Engineering geological map of Oporto: A municipal tool for planning and awareness of urban geoscience

RICARDO OLIVEIRA[1], CRISTINA GOMES[2] & SOFIA GUIMARÃES[3]

[1] *COBA, SA and New University of Lisbon. (e-mail: coba@coba.pt)*
[2] *COBA, SA. (e-mail: coba@coba.pt)*
[3] *ENGICO, LDA (e-mail: engico@engico.pt)*

Abstract: The importance of the city of Oporto as the second largest Portuguese city and as a centre of intense economic and cultural activity leads to a constant need for development and expansion. The strong pressure for urbanisation increases urban population density and, in turn, leads to the undertaking of complex engineering projects, using the subsoil for underground construction or, often, undertaking construction on ground which has unfavourable geotechnical characteristics.

These reasons, associated with limited scientific work on the geological and geotechnical nature of Oporto, justified the preparation of a comprehensive Engineering Geological Map of the City. This map synthesises and interprets a wide range of geotechnical information from the many investigations carried out over the years, and provides an overview of the main characteristics of the soils and rocks of the city, in addition to other relevant information on Oporto's subsoil.

The Engineering Geological Map of the City of Oporto, consists of 9 maps (7 factors maps and 2 syntheses) and a database with all the compiled geotechnical information (GEODATA). It is a very important contribution to the land planning and management of the city, and the definition of natural risk zones. It provides an excellent geotechnical data source to be consulted when new projects are being planned and designed for the city of Oporto.

Résumé: La ville de Porto est la deuxième ville du Portugal étant un pôle d'intensive activité économique et culturelle, ce qui implique le besoin permanent de développement et d'expansion. La forte pression urbanistique mène à la densification de l'occupation urbaine et, par conséquent, à l'exécution d'ouvrages de grande complexité, par l'usage du sous-sol et des terrains aux caractéristiques géotechniques moins favorables à la construction.

Ces raisons, associées au nombre réduit de travaux scientifiques de nature géologique et géotechnique sur la ville de Porto, ont justifié l'élaboration de la Carte Géotechnique de Porto. Cette carte rassemble et interprète une vaste quantité d'information géotechnique obtenue de travaux réalisés au cours de plusieurs années, offrant une vue générale des sols de la ville ainsi que d'autre information importante relative au sous-sol de Porto.

La Carte Géotechnique de Porto, avec 9 cartes (7 de facteurs et 2 de synthèse), est un élément fondamental pour la planification de la ville, pour la définition de zones soumises aux risques naturels ou en tant qu'un outil optimal de consultation d'information géotechnique importante pour l'exécution d'ouvrages et projets.

Keywords: Engineering Geology Maps, Database Systems, Geographic Information Systems, Land use

INTRODUCTION

The city of Oporto is the second largest city in Portugal and is located in the NW of the country. It covers an area of 41,5 km² and it has a population of 263.000 inhabitants.

The Historic Centre of the city is an outstanding urban landscape with a very important historic and cultural heritage dating back to Roman and Medieval times. Given the cultural value of the old parts of the city, in 1996, the UNESCO placed it on its list of "World Heritage Cities".

Oporto is built along the hillsides on an even platform (with the highest point at 161m above sea level) going down gently to the sea. This platform was cut by the Douro river which has a steep-walled valley with steep and high slopes that provide the so-called "zona ribeirinha" (riverside downtown) with its typical morphological characteristics.

The strong urban pressure in this area and the consequent growth of urban population leads to the undertaking of complex engineering projects, including the heightening of structures or underground construction as the recent case of the construction of the Oporto Metro. Urbanisation also leads to demands for construction on ground with less favourable geotechnical characteristics for instance the steep cliffs associated with the banks of the Douro banks or construction on clayey layers or on ancient waste landfills.

These issues, and the limited amount of scientific work on the geological and geotechnical nature of Oporto justified the preparation of a comprehensive Engineering Geological Map as an important tool for land planning and management of the city.

