Data analysis and geotechnical properties modelling of urban soils : Case of Pessac, Gironde

DENYS BREYSSE[1], CHRISTOPHE PIETTE[2], ANTOINE MARACHE[3] & RICHARD FABRE[4]

[1] *CDGA, Université Bordeaux 1, France. (e-mail: d.breysse@cdga.u-bordeaux1.fr)*
[2] *Ville de Pessac, France. (e-mail: christophe.piette@mairie-pessac.fr)*
[3] *CDGA, Université Bordeaux 1, France. (e-mail: a.marache@cdga.u-bordeaux1.fr)*
[4] *CDGA, Université Bordeaux 1, France. (e-mail: r.fabre@cdga.u-bordeaux1.fr)*

Abstract: Within the framework of the RIVIERA project (french acronym for Risks in the city: amenities, networks, archaelogy), a research study aims at the building of a 3D geological model at the city scale. Data are also analyzed on specific geographical areas with the purpose of professionnal applications regarding geotechnical engineering, urban archaelogy and asset management of buried networks. This paper regards the geotechnical modelling at the town scale and it is focussed on the Pessac town case, in the southern part of Bordeaux city. The purpose is, from the global geological model built for the near-surface layers, to give information useful for urban planning, in relation with underground properties. These information will condition site prospection or urban planning choices. In a first step, a large amount of data have been gathered from various geotechnical prospection reports. Thus, we have;

- identified geotechnical layers most frequently found in this area, laying on data analysis and on the global geological model, built in parallel in the RIVIERA project,
- analyzed geotechnical information, to replace it in the general geographic and geotechnical frame,
- made an inventory, for all the representative layers, of geotechnical properties which are well-enough documented such as to enable a modelling strategy,
- performed a statistical analysis of these data, to check how (and at what scale) laws can be assessed regarding the spatial distribution of these layers or of their properties.

These data are managed such as to rebuild a synthetic 3D picture of the underground in the area considered.

Résumé: Dans le cadre du projet RIVIERA (Risques en Villes: Equipement, Réseaux, Archéologie), une recherche est menée sur la construction de modèles géologiques 3D intégrés à l'échelle d'une agglomération. Les données sont aussi analysées sur des secteurs géographiques plus limités dans l'optique d'applications professionnalisées, dans les domaines de l'ingénierie géotechnique, de l'archéologie urbaine et de la gestion des réseaux techniques urbains. Cette communication porte sur la modélisation des données géotechniques à l'échelle de la ville et s'appuie sur l'étude menée sur la Ville de Pessac, en banlieue de Bordeaux. Il s'agit, en s'appuyant sur le modèle géologique global des formations superficielles établi à l'échelle de l'agglomération, de fournir, en amont des opérations d'aménagement, des informations relatives au sous-sol et de nature à orienter les stratégies de reconnaissance des sites ou les perspectives d'aménagement. Nous avons dans un premier temps rassemblé un grand nombre de dossiers d'études géotechniques, qui sont venus compléter les données géotechniques qui accompagnent parfois les forages géologiques documentés dans le cadre du Projet RIVIERA. Nous avons ensuite :

- identifié les formations géotechniques rencontrées usuellement sur le secteur, en nous appuyant sur les données recueillies et sur le modèle géologique construit en parallèle dans le Projet RIVIERA,
- analysé les dossiers géotechniques pour les replacer dans ce contexte général, géographique et géotechnique,
- fait l'inventaire, pour les formations choisies comme représentatives du sous-sol, des propriétés géotechniques suffisamment documentées pour qu'une modélisation puisse être menée,
- procédé à l'analyse statistique de ces données pour voir dans quelle mesure (et à quelle échelle) on peut établir des lois sur la distribution spatiale des formations ou sur leurs propriétés.

Ces informations sont destinées à être synthétisées pour reconstruire une image géotechnique tridimensionnelle du sous-sol du secteur concerné.

Keywords: 3D models, geographic information systems, geotechnical engineering, mechanical properties, risk assessment

INTRODUCTION

Geotechnical uncertainties and their consequences

Urban underground is, in spite of its development, a mainly unknown space (Barles et al. 1999, Breysse et Kastner 2003). One of the purposes of the Europeen Construction Technology Platform is to "make undergound transparent" (http://www:ectp.org) before year 2030. An improved mastering of geometry and mechanical properties of undergound layers would make projects safer from an economical point of view as well as from a technological point of view. It would also help to justify decisions regarding works or urban planning and would help in assessing their impact on the natural environment.

Our knowledge of this medium mostly come from the disordered accumulation of data resulting from prospection campaigns, instead of an organized strategy. Usually, data are gathered to fulfill short term requirements and their memory is quickly lost. The expertise and individual memory of some practitioners is the only way to remember them. Decades after decades, a huge amount of information has been gathered, which constitutes today a "deposit" which remains to be worked. Few experiments of coding and analysis of urban data have been undertaken (Auvinet et al. 2005, Usseglio 1980, Boitte 1999) either to build representative sections, or with a statistical or geostatistical purpose. A trial had even been undertaken in the Bordeaux city (Largillier et al. 1974) when it was question of building an underground metro, later abandoned.

