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Flood modelling on Ile de Ré during Xynthia

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***Abstract*— Xynthia event has generated a significant storm surge on Ile de Ré the 28th of February 2010. Storm impact feedback showed that overtopping was responsible for several failures of coastal defences leading to important flood area and damages. This paper aims to describe the methodology used to assess the flood risk based on coupled Telemac2D - Tomawac models.**

Engineering approach usually employs a high resolution flooding grid forced by time series of water levels computed in a larger scale and lower resolution run. Weir law can also be used to impose water discharge caused by overflowing or wave overtopping. A recent study [6] suggests that these approaches are only valid if a two-way nesting is employed. Otherwise the flooding in the finer grid may be strongly overestimated.

Other studies [1] [3], have shown that storm surge associated to Xynthia was amplified by the presence of very young and steep waves, which increase sea surface roughness. Moreover, oceanic processes must be well represented in order to have accurate storm surge distribution.

This paper describes the methodology adopted to set up a unique regional allowing for adequate integration of land/sea interactions and representation of the main water propagation obstacles, while keeping reasonable computation time.

In this approach, overtopping calculation is more complex compared to a classical weir law. Hence, an innovating internal routine has been developed to represent wave overtopping based on Eurotop manual [5]. It allows introducing discharge caused by wave overtopping combined or not with overflowing. The method also takes into account the eventual breach formation in coastal structures. The accurate estimation of hydraulic forces on coastal structures allows for a better assessment of defense failures threshold. These results add strength to the experience feedback on breach formation and improve the numerical model for flood propagation.

I. INTRODUCTION

The 28th of February 2010, Xynthia storm hits the French Atlantic coast. The storm surge combined with the high tide and waves caused water defences failure along the coastline from the Gironde (Bordeaux) to the Loire Estuary. A significant amount of land, (>50 000 ha) was consequently flooded and 47 people died as a result of the storm.

The highest water level of 4.5 meters NGF (General Levelling of France) was measured at La Rochelle. The storm surge height of 1.5 m caused a lot of water flowing over coastal protections. Even if the volumes of water overflowed significantly the coastal dikes, the major part of floods landward during Xynthia is attributable to the failure of coastal protection.

This study aims to assess the flood risk on Ile de Ré with the reference event Xynthia. A full coupled Telemac2D - Tomawac model is then needed for maritime part in order to represent accurately Xynthia water level on the island's coast. Once the sea level is calculated at the shore, another important issue in this study was to represent the water flowing over the coastal defences and flood propagation landward. This step required to collect accurate topographic measurements on dikes to calculate hydraulic forces on each coastal protection. Hydraulic forces consist mainly on sea level, sea state and resulting overtopping. Overtopping discharge is the most difficult parameter to calculate. A specific module was developed to determine these discharges within the coupled Telemac2d – Tomawac model, from the sea state at the toe of each structure and depending of the typology of the coastal protections. Moreover, the accurate evaluation of hydraulic forces on coastal protections allows making improvements on breach formation simulation.

II. MODEL SETUP

A. *Model strategy*

Xynthia was an untypical storm crossing the studied area in a few hours, with very low pressure, short young waves and shifting wind from South to North-west. In order to properly represent oceanic conditions, it is important to consider a wide enough area to model every concerned process. Forcing must also be considered variable in space and in time to be realistic.

Furthermore, studies [1], [3] show that storm surge was amplified by the presence of very young and steep waves, which increase the sea surface roughness. This sea state is due to the atypical trajectory of Xynthia storm, which crossed the Bay of Biscay from the Southwest towards the Northeast, reducing the zone of wave generation to some hundred kilometers.

Concerning the propagation of landward water volume, engineering approach usually employs a high resolution flooding grid forced by time series of water levels computed in a larger scale and lower resolution run. A basic weir law can also be used to impose water discharge caused by overflowing or wave overtopping [8]. A recent study [6] suggests that these approaches are only valid if a two-way nesting is employed. Otherwise the flooding in the finer grid may be strongly overestimated.

The approach used in this study consists of the implementation of a unique regional model allowing an accurate consideration of land/Sea interactions while keeping reasonable computation times. It requires the integration of wave overtopping phenomena according to sea conditions, coastal defences and their structural failures. Meanwhile, the volumes of water overflowing must be able to go out freely of the model through the coastal protections.

B. Marine part

The maritime area of the numerical model takes into account the oscillating volumes of Charente estuaries. North limit of the model is situated north to Les Sables d'Olonne whereas south limit is located in front of Royan. The mesh width is about 100km large.