Given the continuous growth of construction in the city, much geological and geotechnical data has been secured by different private and public organisations. One of the first steps for preparation of the Oporto Engineering Geological Map was the compilation and interpretation of these data.

The handling, interpretation and graphic representation of such an amount of information has been achieved by the development and application of software that were essential to the preparation of:

- georeferenced mapping of all data pertaining to the different analytical and summary maps;
- application of data management software, called GEODATA, that allows the consultation and analysis of geological and geotechnical data.

The preparation of the Oporto Engineering Geological Map was followed by the representation of the cartography in a Geographic Information System (GIS). This is a versatile facility, easily handled and updated when further data are obtained.

A first edition of the Engineering Geological Map was finished in 1993 and an updated edition was prepared in 2003.

CARTOGRAPHY

Figure 1 presents a layout of elements constituting the Oporto Engineering Geological Map indicating the types of factors and synthesis maps.

A 1:10.000 scale was used in the final graphic representation of information.

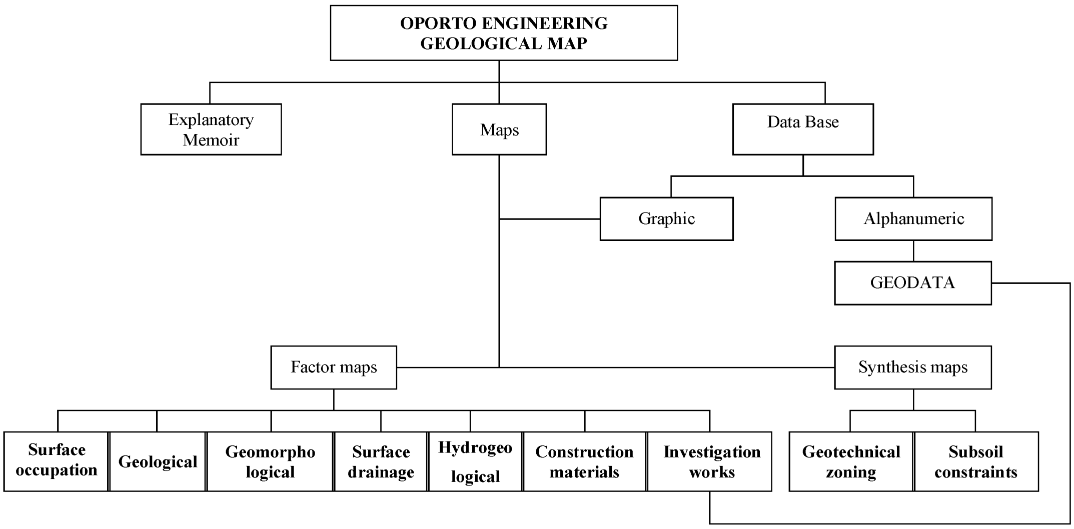

Figure 1. Elements composing the Oporto Geotechnical Map

Factor Maps

Site Investigation Works Map

This map contains all geotechnical investigation works and tests collected from the numerous reports provided by different public and private organizations concerning the numerous actions undertaken in the city over the years. The oldest report dates back to 1948 and the most recent is from January 2001.

The total data included 3673 mechanical boreholes, 523 shafts and augers, 112 seismic refraction profiles, 456 dynamic penetrometer tests, 33 CPT tests, 128 plate-bearing tests, 21.793 SPT tests, 108 pressiometer tests, 309 permeability (Lugeon-Lefranc) tests, 79 pump tests and numerous laboratory tests including physical, mechanical and compaction tests on 1146 disturbed and undisturbed samples.

The results of all of these were compiled in the GEODATA system.

Surface Occupation Map

This map summarises a lot of information regarding the type of the surface and the subsoil occupation, with emphasis on the cartography of green and built areas; contamination sources (demolition wastes, garbage dumps, scrap yards); subsoil areas with heritage interest (geological and archaeological heritage).