Geotechnical database of the RIVIERA project

Aims of the RIVIERA project

The RIVIERA project, supported by RGC&U network (funded by the french ministries of Research and of Public Works), aims to add value to all soil data available regarding the underground of the Bordeaux city. Project partners (University Bordeaux 1, BRGM, Pessac Municipality, Lyonnaise des Eaux, Regional Direction of Archeology) have decided to gather, analyze and work these data such as to first build a global geological model (Dominique 2004) and develop in a second step professional applications devoted to urban planning, asset management of buried networks and archaelogy. The paper discusses only the geotechnical part of this project.

Geotechnical modelling is here limited to the near-surface layers (in the 0-20 meters depth range), these layers being the more concerned with urban planning. The spatial variability of these layers has important consequences on urban works and on constructions, as it has been shown in several publications on foundation reliability (Ng, 2003, Bauduin, 2003) or on watertable level variations (Bartolomey et al. 2003). The research project aims to answer questions such as:

- what is, at a given point, the depth and the nature of underground layers ?
- what range of mechanical properties can be expected ?
- is it relevant to distinguish layers regarding their spatial arrangement ? their depth ? their lithology ?

Pessac town: the site

The town of Pessac, located in the south/western part of Bordeaux area, covers 38,82 km^2, roughly under a rectangular shape, whose length is about 16 km and width is 4 to 5 km. This rectangle is divided into two parts by the circular motorway. Population is dense in the north-eastern part (limit of Bordeaux city) and slightly decreases when going south-west, which explains the small quantity of data in this area, Figure 1.

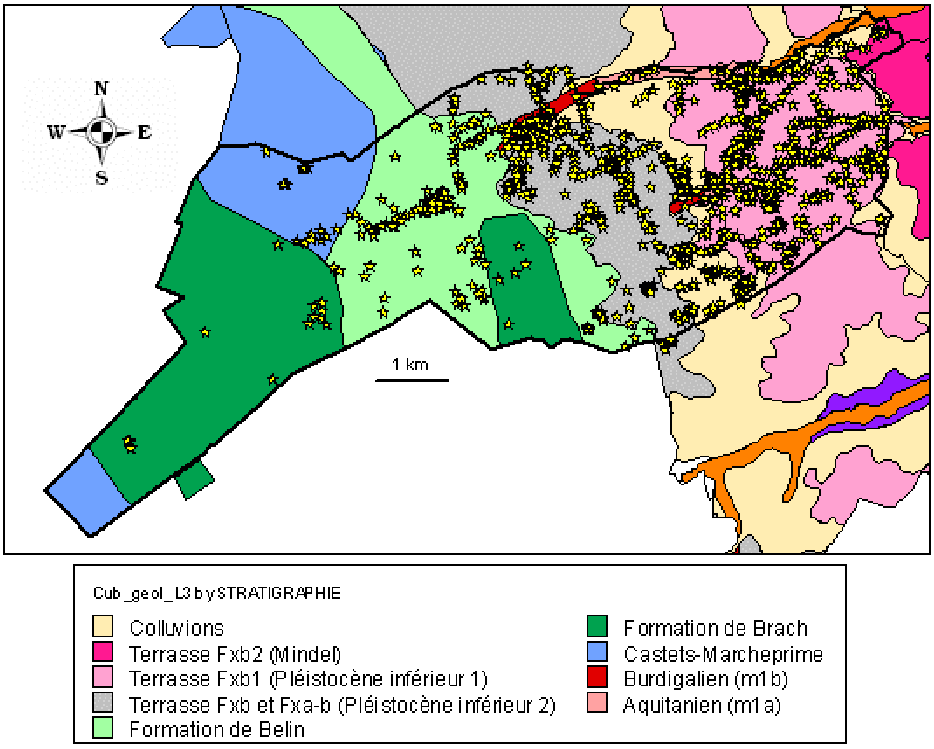

Figure 1. Geologic map of Pessac city and location (stars) of lithological information (from borings)

Topography is smooth, the eastern part of the town being on alluvial terraces of the Garonne river (marked Fxb, Fxb1, Fxb2 on Figures 1 and 2), with a slope approximately 1/200, and western part being in Landes sandy formation, roughly horizontal. The substratum is mostly limestone (from miocene or oligocene era) at 10 meters depth in average.

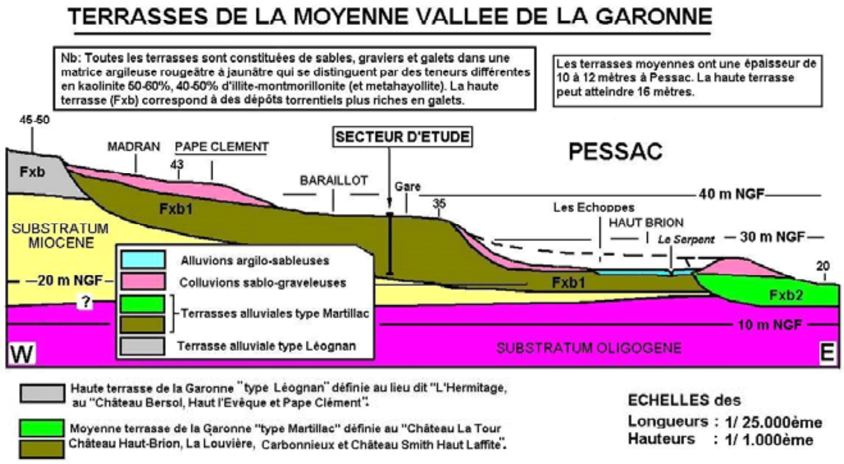

Figure 2. Schematic geologic section in the south-west/north east direction (Fabre 2003)

Data base description

Available data result from

- geologic logs (borings), which provide lithologic and stratigraphic information. These data are the basis for the global geologic model, which must be fitted to urban constraints and accurately describe the near surface layers,
- hydrogeologic data (borings and water table monitoring), which are the basis of the hydrogeologic model, which is also condtioned by geologic data,
- geotechnical data, coming from prospecting reports.

