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3D geological model of Lisbon

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ABSTRACT: Within the GeoSIS_Lx project, a geotechnical data base is being implemented and methodologies to generate tridimensional geological and geotechnical models of the city of Lisbon are being developed. The generation of the tridimensional model is being pursued through an iterative process using a Geographical Information System (GIS) platform, designed to be open to the use of several technicians that may not be geology or software experts. Geological surfaces were derived based on information interpolated from cross-sections, resulting in a simple model where first order geological patterns are present, following a validation with the cartographic patterns of geological outcrops and with selected information of the geological database. Future developments include refinement of modeling of faults and an automatic validation procedure against the borehole database and geologic cartographic patterns taking into account the data uncertainties. Results indicate that the methodology in this test suits the requisites of the geological formations of Lisbon.

1 INTRODUCTION

Geological and geotechnical data of urban areas, resulting from decades of site studies and projects, are available for the city of Lisbon and are a fundamental information source for land planning and natural disaster management. However, such data has only been used locally, and mostly by private companies when working in a previously studied location. Also methodologies for gathering and/or inventorying these data are yet to be established and become common practice, and such information remains not often used. Nowadays, computing developments allow the organizing, managing and processing of large amounts of information, regarding different outputs for different types of users, which permits aspiring to new achievements. However, in order to benefit from such advances, all information, which is mainly still in paper, needs to be first compiled in digital format. Having all information in digital form allows applying geographical information system technology to field geology (De Donatis *et al.*, 2005).

This significantly large set of geological information available for the city is also in the form of surface geological cartography and respective interpretative cross sections. Regarding the geotechnical data, despite some efforts performed during the last few years, Lisbon geotechnical data mapping is a task that has not been completed yet.

The project GeoSIS_Lx aims to contribute to change this scenario, using published geological cartography to establish a conceptual tridimensional geological model, and compiling the geotechnical data existent in different companies and institutions in a structured database. These two modules of research are being pursued simultaneously and will interact throughout an iterative process of both model calibration and database quality validation.

The ultimate goal, with implementing such a tools and knowledge base, is to provide rigorous geological and geotechnical information of any area of the city there is interest in, reducing the need for traditional borehole drilling studies. This possibility will exponentially reduce the need for borehole execution to a state of, quoting M. Culshaw, “no more site investigation”.

2 GENERAL SETTING

The city of Lisbon is located in the centre-south western coast of Portugal (Figure 1). The study area of this project is Lisbon’s official county which presents an area of about 84 km^2.

The city of Lisbon is rich in different subsurface geological formations, dating from the Cretaceous to Miocene, which are covered by formations of the Pleistocene and Holocene. Also present and of significant relevance are the fills and slope debris, highly heterogeneous in nature, extension and thickness. Alluvial deposits (al) are also relevant as the city presents an important fluvial network.

The geological formations that compose Lisbon’s subsurface are well documented in various studies, some dating from the nineteenth century when the developing urban tissue enabled the observation of many outcrops of high quality, and as a result of many engineering projects conducted throughout the twentieth century (e.g. Cotter, 1956). Although urban areas nowadays present less outcrops and surface features, these areas suffer intense investigation through borehole execution, which allows the gathering of geological data.

Except for the Volcanic Complex of Lisbon (CVL) formation, the subsurface geology of Lisbon consists of sedimentary formations, including Cretaceous limestones and marly limestones (Cc), Eocene sandstones, clays and conglomerate rocks (CB). The Miocene (M) is characterized by clayey, sandy and silty soils, calcareous sandstones and limestones. There are important lateral and vertical facies variations, registry of the alternance of sea and continent environments, originating 15 stratigraphic units within the Miocene. The basaltic volcanic formation is characterized by important lateral variations of thickness (Almeida, 1991), and of structure with lava flows, interbedded pyroclastic layers and, in some locations, sedimentary layers within the volcanic formation (Pais *et al.*, 2006). The set of geological formations to model and the geological cartography of Lisbon can be found in Figure 2.

