# GEORISK: A GEOLOGIC RISK MAP FOR THE WORLD HERITAGE AREA OF PORTO CITY (NORTH PORTUGAL)

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## ABSTRACT

The growing concern for the preservation of heritage in face of natural hazards led to the appearance of the Regional Framework Operation (OQR) NOE - Heritage and Prevention of Natural Hazards under the Community Initiative INTERREG III C. The OQR NOE, led by the Provence-Alpes-Côte d'Azur (PACA, France) region, together with the Northern Portuguese regional coordination agency (CCDR-N), Molise and Sicily regions (Italy) and eastern region of Attica (Greece) aimed at developing preventive measures to safeguard the cultural heritage due to occurrence of natural hazards.
The main aims, were to undertake an evaluation of existing practices through a strategy of inter-regional cooperation among the partners NOE and develop concrete actions in the field including strategies for prevention, early warning and intervention adapted to the heritage, awareness and accountability of officials and local decision makers, implementation of trans European experience, development of new technologies, cooperation and support for Euro innovative operations. In this context arised the subproject (SP) GEORISK, that joined an inter-regional cooperation of the City Council Port (CMP), the Bureau de Recherches et Géologiques Mini (BRGM), the Department of Geology, Faculty of Science of the University of Porto (DGFCUP) and the Portuguese Institute of Architectural Heritage (IPPAR), now called the Institute for Management Architectural and Archaeological Heritage (IGESPAR).
For the implementation of the SP four main lines of action were defined: (i) Know the methods of assessment of geological hazards in France and Portugal and to foster the exchange of experiences, (ii) identify the specific level of management in relation to heritage geological risks; (iii) define the relevant actions to develop from local and regional decision makers, and (iv) Prepare a "Map of Geological Hazards in Historic Area of Porto (ZHP), to then therefore define a set of management measures, prevention, protection and intervention that can be generalized to other similar cases and to preserve the existing assets and then outline a plan for sustainable recovery. With these objectives in mind we sought map and integrate in GIS all the available information in order to assess the main geologic hazards of Porto: slope stability and seismic hazard

## 1. INTRODUCTION

The increasing concern regarding the current levels of heritage preservation due to natural risks motivated the appearance of the “Operação Quadro Regional (OQR) - NOÉ – Heritage and Prevention due to Natural Risks” within the scope of the European Community initiative INTERREG III C. The “OQR NOÉ”, led by the region of Provence-Alps-*Quote d' Azur* (PACA, France), involved the region of North Portugal (CCDR-N), the regions of Molise and Sicily (Italy) and the region East Atica (Greece) and aimed at the development of preventive measures to save cultural heritage due to the natural hazards.

In this scope, it was intended to carry out an evaluation of current existing practices by means of a strategy of interregional cooperation between the NOÉ partners and to develop specific field actions together with strategies of prevention, alert and intervention suitable to the heritage, public awareness and responsibility of the local agents and decision makers, implementation of trans-regional experiences, development of new technologies, euro-Mediterranean cooperation and also to support each other in the innovative operations.

It is in this way that the subproject GEORISK appears, that joined, in an interregional cooperation, the City council Porto (CMP), the *Bureau of Recherches Géologiques et Minières* (BRGM), the Department of Geology of the Faculty of Sciences of the University Porto (DGFCUP) and the Portuguese Institute for Cultural and Architectural Heritage (IPPAR), now called Institute of Management Architectural and Archaeological Heritage (IGESPAR).

## 2. OBJECTIVES

For the execution of this SP four main lines of action had been defined: *(I)* To know the methods of geologic hazards evaluation carried out in France and Portugal and to foment the exchange of experiences; *(II)* To identify the specificities on the heritage management level faced with geologic hazards; *(III)* To define the pertinent actions to be developed with the local and regional decision makers; and *(IV)* To make the "Map of Geologic Risks of the Historical Zone Porto (ZHP)", in order to define a set of measures of management, prevention, protection and intervention that can be generalized to other similar cases and in order to preserve the existing heritage and to delineate later sustainable recovery projects.