For practical reasons, the geotechnical approach is developed on a test-area: that of Pessac city, which is, with its 56 000 inhabitants, the third town of the urban area. An improved knowledge of underground properties is supposed to be important by the municipality which is at a turning point of its development (building of a surface transportation line, rehabilitation of the city center...). It will also enable a better assessment of risks induced by sensitive clays, which are located in some parts of the city (Ribeyrols, 2004).

The properties which interest the geotechnician (stiffness, water content, mechanical strength…) depend on lithology, on depth, but also on the history of these layers. To be able to estimate these properties without measuring them directly (i.e. from spatial location, lithology, or any other information) supposes that one is able to qualify and quantify the spatial organization of underground layers and their mechanical consequences. Geotechnical modelling is thus in the follow-up of geologic modelling, which gives the main frame.

Difficulties

About 10 000 borings have been collected for the urban area, Figure 3, and several hundreds of geotechnical borings have been documented of Pessac town, Figure 4, for which specific efforts of data gathering have been undertaken. Regarding lithology, 1232 lithological sections are availbale (141 of them coming from pressuremeter tests), for a cumulated length amounting 12 509 m. Table 1 provides the numbers regarding each classical geotechnical test: static and dynamic penetrometer, and pressuremeter.

Table 1. Inventory of geotechnical information (PD : dynamic penetrometer, PS : static penetrometer, SP : pressuremeter). Pessac : numbers for the whole town, Fxb1 : terrace only.

	PD		PS		SP	
	Pessac	Fxb1	Pessac	Fxb1	Pessac	Fxb1
number of logs	155	39	62	42	141	46
number of data points	1430	355	764	418	1203	357
number of useful mechanical recordings						
	Q_d : 1430	Q_d : 355	q_c : 751	q_c : 406	E_M : 1203	E_M : 357
			f_s : 691	f_s : 368	p_l : 1203	p_l : 357
			f_s/q_c : 679	f_s/q_c : 356	p_f : 961	p_f : 296
					E_M/p_l : 1203	E_M/p_l : 357

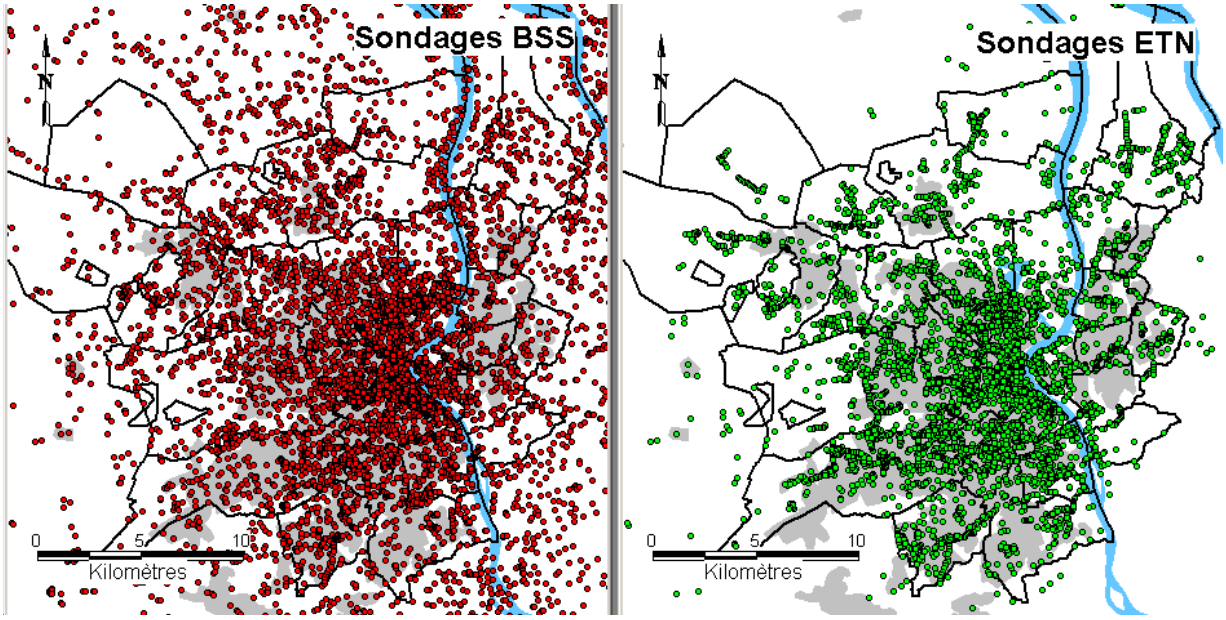

Figure 3. Respective location of data for two sources of information (BRGM on left, Lyonnaise des Eaux on right)

