Tools and methods for constructing 3D geological models in the urban environment: the case of Bordeaux

BERNARD BOURGINE[1], SOPHIE DOMINIQUE[2], ANTOINE MARACHE[3] & PIERRE THIERRY[4]

[1] *BRGM, Orléans, France. (e-mail: b.bourgine@brgm.fr)*
[2] *CDGA, Université Bordeaux 1, France. (e-mail: s.dominique@cdga.u-bordeaux1.fr)*
[3] *CDGA, Université Bordeaux 1, France. (e-mail: a.marache@cdga.u-bordeaux1.fr)*
[4] *BRGM, Orléans, France. (e-mail: p.thierry@brgm.fr)*

Abstract: Research is being conducted within the scope of the RIVIERA project (Risks in Towns and Cities: Equipment, Networks and Archaeology) on the construction, at the scale of a built-up area, of integrated 3D geological models. This research aims to resolve the following specific difficulties:

- necessity of handling a very large amount of data (several thousand drill holes). This involves the design processing methods that are as automated as possible,
- frequent presence of redundant data or, conversely, apparently contradictory data and non-uniformity of the spatial distribution of data. This means it is necessary to have at one's disposal tools that enable similarities or inconsistencies between similar data to be rapidly identified as a function of the context and geological hypotheses,
- high spatial variability of the formations to be modelled, due to the fact that the relevant slice of ground for the planner is located at the level of surficial formations (fluvial alluviums, for example). It is then necessary to integrate as far as possible the geological rules governing their emplacement in order to control their interpolation, particularly in sectors where data is lacking. The nature of the processes must be taken into account (deposition, erosion, unconformity), as must the geometric constraints resulting from them (maximum altitude of an alluvial terrace, position of colluviums in relation to the slope or the nature of the terrain),
- beyond the description of the geological formations, it is the geo-mechanical or hydrological properties of the ground that are important for those working in the field: these aspects must be included in the modelling,
- evaluation of the local reliability of the model: this constitutes an imperative for its exploitation.

We describe a series of methods intended to solve the above-mentioned difficulties, when they are poorly or incorrectly resolved by usual modelling methods. These methods, either novel or adapted from existing geostatistical methods, facilitate the automation of the construction of 3D models and take problems of updating into account. We illustrate their implementation using the example of the city of Bordeaux (France).

Résumé: Dans le cadre du projet RIVIERA (Risques en Villes: Equipement, Réseaux, Archéologie), une recherche est menée sur la construction, à l'échelle d'une agglomération, de modèles géologiques 3D intégrés. Cette recherche vise à résoudre les difficultés spécifiques suivantes:

- nécessité de manipuler un très grand nombre de données (plusieurs milliers de forages), ce qui impose de concevoir des traitements aussi automatisés que possible;
- présence fréquente de données redondantes ou, à l'inverse, apparemment contradictoires, non uniformité de la répartition spatiale des données : il faut disposer d'outils permettant d'identifier rapidement les similarités ou incohérences entre données proches, en fonction du contexte et des hypothèses géologiques;
- forte variabilité spatiale des formations à modéliser, du fait que la tranche de sols pertinente pour l'aménageur se situe au niveau des formations superficielles (alluvions fluviatiles par exemple). Il faut alors intégrer au maximum les règles géologiques gouvernant leur mise en place afin de contrôler leur interpolation, notamment dans les secteurs sous-informés. La nature des processus doit être prise en compte (dépôt, érosion, non conformité), tout comme les contraintes géométriques qui en découlent (altitude maximale d'une terrasse alluviale, position des colluvions en relation avec la pente ou la nature du terrain);
- au-delà de la description des formations géologiques, ce sont les propriétés géo-mécaniques ou hydrologiques des sols qui importent aux praticiens : ces aspects doivent être intégrés dans la modélisation;
- évaluation de la fiabilité locale du modèle : ceci constitue un impératif pour son exploitation.

Nous présentons un ensemble de méthodes destinées à résoudre les difficultés évoquées ci-dessus, lorsqu'elles sont peu ou mal résolues par les méthodes de modélisation habituelles. Ces méthodes, nouvelles ou adaptées à partir de méthodes géostatistiques existantes, facilitent l'automatisation de la construction de modèles 3D, tout en prenant en compte les problèmes de mise à jour. Nous illustrons leur mise en oeuvre sur l'exemple de la ville de Bordeaux (France).

Keywords: 3D models, engineering geology, geology of cities, urban geosciences

INTRODUCTION

Many of the problems of today's major urban centres are directly or indirectly related to the geological, geotechnical and hydrogeological conditions beneath and around the city (McCall, De Mulder & Marker 1996). For example, landslides and ground instabilities cause substantial losses of life and property in urbanized areas (Thierry 2003, Thierry *et al*. 2004), and micro seismic behaviour has to be evaluated for risk assessment (Courrioux *et al*.

2003). When planning new infrastructures it is vital to anticipate what geological conditions are likely to be encountered, before carrying out any specific survey or investigation work (Chilès & Blanchin 1995). In a similar way, the design or management of underground sewer networks can be better planned with an appropriate knowledge of the nature of the terrains that are likely to be intersected by the network. This is why a 3-D (3-dimensionnal) geological model integrating various geo-engineering parameters is a key component of city management. However, building a geological model in an urban context is still a difficult task due to several factors. Firstly, a large amount of data needs to be handled – typically thousands of drill holes. This poses problems of controlling the consistency of data, as well as storing and easily displaying available information. Secondly, the quality of this information, gathered throughout the city's history, is often very heterogeneous. Available geological descriptions can range from the highest to the lowest quality, and do not always use the same vocabulary because data has not been acquired for the same purpose. As a consequence, data has to be reinterpreted prior to any use. Furthermore, the geological model must include geotechnical and hydrogeological parameters, which are generally available at a much lower density than is the case for geological information.

Despite experience provided by several urban-geological models realized or attempted in the past (Auvinet, Juarez & Medina-Cetina 2001, Bozzano *et al.* 1999, Dominique 2004, Ellison, Booth & Strange 1996, Maurenbrecher & Herbschleb 1995, Morfeldt & Persson 1997, Thierry 2003, Thierry *et al.* 2000, 2004) there is still a need for methods aiming to help combine data of different quality stemming from different sources and for procedures to help automation of data management and control. The objective of this paper is to present new tools that are being developed to control the data and model the geology of the city of Bordeaux and its suburbs (France) in the framework of a research program named RIVIERA. After presenting the objectives of the RIVIERA project and the geology of Greater Bordeaux, we will detail the first step of the work, *i.e.* data preparation and control and, specifically, the procedures developed in order to check the consistency of data. We will then focus on the construction of the geological model, which is based on the use of geological rules and on the definition of a litho-stratigraphic sequence. This paper will only address the geometrical aspect of geology modelling. Issues concerning improvement of the actual modelling process, as well as modelling of the properties of the terrain, which are the future phases of the RIVIERA project, will be introduced as future prospects in the final section of the paper.