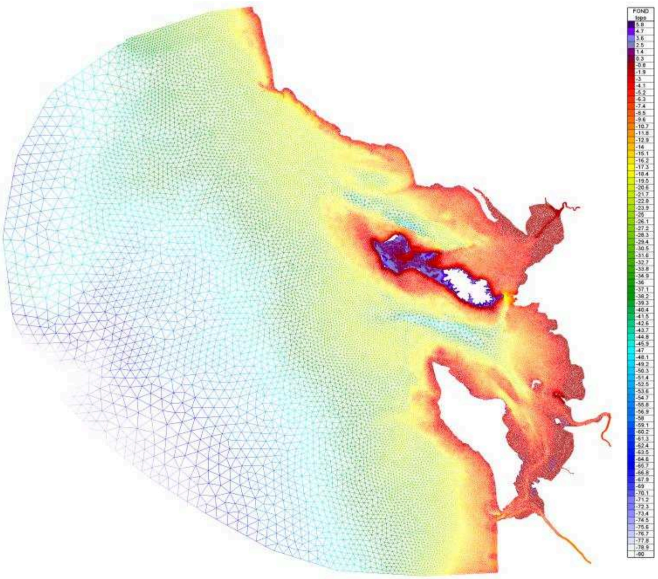

Figure 1. Global computanional mesh.

The model is forced to its oceanic boundaries by the global oceanic tide model (TPXO).

Wind is forced by the Meteo France model "AROME" validated by several meteorological stations located inside the study area (Sables d'Olonne, La Rochelle, Saint-Clément-des-Baleines, Chassiron). The wind data are varying in time and space.

Storm surge generated by the atmospheric pressure gradient is imposed on the model by the inverted barometer method. A reduction of 1hPa in pressure corresponds to a rise of 1 cm of sea level. A gap of 2 hours is considered to take into account the distance of the measurement station (La Rochelle) from the oceanic border of the model.

Waves are imposed on the oceanic boundary with a temporal series which was adjusted with the observations of a wave gauge located at the border of the model ocean boundary. Waves are then modified by wind and currents. Unfortunately, there are no available measurements to calibrate the wave model close to Ile de Ré.

C. Land part

Dikes and embankments are the main obstacles to the flood propagation. It is thus necessary to represent them correctly in the mesh. Every coastal dike was investigated along 100 m spaced cross-sections. Crest topographic measurements were also performed in order to evaluate discontinuities between the cross-sections. This survey collected the different dike typologies, the presence of parapets, the general state, the foreshore and structure slopes. All the geometry characteristics are implemented in the global mesh.

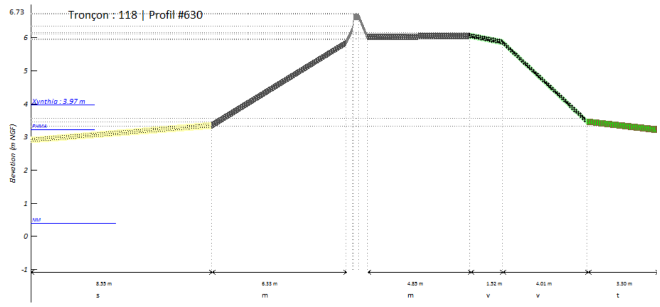

Figure 2. Example of cross profile surveyed.

Main considered embankments are: roads, secondary flood protections and marshes edges. They were determined from both Lidar topography and field surveys. To represent those structures, meshes are imposed following lines corresponding to the crest or the toe of the structures. To represent correctly a dike, 4 nodes are needed (2 at crest and 2 at toes). Furthermore, for dikes which may be overflowed, one node heightened by 2 cm has been added in the middle of the crest to avoid numerical leaking phenomena (figure below).

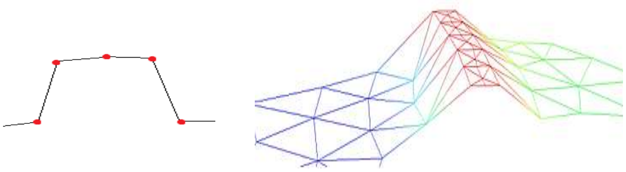

Figure 3. Representation of coastal defence

For the resolution of distribution equations, the slope cannot be vertical. This method is thus applicable on Ile de Re as there is no vertical wall as coastal protections.

The hydraulic works are integrated into the model. For marshes, the hypothesis generally made is a closed lock. However, some hydraulic works are opened or with check valve when technicians or local residents feedbacks are available.

The land nature and the corresponding friction coefficients are taken into account in the modelling with a Strickler law (figure below). This coefficients distribution was realized with the local GIS data base on land occupation. The value of the coefficients was then adjusted to calibrate the model. Buildings are not represented in the mesh. They have however a very important role in flood dynamic because of the volume of water removed, the effects of blocking, drainage anomalies... The presence of numerous buildings in the urban area is partially represented by local roughness modifications. For instance, in La Flotte- en-Ré, a Strickler coefficient of 1 has been applied after calibration as the flood propagation is faster than observations due to building effects and very narrow streets.