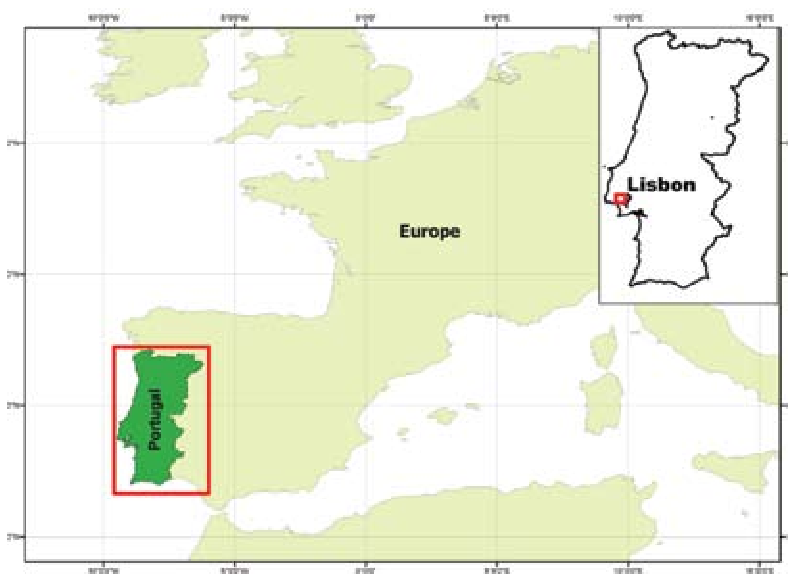

Figure 1. Location of the study area.

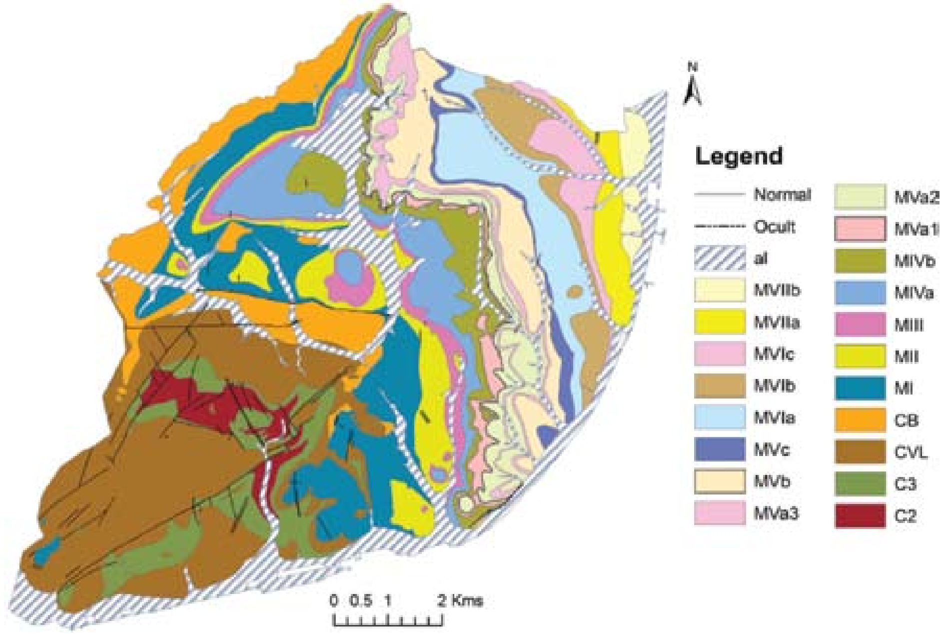

Figure 2. Geological setting of Lisbon.

Structurally, the geological layers suffer smooth folding, resulting in several monoclines and synclines throughout the entire region. The southwestern region, as well as more constrained locations in the east, presents complex systems of intersecting faults which, together with erosion, create irregular geological patterns at the surface.

3 MODELLING THE GEOLOGY OF LISBON IN 3D

One of the main objectives of this project, as referred, is to serve as a support tool for land management and planning. It is intended that several users that are neither geology nor software experts can use the model in their studies and assessments. Therefore it was decided to use a standard GIS platform (ESRI® ArcGIS 9.3) and so far all modelling has been executed in this software.

In the first phase of this project, it is intended to develop a conceptual model of Lisbon's geology, based solely on the surface geological cartography and its interpretative cross sections. Afterwards the intention is to confront and refine it with the borehole database. The geology of the tridimensional model can be constructed using superimposed surfaces, created through interpolation of several geological profiles along the study area (Tonini *et al.*, 2008). Each one of these surfaces represents an existing stratigraphic layer, referenced to the topographic surface in the form of a digital terrain model. Before the implementation of a model it is necessary to understand and define the correlation of all units, create boundaries of these units at the surface and at depth, and define the local stratigraphy (Culshaw 2005).

3.1 *Data acquisition*

This conceptual model was built based on a multi-source data integration method (Wu *et al.*, 2005), as it relies also on topographic data, which is a fundamental tool for the correct modelling of the geology. A digital terrain model was available for the city of Lisbon, with a 5 m resolution.