THE RIVIERA PROJECT

The RIVIERA project is a project funded by the French government. It aims at developing methods and tools for the preliminary evaluation of geotechnical, hydrogeological and archaeological hazards at the scale of a city and its suburbs. The chosen test site is Greater Bordeaux (France). The idea is to propose operational tools that could be used by technical staff in charge of city development, in order to estimate, prior to a given project, the probability that difficulties could occur, with an estimation of the nature and extent of these difficulties. For the management of existing infrastructures, such as sewer networks, these tools could also help to identify vulnerable zones, for example in the event of a leakage. Three typical applications have been selected to test the methodology:

- the preliminary design of investigation work and evaluation of potential geotechnical difficulties in the case of a new urban project. This implies being able to delimit the geological formations that are likely to be encountered in a given area, as well as estimate their geotechnical properties (Breysse *et al.* 2006),
- optimisation of the monitoring of sewer networks and knowing - from preliminary modelling - the nature and hydrogeological characteristics of geological terrains intersected by these networks (Marache *et al.* 2006),
- evaluation of archaeological potential: for this particular application, the aim is to image the natural topography before the "modern" city development. This is equivalent to constructing the natural topography below the anthropogenic fill in.

To achieve these goals, it is necessary:

- to gather available data,
- to control, homogenize and interpret these data,
- to define the geological bodies to be modelled and to define the geotechnical/hydrogeological parameters that are to be taken into account within these bodies,
- to build a 3-D geological model integrating these various aspects,
- to design specific tools to exploit the 3-D model.

Two public research partners are involved in this project: Bordeaux 1 University, BRGM (French Geological Survey) as well as three partners from the city stakeholders: the Lyonnaise des Eaux Company (sewer application), Pessac City (geotechnical application), the Regional Archaeology Department (archaeology application). The LRPC (a civil engineering research centre) has also joined the project as an associated partner.

Geological context of Greater Bordeaux

Greater Bordeaux is located on the north west border of the Aquitaine sedimentary basin (France). The geological formations that can be encountered in the studied area within the first tens of metres consist of Cenozoic deposits and Quaternary alluviums (Dubreuilh 1976). From bottom to top, the Cenozoic deposits include (Figure 1 & 2): limestones, locally karstified (Rupelian), carbonated clays (Chattian), and two levels of sand or limestone linked to two transgressions in the Miocene period (Aquitanian and Burdigalian). At the end of the Miocene, the area was affected by an important erosion. During the Pleistocene, the area was subjected to several phases of erosion and deposition of fluvial alluviums, which led to the formation of seven staircases of terraces. These terraces are composed of sands and gravels with a more or less clayey matrix. Some of them can be more than 10 metres thick. During this period, colluviums covering terrace scarps also appeared. Finally during the Flandrian (early Holocene), recent alluviums filled the alluvial plains near the two rivers Garonne and Dordogne. These latter alluviums are made of peaty clays including more or less sand and can total up to a thickness of 15-20 m. The Cenozoic deposits are sub-horizontal, with a maximum dip of 2° towards the WSW. It should be noted that, due to the succession of deposition and erosion forming terraces during the Pleistocene and the Holocene, the most recent alluviums are located topographically below the oldest ones. It should also be noted that the different terraces and colluviums can be mistaken with each other when interpreting cuttings of a drill hole, if they are not carefully interpreted by a geologist, because they are composed of similar material. Moreover, the sand of the terraces can be mistakenly attributed to Miocene sand by non-specialists. This is why, despite the absence of tectonics, the interpretation of drill holes is not easy.

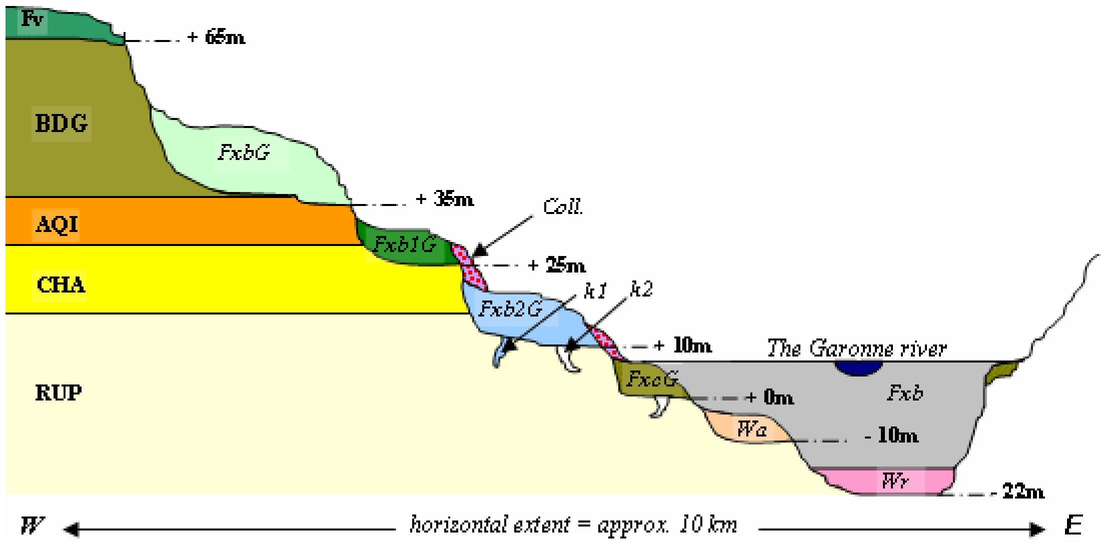

Figure 1. Synthetic W-E geological cross-section of Greater Bordeaux

Oligocene substratum: RUP = Rupelian; CHA = Chattian. Miocene substratum: AQI = Aquitanian; BDG = Burdigalian. Quaternary terraces: *Fv* = Basal lower Pleistocene; *FxbG*= middle lower Pleistocene; *Fxb1G*= terminal lower Pleistocene; *Fxb2G*= Mindel; *FxcG*= Riss; *Wa* and *Wr*= old and recent Wurm. Holocene : *Fxb*=Flandrian (early Holocene). *k1*and *k2*: filled and empty karst; *Coll.*=Colluviums

