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Simulation of 3D karst conduits with an object-distance based method integrating geological knowledge

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ABSTRACT

Karst conduit shapes have a high influence on fluid flows. As these underground hidden systems are partially inaccessible, their stochastic simulation is an essential tool to assess the uncertainties related to these highly exploited water resources. The object-distance simulation method (ODSIM) is a hybrid dual-scale approach that has been recently proposed to model geological underground structures due to late processes such as dolomitized rocks, mineralized veins or karsts. Using a perturbed Euclidean distance field around a curve representing roughly the conduit centre and called a skeleton, the resulting shapes are globally cylindrical-like 3D envelopes. But at a drain scale, karstic conduits are elongated along weakness planes such as lithostratigraphic horizons, bedding planes, fractures or faults. In addition to those planes the influence of the water table is added. This work presents different improvements of ODSIM methodology for simulating more realistic shapes in the particular case of karst. Firstly, we propose using a custom distance field computed with a fast marching method. Considering the “velocity” field to be proportional to the permeability allows the resulting features to be elongated along the weakness planes. Secondly, to handle specific shapes due to the proximity of the water table, such as trenches or notches, we impose areas of higher velocity between the skeleton and the water table. Finally, we generate a custom random threshold with several variograms and/or distributions depending on the different features integrated in the “velocity” field. Applied on different models, it is shown that the resulting karst conduits have more realistic shapes than those obtained with the previous workflow, while the variability of structures which can be modelled with ODSIM is preserved.

1. Introduction

Karstic systems are underground hydrographic networks made of conduits and caves that have grown by dissolution of the surrounding rocks. They cover approximately 20% of the planet's dry ice-free land (e.g., Ford & Williams, 2007; De Waele et al., 2009) and are therefore important fluid reservoirs, providing water for probably 20 to 25% of the world's population (Ford & Williams, 2007). Development of caves is also responsible for substantial human and financial disasters by causing sinkholes in urbanized zones. These karst features can be dramatic as the surface land usually stays intact until there is insufficient support: the soil suddenly collapses, swallowing everything above (e.g., (Brinkmann et al., 2008; Frumkin et al., 2009; Parise et al., 2009)). Recent works have shown that karsts may also be a major source of paleoclimate records (e.g., Mongelli, 2002; Horvatinčić et al., 2003; Onac & Constantin, 2008; Kuo et al., 2011). Nowadays human activities are a major threat for karstic environments (e.g., De Waele et al., 2011), and furthermore climate changes may have a considerable impact on them in the future (e.g., Viles, 2003; Hartmann et al., 2012).

Despite the importance of karstic networks, their location and exact geometry remain poorly known, mainly due to the partial inaccessibility of these underground systems. These networks actually play a major role in the flow regime of most carbonate aquifers and reservoirs (e.g., Lü et al., 2008; Chaojun et al., 2010): their conduits act as preferential flow paths and concentrate the fluids. As conduit shapes result from a complex dissolution process (e.g., Ford & Williams, 2007), a straightforward modelling approach of fluid flows would represent karstic conduits as equivalent to cylindrical tubes. This approach does not take into account the shape variations like abrupt narrowings or enlargements which also greatly impact fluid flows (e.g., Field & Pinsky, 2000; Hauns et al., 2001; Goldscheider, 2008; Morales et al., 2010). Thus, knowing and modelling the shapes of these three-dimensional geological objects could be an important improvement for both water and oil and gas reservoir exploitation. The goal of this paper is to propose a tool to realize such three-dimensional modelling of karstic systems.