The information gathered in this map is the starting point for the preparation of Surface Drainage, Hydrogeological and Constraints Maps. In addition, it provided useful information on the locations of contamination sources and the subsoil heritage areas that can constrain construction or other types of land use.

Geological Map

This was based on the existing Geological Map, dating from 1957, at scale of 1:50.000, updated in the light of present knowledge and understanding of tectonics and seismicity.

Basically, the city is founded on igneous rocks, represented by Hercynian granites, Precambrian and Cambrian metamorphic rocks, of different complexes and units, and Quaternary sedimentary formations composed of marine and fluvial deposits.

In addition to showing the different lithologies, the map indicates the main orientations of discontinuities, schistosity and other structural alignments.

Most of this geological work was conducted by the Geological Department of the University of Oporto.

Geomorphological Map

The Geomorphological Map show some of major morphologic elements of the city of Oporto (namely thalweg lines, ridges, hypsometry and fracture alignments) and provides a reasonable overview of the main land relief.

With regard to the land morphology, one of the greatest concerns is evolution of natural and anthropogenic slopes since these are often associated with instability that can endanger people and property. These concerns are confirmed by periodical reports of landslides and block falls that occur on the slopes adjacent to the banks of the Douro river.

Thus, major slopes of the city have been surveyed and characterised and, in the case of rock slopes, an additional study on the rock mass fracturing as well as on other factors promoting instability has been carried out. Based on this characterization and on the gathered data, different zones have been qualitatively classified in terms of degree of instability.

Water levels frequently associated with floods, settling of land, erosion and sedimentation were identified.

These cartographic elements, in addition to being a basis for city planning, were a stimulus for the municipal authorities to understand the need of implementing emergency plans and to undertake stability studies of the most critical areas.

Surface Drainage Map

The various hydrologic elements, including rivers, streams and other waterlines were mapped and the associated catchment boundaries were studied. Zones for which different runoff coefficients were proposed to be adopted for the calculation of the peak flood were delimited. In relation to the water courses, a distinction was made between the natural and present courses since many had been subject to deviations along the years. In the present courses, a distinction was made between open channels and culverted sections. The distribution of natural water courses was taken from the oldest maps of the city, dating from 1892, and on the geotechnical investigation data.

This map can be sued in drainage design (rainfall water networks, hydraulic works) and also in defining the main infiltration (groundwater recharge, vulnerability) and flooding areas.

Hydrogeological map

This map presents hydrogeological information from wells, boreholes and hydrogeological tests. A survey was made of water associated with mines existing in the city and of some springs. The existence of numerous ancient mines subsoil is frequently associated with the occurrence of serious geotechnical problems, notably subsidence and flooding.

Based on the lithological, structural and geomorphological characteristics, and on statistical processing of the collected information, hydrogeological zoning was undertaken principally to study the effects of hydrogeologcal conditions on the geotechnical behaviour of the ground.

Each hydrogeological unit has been characterised in respect of its permeability, type of source, importance, and vulnerability to pollution - a key aspect in the protection of underground resources.

The study of the pollution vulnerability of the groundwater was based on the DRASTIC index (US Environmental Protection Agency 1987), which allowed a relative assessment of the different units.

Building Materials Map

Given the absence of quarries and borrow areas inside the city, it was considered useful to identify, in the neighbouring countryside, the locations of quarries liable to supply construction materials for the civil engineering projects.

The materials required for the works executed in the city come from neighbouring zones, thus the distance between the quarry and the site is very important in terms of costs.

Therefore, the definition of the area covered by this survey took into account the usually acceptable economic distance for a source of construction materials for current engineering works considering its road transport.

Since this covers a wider area this is the only map presented at a scale of 1/25.000.

Synthesis Maps

Geotechnical Zoning Map

The geotechnical zoning map constitutes an excellent tool for planning. It is a very good base for preliminary design, allowing to anticipate possible constraints or plus values of a certain site for a given intervention and as well to anticipate the estimated of costs of works.

This map was based on the information from the Geological Map and from the investigations and geotechnical tests (Investigation Works Map/GEODATA) and from other factors maps, such as the Geomorphological and the Surface Occupation Maps.