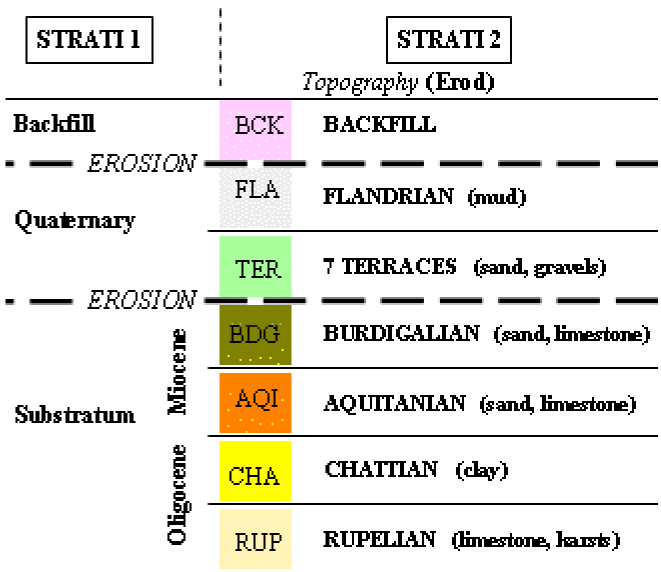

Figure 2. Stratigraphic referential

DATA PREPARATION AND CONTROL

Gathering data and defining a common referential

The more tedious - but necessary - work consists in gathering available data. Data can be of a very heterogeneous nature and can come from various sources: topography surveys, geological mapping, drill holes for geological, geotechnical or hydrogeological investigations, geological cross-sections of the first few metres intersected during civil engineering works (water or other networks, underground). Since the data are acquired initially for a specific purpose, their description can employ heterogeneous vocabulary. For example, geotechnical data focus more on a facies classification, while geological logs use a stratigraphic classification. Moreover, for a better comprehension for non-geologist users, a specific qualitative vocabulary is sometimes used. For example the Lyonnaise des Eaux Company, in charge of the sewer network management of Bordeaux, uses a description of terrain based on three attributes: the type of terrain (sand, gravels, etc.), the nature of this terrain (colour, alteration, etc.), and a third parameter defining the consistency of the terrain (compact, soft, plastic, etc.). Each attribute can be chosen within a specific lexicon, which was designed according to the needs of the sewer network management. To homogenize the different types of data, it is then necessary to define a common referential and express all data according to a standardized vocabulary. The other reason why this referential is necessary is that geological models aim to represent geological objects that make sense and that have their own characteristics in terms of geometry or lithology. When using or interpreting geotechnical or hydrogeological data, it is necessary to know from which geological object the data is related to, in order to know whether it is possible to interpolate / extrapolate this information.

In our case the geological referential is composed of three referentials managed through lexicons in an ACCESS© database:

- a stratigraphic referential (Figure 2)
- a lithologic referential (Table 1)
- a geotechnical referential

The stratigraphic referential is necessary to delimit the geological objects at the scale of the studied area. The main envelopes of geological objects are modelled using this referential, namely the Cenozoic substratum, the terraces and the Holocene alluviums. At this stage, each terrace is considered as a whole, *i.e.* there is no attempt to define channels or meanders within each terrace.

The lithologic referential is then used to characterize the geological formation within each of the stratigraphic units defined above. This referential is based on four attributes. The first one indicates the dominant lithology (*e.g.* gravels, sand). The second and third ones add precision to the dominant lithology (*e.g.* sandy, clayey) with a decreasing order of importance. The fourth one gives the colour, which can be a key parameter for discriminating two formations. A free text field is also available to store the full description of the geological formation encountered.

The geotechnical referential is used to manage and interpret geotechnical data. Since the objective of this paper is not to detail this geotechnical referential, the reader can refer to Breysse *et al.* 2005 & 2006 for more information.

Table 1. Lexicons for the lithologic referential

Lithology 1	Lithology 2 & 3	Color
gravels	pebbly	brown
sand	sandy	beige
fluvial silt	silty	maroon
clay	clayey	fawn
peat	peaty	red
marls	marly	blue
"faluns" (crags)	shelly	grey
limestone	calcareous	black
sandstone	sandy	ochre
Backfill		orange
unknown	*unknown*	*etc…*

For the preliminary geometry modelling, we intend to model the main geological objects, *i.e.* the four units forming the substratum, the seven terraces, the Flandrian and the backfill (Figure 2).

Applying the geological referential to geotechnical data

In Greater Bordeaux around 5 100 drill holes are available and had been coded, prior to the RIVIERA project, according to a geological referential based on the stratigraphic sequence of Figure 2 and including a lithology description. On the other hand, there are hundreds of geotechnical logs which are only described using the lithologic referential and a free text description. In order to be able to associate the appropriate stratigraphic attribute to each run of the geotechnical log, an algorithm was developed (Figure 3). For each run of the geotechnical log, this algorithm examines the values of the 3 lithology fields, of the colour field (Table 1) as well as the complete description. Then, according to the combination of these values, the algorithm attributes the stratigraphy using the terms of the stratigraphic referential (Figure 2). In the case of Bordeaux, this algorithm enables the stratigraphy to be attributed in

50 % of cases, which represents significant time savings given the considerable amount of data that needs to be processed. The coding must then be completed manually. Thanks to the stratigraphy – lithology match, it is thus possible to enrich the lithological data base. Obviously, the algorithm must be adapted to the geology of each site.

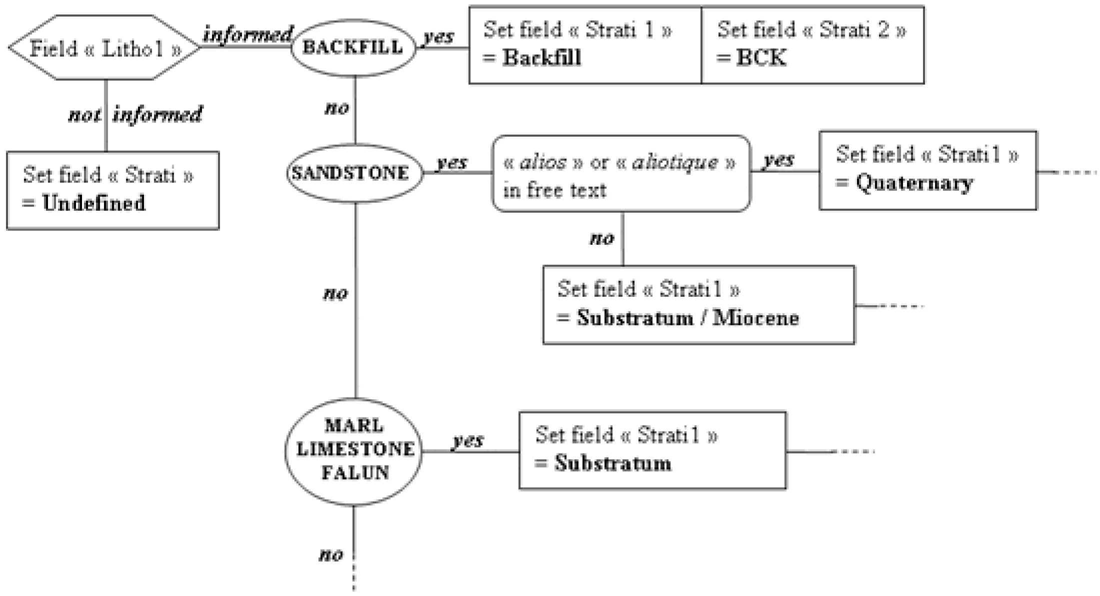

Figure 3. Zoom on a branch of the algorithm for the automatic determination of stratigraphy from the lithology