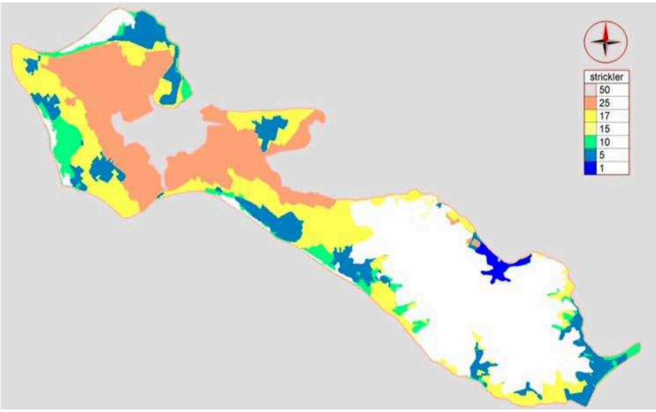

Figure 4. Repartition of rugosity coefficient regarding the land occupation

The final mesh is composed of 369 464 computational nodes. Concerning land part, size of triangles range between 1 and 50 m and for marine part, the size of meshes range between 20 m on the coast up to 3 km offshore.

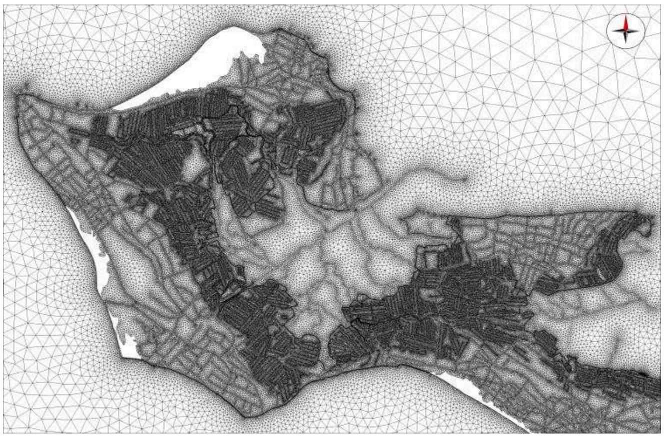

Figure 5. Mesh detail in the zone of interest.

III. Representation of coastal protection failures

Even if the volumes of water overflowing the coastal protection are significant, the major part of flood impact during Xynthia is attributable to coastal protection failures. An important work has been carried out in order to get information on coastal protection failures. Figure below shows the location of failures and the flooded area validated by the councils of Ile de Ré [4].

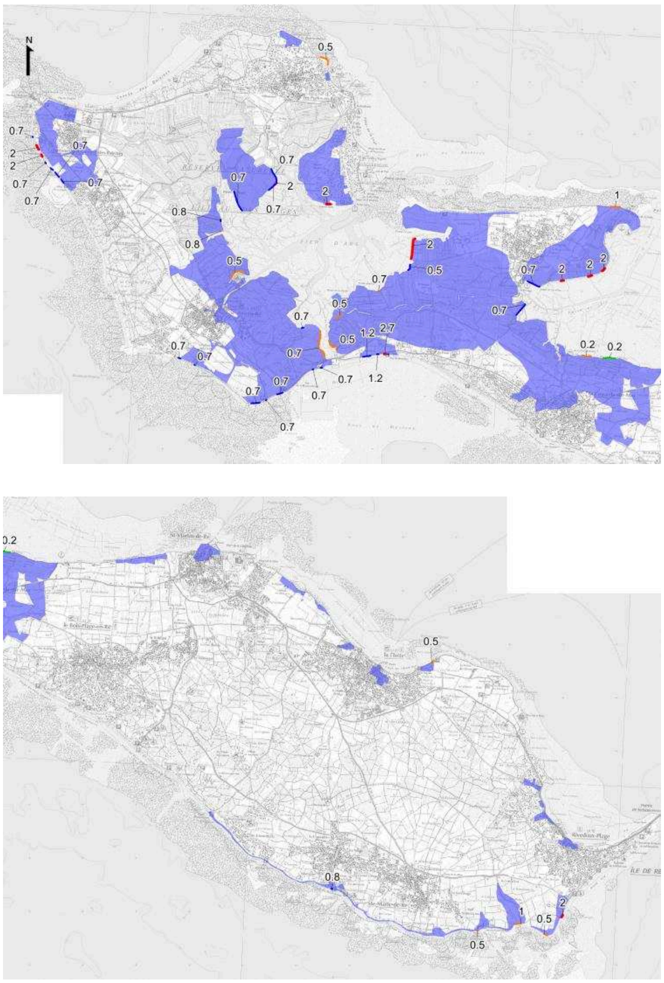

Figure 6. Coastal defence failures (red : breach; orange:head-cutting erosion; green : gabions dislocation ; blue : parapets failure) and area flooded during Xynthia. The numero gives the information on failure height.

