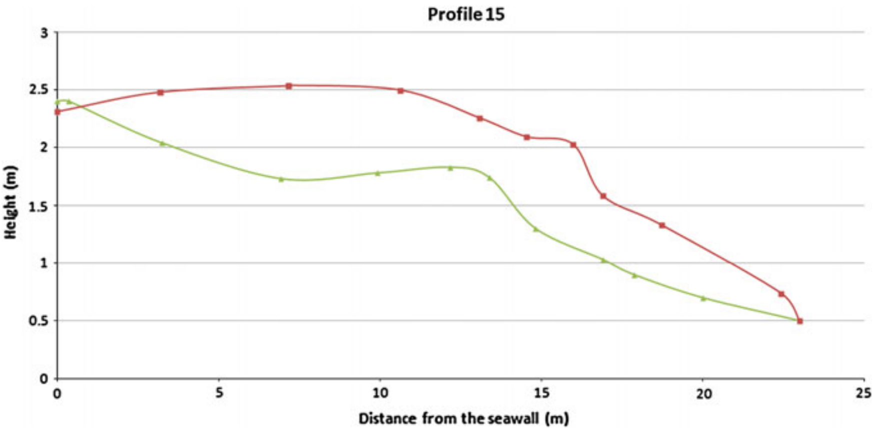


Fig. 9 Beach profile variations between the 10/12/13 (*green curve*) and the 06/01/14 (*red curve*)

In fact, the purpose of our simulations is to represent the action of the hydrodynamic forcing terms due to a short storm event (few hours). Several months separate two beach width field campaigns. Because of this time scale, the comparison between our results and the beach width data is not accurate.

Moreover, it is quite common that the beach experiences sediment losses or gains without any variation of the beach width (Fig. 9). In order to overcome these issues, we have started a new field campaign based on GPS measurements. The frequency of these measurements has been increased and varies depending on the storm events. Thanks to the GPS system, we are now able of capturing the beach profile motions and to characterize the variation of sediment volumes. However, more data need to be acquired before validating the previous model.

4 Conclusion

The goal of this paper was to present the erosion phenomena of Nice bay, and to illustrate some of its driving forces through a numerical model. The wave propagation simulations run on TOMAWAC have stressed the variable aspect of the significant wave heights along the coast, due to the special bathymetry of the domain. Thus, around sub-marine caps, concentrations of energy are observed and characterized by an amplification of the offshore wave height. As for the analysis of the currents modeled on TELEMAC2D, they have shown that the direction of the swell propagation directly impacts the direction and the intensity of the alongshore current. For instance, a South–East swell will create an East–West current, which is maximal around the center part of the bay. However, further work needs to be achieved before presenting concrete results of the gravel transport and to validate them.

Of course the phenomena illustrated by the model results were well known, but the major advantage of a modeling approach is to quantify them and furthermore, to understand their interactions with existing structures and future ones. The next step of this study will be to integrate structural solutions to reduce erosion and to analyze their effects by keeping in mind that such a model will not take into account all the complex phenomena of coastal erosion on a gravel beach.

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