Engineering geological mapping for the urban planning of Almada County, Portugal

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Abstract: The urban area of Almada County, in the Lisbon Metropolitan Area, is undergoing a very high rate of growth. However, there have been several examples of land development having taken place in areas with poor geotechnical characteristics, and a number of illegal constructions have disrupted the natural geomorphological evolution of the area, thus creating potential hazards for people and property. The current Almada Municipal Development Plan has not taken adequate account of geological and geotechnical information. Therefore, the authors have undertaken a research project to develop a set of engineering geological maps, as part of a spatial geoscientific database, to be offered online to potential users. This database also includes thousands of results from *in situ* and laboratory tests. The information is integrated into the so-called GEO-ALMADA Information System (SIGEO-ALMADA). Manipulation and analysis of the information in this system has allowed the derivation of several engineering geological maps in digital format (scale 1:10,000) that show geotechnical units, landslide susceptibility and erosion potential. Finally, an engineering geological zoning map was prepared, which shows the main geotechnical restrictions to urban development. This paper describes the methodology used to prepare and store the cartographic information, using geographical information systems, as well as the main results obtained.

Résumé: La commune d'Almada, dans la zone métropolitaine de Lisbonne, a subit, récemment, une forte croissance urbaine. Plusieurs examples d´occupation du sol dans des secteurs aux faibles caractéristiques géotechniques y ont été remarquées. Il y a également un certain nombre de constructions illégales, qui interfèrent avec l'évolution géomorphologique naturelle, produisant des situations dangereuses pour les gens et le patrimoine. Néanmoins, le programme de développement municipal en cour à Almada n'a pas considéré, d´une façon nette, l'information géologique et géotechnique. Les auteurs ont développé un projet pour préparer un ensemble de cartes géotechniques qui intègrent une base de données geospatiale qui sera offert *on line* aux potentiels utilisateurs. Cette base de données renferme aussi de l'information descriptive, de matières diverses, notamment quelques milliers de résultats d'essais en laboratoire et *in situ*. Ces données incorporent le système d'information GEO-ALMADA (SIGEO-ALMADA). La manipulation et l'analyse d'information dans le système ont rendu possible la dérivation de plusieurs cartes géotechniques, en format digital (au 1:10 000), montrant les unités géotechniques, l'aléas de mouvements de terrain et le potentiel pour l'érosion. Finalement, on a élaboré une carte de zonage géotechnique qui montre les contraintes majeures à l'occupation urbaine. L'article présente la méthodologie employée pour préparer et stocker l'information cartographique en employant les systèmes d'information géographiques, ainsi que les principaux résultats obtenus.

Keywords: Engineering geological maps, database systems, geodata, geographical information systems.

INTRODUCTION

Collection of subsurface data is a key component of urban geological and geotechnical studies. Although there are typically large quantities of these and other geological and geotechnical information in urban areas, the data differ greatly in type, quantity, distribution and quality. Also, they are frequently clustered around particular sites, held at different locations, and are often still stored in hard copy, so are both hard to access, and to handle

This paper focuses on the development of the GEO-ALMADA information system, a Geoscientific Information System intended to improve access to geo-information in Almada County (Figure 1), in the Lisbon Metropolitan Area of Portugal. The ultimate aim of the project is to evaluate the characteristics of the ground for planning, design and building purposes, and so ensure best use of the land in future.

The main practical goal has been to develop a set of digital engineering geological maps for use in future planning strategies. Therefore, a set of databases (DB) has been developed that link the geological and geotechnical features to the geometric information of the maps and its alphanumeric attributes (Silva, 2004). This allows the DB to be queried for information on lithology, tectonics, geotechnical characteristics and site investigation data (such as from drill-holes, water wells, pits and trenches), and to be readily expanded as new data become available. A link has also been developed to another DB containing data on the main characteristics of the county's water wells, and water quality. As the City of Almada has already developed a land information system, the so-called System of Information of the Municipality of Almada (SIGMA), which has a 1:1 000-scale digital reference base map, SIGEO-ALMADA will complement it with specialized geoscientific information.