Criteria adopted

The criteria used to identify different geotechnical units in the city of Oporto were based on the International Association of Engineering Geology' specifications (1981) that consider the following aspects:

- identification of lithological type (based on petrographic properties);
- description of rock and soil properties (colour, texture, particle size, weathering degree, compactness or consistency and strength);
- description of the characteristics of the rock masses that are necessary to the assessment of their behaviour (based on the structure, discontinuities and weathering profile).

The identification of lithology and the main petrographic characteristics was based on the Geological Map.

Rock material strength was classified according to the scheme of the International Society for Rock Mechanics, ISRM (1977). In the case of cohesionless soils, the strength was evaluated by the relative density and according to the Terzaghi and Peck classification (1948), and the consistency strength, in the case of cohesive soils, according to Peck, Hanson and Thornburn classification (1974).

These classifications, based on the results of SPT tests, were major factor, were amongst the most important criteria used for the differentiation of some geotechnical units, especially soil formations.

Evaluation of the rock weathering and description of its discontinuities followed the classification proposed by the ISRM (1977). In addition to criteria associated with the degree of weathering and fracturing spacing, the classification of Deere (1964) and Deere *et al.* (1988), based on values of Rock Quality Designation(RQD) were also used.

In the description of the formations, the heterogeneity of both earth and rock masses and their composition were taken into account. The evaluation of heterogeneity was based essentially on the surface reconnaissance and on the results of statistical analysis of different tests. The levels of heterogeneity were considered: high, medium and low.

Graphic representation of non-outcropping geotechnical units used vertical and horizontal bars to represent a first and a second level below the surface, respectively. Whenever possible, the depth to which the represented levels extend was taken into account using classes (I to VI) for different depth intervals (Figure 2).

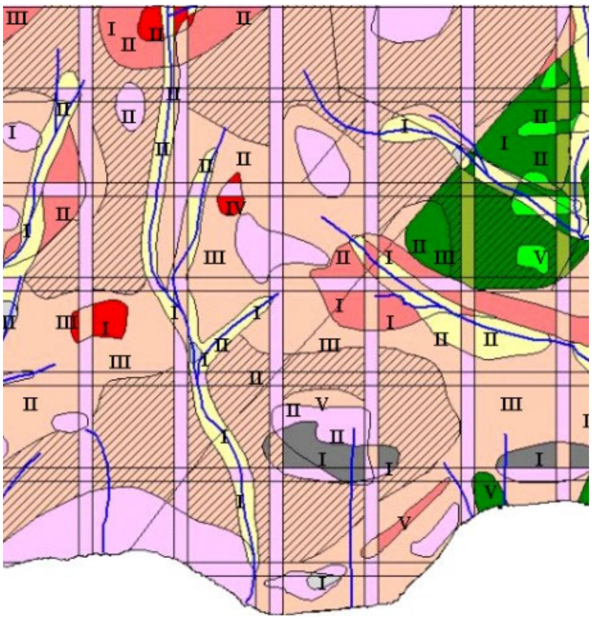

Figure 2. Geotechnical Zoning Map. Orthogonal bars method and classes of depth of occurrence

Geotechnical Units

Based on the above criteria, a total of 10 units were defined. Some of these were divided into subunits. The geotechnical characterisation of each unit was based on the data from site investigations and, *in situ* and laboratory tests (chapter 2.2.1). It is emphasised that, despite the large volume of data collected, significant discrepancies were observed in their spatial distribution, quality and nature.

The gathered data were processed in according to classic descriptive statistical methods, allowing the definition of the most representative values or value intervals for some of the current geotechnical parameters. Some correlations were made between these and the results from *in situ* tests in order to evaluate some of the geomechanical parameters of theses soils. Since these tests were executed by different companies and over a long period of time (between 1953 and 2001), by different methods and for multiple purposes the quality of data was variable and these would not support a study in greater depth that would allow a more complete characterisation of the materials.