## 3. HISTORICAL ELEMENTS

Within the scope of this action a historical research of the registered damages, in the ZHP, provoked by natural hazard occurrences of geologic nature was carried out. Three types of events were defined: seismic events, landslides and rock fall events.

In a first phase a survey was carried out on the sources that indirectly could make reference to the types of occurrences that we set out to investigate. Thus, some historical records kept at the municipality and university archives were consulted. In this way the data of historical seismic activity published by the Geophysical Institute Infante D. Luis of the University of Lisbon [5] and the data of rainfall supplied by the Geophysical Institute of the Faculty of Sciences of the University Porto (IG-FCUP), made it possible to limit our historical survey towards more favorable dates for the occurrence of the three types of events already referred. The research continued with the work of document inquiry in the following archives and institutions: Institute of the National Archives Torre do Tombo; Historical archive CMP; Public library of the Porto Municipality; District archive of Porto; General archive CMP; Municipal division of Salubrity and Security CMP; Fire Brigade; Administration of the Ports of Douro and Leixões; Cabinet of Urban Archeology CMP; Reports and studies of the geologic-geotecnical studies CMP and National Laboratory of Civil Engineering (LNEC) and the book *Old and Modern Portugal* [4].

Registry of 5 seismic events had been found that had provoked damages in buildings of the ZHP. These seismic events refer to the earthquakes of 1st of November of 1755, 31st of March of 1761, 21st of October of 1880, 28th of February of 1969 and 26th of May of 1975. The descriptions of the actual damages for the cited earthquakes mention falling and change in the position of existing elements in buildings and monuments, total or partial ruin of buildings, chapels, churches and walls, rocks fall of façades of buildings and opening of cracks in some houses in the city.

In what respects to the landslides and rock falls of blocks events were registered since the end XVIII century until September of 2006. For the research of occurrences a prior assessment of the rainfall data supplied by the IG-FCUP, through which it was possible to know the corresponding dates of the days of higher rainfall and therefore would provide a higher probability of registering these types of events. Thus, the descriptions of the actual damages for these events mention total or partial ruin of buildings, monuments and walls, destruction of automobiles, cracks in buildings and subsidence, subsidence and cave-in of pavements and railways. It was also verified that some of these events leaded to some deaths and casualties.

In the sense of providing the cartographically collected information the "Map of Occurrences" was made, on a scale of 1:5000 (Figure 1). To each reference number of occurrence, located in the map, corresponds to alphanumeric information in a database, a type of occurrence, its temporal and geographic localization and the description of the actual damages.


Figure 1 - Map of occurrences

## 4. GEOLOGIC RISK MAP OF HISTORICAL ZONE OF PORTO

### 4.1. Cartography of geological hazards

#### 4.1.1. Map of seismic hazards

The "Map of Seismic hazards" had as base a previously available set of information under the form of geotechnical cartography, topographical elements and some geophysical measurements performed on the main geotechnical formations. The Geotechnical Map of Porto [2] was updated with new more recently compiled data and also with the aid of some new field observations. After these corrections were made the geotechnical rock and soil formations were translated in terms of their shear modulus using the formula:

$$\mathbf{G0 = versus * \rho} \qquad (1)$$

In the formula **Vs** corresponds to the velocity of S waves and ρ corresponding density. The shear wave velocity values (**Vs**) were derived from seismic of refraction using horizontal geophones. However some values were also derived through analysis of dispersive waves. The values were grouped into shear modulus classes which are expressed in the resulting scale of the corresponding map (figure 2). This physical property is very influential in terms of the local site response when a seismic energy is received and can thus constitute an amplification factor [3].

