DEVELOPMENT OF A METHODOLOGY TO EVALUATE THE FLOOD RISK AT THE COASTAL ZONE

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ABSTRACT

This paper illustrates the methodology developed to evaluate the risk of flooding of a coastal area, as well as the application of such methodology to Vale do Lobo beach, situated in the Loulé Municipality, a Portuguese coastal area under significant touristic pressure. The methodology is based on four main steps: a) division of the study area into sub-areas with similar characteristics in terms of coastal defense; b) determining the probability of exceedance of pre-set thresholds of flood levels for each study area; c) establishment of qualitative factors related to the consequences of exceedance of pre-set thresholds of flood levels; d) combination of the above steps for expeditious assessment of flood risks.
The determination of flood levels follows the methodology presented in [1] and [2], which is based on the transference of the Faro wave-buoy regime to the study area by using the SWAN model integrated in a geographic information system (GIS).

Index Terms — Geographic information systems, numerical models, coastal planning and management, risk and vulnerability, Vale do Lobo beach

1. INTRODUCTION

The impact of climate change on coastal zone has manifested itself in different ways, including the rise in sea level and increase in number and intensity of phenomena causing risk of flooding. Given the geographic location and concentration of people and infrastructure along the coast, these phenomena are revealed today as genuine challenges in managing the Portuguese coast.
The greater or lesser exposure of infrastructure or the population to events that may cause harm is crucial for risk assessment. This is important because it is possible to identify coastal areas with a high degree of vulnerability to energetic activities of the sea, but without major risks due to lack of human occupation, equipment or natural resources, or otherwise, that is, areas of low vulnerability index, but high human occupation, which confers a high risk. Within this context, the term risk is defined as the probability of an adverse event multiplied by its consequences, [3] and [4].
The extent of the Portuguese coast, the severity of the sea conditions and the concentration of population and economic activities in its coastal zone, justify the importance of carrying out wave induced risk studies. For a correct assessment of these risks, the determination of shares of flooding is essential.
Indeed, emergency situations caused by adverse sea conditions are frequent and put in danger the safety of persons and goods, with a negative impact for society, economy and natural heritage.
The detailed research on the sea waves, currents and tide levels at the local level is essential to improve the methodologies for risk assessment, increasing the reliability of results and enabling timely issue of alerts and the preparation of mitigation plans.
Thus, in this paper, a methodology to evaluate the risk associated with the flooding of coastal areas is proposed, which is essential for the proper planning and land management. The final goals are:

- to provide simple instructions for use by the authorities to increase their effectiveness in responding to emergencies produced by floods whose cause is directly related to the sea;
- to provide information to decision makers on the extent of risk exposure facing the coastal areas, contributing to the mapping of areas with high degree of flood risk;
- to assist those responsible for managing the infrastructure of coastal protection and minimize risk associated with them.

It is in this sense that the system GUIOMAR [5] was developed based on a geographic information system (GIS) and built to support the use of sea wave propagation models. Its intent is to support and be part of the critical process of decision making in current studies of coastal engineering in emergency situations. At present, this system has the capability of coordinating the use of numerical models, including the management of input data, computational mesh generation and geographical analysis of results.
The GUIOMAR system is based on three main components: one is a commercial SIG software; the second is a set of numerical wave propagation models and other pre and post

processing programs developed in FORTRAN™; and the third is a user interface, developed in programming language Visual Basic for Applications ArcGIS™. The system was build in a modular approach, which makes it easily expandable to allow any inclusion/replacement of the following: a) modules for the most updated versions of existing numerical models or other numerical models to simulate more accurately certain physical phenomena, and b) specific modules for analysis and processing of results for the functionality that one might want to give to the results.

The latest developments into the GUIOMAR system include procedures and methodologies to automatic support risk assessment studies. The work presented here represents the development of a methodology for assessing flood risk and its application to Vale do Lobo beach, Municipality of Loulé, Portugal.

After this introduction, section 2 presents a general characterization of the area under study. Section 3 briefly describes the methodology for determining the run-up and flood levels at the study area. In section 4, a risk assessment is provided. Finally, section 5 contains the main conclusions of the work and the future developments.

2. CASE STUDY

Vale do Lobo is located at Loulé Municipality, in the Algarve region. The beach, 2 km long, has a sedimentary origin, and almost vertical cliffs. The cliffs heights may vary between 2 m and 20 m, depending on the location along the beach. The cliffs have different layers of sand from the Plio-plistocenic age and present a medium to gross sand grain in a clay composite structure [6].