An important step in the project was to accurately determine the hydraulic forces on coastal dikes (water level, wave parameters and overtopping discharge) in order to understand the mechanism of the occurred failures during Xynthia. Overtopping discharge is the most difficult parameter to calculate. A specific module was developed to precisely determinate these discharges. The module is function of sea state at the toe of each structure and depending on the typology of the coastal protections.

A. *Wave overtopping*

The method chosen to calculate wave overtopping discharge is based on the Eurotop manual [5].

1) *General formulae for protection with uniform slope:*

Overtopping discharge q is defined as below:

If $\gamma_b . \xi < 2$

$$\frac{q}{\sqrt{g\, H_{m0}^3}} = \frac{0.067}{\sqrt{\tan(\alpha)}} \gamma b\, \xi \exp(-4.3\, \frac{Rc}{H_{m0}} \frac{1}{\gamma_b\ \ \gamma_f\ \gamma_\beta\ \xi}) \quad (1)$$

If $\gamma_b . \xi > 2$

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.2\exp(-2.3 \frac{Rc}{H_{m0}} \frac{1}{\gamma_f\ \ \gamma_\beta}) \quad (2)$$

With : $So = \frac{2\pi\, H_{m0}}{g\, T_{m-1,0}^2}$ the wave steepness, $\xi = \frac{\tan(\alpha)}{\sqrt{S_0}}$ the breaking parameter.

Where H_m0 and $T_{m-1.0}$ are the wave height and the mean period; Rc, the crest freeboard corresponding to the difference between the crest height and the water level ; tan(α), the slope ; $\gamma_f\ \ \gamma_b\ \gamma_\beta$ influence factors corresponding respectively to the presence of berms, the rugosity and the incidence angle of waves. The formula above takes into account a safety margin allowing the determinist calculations or the conception of structure.

2) Case with negative freeboard:

If the water level is higher than the crest of the dike, large quantities of water overflow/overtop the structure. In this situation, the amount of water flowing to the landward side of the structure is composed by a part which can be attributed to overflow and a part to overtopping.

$$Q_{total} = Q_{overflow} + Q_{\ overtopping} \quad (3)$$

The effect of overtopping is then assumed by the formula below (4) and (5) also given by Eurotop manual [5] as the water level reaches or overtakes the crest height of the dike.

$$\text{Si } \xi_{m-1.0} < 2 \quad \frac{q}{\sqrt{g\, H_{m0}^3}} = 0.0537\, \xi_{m-1,0} \quad (4)$$

$$\text{Si } \xi_{m-1.0} > 2 \quad \frac{q}{\sqrt{g\, H_{m0}^3}} = (0.136 - \frac{0.226}{\xi_{m-1,0}^3}) \quad (5)$$

3) Typologies of coastal structures :

The following parameters are taken into account in the calculation of wave overtopping:

- Slope of the beach,
- Height of the structure toe,
- Slope of the foreshore and slope of the structure face,
- Height of the crest with or without parapets,
- Materials constituting the external face of the dike for rugosity matter.

4) Methodology setup:

To make the calculations of wave overtopping, the various parameters are taken at every time step during the simulation. The parameters concerned are:

- Water level at the structure toe,
- Height, direction and period of waves at a distance known from the structure toe,
- Height of the dike crest, breached or not.

A discharge q is then imposed behind each structure representing the overtopping as source point on computation nodes behind dikes.

The wave model gives reliable results to dozens of meters offshore to the structure toe according to bathymetric configuration. In order to have reliable data, the minimum distance was verified for every section (figure below).

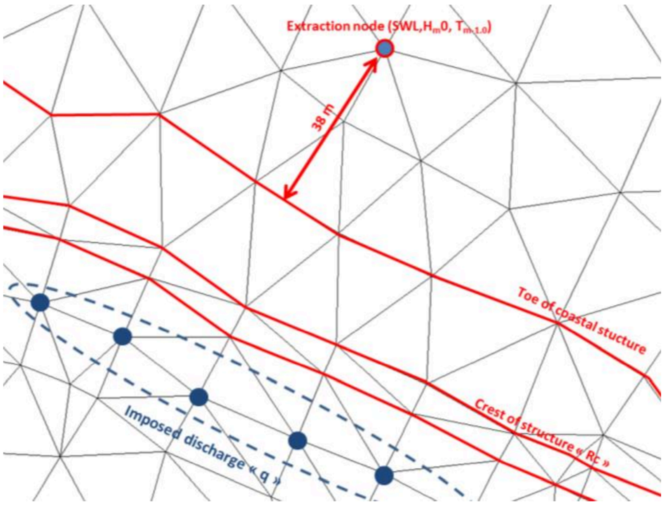

Figure 7. methodology to represent the wave overtopping.