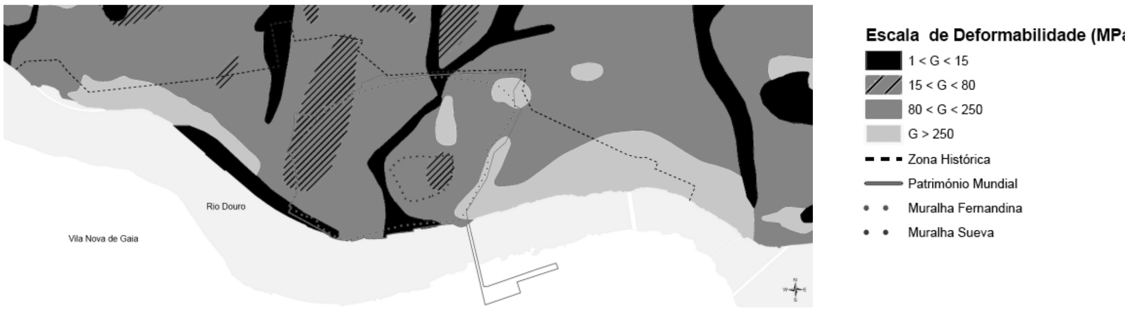


Figure 2 - Shear modulus map (in MPa)

From the previous map it is possible estimate the local site seismic intensity, in the Mercalli, scale using the following formula [6]:

$$\text{Incr.} = [3.3\log(0.8*Sn) + 7] - [3.3\log(0.8) + 7] \quad (2)$$

The base seismic intensity for the Porto zone (6 in the Mercalli scale) suffered thus a refinement, as a function of the local site effect, and thus resulted in the map visible in figure 3.

Table 1 – Site effect as a function of the type of ground

| Type | Factor | Type of ground |
|---|---|---|
| S0 | 1.0 | Slightly weathered granite |
| S1 | 1.2 | Weathered granite |
| S2 | 1.4 | Residual granitic soil |
| S3 | 1.6 | Alluvium |
| S4 | 1.7 | Recent landfill |

From the map depicted in figure 2 it is also possible to estimate the seismic acceleration with the aid of the formula [6]:

$$\text{Accel} = Sn*80 \text{ (in cm.s-2)} \quad (3)$$

The formations depicted in the map of figure 2 were classified in accordance with table 1 and this calculation resulted in the map visible in figure 3.

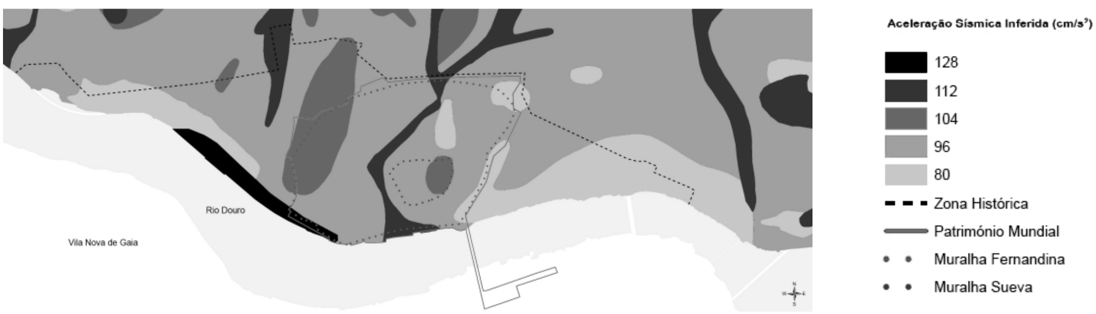


Figure 3 - Map of inferred seismic acceleration (in cm.s-2)

On the other hand, the effects that will be able to reflect in terms of a seismic effect, do not contemplate the dependant induced effects of other factors, namely, the topographical factor and the presence of human intervention such as manmade slopes.

Thus we felt the necessity of integrating characteristic morphological elements of Porto which are particularly influential in terms of secondary seismic effects or sometimes known as the induced effects. One of the factors that we consider was the slope steepness of the terrain which was grouped into four classes, evenly distributed from 0º to higher than 45º, and whose factors range respectively from 1.0 to 1.6. For each of these classes correspond multiplying factors that will increase the effect to the seismic response and which is dependant, essentially, on the type of soil or rock.

