On the use of geophysical methods to characterize heterogeneities of quaternary alluvial deposits. Application to stormwater infiltration

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De l'utilisation de méthodes géophysiques pour caractériser les hétérogénéités de dépôts quaternaires alluvionnaires. Intérêt pour l'infiltration des eaux pluviales.

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ABSTRACT

Stormwater infiltration basins are generally built on geological formations with large values of hydraulic conductivity. Such is the case for quaternary alluvial formations, among which are glaciofluvial deposits. Two geophysical investigation methods, namely ground-penetrating radar and electrical tomography, were tested on an infiltration basin built on a glaciofluvial deposit. Geophysical profiles were calibrated on a trench wall dug in the glaciofluvial formation. A sedimentological study coupled to geophysical measurements behind the trench wall highlights the three-dimensional architecture of the deposit (paleochannels and high energy deposit). A typology of geophysical facies connected to the sedimentary characteristics was thus established. A simple estimation model of saturated hydraulic conductivities was used to quantify the hydraulic properties of glaciofluvial lithofacies. This study shows that sedimentary heterogeneities generate a strong hydraulic heterogeneity, potentially leading to preferential flows. The orientation of paleochannels is a privileged flow direction. Heterogeneity at the scale of lithofacies must be taken into account in the numerical models of water flow underlying stormwater infiltration basins. A preliminary geophysical investigation, coupled to a localized knowledge of alluvial stratigraphy, can be used to define a realistic hydrostratigraphic model.

KEYWORDS

GPR, electrical resistivity, glaciofluvial deposit, stormwater infiltration

RESUME

Les bassins d'infiltration d'eaux pluviales sont généralement construits sur des formations à forte conductivité hydraulique moyenne. C'est le cas des formations alluvionnaires quaternaires, dont les formations fluvioglaciaires. Deux méthodes d'investigation géophysique, le radar géologique et la tomographie électrique, ont été testées sur un bassin d'infiltration construit sur un dépôt fluvioglaciaire. Les réponses géophysiques ont été calibrées sur la paroi d'une tranchée creusée dans les formations fluvioglaciaires. Une étude sédimentologique couplée à une investigation géophysique en arrière de la paroi a permis de mettre en évidence l'architecture en trois dimensions du dépôt (paléochenaux et dépôt de haute énergie de courant proglaciaire). Une typologie de faciès géophysiques reliés aux caractéristiques sédimentaires a ainsi été établie. Un modèle simple d'évaluation des conductivités hydrauliques saturées a été utilisé afin de quantifier les propriétés hydrodynamiques des lithofaciès fluvioglaciaires. Cette étude montre que l'hétérogénéité sédimentaire engendre une forte hétérogénéité hydraulique, pouvant être à l'origine d'écoulements préférentiels. L'orientation des paléochenaux est une direction privilégiée d'écoulement. L'hétérogénéité à l'échelle de l'hydrofaciès doit être prise en compte dans les modèles d'écoulements non-saturés sous-jacents aux bassins d'infiltration. L'investigation géophysique préalable, couplée à une connaissance ponctuelle de la stratigraphie alluvionnaire, permet de disposer d'un modèle hydrostratigraphique réaliste.

1 INTRODUCTION

Stormwater infiltration basins are frequently used in urban areas in France. However, their long-term evolution is not clearly understood and the pollutants contained in stormwater may lead to a contamination of the underlying soils and groundwater resources (Dechesne et al., 2005). It is also important to assess the long-term sustainability of such infiltration systems. This assessment requires an understanding of the subsoil hydrostratigraphy. In France, a large part of urban areas are located on quaternary sediments: for example, within southeast France, 72% of the population is living on surficial deposits (e.g. alluvial deposits, glacial sediments), which cover approximately 25% of this area. This urban concentration, coupled with a localized infiltration, leads to an increasing exposure of the underground media underlying infiltration basin to diverse anthropogenic contaminations (e.g. heavy metals, hydrocarbons). Moreover, because of their large mean hydraulic conductivity, alluvial deposits constitute a large part of the geological formation underlying infiltration basins.