SITE AND GEOLOGY

The municipality of Almada, in the estuary of the River Tagus, is the most densely inhabited county in the southern zone of the Lisbon Metropolitan Area (Figure 1). The county includes eight major urban areas, in which, the expanding population is scattered along the main highways and stream valleys.

The north and west borders of the county are lined by cliffs, which are very susceptible to instability. To the north, the nearly 8 km-long left bank of the River Tagus slopes steeply, and rises locally to more than 120m. To the west, the seacliffs of the *Costa de Caparica* along the Atlantic coast are more than 13 km long and up to 100 m high, and during spring and summer, thousands of visitors are attracted to the beaches below.

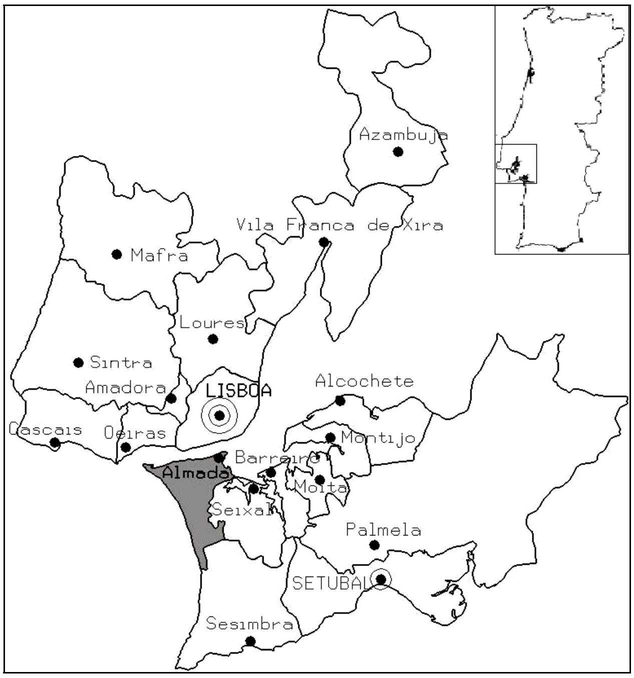

Figure 1 - Location of Almada County in the Lisbon Metropolitan Area, Portugal.

Almada has owed its importance, since the thirteenth century, to its proximity to Lisbon, its good harbour conditions along the riverside, and to the general topography of the area. During the last 100 years, there has been significant growth in the population, and in the industrial development and military occupation of the area. The construction of the Lisbon-Almada Bridge across the River Tagus, during the 1960s, accelerated this growth and at the end of the millennium, there was a new boom in the population following construction of a railway on the bridge. It is estimated that at present, less than 20% of the county area remains undeveloped.

The northern part of Almada County mainly lies on Miocene siltstones and claystones with interbedded calcareous sandstones, sandstones and sandy or marly limestones. These strata have a relatively constant dip of 5 to 8º towards the SSE, and they lie on the northern flank of an open syncline, whose axis trends E–W along the valley defined by Albufeira lagoon/Apostiça stream. The shoreline of the left bank of the River Tagus has a *cuesta* morphology and high scarps sometimes directly abut the river. However, in places along the river bank, there are the remains of ancient beaches, although these are disappearing fast. Several piers have been built for industrial facilities into the deep river waters. Alluvial deposits along the Tagus and its tributaries can reach up to 20 m in thickness, and there are colluvial deposits, some on steep slopes. Pliocene sands and weak sandstones, with interbedded lenses of clay or gravel occur on the south side of the area. To the west, Pleistocene and Holocene dunes cover the seacliffs, with sandy beaches below.