Controlling the data

The control of data is a vital step. The objective, in accordance with a quality procedure, is to identify in a manner as systematic and anticipated as possible all of the errors that could affect the data, before the data are used for modelling (or any) purposes. Given the large volume of data, their unequal quality, the different phases of entering them into the data base, the successive interpretation phases, numerous errors can be introduced at different steps. Reviewing all of the data "by hand" cannot be envisaged due to the quantity of data involved. Therefore, it is necessary to make use of a whole series of automatic tests in order to identify potential anomalies. Many of the tests described below may be performed in GIS tools by sequencing several functions. For our part, we integrated these functions as a part of a modelling tool (MultiLayer software, developed by the BRGM – Bourgine 2004), which offers the advantage of automatically integrating the geological modelling context and objects such as drill holes or geological maps.

Comparison to the Digital Elevation Model (DEM)

The objective being to derive a geometric model of the geological formations, all data must of course share the same coordinate system. It is very frequent that the oldest data have imprecise or erroneous X,Y coordinates. It is also frequent that data have no Z coordinate or an approximate Z coordinate. Coordinates have to be checked carefully and suspicious data must be eliminated at the earliest stage of the study, to avoid misunderstanding of erroneous interpretation. Particular attention must be paid to the vertical coordinate, since urban development mainly concerns the slice involving the first few metres. It is therefore necessary that the data have good precision in Z. When, in addition, a geological map is available, the outcropping boundaries provide passage points of the tops or the bases of the formations, the altitude of which is that of the DEM. A DEM of good precision has to be available to calculate the altitude of these points. Finally, in so far as the upper boundary of the geological model corresponds to the topography, it is necessary that the starting elevation of the drill holes perfectly coincides with the elevation of the DEM. If this is not the case, the thickness and/or the elevation of the top or the base of the outcropping formations cannot be met in the model. In order to control inconsistencies between the starting elevation of the drill holes and the DEM, these two values are compared. The points for which the difference is greater than the precision of the elevation Z must be verified. In the example of the city of Bordeaux, there are thus 300 drill holes, out of the 5 100 available, with a difference of more than 5 m with the DEM. These inconsistencies with regard to the elevation Z may in reality stem from an error in the coordinates X,Y of the point. Since the topography in urban environments varies over time, it is also necessary to take into account specific situations such as: drill hole starting under the present topography (for example a drill hole bored to the base of an excavation or in a zone that has now been backfilled), or above (drill hole bored in a bridge pile on a river embankment that has been moved). For these specific cases, it may be necessary to modify these drill holes so as to link them up to the present topography. Then, the final phase consists in placing all of the data in the same referential in Z. To do this, all of the data are projected onto the DEM. Thus, the drill holes are assigned an initial elevation equal to that of the DEM. This solution has the advantage of leading to thicknesses and depths in the model being met, which is essential when one wishes to intersect the model with the sewage networks that are located in the first few metres of the ground.

Searching for duplicates

Given the large amount of data, it regularly happens that keyboard input errors or mix-ups with the drill hole numbers lead to different drill holes being allocated the same coordinates. Obviously, this should be subject to systematic screening. Although this may seem obvious, experience has shown that it is something that is too often overlooked.

Consistency between nearby drill holes

Since the data has not always been interpreted by comparing it to neighbouring data and since input errors are always possible, we have developed tests that make it possible to compare the logs of neighbouring drill holes. The user specifies the proximity radius within which the logs of the drill holes are to be compared. The user also specifies the acceptable difference between logs, in terms of maximum variation in the thickness of the formations, maximum variations in the top or base elevations, or minimum similarity of logs. Virtually instantaneously, the tool provides the list of drill hole pairs that do not satisfy the input criteria, with the description of the criterion that has not been met. The example in Figure 4.a shows two drill holes 5 m apart, between which the difference in the thickness of the Aquitanian is 8 m. These two drill holes have to be checked in such a way as to identify if the source of the error stems from an error of interpretation, input, or even incorrect coordinates. This correction phase remains manual and very often necessitates a return to the base data, in other words to the original or scanned documents.

For our case study of Bordeaux, the percentage of drill holes separated by less than 10 m and presenting potential anomalies is thus around 6%, which represents 300 drill holes. However, not all of these drill holes need to be corrected. Indeed, some of these anomalies arise from the fact that the Rupelian limestone has been karstified, which provokes rapid variations in the elevation of its top. An indirect application of this test is therefore the automatic identification of nearby drill hole pairs, one of which has passed through a karstified zone and the other not.

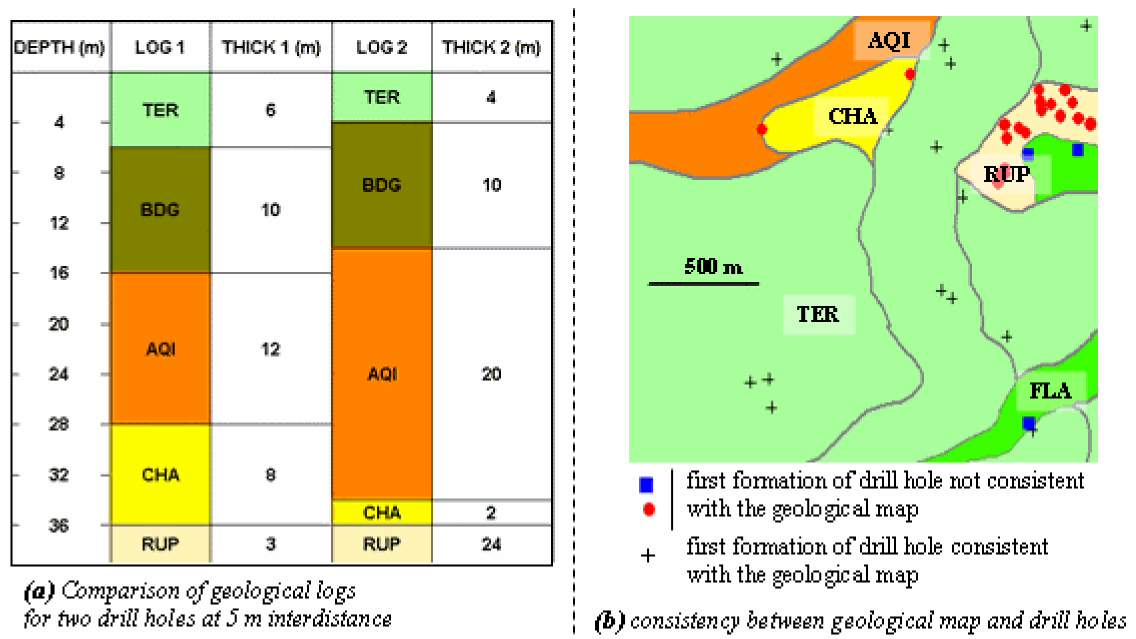

Figure 4. Controlling the consistency of data

FLA = Flandrian; TER = Quaternary terraces; BDG=Burdigalian; AQI = Aquitanian; CHA=Chattian; RUP = Rupelian

