Coastal flood protection systems – concepts and analysis

Marc Igigabel^{1a}, Yves Nédélec², Nathalie Bérenger³, Nicolas Flouest², Alexis Bernard⁴, Patrick Chassé⁵ and Christian Pité⁶

¹Technopôle Brest Iroise BP5, 29280 PLOUZANE CEDEX, France

²24 rue Carton, CS 41635, 33073 BORDEAUX Cedex, France

³23, Avenue de l'Amiral Chauvin, B.P. 69, 49136 LES PONTS DE CE, France

⁴5, rue Jules Vallès, 22015 SAINT BRIEUC, France

⁵134, rue de Beauvais, CS 60039, 60280 MARGNY LES COMPIEGNE, France

⁶38 rue Charles Domercq, 33800 BORDEAUX Cedex, France

Abstract. Storm Xynthia, which hit French coasts on February 28th, 2010, flooded vast territories despite coastal defences. This disaster highlighted the need of studying the behaviour of our coastal flood protection systems at an adapted geographical scale and by taking into account the kinematics of the events. The research project led by Cerema has made significant breakthroughs in the knowledge of mechanisms governing the flooding and in strategies and methods dedicated to their analysis and their representation. The developed methodology was successfully tested on four sites submerged during Xynthia (Loix, Les Boucholeurs and Boyardville in Charente-Maritime, Batz-sur-mer in Loire-Atlantique). It is intended to guide the diagnosis of sites prone to marine flood, since the first investigations until the delivery of study reports.

1 Introduction

A methodology intended to understand the functioning of flood protection systems was elaborated within the framework of storm Xynthia feedback, which affected French Atlantic Coasts in February, 2010. Four sites, selected for their diversity and their representativeness of situations met during this storm, were used to build and to test this methodology, so that the developed analysis methods can be considered as applicable to other sites for similar events. The structure of the methodology [1] is presented on figure 1: a conceptual framework was developed to serve as base for the knowledge of protection systems function and dysfunction (at the global scale and at the scale of the structures), then for the appropriate analysis, investigation and modelling techniques. Finally recommendations for the production of an analysis report are proposed in appendices. Without entering all the developments of the study, the present article aims at underlining some essential aspects: concepts for geographic analysis (taken from the conceptual framework), function and dysfunctions of a system (taken from the presentation at the global scale of the protection system) and finally analysis strategies and methods. Principles will be illustrated with their application in the case study of Loix, a site which is situated on Île de Ré in Charente-Maritime.

This article is a translation of article [2] originally written in French.

Figure 1. Structure of the methodology [Igigabel et al., 2016]

^a Corresponding author: marc.igigabel@cerema.fr

2 Concepts for geographic analysis

The definition of a methodology and its associated methods requires to have a conceptual framework to deal with the complexity of the reality through representation models. This chapter aims at specifying appropriate concepts and definitions to describe and understand these systems in a geographical approach. The topography and the natural features as well as all anthropological structures influence the sequence of events during a flood and thus we need conceptual plans to organize and to understand the functioning of the territory in relation to the risk management. The “protection system” and “hydraulic cells” concepts and the “Source-Pathway-receptor” model are intended to provide these marks.

2.1 Protection system

The definition of a protection system requires to draw an outline which separates the system interior and the exterior environment with which the system interacts. This outline must be continuous and closed. This operation, simple in theory, is represented on figure 2. Generally, the outline will include:

- lines representing the limit of lands which are not submerged under normal circumstances. These lines can be called "defence lines". During a stormy event, important exchanges of water can take place through these lines,
- lines drawn on grounds that are not prone to flood thanks to their elevation or to the distance from the source of the flood. These lines can be called “sheltered lines”. No noticeable exchange takes place through these lines during a flood event.

Figure 2. Demarcation of a protection system

Such as defined, this outline represents an object that is geographically closed but hydraulically opened: controlled or uncontrolled water exchanges exist with the exterior environment (only through defence lines). Besides, the word "lines" is used here to illustrate a concept and to facilitate the schematic representation. Nevertheless some lines have in reality a thickness. Defence lines can represent a single work (a dike for example) as well as a set of natural and anthropogenic features such as a foreshore and a dune on which were implanted seawalls, groynes or breakwaters.