Afterwards a compilation of man made slopes was made and a 20% aggravation factor was considered for them, in other words they were classified with a multiplying factor of 1.2 and with a *buffer* zone of 7.5m corresponding roughly to the damage area influenced by the slope. We also verified that in practice the effect of crests, or some topographical rises, also induces an effect of amplification of the seismic energy [6]. This topographical transition, in the Porto Historical zone, corresponds to an average level of 50m. Considering this, a gradual *buffer* was drawn centered on the level curve of 50m and that have factors that range from 0 to 0.4 but they are now additive.

All the previously described operations allowed to us to obtain the “Map of Seismic Hazard” with direct and induced effects (Figure 4).

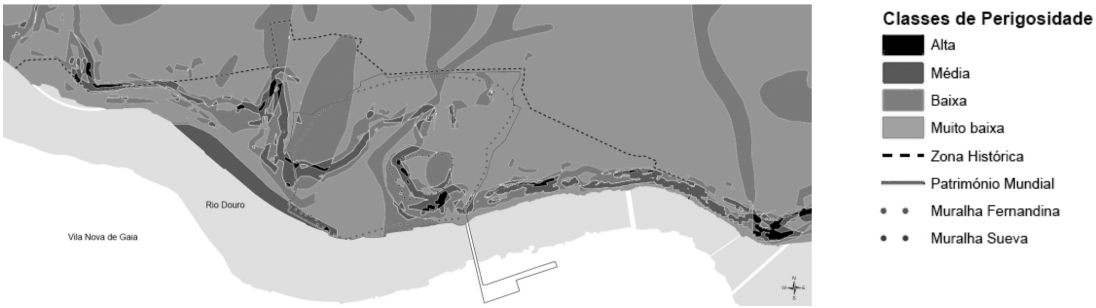


Figure 4 - Map of seismic hazard

4.1.2. Hazard map of slope stability

The analysis of potential instability of rocky slopes was carried out according to the Markland test, considering the possibility of potential slide of masses or rock and block falls: *(I)* Planar landslide ; *(II)* Wedge landslide, resulting from intersection of two families of fracture planes; *(III)* Fall of blocks by *toppling*.

Considering that some of the families of fractures present a small opening and show, in some cases, indications of water circulation we considered a value for the friction angle of 30º.

The results of this analysis were combined with the data from the height of slopes, given that some of these slopes, especially next to the river Douro, present heights in the order of tens of meters. Thus, a high hazard for the high slopes was considered (about 30 m), in which the Markland test indicated a probability of wedge or planar failure, low to average, for high slopes (about 30 m) where the analysis indicated a probability of block and rock fall by *toppling* and low or average slopes (about10 m), in which the Markland test indicated wedge or planar failure, and null to low for slopes with height inferior to 10m or with absence of movement (Figure 5).


Figure 5 – Slope instability hazard map

### 4.2. Characterization of construction with a heritage value

#### 4.2.1. Information research

The work was composed for two types of tasks: filling out a field form along with photographic documentation of the constructions.

The information collected through the field form is composed of quantitative and qualitative data on the buildings, whose survey was carried out by direct observation of the exterior of the constructions. The photographic survey included, as minimum elements, a photograph of the front of the building, and as documentary elements, photographs of details of constructive anomalies. The characteristic narrowness of some streets made it difficult to obtain good quality images.

The diversity of construction periods, in the ZHP, compelled us to study the historical evolution on the urban and constructive development, in order to perceive the various temporal layers of the streets and constructions.

#### 4.2.2. Analysis of information

The “City Map of Port” [1] does not take into account the registry of urban property. This characteristic made it difficult to delimit the lots and constructions in terms of mapping and led to creation of the concept of “Structural Unit” (UE).