Consistency between drill hole data and the geological map

Another type of data consistency check consists in comparing the geological formation at the outcrop, indicated by the geological map, with the first formation identified by the drill holes. Figure 4.b provides an example of the graphic output produced by this test. In this test, the geological map used is the 1/50 000 scale geological map, which is of insufficient precision for a study on a local scale where the precision of the geological map has to be around 1/10 000. The software shows in red the drill holes for which the first formation identified by the drill hole is more recent than the outcropping formation mapped on the geological map, and in blue the drill holes for which the reverse situation is observed. The drill holes consistent with the geological map are marked with a cross. In the zone represented here, a group of drill holes, to the north east, indicates the Quaternary at the outcrop, in the spot where the geological map indicates the Rupelian. After verification, it appears that the thickness of the Quaternary intersected by the drill holes is quite low. The geologist has therefore decided not to mention this Quaternary on the geological map. In other places, it is the boundaries between two formations that are not positioned exactly in the right place, and which need to be shifted by few tens of metres to tie in with the information provided by the drill hole. Sometimes, an error also arises in the interpretation of the drill hole, or instead in an incorrectly positioned drill hole. In the case of Bordeaux, it may be observed that the geological map is not consistent with around 31% of the drill holes, *i.e.* around 1600 drill holes. In such a case it is not possible to use the geological map as such to force the model. The geological map must be redrawn locally so as to make it consistent with the drill holes. This can either be done beforehand or during the construction of the 3D geological model. Whatever the case, it is clear that the geological map must be raised to the scale of the studied zone, which poses a major problem due to the fact that today the surface of the town is already built up and that the outcrops are therefore no longer accessible.

BUILDING THE GEOLOGICAL MODEL

Modelling method adopted: defining geological rules

Among possible methods for geometry modelling of sedimentary formations, geostatistics offers a wide range of tools. The choice of the most appropriate tool depends on what is to be modelled: (co)-kriging for the elevation of the top or base of layers, or for the layer thickness, object-base modelling for specific geometry, truncated plurigaussian simulations for facies modelling (Chilès & Delfiner 1999). Other alternatives are also possible, especially those involving the interpolation of a 3D potential field (BRGM geomodeler, using an algorithm developed by Lajaunie, Courrioux & Manuel 1997, and applied by Courrrioux *et al.* 2003 and by Aug 2004; EarthVision© software, Dymamic graphics 2005). For preliminary modelling of the main interfaces, a "standard" (co)-kriging procedure is probably the best methodology available and has the advantage of providing an estimation of the interpolation error, which is essential for risk analysis (Chilès & Blanchin 1995). Nevertheless, even when kriging, it is important to select which interfaces are to be modelled and how to model them. As a matter of fact, the way the geological formations have deposited or have been eroded must be taken into account.

The usual way of constructing the top and base surfaces of formations consists in interpolating the values of the tops and bases observed along the drill holes and on the geological map, or in interpolating the thicknesses of the formations. In this latter case, the tops and bases are then deduced by cumulating the interpolated thicknesses compared to a reference surface. However, a difficulty arises when a formation disappears laterally, by erosion or by deposition gap, such as the formations B, C, D in Figure 5.a. When the extension boundary is situated under capping and cannot therefore be provided by the geological map, a frequently used solution consists in considering virtual surfaces superimposed in areas where the formation does not exist. Thus, in Figure 5.b the virtual tops of B and C are considered as superimposed with the top of A at the point P (or instead the thicknesses of C and B are considered as zero at point P). The interpolation of the surfaces of the tops of the formations integrating this supplementary virtual data may then generate forms or bevels that do not exist in reality (example Figure 5.b). The correct solution, which we propose, consists in constructing in the first instance the theoretical stratigraphic surfaces from the passage points of these surfaces, points known from the available data. Then, when these interpolated surfaces cross, the branches that cannot exist due to the logic of deposition of formations are eliminated. Thus, in the example of Figure 5.c, the surfaces *SA*, *TB* and *TC* are first of all constructed from the passage points of these surfaces (3 points for *SA*; 2 for *TB* and *TC*). Then, the left branches from the surfaces of *TC* and *TB* (passing underneath the surface *SA*) are eliminated, the formations B and C not having been able to be deposited in this spot since the formation A was already in place.

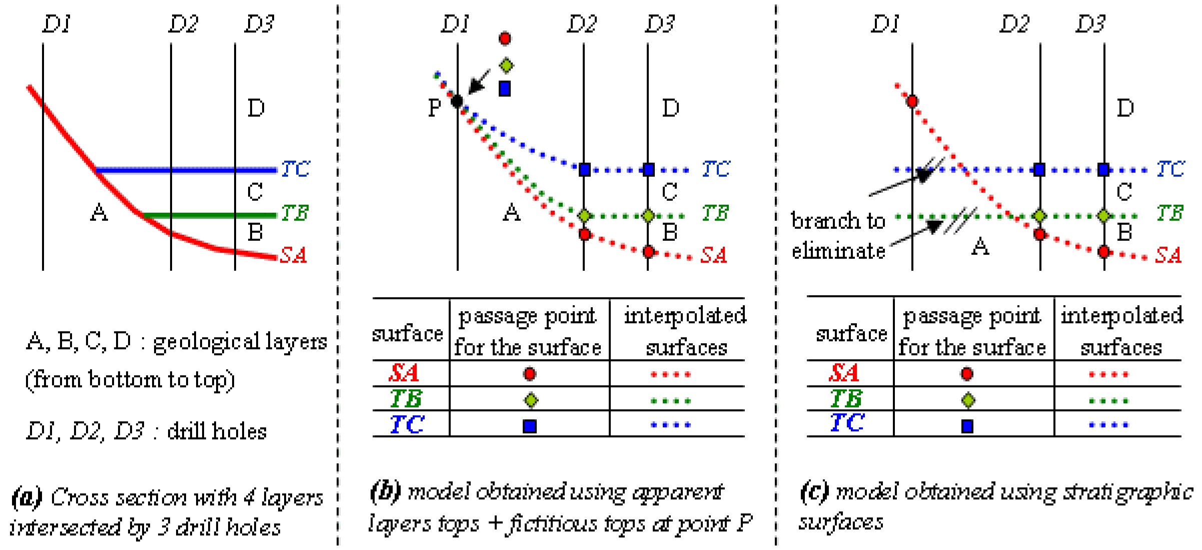

Figure 5. Interpolating apparent or stratigraphic surfaces

The simple example shown above may be generalized by using the following procedure:

- definition of the stratigraphic sequence to be modelled, given by: (a) the list of formations that have been successively emplaced, and (b) the type of relation between two successive formations, which can be of two types: "*Onlap*" when a formation is deposited following the previous formation without intermediate erosion, or "*Erod*" when there is an intermediate erosion phase. Thus, in Figure 5, the *TB* and *TC* surfaces are the

"*Onlap*" type and can be consideration as the tops of B and C, whereas the surface *SA* is more certainly the "*Erod*" type

- construction of the erosion surfaces, by interpolation from the passage points of these surfaces
- combination/intersection of the erosion surfaces, giving priority to the most recent erosion, which erodes everything that precedes
- construction of "*Onlap*" surfaces, by interpolation from the passage points of these surfaces
- combination/intersection of "*Onlap*" surfaces: elimination of branches that have been eroded, followed by successive introduction of these surfaces in the model, from the bottom to the top, while eliminating any parts that could not have been deposited since an older formation was already in place.