Now if we have a look inside the outline, this zone, in its entirety, can be called in unambiguous terms “interior zone”. Stakes are not uniformly distributed in this zone: they are sometimes locally, even widely, absent. In the interior zone, the expression of the hazard is also variable. To lead analyses with more precision, restricted geographical areas must be delimited in the interior zone. As these outlines aim at indicating the stakes location, each delimited area can be called in unambiguous terms “stakes zone”. In the same way as for the demarcation of the system, these outlines are geographical objects that shall in no way prejudice hydraulic phenomena that can occur in their location.

2.2 Hydraulic cells

It ensues from previous definitions that a protection system contains two types of components, which roles are well differentiated:

- defence elements against water entrances situated on the system outline,
- water management elements situated in the interior zone.

This observation leads us to introduce the concept of hydraulic cell represented in figure 3.

Figure 3. Schematic representation of cells within a protection system

In order to analyse correctly the hydraulic phenomena within a territory which can extend over several square kilometres, it is necessary to research the scale that is the most appropriate to study the main phenomena. For this purpose, a classic choice for hydraulic studies consists in defining “hydraulic cells”, which can be assimilated, to use a visual image, to a container:

- which edges fit relief elements: defence works, internal levees, infrastructures, etc., or the natural topography if it reaches sufficient elevation. In plan, these edges form a continuous and closed line,
- which bottom is constituted by the topography in depression included in the perimeter previously described.

Note that Figure 3 represents cells inside a system in the frequent case where relief elements are only marked on certain parts of the interior zone.

Illustration of the concepts of protection system and hydraulic cells with the case study of Loix

The topography analysis makes the most important reliefs of the territory appear and corresponds to the main mean to determine the outlines of a protection system and its cells. Figure 4 shows the implementation of this method on the site of Loix.

Figure 4. Synthetic topographic map (above) and schematic representation of Loix-East protection system (below)

2.3 “Source-pathway-receptor” model

In addition to the previously exposed approaches, flood risk analysis can use the source-pathway-receptor model [3]. This model represents interactions between the environment and the protection system. It helps to identify the links between:

- natural phenomena that initiate the event (source),
- zones with vulnerable stakes (receptor),
- flood routes from the exterior environment towards the receptor (pathway).

A schematic representation of the “source-pathway-receptor” model is shown in Figure 5.

Figure 5. Representation of the source-pathway-receptor model

Illustration of the “source-pathway-receptor” model through the case study of Loix

On the basis of the outlines demarcation of the system and its cells, a flowchart can be established to represent the potential hydraulic pathways that connect the sea front (and possibly other « sources ») with the stakes zone. Figure 6 shows the implementation of this method on the site of Loix. The elements of the “source-pathway-receptor” model are annotated there.

Figure 6. Synthetic flowchart of Loix system

3 Function and dysfunction of a system

The study of a system, led within the framework of an experience feedback, aims at understanding, in relation with the protection objectives and the expected functioning, the mechanisms that engendered the noticed dysfunctions. In this part, we consider successively:

- the natural phenomena to understand the physical phenomena,
- the behavior of the protection system facing these phenomena.

3.1 Natural phenomena at the origin of the flood

Physical phenomena that produce a flood are generally multiple and occur on wide time and space scales.

The analysis of an event requires generally to study:

- the meteorological phenomena,
- the evolution of water levels during the event by considering their components (astronomical tide, storm surge, dynamic effect due to the propagation of this surge, effects of the local wind...),
- sea states (direction, significant height, period) and currents,
- where necessary, the flow characteristics in rivers (water levels, discharges, speeds),
- the morphological evolutions.

Hydraulic phenomena observed on Loix coast

2D hydraulic modelling of the ocean during Xynthia was realized by the laboratory UMR 7266 LIENSs, CNRS-University (National Center for Scientific Research-University) of La Rochelle [4]. The results of these works supply water level and significant wave height values variations in diverse points of Loix coasts (cf. Figure 7). The graph of the point n°6 is presented below as an example. (The maximal water level is 4,1m NGF and the maximal significant height of waves is very low: 0,4 m.)

Figure 7. Localization of temporal series (above) and representation of values in the point n°6 (below)

Numerous sites are exposed to several dependent or independent natural phenomena: floods of a river, water table rise and runoff can occur in conjunction of extreme marine levels. The swell and wind waves can accompany these extreme levels... An analysis of the combinations and interactions between these forcings may be necessary.