In table 1, for example, a summary of results from the statistical processing for some of the units is presented.

Table 1. Example of main characteristics of some Geotechnical Units

Unit	Classification		Quality (a)	Angle of Friction (°)	Cohesion (kPa)	E (MPa)	V_L (m/s)	Heterog.
	ASTM	AASHTO						
G4-G	SM,SC (CL, ML)	A-2, A-1, A-4 (A-6, A-7, A-5)	$10 < N_{SPT} < 30$ ($4 < N_{SPT} < 10$)	30 a 36	10 a 20	10 a 30	450 a 900	Low
G4-C	SM, SC, CL (MH, ML)	A-4, A-2, A-1 (A-6, A-7, A-5)	$10 < N_{SPT} < 30$ ($4 < N_{SPT} < 10$)	30 a 34	8 a 18	10 a 30	-	Medium
G8-A	SM (SC)	A-2, A-1, A-4	$N_{SPT} > 30$ R0 (R1)	32 a 37	12 a 25	30 a 60	1000 a 1350	Low
G8-B	SM (SC)	A-2, A-1 (A-4)	$N_{SPT} > 50$ R1-0 (R2)	>38	Undefined	50 a 120	1250 a 1950	Low

Unit	Weather.	Fracture spacing	Quality (b)	Angle of Friction (°)	Cohesion (MPa)	Uniax. Compres. Strength (MPa)	Ei (GPa)	V_L (m/s)	Heterog.
G9-A	W3 (W4)	F2-4 (F5)	25%<RQD<75% R2-3 (R1, R4)	45° a 55°	0,5 a 1,3 (W4) 2,2 a 7,0 (W3)	3,0 a 10 (W4) 15 a 50 (W3) 35 a 75 (W2	0,5 a 3 (W4) 1 a 6 (W3)	1950-2700	Low
G9-B	W2-3	F2-3 (F1-2, F3-4)	RQD >75% R2-4 (R5)	-	-	70 a 120	15 a 25	2750 - 4200	Low

(a) soils: density or consistency classification (based on SPT tests)
(b) Rock masses: classification based on RQD and uniaxial compressive strength (R)

This information supported the definition of relevant aspects of behaviour of some geotechnical units in accordance with the types of construction work to be undertaken, as exemplified in Table 2.

Table 2. Relevant aspects of behaviour during construction

Unit	Excavations		Embankment materials	Foundations	Underground works
	Excavability	Slope stability			
G4-G	Digging (interference with the water table)	Poor to fair Shallow to medium slopes	Generally good to excellent. Fair to weak when silt-clay fraction prevails	Poor Low bearing capacity	Very poor
G4-C	Digging (interference with the water table and landslide)	Poor Shallow slopes. Masks and drainage trenches	N/A	Bad Avoid its use	Bad. Avoid its use
G8-A	Digging	Fair. Shallow to medium slopes according to discontinuities	Generally good to excellent	Fair	Poor
G8-B	Digging to Ripping		Very variable according to material	Good	Fair. Drainage precautions and immediate support
G9-A	Ripping and blasting	Fair to good. Medium to high slopes according to discontinuities	Appropriate for construction of rockfill embankments	Good to excellent	Fair to good according to characteristics of discontinuities
G9-B	Blasting				

Subsoil Constraints Map

This map is intended to anticipate major problems liable to occur during occupation or construction in certain areas of the city and, therefore, is a tool for urban planning to help ensure that the characteristics of each zone are compatible with its use, as well for supporting the design of civil engineering projects.

The map shows some relevant constraints to construction and occupation, that depend on various factors, especially the geological and geotechnical characteristics of materials, hydrogeological and surface drainage characteristics, the slope instability and subsoil uses of land.

The map is zoned in terms of these constraints. The following classes of constraints were identified:

- poor strength and deformability characteristics, sometimes associated with high water tables and significant thicknesses
- zones of unstable or potentially unstable slopes
- groundwater direct recharge zones
- most vulnerable formations to aquifer contamination.