This mechanism, to our knowledge, was implemented for the first time in the EarthVision software in 1990, through the model building process "Streamline" (apparently never published, but mentioned in the website of Dynamics graphics 2005). It was then, in particular, taken up by the BRGM in 1999 in its Geomodeler (Courrioux 2003, Aug 2004) or in other applications (Thierry *et al.* 2000). We implemented it in the MultiLayer software, which is developed by the BRGM and used within the scope of the RIVIERA project (Dominique 2004).

A more complete example than that illustrated in Figure 5 is given Figure 6. The model to be constructed is represented in Figure 6.a. In this figure, there are five drill holes crossing through all of the formations. The corresponding stratigraphic sequence (Figure 6.b) summarises the emplacement of the formations: deposition of formation *A*, followed by a phase of erosion (*Erod S1*), then deposition of formations *B, C, D* (this giving two "*Onlap*" surfaces: "*Top of B*" and "*Top of C*"), followed by an erosion phase (*Erod S2*) and finally deposition of the formation *E*. The upper surface of the model is the topography, which is also an erosion surface. The construction of the model begins with the construction of the two erosion surfaces *S1* and *S2* and of the topography (Figure 6.c). These surfaces are then intersected. Since the erosion *S2* is subsequent to the erosion *S1*, a branch of *S1* is eliminated (on the right of Figure 6.c). In the same way, the branch of *S2* going beyond the topography is eliminated. All that remains is to construct the deposition surfaces ("*Onlap*" surfaces) "*Top of B*" and "*Top of C*" (Figure 6.d) from the corresponding passage points. These surfaces are then intersected with the formations already in place: the branches passing underneath the surface *S1* are eliminated (*A* is already in place). The same holds true for the parts eroded by *S2* (on the extreme right). Finally, the segment of the top of *C* passing underneath the top of *B*, in the right hand part of the channel, is also eliminated (*B* is already in place). The final model obtained is that shown in Figure 6.a. It should be noted that the formation *D* is not modelled as such: in fact, it corresponds to the volume remaining between the top of *C* and the erosion surface *S2* once these surfaces have been modelled and correctly intersected.

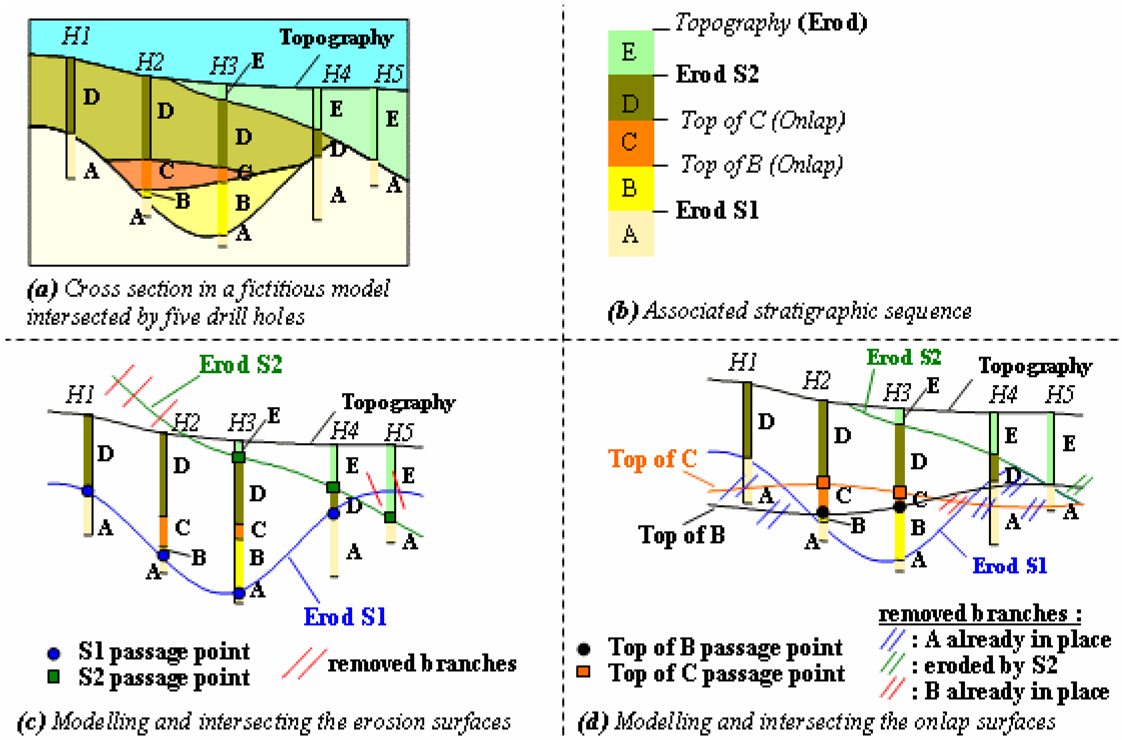

Figure 6. Constructing and intersecting the surfaces

In order to enable this method to be implemented, the passage points of the "*Onlap*" and "*Erod*" surfaces need to be determined in an appropriate manner. To do this, the following algorithm is used as a basis:

- let *FZ / FA* be a contact between two formations *FZ* and *FA*, observed along a borehole or at the outcrop, *FZ* being the most recent of these two formations

- let *N_Erod* be the number of erosion surfaces included between *FA* and *FZ* in the stratigraphic sequence, and let *Last_Erod* be the last of them
- if *N_Erod* = 0 (no erosion between the deposition of *FA* and that of *FZ*), the contact *FZ / FA* is a passage point of the top of *FA*
- if *N_Erod* > 0, the contact *FZ / FA* is a passage point of the erosion surface *Last_Erod*.

