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Improving a 3D geological model using multiple geophysical methods

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Abstract

Due to strong lateral and vertical heterogeneities, enhanced characterization of the karst Unsaturated Zone (UZ) is a challenging task. Many geological, geotechnical and geophysical techniques allow collecting varied underground data on different spatial and temporal scales. However, coupled interpretation of these data remains difficult as the number of techniques increases and the interdependence of the measured properties is not straightforward. 3D modeling provides a framework for the global interpretation of the data. We propose a structural workflow mainly base on geophysical information to build the geological model of the karst UZ. Geological map, geotechnical cross-section and field observations described regional geological structures. Locally, Electric Resistivity Tomography (ERT), Ground Penetration Radar (GPR), and seismic surveys are used to refine the geological structures in a fine scale. The lithological interfaces, faults and fractures network are specified with metric resolution. This local geomodel will be used to constraint dimensions and discontinuities of a hydrogeological model for water flow simulations.

1. Introduction

The structure of karst hydrosystems is highly heterogeneous and the related hydrodynamic functioning can be complex in both unsaturated and saturated zones (Mangin, 1975; Bakalowicz, 1995; Ford and Williams, 2007; Goldscheider and Drew, 2007; White, 2007). Due to triple porosity (matrix rock, fracture and karst conduits), complexity of karst environment makes water exploitation and protection difficult and challenging. The methodology classically used in hydrogeology (borehole, pumping test and distributed models) is generally invalid and unsuccessful for karst aquifers, because local results cannot be extended to the whole aquifer or to some parts. Generally, karst hydrogeologists use a specific investigation methodology (described in Bakalowicz, 2005), which is comparable to that used in surface hydrology. Most of the time, karst aquifer hydrodynamics are modelled with rainfall-runoff models (e.g. Marsaud, 1996; Fleury et al., 2007; Moussu et al., 2011). The lack of knowledge on karst aquifers makes the parameterization of distributed model difficult, but few authors take up the challenge (Worthington, 2009). Therefore improving the knowledge and understanding of karst structures and functioning is still necessary.

This research is focused on the karst UZ. Indeed, UZ is now recognized as a main storage reservoir that can retain significant amounts of water for prolonged periods of time (Emblanch et al., 2003; Perrin et al., 2003; Charlier et al., 2012). Flows via the UZ to the saturated zone can be delayed, circulating in fissured matrix, or direct through conduits (Blondel, 2008; Peyraube, 2012).

Our global goal is to develop an effective methodology for near surface geophysics aiming towards a better understanding of water transfer and storage within the UZ of karst hydrosystems. Firstly, a good knowledge (i.e. high resolution compared to the scales) of the geological context is required. Secondly, the high sensitivity of geophysical methods to water content can be useful to study water storage and water transfer. This paper is devoted to the first step: a geological model is built to propose a geometrical solution in coherence with geophysical surveys' results and global geology.

We propose an applied and adaptive method to build a 3D geological model of karst UZ with data from multiple geophysical methods. After a rapid overview of the geological and hydrological context of the test site (part 2), the database is described (part 3.1) with a focus on data resolution and interpretation issues. The geological framework is built with a classical structural workflow (Caumon et al., 2004; Kaufman and Martin, 2008; Wu et al., 2005) where coupled interpretation of various data allows collecting clues of geological features (part 3.2). This approach is developed and tested at a hectometric scale where local heterogeneities of karst UZ play an important hydrogeological role. In addition, most of the ground-based geophysical methods can be applied at this scale. 3D modelling provides a framework for the global interpretation of the data (part 3.3). Locally, Electric Resistivity Tomography (ERT), Ground Penetration Radar (GPR), and seismic surveys are used to refine the geological framework (Carrière et al., 2013). The obtained 3D geological model highlights the complex underground geometry and the near-surface features (part. 4).

2. Hydrogeology and geology of the test site

The test site is located within the karst hydrosystem of the Fontaine de Vaucluse in the South-East of France (Fig. 1a) on the LSBB area (http://www.lsbb.eu). The Fontaine de Vaucluse spring is the main outlet of the system and is the biggest karst spring in Europe with an average discharge of 19m³/s from 1970 to 2006 (Cognard-Plancq et al., 2006). The karst system is partially developed in the low Cretaceous limestone (so-called Urgonian) described in detail by Masse (1976).