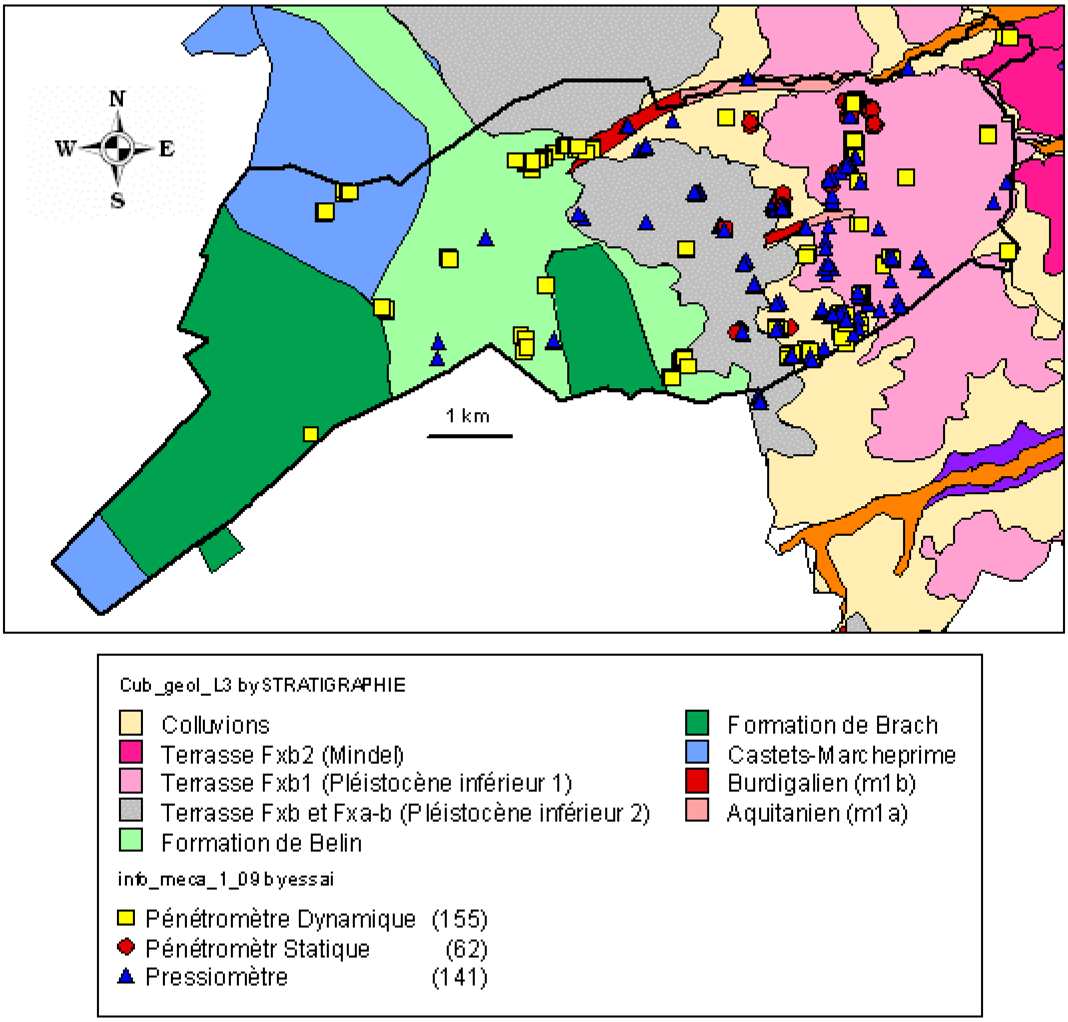

Figure 4. Location of geotechnical information.

The analysis of data encounters many difficulties. Main difficulties are:

- the kind of geotechnical prospection (pressuremeter, static and dynamic pentrometer, laboratory tests…). Since there does not exist any normalized technique for translating all these data in a unique reference format, each data set must be analyzed separately,
- the intrinsic spatial variability within layers, in both horizontal and vertical directions. This variability comes from changes in the geologic nature (substratum, terraces…), but also from very high variations at short distance in a given layer. Largillier, 1973, did not succeed in finding any classification system or zoning criterion, or deposit laws, and he speaks of a "apparent anarchy" for the spatial distribution of these soils. This disorder justifies the fact that we only aim at a statistical estimation of properties (in spite of the high number of data, the mean density of lithological borings is lower than 1 for 3 hectares),
- the quality, often poor, of data: available test results have often been synthetized and the original measurements have been lost. The loss of normalized protocols for geotechnical tests (or the fact that, when they exist, they are not followed), often leads to poor results. In a first stage, all data are however considered to be relevant. The loss of accuracy also concerns geographic positioning in (X, Y, Z), which make a serious check mandatory, to avoid spurious information to be considered as relevant. Figure 5 shows how two data sets coming from two sources are, in fact, identical, once uncertainty on (X, Y) has been identified.
- the absence of a geotechnical lexicon, and the large variety of lithological descriptions used by geotechnicians during originale data gathering.

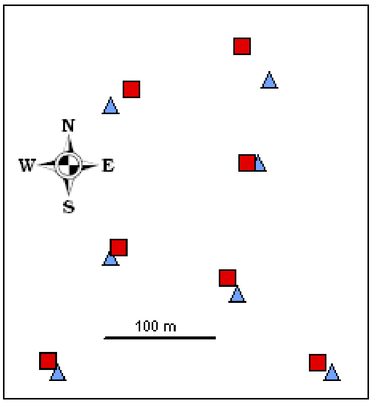

Figure 5. Identifying spurious twinned data sets.