The data are then calculated at the dike toes with formulae described above. These formulae depend on breaking parameter, wave steepness, foreshore slope, and depth of water at the structure toe. During a breach formation, the height of the crest decreases. The progressive diminution of the crest freeboard causes the increase of the overtopping discharge. Same process is applied during parapets breaking.

A precise analysis of field data set consists in defining the dikes which can be potentially overflowed, then locate breaches, configure the parameters and the mesh nodes used to calculate the wave overtopping discharge.

An output is then written for each dike to control wave overtopping discharge introduced landward.

B. Coastal protection failure

Breaches or head-cutting erosion of dikes are represented in the numerical model through the breach module available in the V6P3 version of Telemac 2D. Four parameters are considered to represent a breach:

- Initial time
- Development time
- Final crest height

- Failure length

Two of those parameters (final crest height and failure length) are well known with the feedback completed after Xynthia [4]. To estimate the two other parameters, a study has been carried out on each dike to know hydraulic forces which occurred during Xynthia. The figure below illustrates the front of a dike (grey), the height of foreshore slope (yellow), the water level (blue line), the wave parameters (red and green lines), the overtopping discharge (magenta line) and the breaches (cyan dots). The vertical black lines represent the surveyed cross-sections.

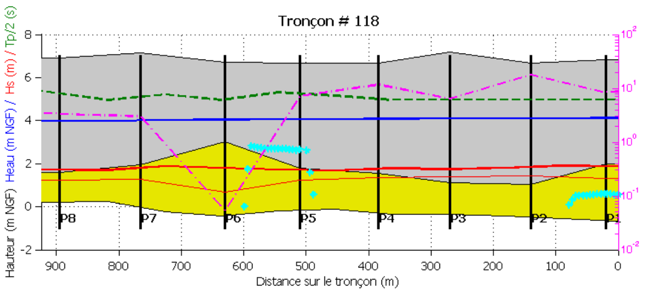

Figure 8. Hydraulic forces on dike.

With this outputs on each dike, initial time and development speed for failures have been chosen according to structure typology. According to Morris, 2008 [9], the formation of a failure can change significantly regarding the type of material used in the dike core. Three categories from different materials, typically used in the construction of dike (non-cohesive materials, cohesive materials and boulder rocks), have different behavior during failure. For parapets or dikes made of rocks or sands, the failure can be done in a quasi-immediate way. However, head-cut erosion in a dike made of highly cohesive material, like clay, can be much longer (> 1h).

A velocity of 0.5 m/hours downward for failures development in dikes made of clay has been taken as first hypothesis according to experience feedback [4]. Two types of failures have been observed after Xynthia in these dikes:

- Protection with cohesive fill exposed to wave (Hs>0.7m) inducing significant wave overtopping (Height of failure ≈ 2 m),
- Protection with cohesive fill overflowed without significant wave attack (Height of failure ≈ 0.6 m).

The figure below represents the water level during Xynthia into the “Fier d’Ars” (blue line) and the development of crest erosion for two similar dikes made of clay with the speed of 0.5 m/hours. The first dike (black line) is located on a sheltered area without wave attack. Its failure is initialized only by water overflow and finished when water level is lower than crest height. Applying the same erosion velocity for a dike exposed to short period waves (red line) and with the final crest height of 2 m, the initialization is then estimated approximately 1 hour before water overflowing. The failure initialization is explained by wave overtopping erosion.

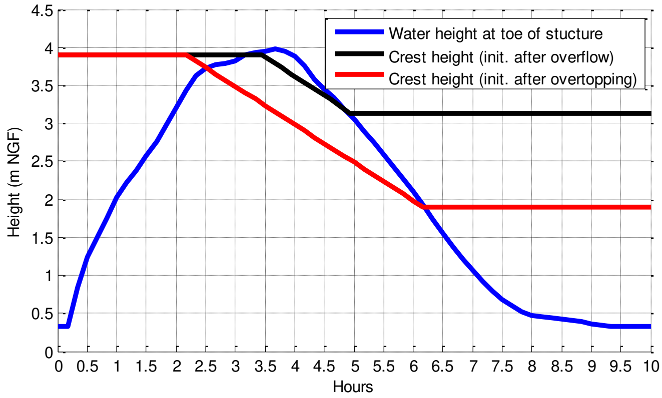

Figure 9. Breach development on dike made of clay regarding initial time after wave overtopping or water overflow.