Figure 1: (a) Fontaine de Vaucluse basin location in France (b): LSBB location in Fontaine de Vaucluse basin (after Puig, 1990); (c): Extract of local geologic map, n° 942 (Blanc et al., 1973); (d): Regional lithostratigraphic log (Masse and Fenerci-Masse, 2011 (modified)), after Carrière (2013).

The LSBB is an underground research laboratory located near Rustrel village, in the southern part of the Fontaine de Vaucluse catchment area (Fig. 1b). The laboratory is made of a 3.8 km long gallery with a diameter varying between 2 and 4m. It is almost horizontal under the mountain so that the rock cover above the gallery varies from 0 to 519m due to the topography. As the gallery comes across the karst medium, the fault networks, it also intersects arbitrarily some flow paths throughout the UZ. Consequently, several perennial and intermittent flow points are identified in the gallery, at different depths (from 35 to about 440m). One of these permanent flow points is near the western extremity of the LSBB tunnel (Fig. 1c) where the tunnel is located only 35m below the surface. This point is called "point D" and its average discharge is around 135 mL/min (Perineau et al., 2011). Such a geometrical context encouraged us to focus our investigations on the area located above point D. In addition to the usual approach, which consists in surface geophysical investigation, the LSBB tunnel provides unique underground information about karst UZ.

At this place, the outcrops correspond to the U3 subdivision of Urgonian facies (Leenhart, 1883). The U3 subdivision presents several facies (Fig. 1c) that are not always laterally continuous. Therefore, interpretations of geophysical results are very challenging and require precise geological knowledge. The limestone facies outcropping on this site is a biocalcarenite with possible cross stratifications (Fig. 1d). The limestone stratigraphic dip varies from 15° and 20° in a southernly direction. The carbonate platform is affected by two main sets of faults and fractures: 10 to 25°N and 100° and 120°N (Carrière et al., 2013). The topography dips approximately to around 13° to the South and the surface is covered by a typical Mediterranean shrubby forest mainly composed by Holm oak (called in French garrigue). At the surface we can identify humus horizons, clayey soil and some terra rossa with limestone fragments and mainly outcropping limestone. Many studies have been done on the local geology but the complexity of the karst medium still makes it challenging to characterize.

3. Methodology and tools

3.1. Geophysical database

Ground-based geophysical methods can play an important role in the study of karst systems. But suitable characterization of heterogeneities in this environment is very challenging and the choice of adequate methods remains mainly site related (Chalikakis et al., 2011). During the last three years, multiple field investigations took place on this test site to improve local karst UZ knowledge (Carrière, 2010-2013).

Field investigations were performed in two dimensions in order to get a large amount of information, and cover an important surface with an optimized field time. Measurements integrate a certain volume of rock and this volume increases with depth. Thus measure resolution and precision decreases with depth and the interpretation is more accurate for near surface features than deeper features. In order to ensure favourable interpretation and modelling conditions all field investigations have been performed on 14 defined lines oriented North-South (9 lines), East-West (4 lines) and North-West to South-East (1 line).

3.1.1. Electric resistivity tomography (ERT)

Compact limestone is characterised by high electric resistivities whereas karst features are often filled by clay and/or water that cause resistivity decrease. Due to the contrast in electrical resistivity ERT is an efficient tool to characterise fractured or karstic zones (e.g. Deceuster et al., 2006; Nguyen et al., 2007, Robert et al., 2011). ERT measurement can also be limited when the medium presents too much structural complexity and heterogeneities.

Depending on water content the electrical resistivity of rock is time-variable. Measurements of 4 field campaigns (21 cross sections) are compared. Underground heterogeneities like soil and degraded rock can be identified where a strong resistivity contrast appears between two campaigns.

3.1.2. Ground penetration radar (GPR)

This method is well adapted to the analysis of the near-surface (< 20 m in depth) structure of the karst (e.g. Benson, 1995; Grandjean and Gourry, 1996; Beres et al., 2001; Al-Fares et al., 2002). Sénéchal et al.

(2013) noticed the exceptional limestone rock properties inside the LSBB, which allowed the interpretation of the permittivity variation and geometrical information. Moreover, conductive zones due to clay or water induced attenuated GPR signal amplitude. 14 GPR cross sections are used to support modelling; with an average wave velocity of 8.5 cm/ns (Sénéchal et al., 2013) investigation is about 14m depth. GPR underlines underground reflectors as fractures and sediments geometry.