There are several sub-vertical dip-slip and reverse faults in the area, striking usually N-NNE and NE. These are sometimes cut by a set of faults striking E-W. There are joint sets in the weak Miocene rocks, but only near to the faults. Natural springs are associated with major tectonic discontinuities in the Miocene beds.

In the last 100 years, man has continuously modified the terrain, through major excavations and fills and as a result of the exploitation of some Miocene clays (to produce bricks) and Pliocene sands. Human activity along the north and west scarps and cliffs has accelerated erosion and mass movements, and rock falls, landslides and earth flows have occurred more frequently in recent years. These have resulted in casualties amongst local inhabitants and severe economic damage. As a result, a number of studies have been undertaken since the 1960s to assess the stability of the slopes along the left bank of the River Tagus.

Almada County is included in the highest seismic risk zone in Portugal, and was very severely affected by the Lisbon Earthquake of November 1st 1755.

METHODOLOGY

The initial phase of the project involved collection of geological and geotechnical information about the research area. Substantial data were gathered. As the drill-holes dated back over a very long time, their quality was evaluated. Those that were geotechnically inadequate, or were poorly located, were rejected. The terminology and methods of description also varied greatly. For instance, silts would be distinguished from clays in some site investigation works, but in others, even in the same area, only silty clays would be described. As a result, the DB only distinguishes coarse soils, like gravels and sands, from cohesive soils (silts and clays). Regarding *in situ* test data, although several thousand SPT tests were potentially available, most of the data from the 1970s could not be used, as the testing was not sufficiently reliable. The DB therefore has about ten data points per square kilometre, and includes some data that must remain confidential (e.g., private drill-holes).

An extensive field survey (lithological and tectonic mapping at 1:5 000 scale) was carried out and more than two hundred undisturbed and disturbed soil samples and rock block samples were collected. The sampling was reduced in areas where access was poor (e.g. steeply sloping ground, or human occupation), and physical and mechanical tests were carried out on the samples.

Digital maps were prepared at a scale of 1:5 000, and cover the following themes:

- Slope map (derived from a digital terrain model), using seven slope angle classes (0-2%, 2-5%, 5-8%, 8-15%, 15-30%, 30-50% and >50%), chosen to reflect the main slope intervals usually considered in land use planning, and to enable relationships of slope angle to landsliding and erosion – the main geological hazards to be assessed in Almada County
- Lithology and tectonics map
- Landsliding and erosion inventory maps
- Data (site investigation and wells) location map

All of the data were subject to rigorous validation, after their capture in a set of ACCESS® DBs. The data model was developed with the complex geological objectives in mind, and to enable efficient querying of the large volume of data, and the future expansion of the DB to include further fields. The description of the data model is beyond the scope of this paper, but the model is similar to that adopted by Alberico *et al*. (2005).

Intergraph GEOMEDIA PROFESSIONAL® software was used in the extensive analysis of the geodata sets, and in manipulating the relational tables and digital maps to generate additional maps (geotechnical units map, landslide susceptibility, and erosion potential), and a synthesis map (suitability for construction). The geotechnical (lithogenetic) units map was one of the first to be generated, and was based on correlations established between site investigation and laboratory results, and on the geotechnical characteristics of the lithological units, and their variations near surface and at depth.

By combining the lithology data with average slope angles, and by reclassifying and weighting the different attributes (Figure 2), two other maps were developed: landslide susceptibility and erosion potential. These maps were then validated by direct comparison with the previously prepared inventory maps.