3.2 System behaviour during the event

System dysfunctions can often be explained by the absence of analysis at the global scale. As a result, the system design is inadequate for the stakes zones protection. Typically we can observe:

- a discontinuity in the defence line, either by a hydraulic bypassing of existing structures, or by water entrances through openings in coastal structures (staircase, slipway, gates...), or by overtopping of structures, which levels were not defined with the hydraulic actions of the event,
- no coordination between the defence function (around the system) and the water management function (inside the system). A global plan should make water management capacities and defence protection levels consistent for the entire system. Normal conditions and also the case of a breach appearing in the defence line should be considered.

Failures are also often a matter of inadequacies in the maintenance or the operational management of the system.

For a stakes zone, the performance of a system can be estimated according to the characteristic values of the hazard resulting from a given natural phenomenon: maximum water heights, flow speeds, water level rise speeds, flood duration... Performance criteria can be defined for each of these characteristic values. If these criteria are established according to the vulnerability of the people, it is for example possible to adopt values such as (values given for information purposes):

- maximum water height should not exceed 0,5 m,
- flood duration should not exceed a tide cycle,
- flow speed should not exceed 0,25 m/s.
- overtopping should not exceed an average discharge of 0,1 l/s.

Behavior of Loix system – Photointerpretation and hydraulic modelling

To better understand the flood dynamics, aerial photographs were analysed to identify the diverse hydraulic (flow dynamics, submersion) and mechanical (damages and breaches on dikes) phenomena appearing after the storm Xynthia, as shown in figure 8. On this document, were also indicated two high water marks (as well as their quotations NGF) found in the report [5] (in green: 4,01 m NGF in Lavaud district and 4,40 m NGF in the North of Petite Tonille).

Figure 8. Synthesis map of Xynthia event

A hydraulic modelling was developed (cf. figure 9). An overall consistency was sought in the representation of data previously described (and other data).

Figure 9. Modelling grid and results

4 Study strategy and analysis methods

To study the functioning of a system within the framework of an experience feedback requires to develop

strategies and to have adapted analysis methods. These two points are successively introduced.

4.1 Strategy and organisation of a study

The analysis of the functioning of a site is based on numerous and diverse data, and before formalising the analysis under the shape of a report, an important preliminary work is necessary. This work consists of the collection and the analysis of data. To ensure efficiency and precision, data should also be listed and linked to geographical marks. This need for classification and for localisation can be satisfied by producing preliminary maps, plans (representation of the system outlines, stakes zones, hydraulic cells) and flowcharts.

A risk analysis can be very time-consuming if tasks are realized without anticipating what will be their final utility. It is thus advisable to adopt a tiered approach so that the efforts are produced on condition that results can actually be achieved. Efforts should also be proportionate to the interest of expected results. Analysis tools (flowcharts in connection with plans) can provide useful marks in the definition of this strategy because they allow to review the mechanisms which generate the risks and to decide individually on the necessity of continuing the investigations. Thanks to these “visual aids”, the questioning can be both more relevant and more systematic. By means of plans and flowcharts, the need to continue the investigations can be regularly estimated on each component of the system. A real strategy can be developed to lead the study. In addition, when a modelling of the hydraulic phenomena is developed, the model sensitivity to input data can be also studied to evaluate the necessity of specifying hypotheses.

The analysis of protection systems is subjected both to the natural variability of phenomena and to the uncertainties linked to their observation and to their understanding. These two combined factors often make the margin of error incompressible. It is thus advisable to identify not only the information which will be useful but also the associated degree of precision. Multiple information sources can exist locally on a site. For example, the crossed analysis of punctual information with photographs and LIDAR data interpretation will increase the reliability of conclusions and can be usefully systematized if these data are available and relevant. The development and the use of a model is also a way to ensure the overall consistency of data.

The quality of data is not enough to consider that it is relevant: when a flood occurs, sites quickly evolve, on one hand under the influence of hydraulic actions and on the other hand under the influence of the emergency interventions that are led. It is thus necessary to verify that the available data meet effectively the need and are not anachronistic with regard to the studied situation. A site visit is often very useful to better understand the evolutions.

4.2 Analysis methods

Analysis methods can be implemented to research in an exhaustive way the causes of a failure (in the case of the feedback of a past event) or to examine the reaction of a system to variable actions. In every case, these methods consider the protection structures as components of a system and aspire to exhaustiveness. Three flowchart types, which objectives are different, are presented in the reference study [1]:

- fault tree,
- event tree,
- A combination of previous both trees called “bowtie tree” because of its general shape.