The design of stormwater infiltration systems was initially done by considering a homogeneous hydrogeological formation underneath the basin. However, alluvial deposits present sedimentary heterogeneities which may generate preferential flow paths contributing to a rapid, non-uniform transport of contaminants at depths greater than expected from the hypothesis of a homogeneous deposit. For example, Winiarski et al. (2004) show that the natural sedimentary heterogeneities of a glaciofluvial alluvial deposit underlying an infiltration basin have an impact on unsaturated water flow. An enhanced understanding of the sedimentary and hydraulic heterogeneities within alluvial deposits is also important to assess the impact of infiltration systems on the underground media.

In this study, we consider hydrogeological heterogeneities at the centimetric to decimetric scale of the hydrofacies. Hydrofacies are defined as homogeneous, isotropic or anisotropic units, hydrogeologically relevant for groundwater modelling and solute transport (Anderson, 1989). Hydrofacies are the smallest mappable hydrostratigraphic units, which may result in either pathways for fluid flow or flow barriers (Heinz and Aigner, 2003). A better understanding of unsaturated flow needs a relevant sedimentary characterization at the hydrofacies scale, i.e. a characterization of the lithofacies distribution. Because of their discrete nature, traditional techniques of core analysis are not adapted for this, neither are pumping tests, since they integrate information at the scale of the aquifer formation.

During the last decade, the use of subsurface geophysical methods for sedimentological and hydraulic applications has developed considerably. These methods have the advantage of producing continuous data, which are easily extrapolated into two and three dimensions. However, their resolution is limited, and the use of only one geophysical method is often insufficient to define a reliable stratigraphic distribution. The use of one or more geophysical methods, coupled with a localized knowledge of stratigraphy (i.e. from drilling or outcrop analysis), often allows a good characterization of sedimentary heterogeneities. Among the geophysical techniques most usually used in subsurface applications, Ground Penetrating Radar (GPR) and electrical resistivity can provide an image of the sedimentary structures of gravelly deposits with a resolution between the centimetric and the metric scales.

In this study, these two methods were tested to characterize sedimentary heterogeneities of a glaciofluvial deposit underlying a stormwater infiltration basin in the east of Lyon (France). This infiltration basin is one of the study sites of the multidisciplinary research federation O.T.H.U. (Field Observatory on Water Management), which works towards providing guidance on the management of various urban drainage systems. The aim of this paper is to show how geophysical methods can be used to improve the characterization of alluvial deposits in order to better understand how their sedimentary architecture affects unsaturated water flow underneath a stormwater infiltration basin.

2 ALSO PROPOSED

3

4 METHOD

4.1 Site description

The Django Reinhardt stormwater infiltration basin is located in Chassieu, in the eastern suburbs of Lyon (France). It collects stormwater over an industrial watershed area of 185ha. Before entering the infiltration basin, stormwater first passes through a retention basin. The infiltration basin is 5 m deep and the infiltration area is 1 ha. The basin was dug in a 30 m deep quaternary glaciofluvial formation overlying tertiary molassic sands. The water table is located at a depth of 13 m from the bottom of the basin. According to a previous study, the mean saturated hydraulic conductivity of the glaciofluvial formation ranges from 7.10^{-3} to 9.10^{-3} $m.s^{-1}$ (BURGEAP, 1995).