Vale do Lobo beach has been affected by a strong urban littoral expansion, with undesirable environmental and economical impacts, particularly in the areas of Ria Formosa and of Vale do Lobo tourist resort. The main causes of the damages have been anthropogenic factors, such as construction in the coastal line and coastal erosion. At Vale do Lobo, there are houses built right on the top of the cliffs, beaches with restricted access due to the imminent danger of a land slide and a weak dune system that protects Ria Formosa from the sea.

Vale do Lobo is an example of an occupation in areas of high vulnerability to sea wave attack, including flooding and coastal erosion (Figure 1). The occupations of these vulnerable areas create risks of collapse/demise of the cliff (endangering homes, golf courses and anyone making use of the beach) and coastal erosion (endangering the pool and the Ria Formosa of breach of the front line sand dunes).

Figure 1 – Vale do Lobo Beach Resort (EPRL/IGP)

3. RUN-UP AND FLOOD LEVELS

To calculate the run-up and flood levels at Vale do Lobo beach, it is necessary to characterize the offshore and local wave regimes. In this respect, the methodology presented in [1] and [2] was used and it may be summarized as follows:

- Use of the wave parameters measured at Faro by the WAVERIDER directional buoy of the Portuguese Hydrographic Institute. The buoy is located at -93 m (CD), at 36° 54’ 17’’ N, 07° 53’ 54’’ W. In normal conditions, the data acquisition is carried out every 3 hours for a period of 30 minutes. During storm conditions (conditions with a significant wave height which exceeds 3 m), the data acquisition period is reduced to every 10 minutes. The period of records considered in this work corresponds to 1986 to 1995. With these values, a Faro wave-buoy regime is established;
- Transfer the data from the wave-buoy to Vale do Lobo beach using the wave generation, propagation and dissipation model SWAN [7], through the GUIOMAR system [5]. In this work, a sea water level of +4.64 m (CD) was considered;
- Establishment of the local wave regime at several points along different cross-sections of the beach based upon the above data;
- Calculation of run-up and flood levels according to empirical formulas proposed in [8], [9], [10] and [11], implemented in programs developed in FORTRAN™ language [12].

The following sections provide, as an example, some of the characteristics of the local wave regime in Vale do Lobo beach and the calculation of run-up and flood levels.

3.1. Characteristics of the local wave regime at Vale do Lobo beach

The characteristics of the local wave regime were based upon the 9 years records measured at the Faro wave-buoy, which were transferred to Vale do Lobo beach by using SWAN model through an interface developed for the GUIOMAR system [5] and the module REGIMES/SOPRO [13]. Calculations were performed taking into account a sea-

level of +4.64 m (CD), which results from the sum of the maximum high-water mark recorded in Lagos during 2009, with the estimated value with 100-year return period to account for rise in sea level due to extreme meteorological conditions (value based on studies carried out under the Project SIAM II [14]).
In particular, the wave characteristics – the significant wave height, the zero-crossing wave period and the wave direction - were established in 16 points along 3 profiles across the beach (Figure 2).

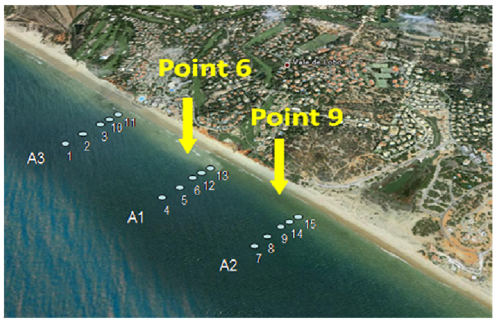

Figure 2 - Location of the 16 points in the three different cross-sections perpendicular to the beach.

To illustrate the calculations performed for the run-up and flood levels, the authors have only considered in this work the results obtained for Point 6 (cross-section A1) and Point 9 (cross-section A2), located just upstream of the surf zone.

3.2. Run-up analyses for Vale do Lobo beach

The calculation of the run-up on beaches is done in most cases by using essentially empirical formulations based on field measurements or tests on two-dimensional scaled models of constant, smooth and impermeable slopes (beaches) [15]. In previous work, [1] and [2], and herein, the run-up on the beach of Vale do Lobo was estimated using the formulas proposed in [8] and [9], developed on the basis of physical model test results, and also in [10] and [11], developed based on field data (Figure 3). Note that the formula presented at [11] is based on field data collected specifically for the study area considered in this work.

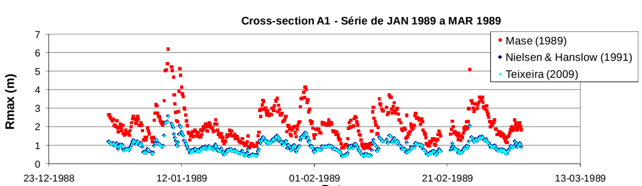

Figure 3 - Run-up values, Rmax, obtained at cross-section A1, for the series of wave data between January and March 1989, using the formulations of Mase (1989) - [8], Nielsen & Hanslow (1991) - [10] and Teixeira (2009) - [11], all with the wave conditions at Faro wave-buoy.