3.1.3. Seismic refraction survey

Seismic methods can detect fractured zones and cavities (e.g. Šumanovac and Weisser, 2001; Vasconcelos and Grechka, 2007; Valois et al., 2010). Two 2D cross sections of P wave velocity link with the mechanical behaviour of the material. The investigation depth is about 25m, one cross section is oriented North-South and the other East-West. The ray coverage enables a great resolution of first 15m. The purpose is to detect main structures such as karst features or fractured limestone.

3.2. Structural workflow

Electrical resistivity and velocity values from ERT and seismic surveys are represented by points; whereas data from geophysical survey integrate a certain volume of rock. Therefore geophysical information is considered as soft data and surfaces are not constrained to honor points. The challenge is to build a geological model mainly based on soft data. Caumon et al. (2009) describe the standard structural workflow which we adapted to the geophysical database (fig. 2): (1) Importation of all available data into Gocad, (2) Coupled interpretation of data, all clues of the same geological interface are reported (pointset or curve), (3) Representation of geological object with 3D surface. In the end, the volume of interest is divided by several surfaces, which represent geological discontinuities (fault, fractures or boundaries).



Figure 2: Structural workflow base on geophysical data.

3.2.1. Gocad database

The Gocad database is prepared and cleaned towards using only reliable and interpreted information. Geophysical surveys (ERT, GPR and seismic) provide indirect information of the underground structure. Aforementioned measures quality decreases with depth. In order to compare information all geophysical cross sections are processed using the same methodology.

LSBB gallery is precisely located by the National Institute of Geographic and Forest Information (www.ign.fr). Furthermore geophysical measurement lines are located using Global Position System with Real Time Kinematic (precision < 2 cm). The digital elevation model, LSBB gallery and geophysical measurement lines are used as references to locate other information.

3.2.2. Coupled interpretation

Gocad software allows representing all geological (geological map), geotechnical (LSBB tunnel plan) and geophysical (ERT, GPR and Seismic surveys) knowledge within the same 3D space. A wide range of information is available, but on different scales. The geological map describes geological outcropping with decametric scale. The location of geophysical data is accurate near the surface and the quality lowers with depth. The location's incertitude is minimized by the coupled interpretation of data (fig.3). The so-called "coupled interpretation" consist of analyse of results from two different geophysical techniques for characterise an object. The object is confirmed by a third source of information. Several geometric solutions can induce the same geophysical signature but the final solution should satisfy geological principle depending of other surfaces.



Figure 3: Conceptual schema of the coupled interpretation. The circle indicates the likelihood of the object's location depending on the information source. The area with the highest probability of the object's location is shown in grey.

3.2.3. 3D geological surface

The underground structures are represented by 3D surfaces. The surfaces are created from points and curves irregularly distributed. The Discrete Smooth Interpolation (DSI) guarantees that the interpolation result is as smooth as possible (Mallet, 1992). The surface is built with an indirect method (Frank et al., 2007): (1) A new surface is created with the appropriate dimension in order to contain the region of interest. (2) The clues are defined as constraint to the surface. (3) The surface is successively interpolated and the triangulation is refined.

The purpose is to build a geomodel for flow simulations in order to improve understanding of the karst UZ functioning. The 3D surface network has to respect geological principles (e.g: law of superposition, crosscutting relationships, inclusions). Finally the geomodel is composed by main geological surfaces as horizons and faults, coherent with geophysical surveys and geological principles.

4. Geomodelling and results

4.1. Interpretations of underground structures

The geophysical signature of the underground is related with water content but also with the geophysical method. The main concept is that geological structures have not changed between the first field campaign in April 2011 and the last in December 2012. For this period the only source of variability is the water content. Moreover, each geophysical method provides information about distribution of rock properties. It is possible to suggest a geophysical interpretation of underground geometry for each geophysical technique. The challenge is to coordinate accurately all geophysical interpretations to suggest a unique interpretation. A 3D visualisation of all geophysical data is essential to succeed doing the coupled interpretation.

GPR highlights underground structures (e.g. limestone bedding, fractures) and ERT highlights contrasted zones. The coupled interpretation of both is compared with geological (map or log) or geotechnical (faults and major lithological changes) information (Fig.3). A geological horizon has geometry almost parallel with the topography. Vertical reflectors as faults or fractures are characterised by GPR. A fault induces a vertical zone of contrasted resistivity and seismic wave velocity changes. Major faults have also been reported on the geotechnical plan of the emergency gallery.