The UE is independent of the architectural and official registry of property parts and instead it relates with them and establishes the resistant element, characterized by a degree of structural weakness, influenced by its own physical characteristics and influencing its involving neighbor. A UE allows the necessary flexibility in the crossing of data, due to the wealth information contained in the constructed fabric of the ZHP.

The “Behavioral Unit” (UC) is the set of UEs that due to its proximity and characteristics of mutual influence, act as an element that behaves as a whole and whose behavior can be predicted and is independent neighborhood block concept. These units are mapped out on a map and are associated with specific coding within the GIS database.

#### 4.2.3. Perception of the degree of vulnerability

The set of variables associated with the stability, whether of construction as a unit, or of the construction in which it is integrated, along with the evaluation of inherent pathologies of materials, or even of the constructive processes, does not facilitate the quantitative attribution of a vulnerability degree. Added to this is the fact that these structurally discontinuous housing sets, constructed with certain characteristic materials are more vulnerable to adaptation implies that the attribution vulnerability degree will possibly be permanently evaluated.

In the current case study we have a constructive system that adapts itself as a function socio-economic characteristic of its occupants and, consequently, with historic technological evolution in the construction industry and occupation of the urban center. Because of this uncertainty the concept of perception of the Degree of Vulnerability was introduced.

We looked towards reducing the number of discrete values attributed with the aid of: *(I)* the identification elementary structural units; *(II)* the establishment of ways of spatial relationship and volume analysis; *(III)* the determination of the constructive processes through the probable dating of the base architectural elements; *(IV)* the attribution to each structural unit an alteration degree due to the visible elements and *(V)* the definition of the degree of the observed characteristic conservation degradation.

The obtained data was compiled in a table of vulnerability as three classes - Low (0%< >30%), Average (30%< >60%) and High (60%< >100%) - considering that 100% corresponds to the incapacity construction to carry out any function. Thus, the “Map of construction vulnerability”, in Figure 6, was obtained.


Figure 6 - Map of construction vulnerability

4.3. Map of seismic risk

From the previous map the corresponding seismic risk map was therefore limited to the construction elements characterized with patrimonial value within the World Heritage UNESCO classified zone. The risk matrix was surveyed on the basis of the crossing seismic hazard and construction vulnerability with patrimonial value, resulting in the “Map of Seismic Risk” (Figure 7).

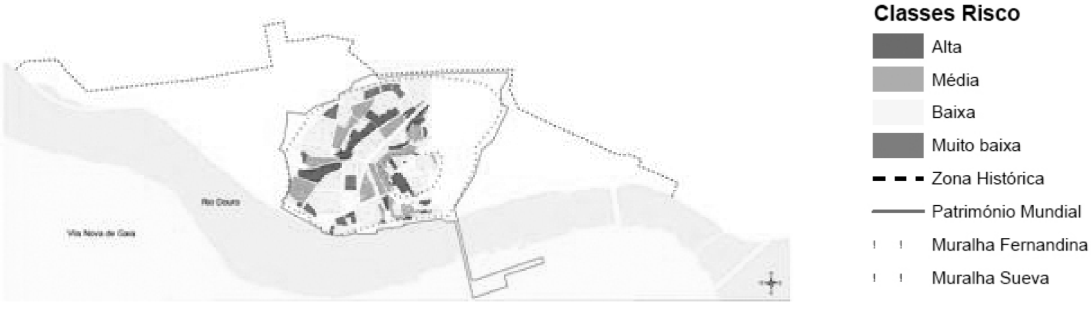


Figure 7 - Seismic risk map

## 5. CONCLUSIONS

It is intended that the "Map of Geologic Risks of the ZHP" can constitute a indicative working instrument, whether it be for teams of technicians of the participant institutions in this project, or for the heritage and the civil protection institutions. It can also lead to rethinking of practical politics and programs to evaluate the emergency and security plans or for improving management of risk, minimizing its effects on the population as well as the heritage.

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