3.3. Calculation of the flood levels

Once the run-up values for given wave conditions have been estimated, the flood levels, FL, can be determined assuming that they result simply from the sum of the contributions of the astronomical tide, AT, of meteorological elevations, MS, and of the run-up, R:

$$FL = AT + MS + R \qquad \text{(eq. 1)}$$

The astronomical tide can be accurately estimated for the majority of the locations. In general, tides can be predicted by harmonic analysis, which is the superposition of many sinusoidal components with amplitudes and frequencies determined by a local analysis of the measured tide.
The meteorological elevations may be obtained from the difference between the values of the water level measured by tide gauges and the corresponding ones estimated for the astronomical tide. These elevations are considered to be induced by strong or long duration winds and/or by abnormal high or low atmospheric pressures.
In this work, due to the lack of tide gauge data for the period between 1986 and 1995, we extrapolate the two full years of recorded tide, RT, for the whole period of nine years under study.
R-values considered correspond to the estimates of Rmax obtained with the methods presented in [8], [10] and [11] for the conditions of sea waves for the period 1986 to 1995.
Table 1 shows the maximum values of FL in the cross-sections A1 and A2 for the conditions mentioned above. Table 1 shows that the maximum value of FL is very similar for the methods described in [10] and [11] and much lower than the value obtained by the methodology shown in [8], since the later is based on tests on impermeable slopes. For the methods presented in [10] and [11], the contribution of Rmax for FL is less than the contribution of AT+MS, while for the method in [8] it is not.

Table 1 – Maximum flood levels estimated with different methodologies for cross-sections A1 and A2.

Methodology	Cross-section	Rmax (m)	FL (m CD)
MASE (1989) - [8]	A1	6.60	9.56
	A2	6.91	9.87
NIELSEN & HANSLOW (1991) - [10]	A1	2.71	6.40
	A2	2.88	6.57
TEIXEIRA (2009) – [11]	A1	2.70	6.39
	A2	2.87	6.56

4. RISK ASSESSMENT

4.1. Methodology

For the development of the methodology for assessing the risk of flooding of coastal areas three tables have been used: i) a table of probability of occurrence of an adverse event, as the wave induced flooding; ii) a table with the consequences of flooding; and iii) based on the two previous tables, a table of risk of coastal flooding. The contents of these tables is supported on earlier studies, [3], [4] and [16], taking into account that, since the 90's, the coast under study reveals a lower resistance, to episodes of storm or episodes of tides, which shows the beginning of a new cycle timer.

The methodology is based on four main steps:

1. division of the study area into sub-areas with similar characteristics in terms of coastal defense;
2. determining the probability of exceedance of pre-set thresholds of flood levels for each study area;
3. establishment of qualitative factors associated with the consequences in terms of property damage in each sub-area, caused by exceedance of those thresholds of flood levels;
4. combination of the above steps in order to proceed to the expeditious assessment of flood risks.

The series of the significant wave heights, run-up and flood levels from 1986 to 1995 in Vale do Lobo beach were used to illustrate the application and validation of methods that identify those areas which are associated with the most serious consequences of flooding and greatest risk.

4.2. Probability

Table 2 shows a preliminary classification of the probability of exceedance of pre-set thresholds of flood levels.

Table 2 – Probability of exceedance of pre-set thresholds of flood levels.

Description	Probability (Guidelines)	Level
Improbable	0 – 1%	**1**
Remote	1 – 10%	**2**
Occasional	10 – 25%	**3**
Probable	25 – 50%	**4**
Frequent	> 50%	**5**

4.3. Definition of critical coastal regions

Table 3 shows a preliminary description of the consequences of exceedance of pre-set thresholds of flood levels.

This table takes into account the intrinsic importance and sensitivity of the coastal area to the occurrence of flooding. It aims to identify natural resources values, cultural-socio-economic and man-made high sensitivity areas. The criteria consider the recognition of ecologically valuable habitats, land use, density of construction and location of buildings in relation to the proximity of the element potential culprit, the permanence of houses and other unique values whose loss would be irreparable. The values of the level of consequences were assigned so that it is possible to calculate the risk level (section 4.4) taking into account the importance of risk in relation to its control and prioritization. For example, it is important to distinguish between an event with high probability of occurrence but with low level of consequences and an event with a low level of probability of occurrence but with a very high level of consequences.

Table 3 – Consequences of exceedance of pre-set thresholds of flood levels.