4.2 Geophysical methods

The Ground-Penetrating Radar (GPR) method is based on the propagation of electromagnetic (EM) waves into the subsurface. A radio-frequency transmitter pulses the EM waves. Some EM energy is reflected by subsurface heterogeneities, due, for instance, to changes in grain size, water content, and grain packing. A receiver regularly records the reflected waves (traces). After processing, the result is a 2D section which represents successive recorded traces as a function of their two-way-travel time in nanoseconds. In our study, GPR measurements were performed with a GSSI (Geophysical Survey System Inc.) SIR 3000 system, with a 400 MHz shielded antenna operating in a monostatic mode (a single antenna for transmitting and receiving EM waves). Data processing was performed with the GSSI Radan 6 software. Our previous work showed that the 400 MHz antenna was a good compromise between high resolution and adequate penetration depth in glaciofluvial deposits (Goutaland et al., 2005). Moreover, Goutaland et al. (2005) translate two-way-travel times (in ns) to actual depth (in meters) by the calibration of GPR profiles on trench walls. The mean EM wave velocity was evaluated at 0,09 $m.ns^{-1}$.

Subsurface electrical resistivity is measured by applying an electric current through two current electrodes and measuring the resulting voltage difference between two potential electrodes. Electrical resistivity is a function of porosity, saturation, resistivity of the pore fluids and the solid phase, and the material texture (Meads et al., 2003). For this study, we used the ABEM Terrameter LUND Imaging System, with a SAS 4000 resistivity instrument. A dipole-dipole array was used with an electrode spacing of 1 m. Two- and three-dimensional inversions were performed with the Res2Dinv and Res3Dinv softwares, respectively. Profiles of apparent resistivity are mapped after processing.

4.3 Experimental procedures

A trench wall (15 m long, 2,5 m deep) was exposed by excavating the glaciofluvial deposit with a power shovel. Geophysical data were measured on an orthogonal grid covering a 15 m N-S x 8 m W-E area behind the trench wall. The line spacing was 1 m in each direction. The GPR investigation was conducted on the orthogonal grid, while electrical tomography was only performed on the N-S lines. GPR and electrical resistivity profiles corresponding to the trench wall were calibrated on the lithological units, water contents and the fraction of fine particles in each unit. Units characterized by geophysical methods were defined by changes in the dip of GPR reflections.

Geophysical profiles measured behind the trench wall were indirectly compared to the trench wall. To understand the three-dimensional distribution of structural and textural glaciofluvial units and thus interpolate geophysical data between survey lines, a sedimentological study was carried out. The sedimentological study of natural deposits allows the three-dimensional reconstruction of the palaeoenvironment, which can be used to interpret the genetically homogeneous distribution of structural units and associated lithofacies. A typology of GPR and electrical resistivity features associated to sedimentary structures (depositional elements, i.e. structural scale, and lithofacies, i.e. textural scale) was defined. Dry sieve analyses were performed on each lithofacies. The sedimentological code of Miall (1978), presented in table 1, was used for the identification of the lithofacies.

Finally, a hydrostratigraphic model of the glaciofluvial deposit was defined. Estimations of saturated hydraulic conductivities were performed using the Kozeny-Carman expression proposed by Chapuis and Aubertin (2003), which requires lithofacies grain-size distribution (measured) and void ratio (determined from literature data on analogous lithofacies). We identified the hydrofacies likely to act as preferential flow paths in either saturated or unsaturated conditions.

5 A CONCEPTUAL STRATIGRAPHIC MODEL OF LITHOFACIES DISTRIBUTION WAS DEFINED.

6

7 RESULTS AND DISCUSSIONS

7.1 Geophysical methods

Figure 1a) summarizes the main stratigraphic features of the trench wall, and the corresponding GPR and apparent resistivity profiles. The investigation depth is 3 m with GPR and 4,6 m with electrical resistivity.