One or more types of factors shown in the previously described maps are associated with each one of the defined classes of constraints to the ground occupation.

GEODATA

Within the Oporto Engineering Geological Map study, software for the management of geological and geotechnical information has been developed. The purpose is to provide rapid and easy access to all compiled information concerning the geotechnical investigation works and tests.

GEODATA was developed in Windows environment, using the Visual Basic 6.0, supported by a Relational Data Base (*GEODATA.mdb*), format MsAccess 97. Basically, the program consists of three main modules: Geophysical Investigations, Mechanical Investigations and *In Situ* Test Results.

Each one of the menus conducts the user to one of the associated sub-menus that contain one or more tables. The tables containing data from the same source are automatically cross-referenced from an index number. The numbers are the same as those used in the Investigation Works Map and, through these, the GEODATA system interrelates with the location of data on that map.

The programme can be consulted by type of work, location, number, lithology or geotechnical type and the printing has an independent access from the respective general menus

Figure 3 shows a layout of the modular structure of the programme.

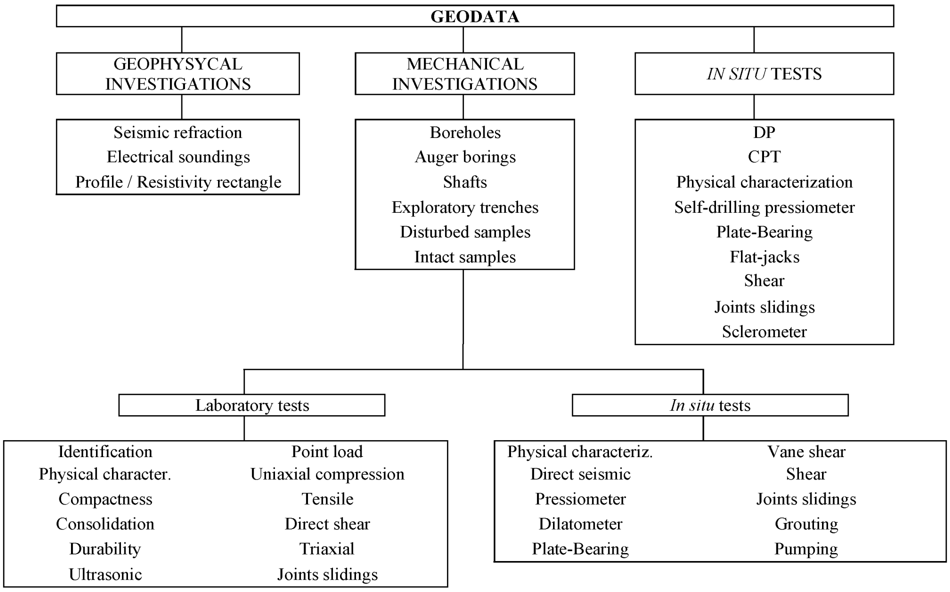

Figure 3. GEODATA modular structure

Figure 4 presents some menus, submenus and tables of the program.