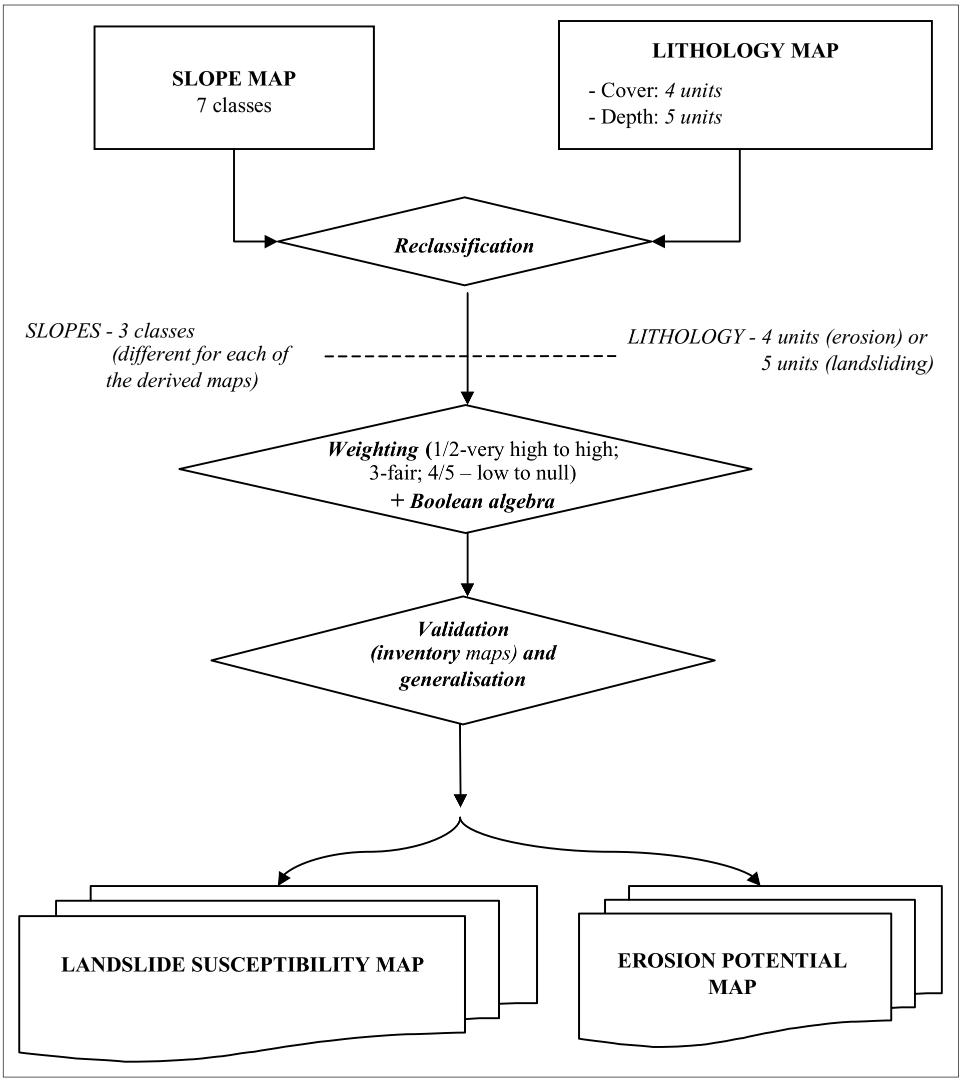

Figure 2 - Flowchart of the general methodology used to prepare the set of derived maps (Silva, 2004).

Finally, Boolean algebra, duly weighted, was used to integrate the thematic maps for slopes, geotechnical units, landslide susceptibility and erosion potential (Figure 3), to prepare a zoning map for suitability for construction.