These values have been tested further with sensitivity analysis in order to match the observed failures after Xynthia storm.

IV. Model Calibration

For this study of flood on Ile de Ré, the reference event is the storm Xynthia. The validation data (levels of water, flood marks, area flooded, swell, wind and atmospheric pressure data) are numerous and relatively accurate. Other storms like Martin (1999) can supply validation data on water level during storm conditions but the flooded area was not significant enough to calibrate our model. Older storms and flooding on Ile de Ré have not enough information on storm surge and flooded area.

A. Astronomical tide validation

The model is firstly calibrated for astronomical tide only, without processes impacting the sea level (wind, atmospheric pressure or waves). This calibration is done comparing the predictions supplied by the SHOM for different tide gauges in the study area. This comparison is made on 22 days, from February 14th to March 8th, 2010. This period covers period of neap and spring tide. An example of results is illustrated below.

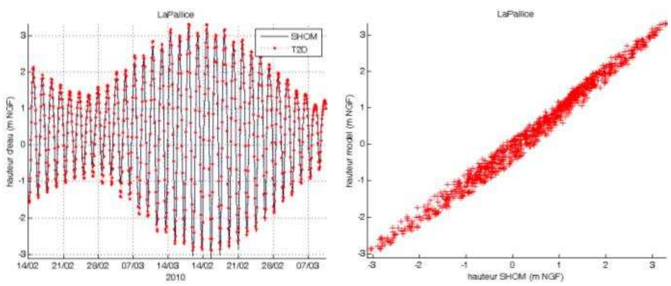

Figure 10. Comparison between model results and SHOM data at La Rochelle.

The numerical model outputs are very close to SHOM predictions. The main statistical indices of the comparison are presented in the table below:

TABLE I. STATISTICAL INDICES ABOUT MODEL RESULTS ON ASTRONOMICAL TIDE

Tide gauge	**La Rochelle**	**Les Sables d'Olonne**	**L'île d'Aix**	**La Cotinière**	**Saint Martin**	**Pointe de Gatseau**	**Saint Denis-d'oléron**
Correlation r² (%)	99.3	98.5	99.3	99.4	99.3	99.3	99.1
Bias (m)	0.07	0.02	0.11	0.11	0.01	0.07	0.04
RMSE (m)	0.17	0.11	0.21	0.17	0.15	0.17	0.19

B. Water level during storm conditions

1) Water level at tide gauges:

The water level modelled by the numerical model is compared with the observations of the tide gauges of La Rochelle-La Pallice, Château d'Olonne and La Cotinière. The main statistical indices of the comparison are presented in the table below.

TABLE II. STATISTICAL INDICES ABOUT MODEL RESULTS ON XYNTHIA WATER LEVEL

Tide gauges	**La Pallice**	**Les Sables d'Olonne**	**La Cotinière**
Correlation r²	99.34 %	99.25%	99.09%
Bias (m)	-0.005	0.08	0.09
RMSE (m)	0.23	0.26	0.23

The results illustrated on the following figures, show that the model represents well the storm surge (amplitude and phase) on the tide gauge of La Rochelle, and in a correct way in the North (Sables d'Olonne) and in the South (La Cotinière).

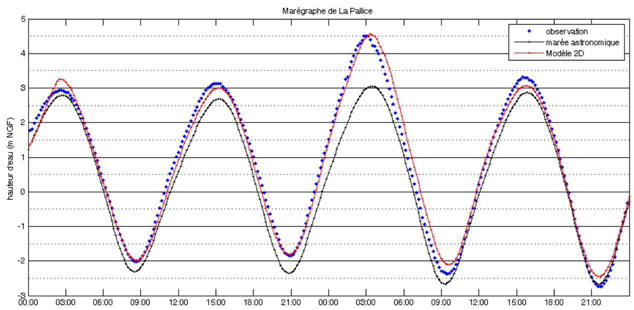

Figure 11. Model results compared with tide gauge at La Rochelle.

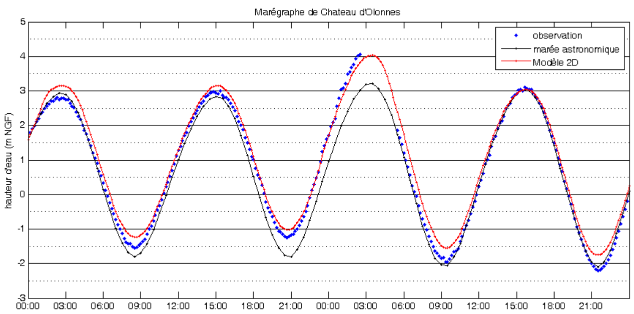

Figure 12. Model results compared with tide gauge at Sable d'Olonne.