Unit 1 corresponds to continuous parallel GPR reflections dipping northward. Corresponding resistivity values range from 1000 to 1400 Ω.m. This unit corresponds to unsaturated sands and gravels mixture with a major gravel fraction. Unit 2 is relatively thin, it corresponds to subparallel, high-amplitude GPR reflections dipping southward. This structure is not clearly identifiable on the resistivity profile, but resistivity values are high (1000 Ω.m). Such geophysical features are related to thin gravel beds on the trench wall. Unit 3 is characterized by oblique (dipping northward) and curved reflections at depths between 1 and 2 m. The upper part of unit 3 is characterized by subparallel higher amplitude reflections dipping northward. The curved shape of unit 3 is observable on the resistivity profile. Resistivity values decrease in the curved shape, ranging from 500 to 1000 Ω.m and corresponding to a change in the lithology (sand lens). The upper unit (unit 4) is characterized by continuous subhorizontal high amplitude reflections. Resistivity values in the first meter are low; they range from 200 to 500 Ω.m. Due to its proximity to the basin surface, this unit has a higher quantity of fine particles (Ganaye et al., 2007). This leads to a high water content and explains the accentuation of the high amplitude GPR reflections and the low resistivity values. At depths between 3 and 4,6 m, where only resistivity data are available, the resistive lobe in the middle is interpreted as a large quantity of coarse gravel. This calibration shows that the main structural and textural features of the trench wall are characterized by both geophysical methods. GPR and electrical resisitivity methods are complementary. GPR reflections give details which are easier to correlate with stratigraphic units (dip). However, a better understanding of the spatial distribution of the stratigraphic units is needed to define a realistic model of lithofacies geometry.

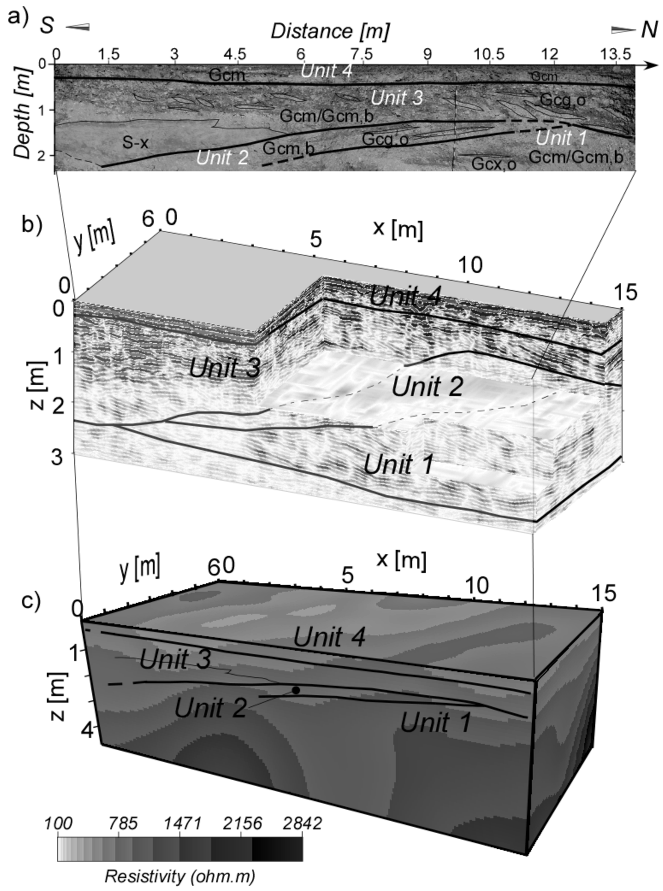


Figure 1: cross interpretation of the trench wall (a) decomposed in structural units and lithofacies (table 1), and the surrounding geophysical investigations [GPR pseudo-3D bloc (b) and apparent electrical resistivity 3D bloc (c)].

7.2 Typology of geophysical features

We relate the different geophysical features outlined above to a sedimentological description, in order to set up a typology of geophysical features. The sedimentological study described below organizes the structural (metric scale - architectural elements) and textural (decimetric scale – lithofacies) heterogeneities into genetically related depositional units.