Reference lexicon

Data are coded in an Access® Data Base. A certain number of properties are attached to each material point (x, y, z). Defining a reference lexicon must fulfill concision requirements, and possible use for geological (being able to distinguish between geologic formations), hydrogeological (enabling the description of permeability) and geotechnical purposes. A unique lexicon has been defined, resulting from a compromise between the requested time for coding and the loss of information which results from any coding process. It is made of a series of fields:

- a stratigraphy field, which enables the coding of a value within the set {substratum, decalcification clays, quaternary, fills}. The spelling "quaternary" corresponds, for the Pessac area, to two terraces and a slope formation between the two terraces. These three formations can easily be distinguished by their (x, y) values,
- three lithology fields : "lithology 1", "lithology 2", "lithology 3" which enable to provide increasingly detailed information on lithology at a given point. For instance, a "sandy gravel with some clayey parts" can be coded "gravel" + "sand" + "clay",
- a last field, which gives relevant information regarding the geologic context, about the colour, the consistency or the degree of alteration...

Quality and reliability of data

Statistical analysis in soil mechanics encounters many difficulties, the first of them being the poor quality of geotechnical tests and of their results (Moussouteguy et al. 2002, Breysse 2003). It is therefore important to assess the data quality. Thus it will be possible to validate any statistical result by testing its stability when sampling more or less "reliable" data set.

A specific index is introduced, quantifying the « quality of lithologic information », according to rules specified in Table 2, in which the alphabetical order does not prejudge the real quality order. At present time, the used coding are only a, b and f, but one can hope that, in a near future, statistical analysis will be a means to estimate lithology (index d).

The « b » coding is also detailed, depending on the distance at which direct information has been obtained. It is assumed that the lithology at the (x, y, z) point is that seen at the same altitude in the nearest boring. This can be criticized, since stratigraphic variations are the rule (boundaries between layers are not horizontal). It is estimated that the average bias is about 50 cm to 1 m on the boundary altitude. Table 3 provides the statistical distribution for the b coding.

Table 2. Index for the quality of lithologic information

quality index	**source of information**
a	description comes from the test itself (f.i. pressuremeter)
b	description comes from a nearby boring
c	description comes from interpolation on a section
d	description comes from statistical analysis
e	description comes from the site expertise
f	description not available

Table 3. Statistical distribution of distances to the nearest boring

	a	**b1**	**b2**	**b3**	**b4**	**b5**
		d < 10 m	d < 30 m	d < 50 m	d < 100 m	d > 100 m
SP	1203					
PD	43	409	452	268	157	101
PS	24	183	364	58	74	61

DATA ANALYSIS

Aims

It is looked for a tool enabling to provide added value to geological and geotechnical data, either adding information on the probable lithology (this is useful for penetrometric tests), or estimating the value of geotechnical properties where and when they are not available (this is useful when samples exist, but without mechanical testing). Probabilistic methods are the core of such a tool.

Principles and methods : bayesian inference

A unique boring gives information like :

"At a given depth z_1 one finds the S_1 soil with mechanical properties M_1".

The analysis of several borings gives different information:

" At a given depth z_1, the probability of finding the S_1 soil is p_1. Knowing that, one also knows that the probability of having the mechanical properties M_1 is p'_1".

This method can be used for pressuremeter tests (SP) as well as for dynamic penetrometer tests (PD). For pressuremeter, one has usually both a lithologic description from the cuttings or from the boring muds, and mechanical properties (modulus, creep pressure, limit pressure). In the case of penetrometer, lithology is not available, and it must be assessed from nearby borings, as described above.

The bayesian inference comes from the equation :

$$P\,(X/Y) = P\,(Y/X)\,.\,P\,(X)\,/\,P\,(Y)$$

which can be used either

- for estimating the mechanical properties M from the lithologic description :

$$P\,(M/\text{litho}) = P\,(\text{litho}/M)\,.\,P\,(M)\,/\,P\,(\text{litho}) \qquad [1]$$

- or for estimating the lithology from M :

$$P\,(\text{litho}/M) = P\,(M/\text{litho}).\,P\,(\text{litho})\,/\,P\,(M) \qquad [2]$$

P(M) and P(litho) are inferred from the statistical analysis of the whole coded data set. P (litho/M) and P (M/litho) values are inferred from analysis on selected subsets.

Curves on Figure 6 and Figure 7 respectively show the cumulated distribution of pressuremeter modulus E_M and of cone strength Q_d for the most usual lithologies. Table 4 provides the statistical results for pressuremeter properties (regarding clays, the decalcification clays will have to be distinguished from the clay layers in the sandy-gravel layers).