Description	Consequences (Guidelines)	Level
Insignificant	Places with geotechnical characteristics relatively stable, natural sand beach, squats in habitats of low ecological value; local paths or drainage ditches	1
Marginal	Sites with soil geotechnical characteristics of weak or processing any type of woody vegetation or other that would give some stability, areas occupied by habitat conditions weak plant	2
Serious	Places to infrastructure and coastal protection, local structures relevant to economic activities, local geotechnical characteristics very weak, unstable and low resistance to breakdown, areas occupied by some habitats with ecological interest.	5
Critical	Places with permanent human habitation (urban planned); local geotechnical characteristics very weak, very unstable and very low resistance to breakdown, without stabilizing vegetation, sites with natural elements of great value whose loss would be difficult to compensate.	10
Catastrophic	Places with permanent human occupation; sites absolutely unique and of tremendous value, the loss would be irreparable, beach-dune system.	25

4.4. Risk

Risk is the product of the probability of an adverse event by the value assigned to its consequences. The methodology presented here is a qualitative assessment of the risk of flooding being the degree of risk the product of the probability of flooding (Table 2) by the consequences of flooding (Table 3). The array provided by the product of these two variables is presented in Table 4 while Table 5 describes the assessment and acceptability of the obtained level of risk.

Table 4 – Risk level.

Risk Level		Consequences				
		1	2	5	10	25
Probability	1	1	2	5	10	25
	2	2	4	10	20	50
	3	3	6	15	30	75
	4	4	8	20	40	100
	5	5	10	25	50	125

Table 5 – Assessment of the acceptability of the risk level**.**

Level	Description	Risk Mitigation (Guidelines)
1 – 3	**Negligible**	Insignificant risk; no further consideration needed.
4 – 10	**Acceptable**	Risk can be considered acceptable/tolerable provided the risk is managed.
15 – 30	**Undesirable**	Risk should be avoided if reasonably practicable; detailed investigation and cost/programme benefit justification required; top level approval needed; monitoring essential.
40 – 125	**Unacceptable**	Intolerable risk; it is mandatory to undertake risk mitigation (e.g. eliminate the source of risk, change the probability and/or consequences, transfer risk).

After the assessment of the risk impact into the areas affected by the flooding, the use of the GIS and its database, allows a quick, precise and efficient creation of flood maps, and its respective risk maps. For the creation of the flood maps, it is required to identify the areas below the pre-set threshold of flood level, while its respective risk map provides the associated risk level for each sub-zone of the areas of study.

In this work and for illustrative purposes only, two scenarios were considered:

- Scenario 1 - Occurrence of flood levels exceeding the threshold of +3 m (CD);
- Scenario 2 - Occurrence of flood levels exceeding the threshold of +6.5 m (CD).

Figures 4 to 7 present the flood and risk maps for these two scenarios, for cross-section A2. As it can be seen, at the central part of the beach, where the cliffs have a lower crest level, the risk level is higher than at both ends of the beach.

Figure 4 - Flood level +3 m (CD).

Figure 5 - Flood level +6.5 m (CD).

Figure 6 - Risk map +3 m (CD).

Figure 7 - Risk map +6.5 m (CD).

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

Effective coastal management, based on the assessment of vulnerable areas and associated risks, should allow preventing degradation and irreversible loss of natural resources. This paper presents the latest results of the development of a methodology for assessing flood risk and its application to Vale do Lobo beach, Municipality of Loulé, Portugal.

The methodology presented here is a qualitative assessment of the risk of flooding, considered as the product of the probability of flooding by its consequences.

Based upon the local wave regime and the corresponding series of run-up and flood levels from 1986 to 1995 in Vale do Lobo beach, it was possible to assess the risk, using the new methodology, taking into account two scenarios: occurrence of flood levels exceeding the threshold of +3 m (CD) and of +6.5 m (CD). Using GIS tools, the corresponding flood and risk maps were constructed.

The application of this methodology to the beach of Vale do Lobo has shown its potentialities, namely its fast and efficient capacity to evaluate risks and moreover it can be easily extended to other locations. The GIS is an essential tool in the analysis of land use and the creation of maps and related flood risk maps.

However, it is very important to continue the development of the content of the tables that describe the probability of flooding and its consequences. The contents of these tables are essential to obtain realistic and reliable results. It is also important to determine the occurrence of flooding based not only on the calculation of run-up but also on the calculation of wave overtopping.

Current work is being performed on the incorporation of this methodology and software into the GUIOMAR system in order to make it an effective tool to support planning and sustainable management of coastal zone. The development of a system for flood forecasting and warning for coastal areas and ports is one of the future steps in the development and application of this methodology.

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