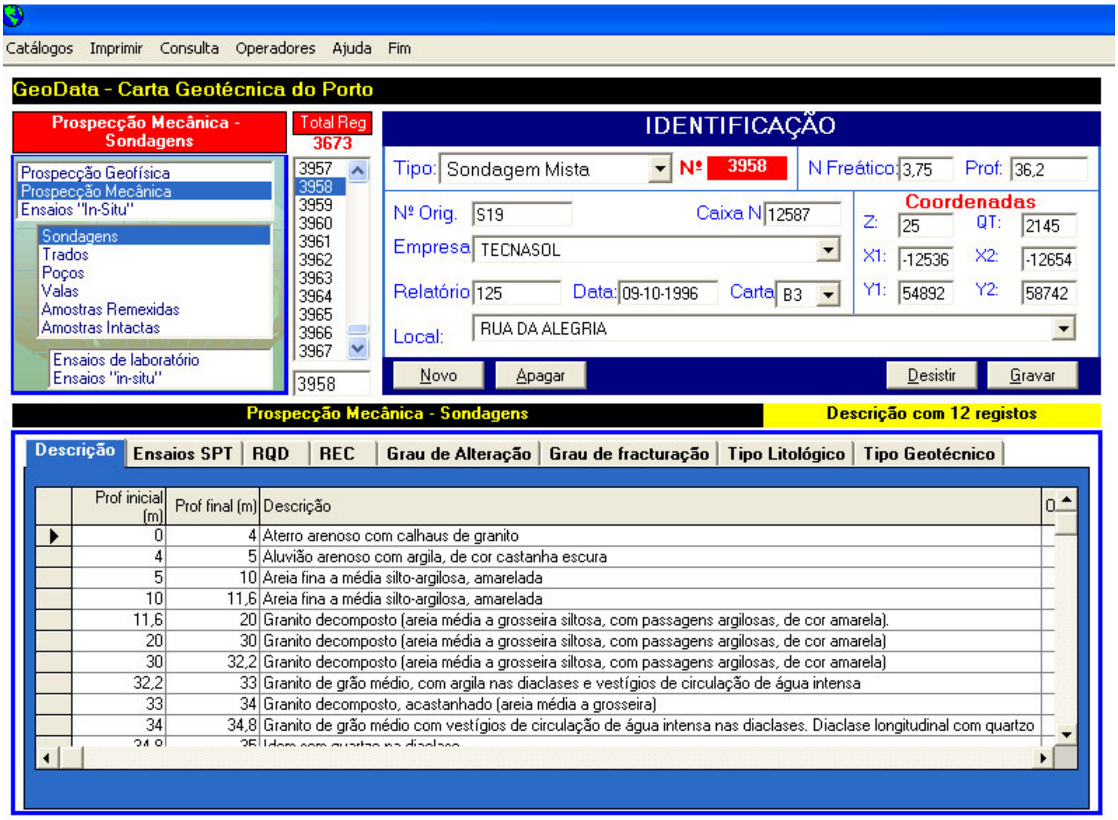

Figure 4. Principal menus, submenus and tables of GEODATA

REFERENCES

AIGE, 1981. Com. on Eng. Geol. Mapp. Rock and Soil Description and Classification for Engineering Geological Mapping. Bull. IAEG nº24, pp 235-274.

COBA, S.A., Faculdade de Ciências da Universidade do Porto, 1993. *Carta Geotécnica do Porto*. 1ª edição. Câmara Municipal do Porto (in Portuguese).

COBA, S.A., Faculdade de Ciências da Universidade do Porto, 2003. *Carta Geotécnica do Porto*. 2ª edição. Câmara Municipal do Porto (in Portuguese).

DEERE, D.U., 1964. Technical description of rock cores for engineering purposes. *Rock Mechanics and Engineering Geology, Vol. 1, Nº.1, 17-22*.

DEERE, D.U., Deere, D.W., 1988. The RQD index practice. Proc. Symp. Rock Classif. Eng. Purp., *ASTM, Special Technical Publication 984, pp. 91-101*, Philadelphia.

PECK, R., HANSON, W.E., THORNBURN, R.H., 1974. Foundation engineering. *2nd Edition, John Wiley & Sons, Inc, New York.*

SIMR, 1977. Commission on Standardization of Laboratory and Field Tests. Suggested methods for the qualitative description of discontinuities in rock masses. Committee on field tests. *Document nº 4. pp 320-368*.

TERZAGHI, K., PECK, R.B., 1948. Soil Mechanics in Engineering Practice. *1st Edition, John Wiley & Sons, New York.*

UNESCO, AIEG, 1976. Guide pour la préparation des cartes géotechniques. Sciences de la terre. Paris. *Les Presses de l'Unesco* (in French).

US ENVIRONMENTAL PROTECTION AGENCY 1987 DRASTIC: a standardised system for evaluating ground water pollution potential using hydrogeologic settings. EPA No 600287035. (Washington DC) 643pp