Table 4. Statistics upon pressumeter parameter for main types of soils (points with $E_M/p_l > 35$ have been removed)

lithology	number of points	mean depth (m)	mean E_M (MPa)	mean p_l (MPa)	mean E_M/p_l (MPa)
all soils	1107	7,2	16,5		
fillings	19	1,3	6,7	0,6	9,6
sands	446	5,1	10,8	1,2	8,2
gravels	121	5,0	16,5	1,6	9,9
clays	193	5,6	9,4	0,9	8,4
limestones	29	9,3	25,5	2,2	10,5
marls	273	14,1	63,5	3,2	19,1

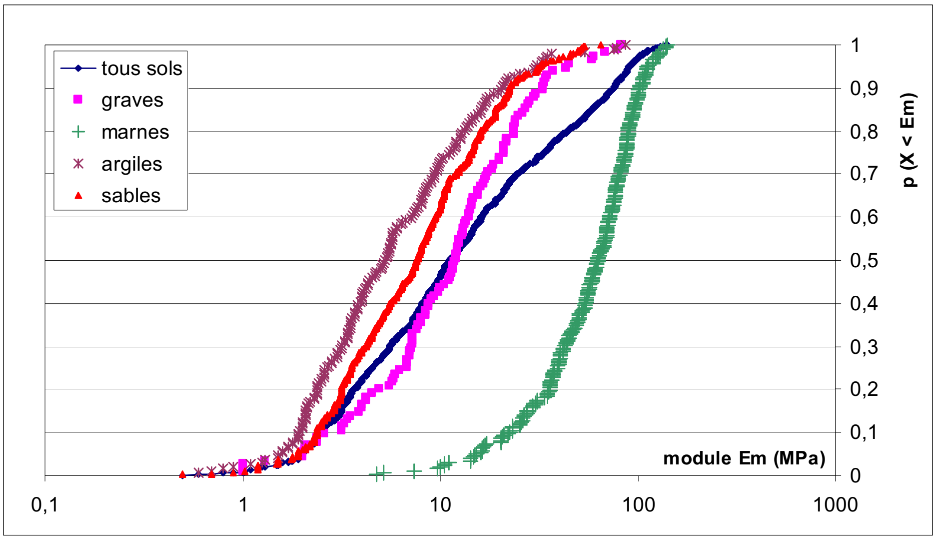

Figure 6. Cumulated distribution function of pressuremeter modulus E_M.

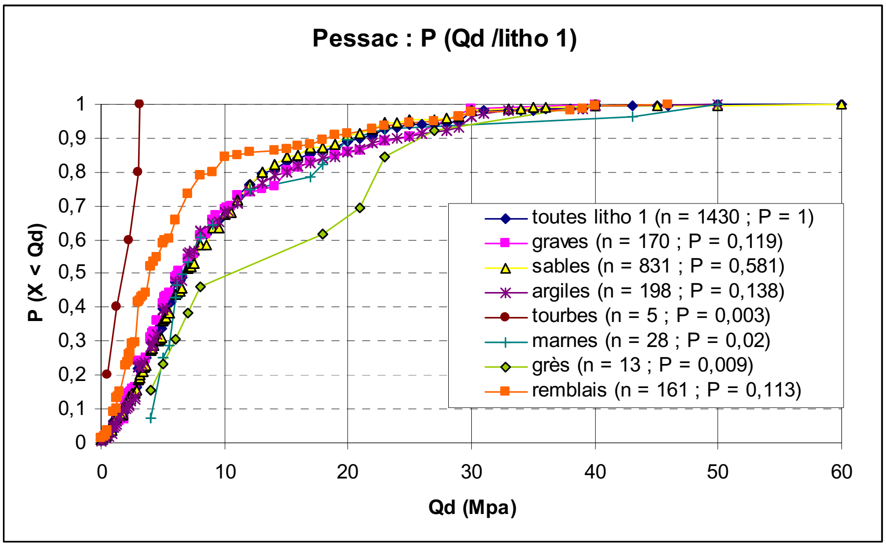

Figure 7. Cumulated distribution function of cone strength Q_d.

It can be ssen that the mean pressuremeter properties significantly vary according to the lithology. Fillings and marls (that are encountered at higher depths) have respectively lower and higher properties. The properties of clays, sands and gravels have the same magnitude, but they are however slightly different, for the same average depth.

Analysis of pressuremeter data

If only the most usual soils are considered, Figure 8 shows what can be provided by conditional probabilities, comparing the probability of finding a specific lithology without any mechanical information and that of finding it knowing the mechanical property (here p_l) in the surroundings. One can see that the *a posteriori* probabilities are significantly different from the *a priori* probabilities, even if the curves mutually overlap.

The same reasoning can be done for the modulus, or for the limit pressure/modulus pair. The practical limit of such a method is the size of the set on which the probabilities are built, which can be too small to be considered as representative.

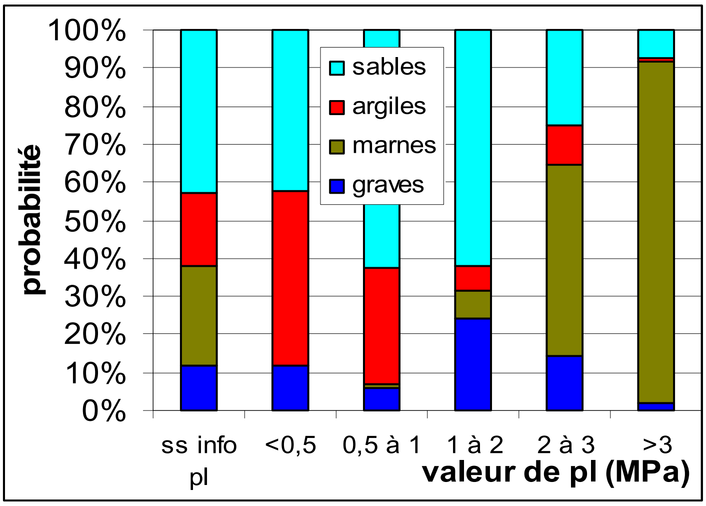

Figure 8. A priori and a posteriori probabilities for lithology, given the p_l value.