The published 1:10,000 geological cartography, surface map and cross sections, available in analog format as well as four other cross sections performed by Almeida (1991), were digitized using a standard scanner. To carry out such cross sections, the topographic reference implemented in the published cartography, which is made up of contour lines with 10 m intervals, was used.

The geological map was easily georeferenced to its original spatial reference, Hayford Gauss Datum Lisboa. Twenty cross sections, as vertical sections of the ground in different directions, were referenced to its spatial reference of distance vs. depth. For each cross-section, all geological boundaries were digitized, considering their structure and stratigraphy, and a point format file was created (Figure 3). A geological database was then built, composed of a large set of files: 1 point format file for each stratigraphic unit per cross-section.

Actually, the collected information represents the top of the respective stratigraphic unit in a determined cross-section and its thickness is given by the depth to the unit below. The necessary mathematical operations to transform the spatial reference of the cross sections for each file to the geological cartography spatial reference were implemented: for each point of distance to origin and depth, a tridimensional terrain referenced point was obtained. Given the large amount of files and information, it was necessary to program all calculations in Matlab®. This pre-processing phase consumed a significant amount of time and demanded a previous highly careful data analysis, not only of geological layer relations within a cross section but also amongst all the cross sections available.

After the data processing phase was concluded, it was a necessary to gather all the information about each stratigraphy in order to create surfaces representing the extension of the subsurface geological units, with its specific features such as folding or other complex structures.

3.2 *Creating geological surfaces*

The kriging interpolation method was used to generate each geological surface. This method not only takes into account the spatial behaviour of the data but also provides a measure of the error or uncertainty at the unsampled points (Li *et al*., 2008).

The data of each stratigraphic unit, gathered in a single point format originated by merging the available cross sections (where occurring), was the input information for the interpolation algorithm. Definition of parameters, such as first order trend and nugget effect removal, when using the kriging interpolation allowed smooth surfaces to be obtained, where folding, when present, is well represented (Figure 4).

Faults presented an interesting challenge to the tridimensional modelling as they consist of break areas within a same surface. As referred, the kriging method allowed surfaces well representative of the subsurface geology to be obtained but failed to represent faulted areas properly. In the geological cartography of the city, there is a high concentration of faults in the southwestern region that contrasts with the remaining areas, where no significant faulting occurs. In that area, structurally complex but simpler in stratigraphy, the spline interpolation method was applied to the stratigraphic units affected by faults. Using the spline with barriers interpolation method, it was possible to input barrier features, which, in this

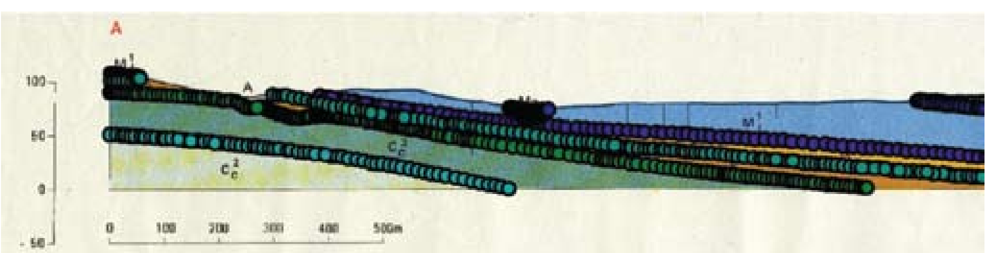

Figure 3. Point acquisition for each stratigraphic layer.

Figure 4. Example of stratigraphic layers interpolated from the correspondent point data by kringing method (Vertical exaggeration 6x).

Figure 5. Faults system and interpolation of surfaces affected by it (Sheet number 3 of the Geological Map of Lisbon 1: 10000).

case, are faults allowing each block of the surfaces to be interpolated independently, forming stratigraphic units displaced where a fault occurs (Figure 5).

In order to represent the reality of the geological layers it was necessary to refer each layer to the topographic surface. This was done using a digital terrain model of 5 m resolution as a reference. Every pixel of the interpolated surface above the digital terrain model is eliminated, so that only the subsurface geology is represented in the model. This task is applied sequentially to all geological layers, and in order to create an automated procedure, the sequence was structured using the ArcGIS Model Builder application.

4 MODEL VALIDATION

Once the conceptual tridimensional model is built it is necessary to compare the results with an independent data source.