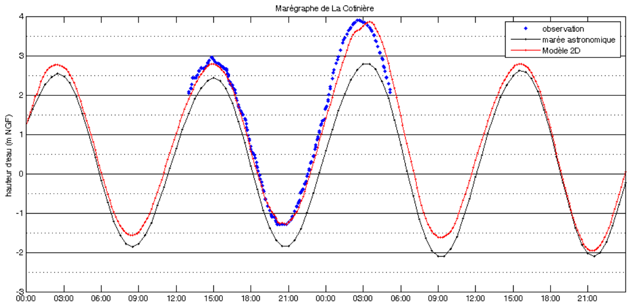

Figure 13. Model results compared with tide gauge at La Cotinière.

2) Water level on Ile de Ré coast during Xynthia:

The marine model shows that there is a strong gradient of water level (upper to 50 cm) between south part and north part of the Island (figure 13). It is thus advisable to compare sea levels reached during Xynthia on sectors at the back of coastal protection (not influenced by waves or by water propagation on land).

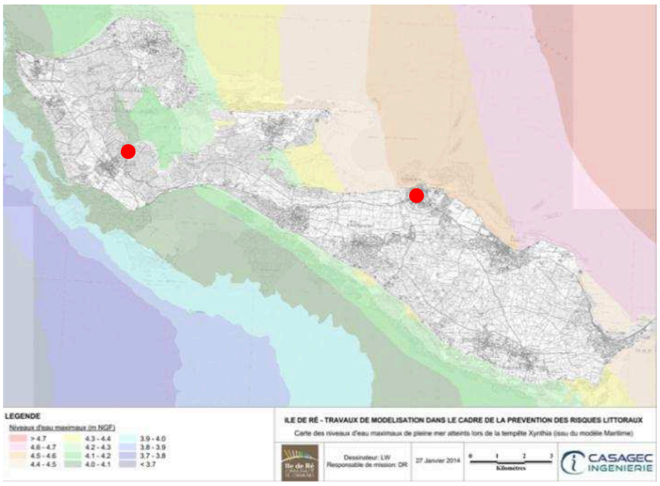

Figure 14. Water level on the Ile de Ré coast and the two harbor offices used for water level control (red dots).

Two sites have been selected on the east coast (represented by the red dots on the map above). These flood marks located on two harbor offices have been confirmed by different people and seemed to be sheltered of waves.

TABLE III. VALIDATION OF WATER LEVEL ON THE COAST

Harbor office	**Highest water mark**	**Highest water level modelled**
Saint-Martin	4.43 m	4.40 m
Ars-en-Ré	4.05 m	4.00 m

The model results present a good coherence, so the marine part for the event Xynthia is considered calibrated.

C. Flooding landward

1) Experience feedback:

The calibration of the flooded area is an exercise much more complex than the marine part. Indeed, flood expansion data and level of water reached are provided from photos, feedbacks and water marks surveyed on field. These data have a more or less subjective nature and their reliability is to take with care.

2) Calibration of area flooded:

The figure below represents the flooding area simulated by the numerical model for Xynthia. The influence of sectors flooded is correctly represented by the model on the whole territory of the study. Some improvements could however be brought on different aspect. Indeed, when topography is flat, the sensitivity of the model about water propagation is high. A sensitivity analysis should be carried out to evaluate the error margins. These uncertainties should be taken into account for the flood risk assessment.