Analysis of penetrometer data

Figure 9 gives results analogous to those of Figure 8, regarding the cone strength. It can be seen that the knowledge of the cone strength brings few information (this could be seen on Figure 7, where the curves where largely overlapping). Three reasons can be invoked for that:

- the cone strength is really (statistically) the same for sands, clays and gravels,
- existing possible differences are masked due to acquisition noise. It is well known that penetrometer measurements are very sensitive to local noise (Breysse et al 2002). It will be interesting to compare these results with those of static penetrometer, for which the pair cone strength-friction is known to be more discriminating, is available,
- our rule used for assessing the lithology creates too noisy information and it must be improved. It is possible that the "gravels" curve on Figure 7 is in fact a mixed curve of gravels, sands and clays encountered at this depth.

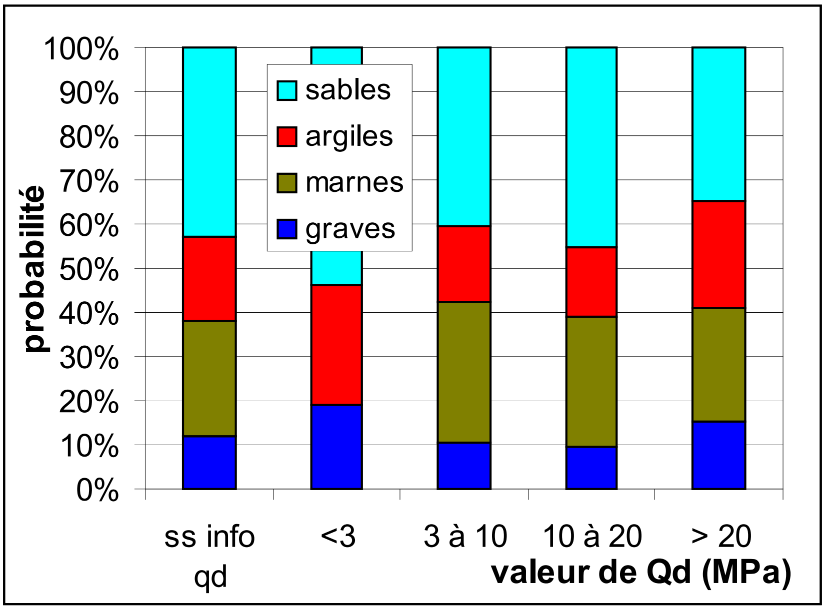

Figure 9. A priori and a posteriori probabilities for lithology, knowing cone strength.

To go further

In fact, this first analysis, even if it brings some information, is too rough, since it ignores the influence of several factors:

- influence of depth, on one hand because the geostatic phenomenon, on the other hand because all soils have not the same statistical distribution in depth, for purely obvious geologic reasons. Figure 10 gives, for instance, the "statistical lithology" (probability of finding a given lithology at a given depth), built from pressuremeter data. It confirms the most frequent presence of marls below 10 meters, but gives no clues for separating sands, clays and gravels. In addition, a preliminary statistical analysis has shown that, for these soils, the pressuremeter properties are not significantly correlated with depth. For marls, a significant effect has been found, with a slight and regular increase of modulus and limit pressure with depth (in average, the modulus is doubled and the limit pressure increased by 50 % between 10 and 20 m) ;

- the geometrical spatial fabric of layers: terraces are bounded in the (x, y) domain and it can be assumed that a given lithology does not correspond to identical mechanical properties depending on the fact that the layer is in such or such geological formation (this assumption of course needs to be validated).

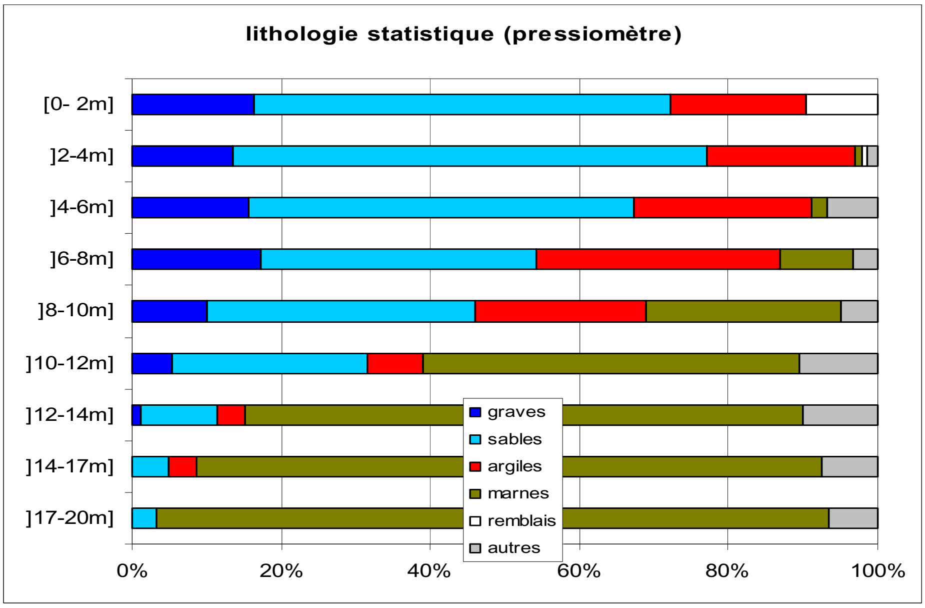

Figure 10. Statistical lithology, obtained from pressuremeter.