Table 1 : typology of glaciofluvial lithofacies and associated hydraulic parameters (porosity n and saturated hydraulic conductivity Ks). The sedimentological code is that of Miall (1978): I_1, grain-size of the main components (G: gravel, S: sand); i_2, fabric (c: clast-supported, -: without matrix); i_3, sedimentary structure (m: massive, x: stratified); i_4 (optional), additional information (o: open framework, b: bimodal)

Lithofacies code ($I_1i_2i_3$,i_4)	Description	n*	Ks**
S-x	Poorly to moderately well sorted medium sands (D = 385 µm), with internal laminations	0,42	$7{,}0.10^{-4}$ m/s
Gcx,o	Poorly to moderately well sorted clast-supported gravels, without sandy matrix, often prograding	0,36	$9{,}0.10^{-2}$ m/s
Gcm	Poorly sorted clast-supported massive sands and gravels, wide grain-size distribution	0,27	$7{,}5.10^{-3}$ m/s
Gcm,b	Poorly sorted clast-supported massive sands and gravels, bimodal grain-size distribution (a medium and coarse gravel mode, and a fine and medium sand matrix)	0,3	$1{,}8.10^{-3}$ m/s

* Literature data, from Klingbeil et al. (1999)

** calculated using the Kozeny-Carman expression described in Chapuis et Aubertin (2003)

Four lithofacies were described. They are summarized in table 1, with their associated estimation of saturated hydraulic conductivity. Concerning the structural description, two main braided-stream palaeoenvironments were described (figure 2a):

- a lower structural unit corresponding to successive palaeochannels characterized by a homogeneous dip of internal lithofacies, composed of a channel fill S-x lithofacies (bottom of unit 3, figure 1), and alternating Gcx,o and Gcm,b progradations (units 1, 2 and top of unit 3, figure 1);
- an upper unit corresponding to a high current energy deposit, with the associated lithofacies Gcm having a wide grain-size distribution (unit 4, figure 1).

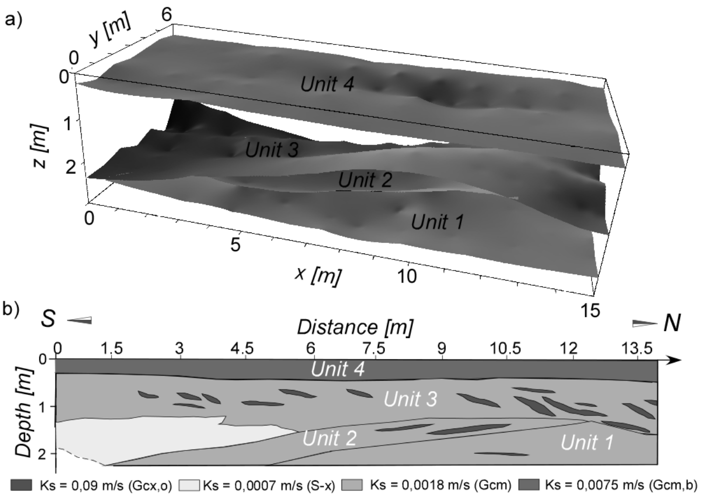
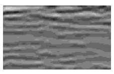
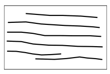
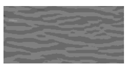
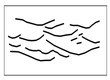
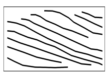


Figure 2 : a) three-dimensional interpretation of the depositional elements (units 1, 2, 3 : palaeochannel; unit 4 : high current energy deposit), and b) hydrostratigraphic model of the

glaciofluvial deposits

Table 2: typology of GPR reflections and electrical resistivity features linked to lithofacies organisation, depositional elements and depositional events.