4.1.1. Horizons

The vertical succession of three horizons is shown by all geophysical methods. The first horizon is located about 2m deeper than topography. It presents an important variation of electric resistivity depending on the measurement date. Moreover, velocities of seismic waves are lower than deeper. This horizon is soil and strongly altered limestone.

The second horizon is a succession of regular limestone beddings parallel to the topography.

The 2D coupled interpretation of GPR and ERT performed by Carrière et al. (2013) on the studied site highlighted that an electrical conductive zone and cross bedded biocalcarenite are correlated. The 3D coupled interpretation confirms the correlation. The top of cross bedded limestone unit is identified on several GPR and ERT cross sections and represented with a surface (fig.4). This geological limit is sub-parallel to the topography at about 6m of depth. Three beds with cross stratifications are identified; their thickness is about 2 meters each. The bottom of this boundary is not clearly imaged with geophysical survey but two largest ERT sections (252m long) highlight a resistive zone sub-parallel to the topography at around 20m of depth.



Figure 4: View of the 3d geomodel: the top of cross bedded limestone unit (grey and transparency) with two GPR sections.

4.1.2. Fractures and faults

Limestone is affected by fractures, faults and karst patterns. GPR images numerous vertical discontinuities. Fractures are considered as oriented alteration of the first horizon, they will be used to guide rock properties distribution. Faults are relevant objects which influence the geophysical underground signature (Seismic and ERT). Additionally, the fault network involves preferential water flow which is clearly shown by the different campaign of ERT. The coupled interpretation of multiple geophysical methods highlight three main faults oriented North-South called: East-Fault, Center-Fault and West-Fault. The coupled interpretation of ERT, GPR and seismic surveys highlight underground structures of the karst UZ.

4.2. Discussion

All available data on geology and hydrogeology of the test site were gathered in the same 3D space. There is no more information about the test site, so the geomodel is the actual most complete and robust local model of karst UZ. It helps to enhance understanding of water flows. The test site is above the pour point called "point D" which is observed in the emergency gallery of the LSBB.

On one hand, the point D is located at 33m of depth and has a permanent flow despite dry periods. On the other hand, limestone with cross stratifications has a lower electrical resistivity (900 ohm.m) than compact limestone (3000 ohm.m). This decrease of resistivity is attributable to a higher content of water. The cross bedded limestone unit is the potential water tank which supplies the point D (fig.5). An important fault

and fracture network is identified by geophysical surveys. These vertical discontinuities manage vertical water flow through karst medium (fig.5). It could be a preferential pathway for water infiltrations. The first horizon composed by soil and limestone strongly altered is a buffer zone of rainfall infiltrations. It is also the horizon between the forest and the karst medium, where an amount of water is drawn by the forest. The geomodel makes easier the link between geological structure and water flows.



Figure 5: Interpreted cross section of geology and water flows of the test site.

Conclusion

The knowledge of the geological framework and rock properties distribution of karst UZ involves many uncertainties because of strong lateral and vertical heterogeneities. Geophysical methods provide information on both rock properties and water content. But the geophysical signature is variable with climatic conditions, the water content and rock properties. In order to enhance understanding of karst UZ structures our methodology is based on field investigation with multiple geophysical methods at different time. The main concept is the geological structures are the common point between all cross sections and water content is the only source of variations.

The methodology is based on three geophysical surveys, they are commonly used for geological or hydrogeological purposes. Structural information is extracted from seismic, GPR and ERT surveys. Geophysical surveys are performed in 2D so there are many possibilities to link information from several cross sections. As well as to propose a 3D structure close to the reality, the underground geometry is compared with geological and geotechnical data.

The proposed geomodel is composed of three main faults, several fractures and three horizons. Thus structure is not straightforward with 2D cross sections. Combining geophysical methods and gathering results help to consider 3D variations of rock properties and to characterise the geometry. There is a constant link between measurements and interpreted geological surfaces. The obtained geological model is coherent with geophysical and geological information. Horizons and faults/fractures networks were specified with metric resolution. The understanding of structures has been locally improved and leads to enhanced knowledge of the karst UZ functioning. In a second time, this local model will be used to constraint dimensions and discontinuities of the hydrogeological model for water flow simulations.

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