Thus, in Figure 6.d, the contacts *D/C* along drill holes *H2* and *H3* are interpreted as passage points of the top of *C* (no erosion between the deposition of *C* and that of *D* in the stratigraphic sequence Figure 6.b). In the same way, the contacts *C/B* correspond to passage points of the top of *B*. If a drill hole was available between *H3* and *H4*, it could intersect the contact *D/B* (Figure 6.a), which would then be considered as the top of *B* (and not of *C*). The passage points of the erosion surfaces are a little more difficult to interpret. Thus, the drill hole *H1* in Figure 6.a shows a contact *D/A* corresponding to a passage point of the erosion surface *S1* (only erosion between *A* and *D* in the stratigraphic sequence Figure 6.b). This contact is not interpreted as the top of *A*, since the latter no longer exists: it has been eroded. One instead constructs the erosion surface that has followed the deposition of *A*, in other words the surface *S1* (Figure 6.c). As for the drill hole *H5* (Figure 6.a), it passes through a contact *E/A*. The stratigraphic sequence Figure 6.b shows that there have been two erosions (*S1* and *S2*) between the depositions of these two formations. The last one being *S2*, the contact is interpreted as a passage point of *S2* (Figure 6.c) and not of the surface *S1* (which itself has been eroded by *S2*).

Taking into account the inequality constraints

The drill holes and the geological map do not only provide passage points for the intersected "*Onlap*" or "*Erod*" surfaces. They also impose inequality constraints on the position of other deposition or erosion surfaces. Figure 7 gives an example of the constraints generated by a drill hole starting in an outcropping formation *FZ* and ending in a formation *FA* (and which may have passed through other formations apart from these two).

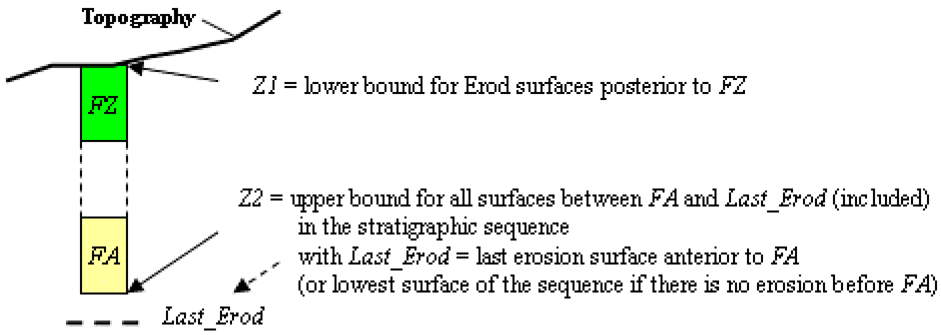

Figure 7. Some inequality constraints for a drill hole starting in formation *FZ* and ending in formation *FA*

Thus, in Figure 8.a, the interpolated erosion surface *S2* cannot intersect the two drill holes *H1* and *H2*. If this was allowed, one would obtain in the model an outcrop of the formation *E* at the level of these two drill holes, which would be in contradiction with the data. The starting elevation of the drill holes *H1* and *H2* is therefore a lower bound for the elevation of surface *S2*. In a symmetrical manner, in Figure 8.b, the ending elevation of the two central drill holes is an upper bound for the top of the Chattian, this formation (CHA) lying underneath the Aquitanian (AQI).

Other inequality constraints are also generated by any *FZ/FA* interface, particularly when the two formations *FZ* and *FA* are not consecutive in the stratigraphic sequence, in other words when there is a gap in one or several formations. This is the case in Figure 8.a: the interpolated top of *C* cannot pass above the contact *D/A* at the level of the drill hole *H1*. If this was allowed, one would obtain in the final model a non-zero thickness of *C* at the level of this drill hole, which would be in contradiction with the data. The elevation of contact *D/A* is in fact an upper bound for all of the deposition surfaces between *S1* and *D*, in other words for the tops of *B* and *C*.

Finally, any point of the geological map where the formation *FZ* outcrops also provides inequality constraints that are obtained by applying the algorithm of Figure 7, where *FA*=*FZ*, and *Z1*=*Z2* = elevation provided by the DEM.

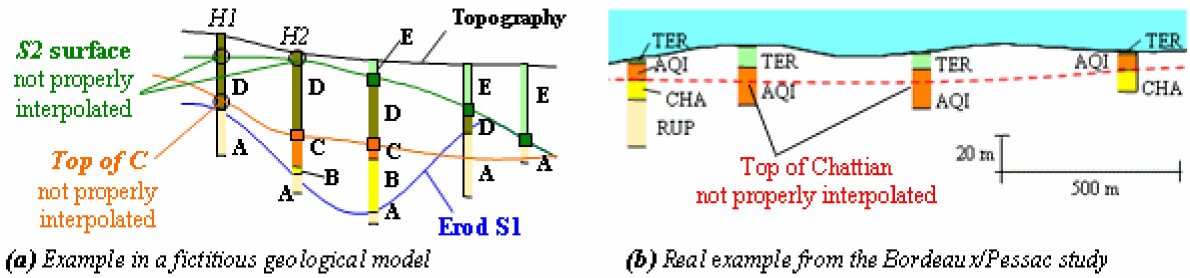

Figure 8. Checking the inequality constraints

The procedure for constructing the surfaces is then as follows:

- the drill holes and other data are interpreted by the software as a function of the stratigraphic sequence
- this provides the passage points of the intersected "*Onlap*" or "*Erod*" surfaces, as well as the inequality constraints for the other surfaces
- the passage points ("hard data"), are used to interpolate the different surfaces, by kriging or co-kriging
- the surfaces thus interpolated are compared to the inequality constraints ("soft data")
- when this test highlights an inconsistency, it is advisable to introduce one or several constraint points intended to force the model to meet the inequality data. These constraint points are introduced as supplementary passage points and the surfaces are then re-interpolated.

The use of software such as MultiLayer makes it possible to automatically calculate all of the passage points and inequalities as a function of the stratigraphic sequence. The automatic geostatistic interpolation of the surfaces from the passage points, then the visualisation of the inequality constraints not met makes it possible to rapidly identify the problems. An example of the display generated by the software in the case of Bordeaux is illustrated in Figure 8.b. Two possibilities then arise for the choice of the constraint points:

- a set of constraint points meeting the inequality constraints may be generated automatically using geostatistical methods (Gibbs sampler based on simulation techniques - Freulon & De Fouquet 1993, Aug 2004). However, this method is not always easily applicable, since it assumes that the data are distributed according to a Gaussian distribution. If this is not the case, the data has to be transformed beforehand (Gaussian anamorphosis techniques). Even more of a nuisance, the method only strictly works if all of the data is taken into account simultaneously when the calculation is made, which limits its use in practice to configurations of few hundreds of data items at the most, which is rarely the case in urban environments.
- if the automatic generation of constraint points is not possible, or if one wishes to introduce an interpretation, the constraint points may be defined manually or digitized on the screen. In practice, it is preferable to proceed in an iterative manner: the biggest anomalies are controlled in such a way as to verify that they have not been generated by errors in the data. Once these errors have been corrected and a first series of constraint points entered, the inequality controls aiming to verify the lower order constraints are reiterated and one introduces a second series of constraint points, etc.