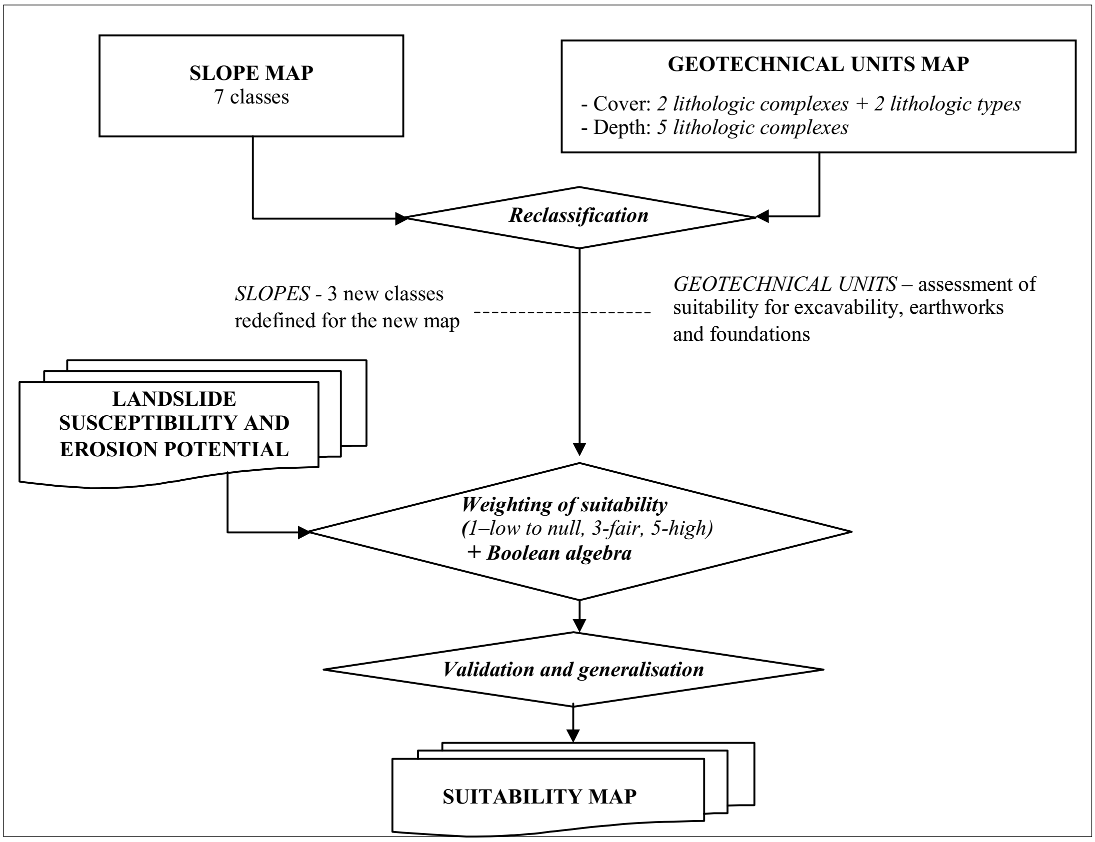

Figure 3 - Flowchart of the general methodology used to prepare the Suitability for Construction Map (Silva, 2004).

All of the basic and derived data can be readily accessed and queried by earth science specialists, and non-specialists alike, and to facilitate this, a basic framework of colours (semaphore colours) has been selected for the maps, and standard terminology and international system units have been adopted.

MAIN RESULTS

The data used to establish the GEO-ALMADA information system are distributed in five main subsets, spatial data analysis of which enabled two further subsets to be derived.

Main subsets of data

The site investigation data (from about seven hundred points) are mainly of two types:

- Geotechnical data, which comprise the large majority, from exploratory drill-holes, trenches and trial pits, and which include some *in situ* and laboratory test results
- Hydrogeological data, including data from water wells (underground water is the most important geological resource in the County), and some water quality analyses associated with the wells

The DB containing the data from geological and geotechnical studies is called ***AlfaGEO,*** and that containing the well data and water quality analyses is ***FurosGEO***. Much of the drill-hole information in the DB was obtained in the 1990s. Most of the holes were by percussion drilling (about 70 %), and about 50 % (203) intercepted the groundwater table. The data include a total of 3329 SPT results, usually performed at 1.5 m intervals, but with spacing varying from 1 to 2 m. All of the laboratory test data, which include the results of over 600 physical and mechanical tests of soils and rocks, are held in an alphanumeric relational DB, called ***Lab_GEO***.