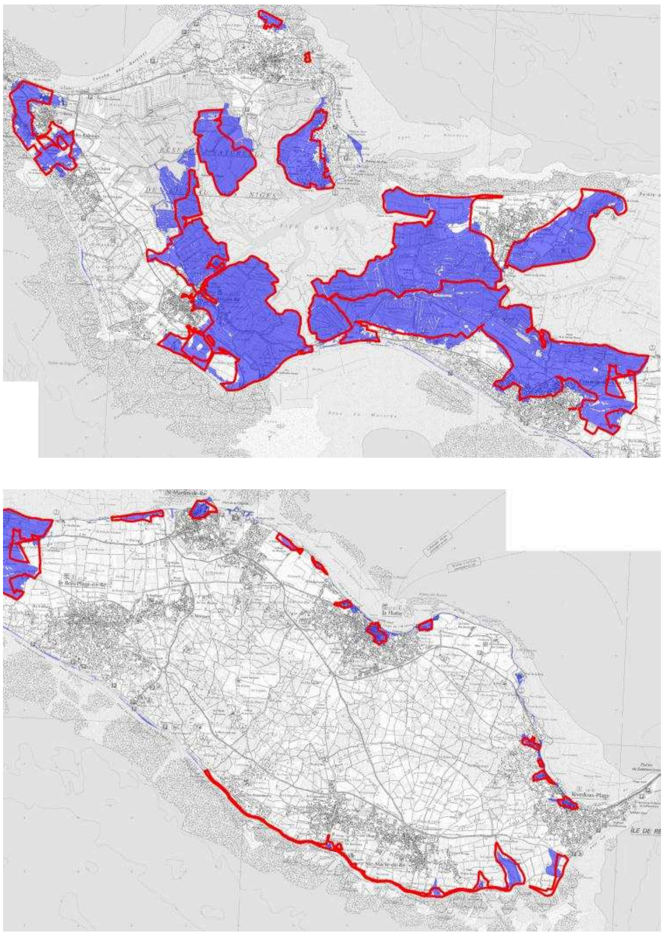

Figure 15. Model results of maximum flood expansion (blue) compared with area flooded observed (red line).

Furthermore, lot of flooded area such as the marshes has not been well surveyed during the storm as they are not easily reachable.

3) Water level on area flooded:

As a supplement to the area flooded, the maximal sea levels reached punctually by the numerical model are compared with the water mark of the study [7] which can be affected by uncertainties. Indeed, certain information corresponds to a maximal water level reached during the event under direct influence of the urbanization (wall creating a stop point for example). The associated water level is thus higher than the "average" level of sea level modelled. Moreover, the analysis of the water marks [7] shows that some of them could be removed from the analysis, because they indicate obvious incoherence on the same sector [2].

So, approximately 67 water marks were compared with the model result. The maximal levels of water modelled are approximately 15 cm under the level of water marks, which is coherent regarding the explained uncertainties. Thus, the model correctly represents the maximal levels of water on the whole Île de Ré.

TABLE IV. VALIDATION OF WATER LEVEL ON WATER MARKS

Cities	Number of water mark	Mean deviation (m)	Absolute mean deviation (m)	Max (m)	Min (m)
Ars en Ré	9	0.23	0.26	0.54	-0.11
Saint Clément	5	0.15	0.15	0.25	0.03
La Couarde	9	0.16	0.19	0.4	-0.07
La Flotte	10	0.00	0.10	0.3	-0.27
Loix	4	0.26	0.26	0.4	0.15
Les Portes	10	0.01	0.15	0.53	-0.29
Rivedoux	11	0.03	0.18	0.3	-0.44
Saint-Marie	3	0.50	0.5	0.5	0.45
Saint-Martin	6	0.05	0.12	0.24	-0.18
TOTAL	67	0.15	0.21	0.53	-0.45

4) Sensitivity analysis

Simulations have been carried out to assess the sensitivity of different hypothesis taken on the coastal protection failure scenario (speed of breach formation, and initial time of failure development). These different tests aimed firstly to calibrate our hypotheses and secondly to measure the sensitivity of these two parameters.

The sectors in the South of the island are less sensitive to the variations of the dike failures because of the nature of the protections (sand cores, parapets or rocks). Moreover, height of the natural land is higher than to the North except for some basins.

Sectors the most sensitive to the variations of the failures are in the 5 cities located in the North and more particularly the flat and low area. On these sectors, often protected by long embankments made of local clay, initiation and speed of failure development are more significant in terms flood influence.

Different simulations included in the sensitivity analysis should be taken into account for the flood risk assessment. Indeed, the numerical modelling of such complex phenomena generates uncertainty at different levels.

V. CONCLUSION

A full coupled Telemac2D - Tomawac model has been developed to asses flood risk on Ile de Ré with the reference storm Xynthia.

Calibration data are various for the maritime part and the representation of sea level during the storm is fairly good. Nevertheless, the calibration on land part is much more complex. Indeed, flood expansion data and level of water reached are provided from photos, testimonies and water marks surveyed on field. These data have a more or less subjective nature and their reliability is to take with care.

If the overflowed amount of water was significant, the major part of floods during Xynthia is due to coastal protection failures. An important work has been carried out in order to get information on coastal protection failures [4]. Furthermore, a detailed topographic survey of coastal protection was performed to calculate accurately the hydraulic forces on them. As overtopping discharge is the most difficult parameter to evaluate, a specific module was developed to calculate these discharges according to the sea state at the toe of each structure and to their typology. Those hydraulic forces are then used to determine coastal defence failure initiation.

Final calibration shows good results on water level at coast and comparison with observation in the land part yield also to fairly weak errors. Finally sensitivity analyses supply an overview of the different parameters which have no validation data.

The methodology developed to assess the flood risk on Ile de Ré has the advantage to be fairly accurate according to [6]. It also contributes understanding coastal defence failure processes that are a major issue in flood risk assessment.

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