In the example of Greater Bordeaux, we have thus constructed the geological model of the Pessac district. The modelled stratigraphic sequence is the sequence "Strati 2" in Figure 2 (all of the 7 terraces are in this first model, grouped together into a single assembly). Initially, 680 drill holes are available in this zone. For all of the 6 surfaces modelled, the number of passage points deduced from the drill holes is 1417. The total number of inequality constraints is, for its part, 1508. The complete geological model required the introduction of 960 constraint points. It should be noted that, given its imprecision at the scale at which we are working, the geological map has not been entered as data, which would have made it possible to obtain supplementary passage points. Constraint points have therefore been introduced manually to allow the model to conform to the geological map in the places where this map was considered satisfactory, which partially explains the large number of constraint points. Generally speaking, it is possible to use the passage points of the geological map by giving them a lighter weighting than the points deduced from the drill holes, in order to take account of the actual imprecision of the mapped contacts. By translating the uncertainty on the position of the contact by an uncertainty in terms of altitude of the point, it is possible to assign an error variance to the passage points of the geological map (Chilès & Delfiner 1999, chapter 3.7). The interpolation obtained by introducing this variance in the kriging does not then exactly honour these points. In zones where the geological map is manifestly incorrect or in clear contradiction with drill hole data, this solution cannot however resolve the problems. In this case, the points of the geological map in the corresponding zones have to be purely and simply ignored.

Controlling, validating, using and enriching the model

The control of the geological model is achieved by drawing isohypse or isopach maps of the different formations, as well as checking, on cross-sections, that the geological objects have been properly reconstituted. Figure 9 shows an example of cross-section in the Pessac district model.

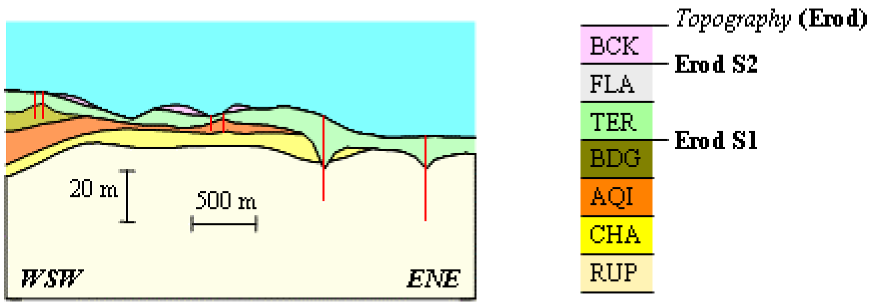

Figure 9. Controlling the model with cross sections. Drill holes are displayed in red.

In the case of Bordeaux, it has been possible to partially validate the model by comparing it to the logs of 3000 supplementary drill holes available at the Lyonnaise des Eaux Company, in charge of the sewer network. As explained above, these data are not described according to the stratigraphic referential, but according to the type, nature and consistency of the terrain. To facilitate the interpretation of this complementary data, we calculated the projected log given by the model, for each of the 3000 supplementary drill holes, and compared this projected log to the description of the true log. For many drill holes, this helped to interpret the Lyonnaise des Eaux data in terms of stratigraphy, at least for some of the modelled "*Onlap*" or "*Erod*" interfaces. For other drill holes, where the Lyonnaise des Eaux description was good enough to identify some of the modelled interfaces, this either allowed the validation of the model where it was in accordance with Lyonnaise des Eaux data, or pointed out some local discrepancies. The feedback of this comparison was that new passage points could be added to the initial passage points, thus allowing a second model with improved accuracy to be built.

Comparison of a given preliminary model to auxiliary data can thus be a way to facilitate the use or interpretation of auxiliary data or to reinforce the model itself.

Another type of comparison is the matching of the geological model with the geotechnical drill holes. The geological model reflects a stratigraphic slicing of the formations. The geotechnical drill holes do not always give this stratigraphic slicing, but rather a lithological description. Since one of the aims of the RIVIERA project is to propose a model of the properties of the sub-soil, it is important to match up stratigraphy and lithology, so as to be able to establish statistics by type of geological formation, and thus facilitate the interpretation of the geotechnical data. This aspect is developed in Breysse and *al.* 2005, 2006.

CONCLUSIONS AND PERSPECTIVES

The data control methods implemented in the RIVIERA project demonstrated that it is possible to automatically and rapidly identify different sources of errors in the data, enabling considerable time savings given the considerable volume of information that needs to be handled. By using geostatistical interpolation methods governed by the taking into account of a stratigraphic sequence and the surface construction rules deduced from this, it is possible to construct quite quickly a geological model of the principal formations. The obtained model is compatible with all of the data, in particular with the inequality data, which is the most numerous and the most difficult to take into account. It has been possible to compare this model with other types of information, particularly geotechnical information, for which stratigraphic coding is not available. This comparison has made it possible either to interpret the geotechnical data in terms of stratigraphy, or to validate the model, or to make it more precise.

Certain improvements are possible, particularly the updating of the model when new data is introduced. In fact, this data can make the constraint points introduced during the preceding phases unnecessary, or even come into contradiction with these points. It is therefore necessary to eliminate the corresponding points and repeat the interpolation of the surfaces. In order to ensure that this backtracking is not too cumbersome, one has to devise automatic algorithms that search for the constraint points to be eliminated, then regenerate the model. The taking into account of the geological map can also be improved. In fact, any point of the geological map where a formation *Fx* outcrops generates inequalities for the subsequent erosion surfaces or the previous deposition surfaces. As a function of the discretisation of the geological map, one can easily find oneself with tens of thousands of inequality data, which can necessitate the introduction of a very large number of constraint points. However, it is not necessary to take all of these points into account and it would be preferable to only introduce those that are relevant, in order to simplify the processing.

Moreover, the use of other methods appears necessary to model non-stratiform geological objects. A search is currently underway to try to grasp the geometric characteristics of geological objects such as paleochannels and meanders of alluvial terraces, or even karsts, and to propose methods for modelling them. It is clear that no universal model exists that enables all geological objects to be modelled. Consequently it is important to clearly define which geological objects one wishes to model, so as to choose and combine the most suitable methods for their representation.

Since the ultimate aim is to obtain a 3-D model of the geotechnical properties of the terrain within geological objects, we are envisaging using the truncated plurigaussian geostatistical method in order to propose a probabilistic model of classes of terrain. This type of approach has been tested within the scope of the RIVIERA project to model permeability classes and appears to give promising results.

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Corresponding author: Dr Bernard Bourgine, BRGM, BP 6009, Orléans Cedex 02, 45060, France. Tel: +33 2 38 64 34 73. Email: b.bourgine@brgm.fr.

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