CONCLUSIONS AND PERSPECTIVES

This paper has described how, in the RIVIERA research project, the coding and analysis of geotechnical informations has been undertaken at the scale of a city. The project is currently under progress and only partial conclusions can be drawn at this date. However, it has yet been shown that:

- data from pressuremeter and penetrometer tests can be worked with,
- it is possible to build the statistical distribution of the various formations, regarding depth, location in the (x, y) domain and geotechnical properties,
- knowing the lithology provides additional information, since it seems possible to improve the a priori knowledge on mechanical properties.

In any case, geotechnical prospecting will remain indispensable. A better knowledge of the undergound will provide a better guidance, for instance, with a more reliable estimate of requested depth to reach the substratum, or marley layers of good characteristics.

Many tracks remain to be studied : the role of geology of near-surface formations, a more accurate description of lithology (until now, only the first field of lithology has been analyzed), the correlations between the presence of clays (even as a secondary lithology) and the occurrence of subsidence…

From a more theoretical point of view, it will be focussed on the spatial organization of lithology, such as to rebuild, using geostatistics, a 3D picture of the undergroung, like it has yet been done for hydrogeologic properties, as shown in a companion paper at this conference.

Acknowledgements: This work has been undertaken in the frame work of the RIVIERA project, which is a research activity sponsored by the RGC&U network, funded by the Ministries of Research and of Public Woorks. The authors thank the project partners for their help (BRGM Orléans, LRPC Bordeaux, DRAC Aquitaine, Lyonnaise des Eaux) and the Communauté Urbaine de Bordeaux, for providing access to the data.

Corresponding author: Pr Denys BREYSSE, CDGA, Université Bordeaux 1, Avenue des Facultés, Talence, 33405, France. Tel: +33 5 40 00 88 40. Email: d.breysse@cdga.u-bordeaux1.fr.

REFERENCES

AUVINET G., JUAREZ M. & VALDEZ Y.P. 2005. Caractérisation géostatistique du sol lacustre de la vallée de Mexico, *Rev. Fr. Géotech*., **110**, 19-26 (in French).

BARLES S., BREYSSE D., GUILLERME A. & LEYVAL C. 1999. *Le sol urbain* , ed. Economica, 278p (in French).

BARTOLOMEY A.A., MAKOVETSKY O.A., PONOMARYOV A.B. & OFRIKHTER V.G. 2003. Geotechnical trends in urban terrains evolution, In: *Proc. XIII ECSMGE Conference,* 573-578, Prague.

BAUDUIN C. 2003. Uncertainties and their relevance for the design of deep excavations near existing structures, *Proc. XIII ECSMGE Conf.,* 445-449, Prague.

BOITTE B. & SOUYAT E. 1999. *Création d'une base de données géotechniques pour le Grand Lyon*, PIRD Report, INSA Lyon, 54 pages (in French).

BREYSSE D., RODIER X., NIANDOU H., GALINIE H. & LAURENT A. 2002. Le pénétromètre et l'hétérogénéité des sols archéologiques urbains, *Rev. Fr. Géotechnique* (special issue Sols Urbains), **100**, 3° trim. 2002, p. 43-58 (in French).

BREYSSE D. 2003. Quantifier l'hétérogénéité du sol urbain et modéliser ses effets, pp. 123-146, in BREYSSE D., KASTNER R., *Sols urbains*, Traité Mécanique et Ingénierie des Matériaux, ISBN 2-7462-0753-2 (in French).

BREYSSE D. & KASTNER R. 2003. *Sols urbains*, Traité MIM, ed. Lavoisier, 462 pages (in French).

DOMINIQUE S. 2004. *Modélisation géologique du sous-sol urbain,* MASTER TOAE report, Université Bordeaux 1, 56 pages (in French).

FABRE R. 2003. *Coupe géologique schématique sud-ouest / nord-est*, RIVIERA Project, unpublished (in French).

LARGILLIER J.F. & GAYET J. 1974. *Géologie – géotechnique : rapport TCSP de l'agglomération bordelaise – étude préliminaire*, Study report, 74 pages (in French).

MOUSSOUTEGUY N., BREYSSE D. & CHASSAGNE P. 2002. Decrease of geotechnical uncertainties via a better knowledge of the soil's heterogeneity, *RFGC* (n° spécial JNF3), 3/2002, pp. 343-354.

NG I.T. 2003. Influence of spatial variability and uncertainty evaluation on reliability analysis of a single pile, In: *Proceedings of ICASP 9 Conference,* San Francisco, 1337-1342.

RIBEYROLS N. 2004. *Projet Riviera : contribution à la modélisation géotechnique du sous-sol de la Ville de Pessac*, MASTER TOAE report, Université Bordeaux 1, 80 p (in French).

USSEGLIO-POLATERA J.M. 1980. Contribution à la cartographie géotechnique de la Ville de Paris – étude de la butte de Belleville, UPMC Thesis, 271p (in French).