The results of the mapping are presented in a set of digital maps, at a scale of 1:5 000, and related alphanumeric data. Each thematic map corresponds to one geodatabase: ***Declives*** (slopes); ***Litologia*** (including lithological and tectonic data); and ***Perigos_Geológicos*** (inventories of landsliding and erosion). These geodatabases, together with a further integrated geodatabase, referred to as ***Derivadas***, comprise the SIGEO-ALMADA.

A digital terrain model has been developed and this has led to the derivation of a slope map (1:5 000 scale), using seven slope classes. Choice of these classes was influenced by the fact that they are the main slope intervals usually considered in land use planning, but also took into account the specific characteristics of the ground responsible for the main geological hazards in the area – landsliding and erosion.

Almada County has several landslide-prone areas, especially along the left bank of the River Tagus in the north. The DB records the locations, types, and other aspects of the landslides in the area, and should encourage research into the development of further hazard maps that will assist development.

Several landslides in the northern and western parts of the city of Almada have been triggered naturally and by intense rain in particular. However, in most cases, the failures were exacerbated by human activity, and particularly along the Tagus River, through disturbance of the toes of slopes and disruption of the natural drainage.

Preliminary analysis of the geohazards information in the SIGEO-ALMADA has revealed that about 65% of the one hundred and ninety landslides in the geodatabase, were interpreted from photogeology alone; only 22% were observed directly on the ground; 3% were identified from information from local inhabitants; and the remaining 10% were both observed on the ground and verified photogeologically. In terms of their activity, more than half the landslides are considered inactive (58%), 9% have been stabilized by engineering works; 22% are considered potentially active, i.e. could be reactivated, e.g. by heavy rainfall; and 5% are considered active (areas of creeping).

At least 56% of the total erosion detected is of 'continental' type, ranging from rills to gullying. Some earthflows occur, generally comprising sand in a fluid argillaceous matrix, and some of these are associated with debris fans. They have also resulted in gullying and their development is related to periods of intense rainfall. Simple erosion largely affects coarse materials at the upper edges of the seacliffs and results commonly in thin, more resistant blocks detaching. Erosion by the sea accounts for 44% of the inventoried erosion and affects the entire Atlantic coast along Almada's western border, and at the northwest and southern ends of this coastline, it significantly exceeds the accumulation of movable sediments. Erosion has been made worse, especially in the last decade, with two main causes:

- Anthropogenic degradation of the natural coastal structures
- Coastal engineering works, built in the 1960s-1970s, to protect the beaches, and also some human occupation along the shoreline

Meanwhile, there has also been a reduction in the amount of sediment supplied to the coast by the River Tagus, due to the construction of dams and dredging of sands.

Derived subsets of data

Based on both the geological data (e.g., lithology and tectonics) and the interpretation of site investigation data, an engineering geological zonation map, showing the distribution of twelve geotechnical units, was prepared in a GIS environment. This map is intended to reflect specific ground conditions in Almada County that are relevant to engineering. It indicates the basic geological and geotechnical conditions prevailing in each unit that a specialist would need in preliminary planning, namely; the composition, thickness and distribution of lithologies; and the physical, mechanical and hydrogeological characteristics. Whenever there is a numerical value for any descriptive feature, the minimum, average and maximum values for that feature are always presented. The descriptive detail is a function of the amount of data available for each unit. The main parameters are supplemented by additional data of relevance, where available – e.g., the thickness of an alluvial deposit obtained from a drill-hole located in another Municipality, but near the Almada border.

Based on the Slope map and the Lithology/tectonic map, two kinds of susceptibility maps were derived: i) landslide susceptibility and ii) erosion potential. Both maps were validated using the digital data in the inventory of mass movements, and registered erosion events. The two maps derived by Boolean analysis enabled zoning to be established in terms of three major units – low to null (green color), medium (yellow color) and high (red color) – Figure 4.