Although currently being implemented, the borehole database is yet to be finalized. As referred previously, the borehole data will allow not only checking of the stratigraphy on selected bores, in order to support an accurate interpretation of such data, but also the refinement of the model where it derives from the subsurface reality.

Therefore the validation method consists, so far, on model-cartography confrontation only. This method allows analyzing whether the interpolation algorithm respects geological structures such as folding, some more abrupt variations and faulting.

Such confrontation is based on a comparison of surface patterns of the geological cartography and the model contact lines (MCL) (Figure 6), generated by the intersection between the digital terrain model and the geological surfaces (Tonini *et al.*, 2008).

It is necessary to highlight the fact that, in some areas, there are known cartographic inconsistencies in the published geological cartography. In such known areas, not crossed by geological profiles, direct confrontation is not possible as the cartography and model will obviously be different; thus the validation is done by a semi-qualitative interpretation of the contact lines of both model and cartography information. In Figure 7 it is possible to observe an approximation of the model contact lines to the digitized cartography below: although the cartographic patterns differ, the general trend is present. It is important to quantify such uncertainties in the data, both in the model and the cartography.

Consisting in a measure of the difference between estimation and reality, these uncertainties originated mainly from potential investigation and interpretation errors (Tegtmeier *et al.*, 2007). It is important to understand the presence of uncertainties and to quantify them, as they play an useful role in the assessment of the model and the database. Concerning the 3D model of the subsurface, although the sources of uncertainty are known, its quantification

Figure 6. Left: MCL projected together with geological surfaces in an orthophoto. Right: 3D visualization of subsurface of geological layers and its MCL.

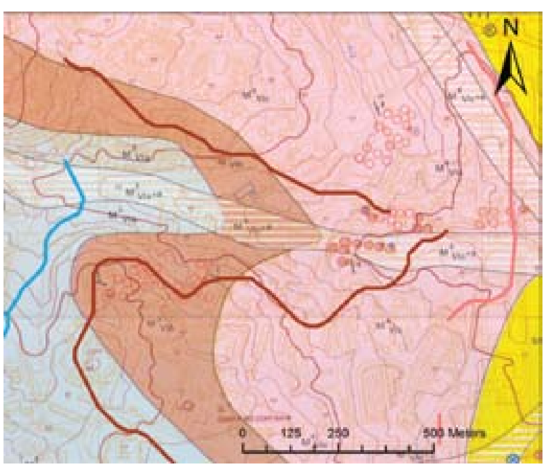

Figure 7. Inconsistencies between geological model (MCL) and cartography.

is a rather subjective procedure and its incorporation into an automatic flow poses some difficulties (Tegtmeier *et al.*, 2007).

5 DISCUSSION

It may be considered that the 3D geological model is implemented, according to the goals of the first phase of the project. There are local adjustments needing extra analysis and correction, such as small areas of erroneous intersecting layers or displacement caused by faulting. These situations are localized and are directly related to the lack of information in some areas of the city where no cross sections have been executed.

Also the altimetric reference of the published cartography, from which the cross sections depth information was derived, is quite different from the reference used to edit the modeled layers to the topographic surface. The first dates from the 1970's, and is in the form of contour lines with 10 m intervals, while the latter was executed in 1998 and was available as a digital terrain model with 5 m resolution. In this digital terrain model it is still possible to identify some artificial structures on the surface indicating that some inconsistencies were introduced in the production of the model and therefore further editing will be required.

6 CONCLUSIONS

The first phase of the tridimensional model generation can be considered implemented, apart from localized corrections regarding especially the fault modelling.

A second phase of borehole database confrontation will now be pursued and will involve an iterative procedure of 3D geological model vs. database. This will allow the calibration and validation of the model, with the input of extra borehole information in the step of data interpolation and the comparison between high quality selected boreholes and the model data in the same locations. It will also allow the validation of the borehole database in which a significant part of data is not always precise from the geological interpretation point of view. Nevertheless, these tasks, where the data acquisition and model generation are included, are always highly dependent on expert judgment in order to select the best information and gather it in a geologically correct structure.

As referred, such a knowledge base would theoretically allow all the work paradigms, from site investigation companies to the planner itself, to be changed, with the benefit of more rigorous, faster and less expendable tasks. Together with other data sources, the synthetic geological cross sections and borehole logs that may be constructed based on this 3D model provide a way of assessing the suitability of a determined site of interest (Kessler *et al.*, 2008).

In fact, Almeida *et al.* (2010) recommends the implementation of a win-win relationship between companies and planners, based on a joint effort of data transfer, which, in a nearby future, will consist of a simple and useful sharing of information.

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