In this paper we will focus on the adaptation of the third type flowchart (the bowtie tree) to coastal floods. Bowtie tree was initially developed to deal with “loss of containment” in the field of industrial risks [6].

Nevertheless, it is advisable to give for the first two flowcharts the definitions necessary for the understanding of the third:

- fault tree: for a given failure, a flowchart which allows the identification of all the intermediate events, the initial causes and their combination.
- event tree: for a given event, this flowchart identifies all the scenarios that can lead to a variety of negative consequences.

The bowtie tree, illustrated in figure 9, allows to represent both parts of this analysis:

- the fault tree which establishes the events chain until the stakes zone flood,
- the event tree which, considering this flood, determine all its potential consequences.

Figure 10. Generic representation of a bowtie tree

The construction of this flowchart requires an identification of the flood protection system, of the interior zone and of the stakes zone which must be necessarily well delimited.

The construction of the flowchart is widely determined by the choice of the central dredged event. Within the framework of our study, the central dredged

event is the flood of the stakes zone (and not the flood of the interior zone). This option to consider the flood of the stakes zone as central dredged event allows to build the part of the bowtie tree relative to the protection system dysfunction by taking into account in a global approach all its components (defence functions and water management functions that aim jointly at preventing or at limiting water entrances in the stakes zone).

It is recommended to model the construction of the fault tree on the geographical configuration of the system to facilitate the dialogue between the flowchart and the plan. Hydraulic cells are used to identify the subsets of the bowtie tree. Then the construction of the part relative to the event tree concentrates on:

- dangerous phenomena that can occur in the stakes zone, depending on the action of the protection barriers that can exist in this perimeter. In addition, factors influencing the flood propagation in the stakes zone (those that cannot be considered as barriers) can be indicated,
- The infringement of the stakes. In addition, the exposure factors of the stakes can be indicated.

Synthesis of the functioning (and dysfunctioning) of Loix protection system

The functioning of Loix protection system can be synthesized by a bowtie tree as shown in figure 10. In this flowchart, the hydraulic pathways appearing in the first phases of the event are represented in full line. The hydraulic pathways appearing on the « north slope » after the filling of the cells are represented in dotted lines.

Figure 11. Bowtie tree of Loix protection system (Xynthia feedback)

5 Conclusion

Flood risk management on a site is made by the implementation of a coherent programme of measures. For coastal sites, the definition of these measures requires to specify the geographical area on which the approach must be led and to undertake on this perimeter the definition of a global functional plan:

- delimitation of the system, understanding of its functioning, to know the conditions in which floods can occur,
- the definition of measures for the maintenance and inspection of the structures and the definition of adequate operations in function of existing or forecast water levels,
- the confrontation of this functional plan to the reality: when an event occurs, the way the system reacted should be compared to the way it should react according to the global functional plan.

The study of past events plays a fundamental role in the implementation of this approach. The precise knowledge of the functioning of a system during a major event such as Xynthia allows to better understand the functioning of the system for other flood scenarios.

This article highlights the guidelines of a methodology developed for the study of protection systems within the framework of an experience feedback. Emphasis was placed on the concepts, the study strategies and the analysis methods.

The concept of protection system, in connection with the “source-pathway-receptor” model paved the way of a schematic cartographic representation of the system composition. This schematic cartographic representation can be usefully completed by a flowchart representing the structure of the system.

The schematization under this double shape (mapping and flowchart) is pertinent for the representation of flood scenarios. It allows to establish precisely relations between the three levels of the “source-pathway-receptor” model: natural phenomena (primarily outside the system for marine floods), flood propagation (in particular through hydraulic cells) and damages on main stakes (on sectors well delimited inside the system).

This double representation makes analyses more systematic and also makes investigations more efficient. Ultimately we can obtain a clear vision of the global functioning of a system and of its failure modes.

The implementation of these guidelines requires besides:

- to master the fundamental notions of flood risk management (natural phenomena, events, hazards, stakes and vulnerability),
- to understand the physical phenomena which occur in these coastal environments, both at the global scale of the system and at the scale of the

structures (including the coastal natural features),

- to implement multiple skills for the investigations and the modelling.

For further information about these subjects, the reader is invited to consult the methodological part of the reference study [1] – figure 1 of the present article reveals its detailed structure – as well as case studies which present concrete examples of implementation.

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