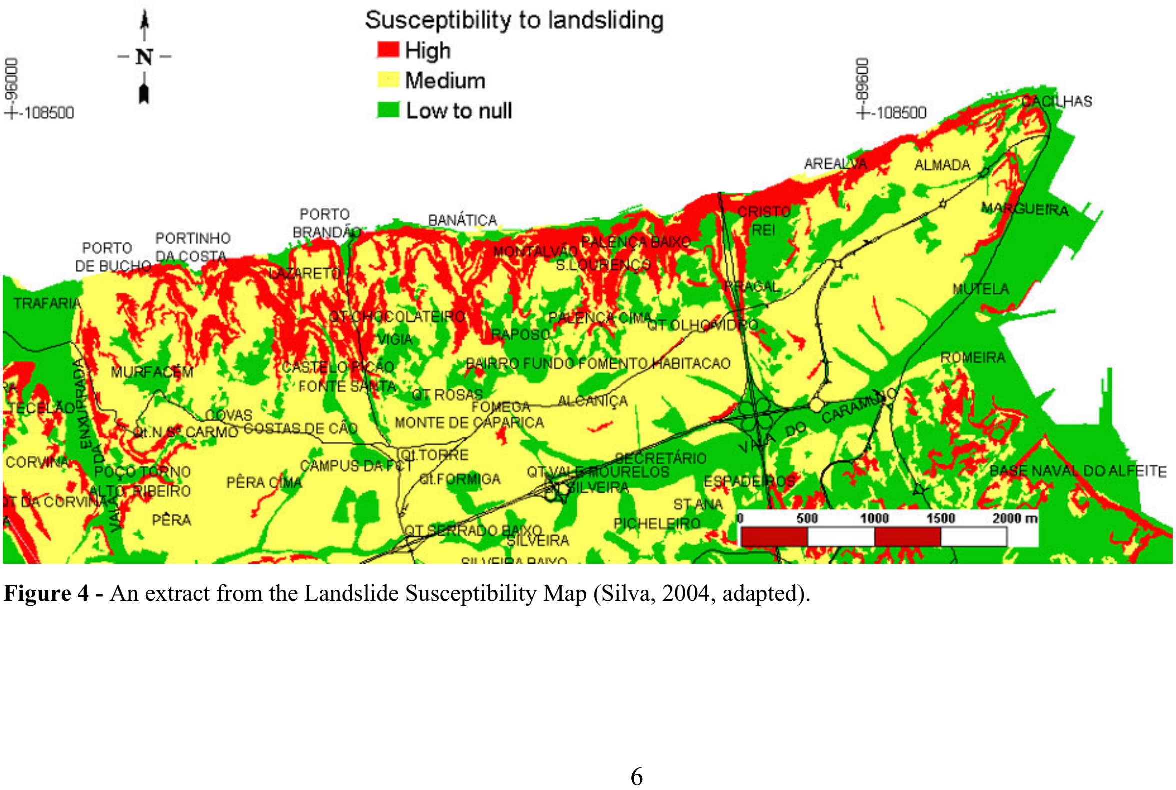

Figure 4 - An extract from the Landslide Susceptibility Map (Silva, 2004, adapted).