Geophysical features				Sedimentary features
Facies	GPR reflection features		Electrical resistivity features	- Associated lithofacies - External shape of depositional elements - Associated depositional event
	Reflections	Internal structure		
f1			Low resistivity values (high water content linked to a high quantity of fine particles)	- Gcm, higher quantity of fine particles - Sheet or wedge shape - High current energy
	High-amplitude, subhorizontal or slightly dip, continuous and parallel			
f2			Local decrease of resistivity values (higher sand fraction)	- Mainly Gcm or Gcm,b ; S-x and Gcx,o lenses - Channel shape - Channel-fill
	Short, wavy or curved			
f3			Local increase of resistivity values (desaturated macropores ; higher gravel fraction)	- Progradation of Gcg,o / Gcm,b alternance - Trough shape - Channel-fill
	Relatively high-amplitude, oblique, continuous, subparallel, sometimes short and curved			

A typology of three geophysical facies relating sedimentary structures and geophysical features was defined (table 2). GPR reflections are easier to relate to sedimentary structures than electrical resistivity. As the variability of electrical resistivity due to subsurface saturation is strong (e.g. from 100 Ω.m in saturated gravels to 1400 Ω.m in dry gravels), no range of resistivity values were proposed in this typology. Only observations on qualitative changes of electrical resistivity were indexed.

7.3 Hydrostratigraphic interpretation

7.3.1

Figure 2a shows the three-dimensional interpretative model of the glaciofluvial depositional elements. The hydrostratigraphic model of figure 2b was build using the estimated saturated conductivities of table 1. In fully saturated conditions, Gcx,o hydraulic conductivity is one to two orders of magnitude higher than other lithofacies. Gcx,o lithofacies may act as preferential flow paths. Water flow may be parallel to this lithofacies bedding, leading to a fast non-vertical flow. Gcx,o lithofacies of the units 1, 2 and 3 may thus concentrate water flow. The knowledge of the three-dimensional hydrostratigraphy is essential because water flow may occur along the longest continuous path through highly conductive lithofacies, in the present case the Gcx,o lithofacies (Heinz et al., 2003). This longest path usually occurs along the maximum lithofacies extension, i.e. in a direction parallel to the palaeochannel. In unsaturated conditions, Gcx,o macropores may desaturate quickly while finer lithofacies (S-x) or lithofacies with a significant sandy matrix (Gcm,b) remain more conductive. Capillary barrier effects may also occur at the interfaces between gravelly lithofacies and sand-matrix lithofacies, leading to local preferential flow paths. Thus, the sedimentary heterogeneity induced a hydraulic heterogeneity, which may lead to preferential water flow during stormwater infiltration. Palaeochannels orientations are privileged directions for preferential flow in either saturated or unsaturated conditions.

8 CONCLUSION

In this study, we consider centimetric to decimetric sedimentary heterogeneities of a glaciofluvial deposit underlying an infiltration basin. We propose two complementary geophysical methods, the ground-penetrating radar and the electrical resistivity, to investigate the stratigraphy of the deposit at this scale. The main structural and textural features of the glaciofluvial deposit were identified. A sedimentological study was carried out to complete the geophysical investigation by a three-dimensional interpretation of the characterized structures. A typology of geophysical features related to sedimentary characteristics was thus defined. A hydrostratigraphic model was proposed from estimations of saturated hydraulic conductivity of each glaciofluvial lithofacies calculated with the Kozeny-Carman equation. Preferential flow paths may occur during stormwater infiltration in either open-framework gravels (fast flows in fully saturated conditions) or at the interface between sand-matrix or sandy lithofacies and gravelly lithofacies (capillary barriers effects in unsaturated conditions). Glaciofluvial palaeochannels orientations are privileged directions for preferential flows. The heterogeneity of alluvial deposits at the hydrofacies scale must be taken into account by infiltration basin managers, as preferential flow paths may induce a long-term contamination at depths greater than expected.

Both geophysical methods used in this study are of major interest for managers of stormwater infiltration basin. Numerical modelling of the unsaturated flow underlying infiltration basins may be performed from geophysical investigations and a localized knowledge of the sedimentary palaeoenvironment. This modelling may help to assess the potentiality of a site to infiltrate stormwater.

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