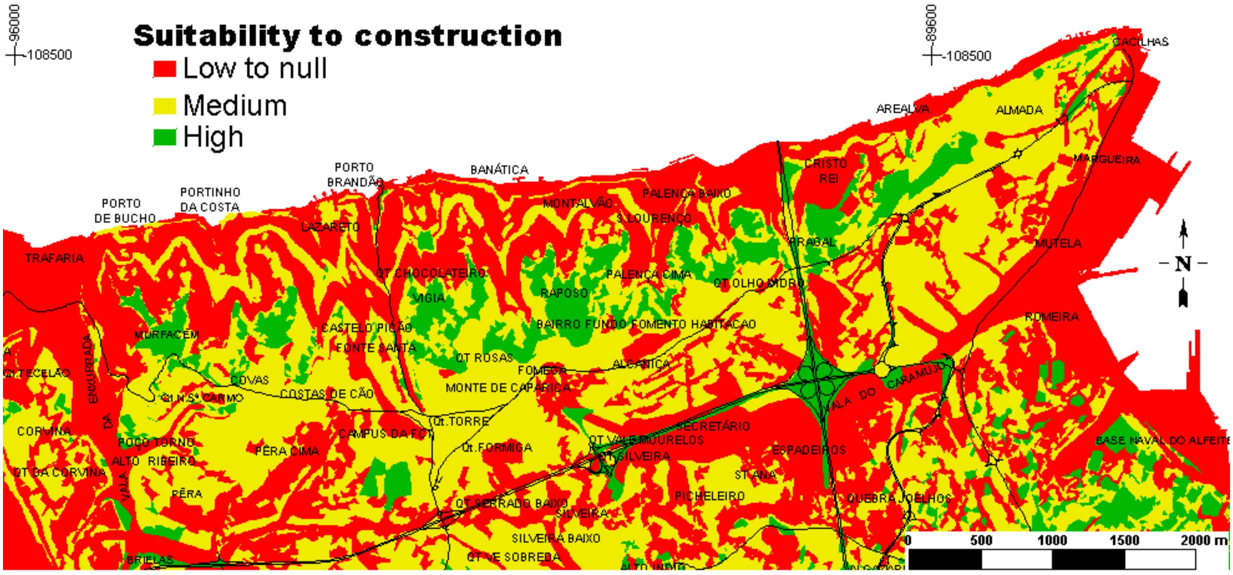

Figure 5 - An extract from the Suitability for Construction Zoning Map (Silva, 2004, adapted).

Finally, each geotechnical unit was assessed according to its major geological and geotechnical constraints to construction (Figure 5). To accomplish this, each geotechnical unit was re-evaluated qualitatively and ranked in one of three classes (high, medium and low to null) and then subjected to Boolean analysis with the two susceptibility maps, and also with the slope classes (reclassified into three classes for this purpose), in order to define suitability for construction.

Once more, a user-friendly map with a basic framework of colours (semaphore colours) resulted from this final synthesis. The map was validated by direct comparison with geo-environmental knowledge gathered from the SIGEO-ALMADA.

CONCLUSIONS

This research reflects close practical collaboration between the Portuguese earth science community and its society at large. The methodology presented here is sufficiently generic that it can be applied to regions other than Almada County.

The DB already available can be extremely helpful as a tool for multidisciplinary research and as a guide for extending knowledge of the ground in the Almada County. It will be especially important in supporting revisions of Almada land use plans, and in achieving sustainable development and management of the area. It should also support, and help to promote, further studies in the earth sciences domain (e.g. landslide hazard zonation of Almada County), and in planning (e.g., geo-environmental mapping). Most of the information will be available soon for public consultation through an Internet portal (the Almada Digital City), now under construction by the municipal authorities.

In future, both the extent and overall cost of site investigation needed for urban development in the study area can be greatly reduced as a result of these geodata (whose accuracy has been verified) having been made available.

Geological and geotechnical conditions are essential physical factors that must be taken into account in planning. In the case of Almada Municipality, neither were considered in the first generation Municipality Development Plan. However, revision of that Plan is now underway, and this will benefit from the information already made available in the SIGEO-ALMADA.

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REFERENCES

ALBERICO I. *et al*., 2005. GEOCITY: a drill-hole database as a tool to assess geological hazard in *Napoli* urban area. *Environmental Geology*, **47**:751-762.

SILVA, A. P. 2004. *Engineering geological mapping of the Almada County and the Geo-Almada Information System*. PhD thesis, New University of Lisbon, Lisbon (in Portuguese).