Two different contexts of application are examined. First, as large parts of cave systems are still unexplored, three-dimensional stochastic simulations offer a way to better assess the associated uncertainty. However, the current methods focus on the global architecture of the conduit networks (e.g., Borghi et al., 2012; Collon-Drouaillet et al.,

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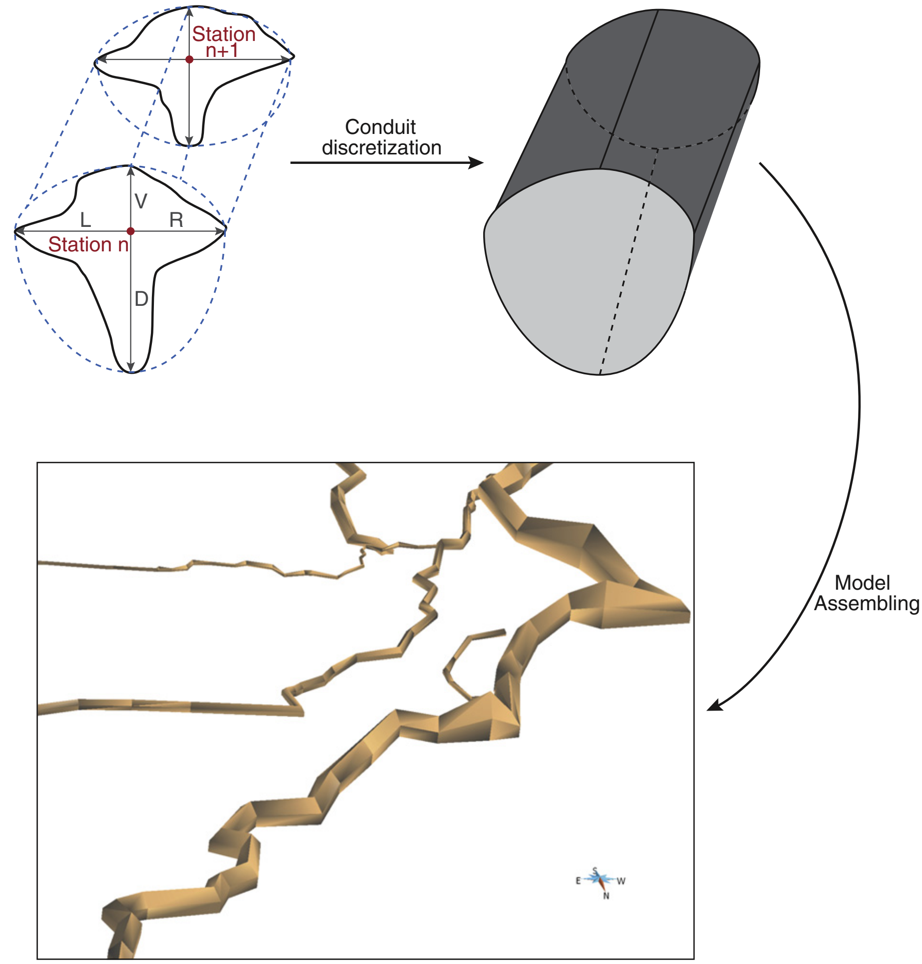

Fig. 1. Classical conduit discretization process and 3D "reconstruction" used in common speleological programs (here with GHTopo).

2012; Pardo-Igúzquiza et al., 2012). They stochastically generate several possible skeletons representing roughly the conduit centre and highlighting the uncertainties related to the conduit location. The proposed methodology is complementary to those works by providing volumetric information around those skeletons consistent with local geological settings, highlighting the uncertainties related to the conduit size and shape. Second, it provides a solution to reconstruct the three-dimensional geometry of explored and monitored cave systems. Indeed, new technologies like LiDAR have permitted precise mapping of cave conduits (e.g., Jaillet et al., 2011). But this type of acquisition is time consuming, needs specific equipment and requires a post-treatment of huge amounts of data. It is thus far more adapted to explore and model karst at the drain scale. For larger scales, there are two categories of data: i) two-dimensional maps (plan and/or profile views) which result of a projection of a three-dimensional network on a two-dimensional plane — this is the oldest and most common type of data; ii) three-dimensional information provided by "modern" cave survey. In the latter case, the underground topographic information is given by a sequence of topographic stations, located in order to fit exploration requirements: access easiness, clear sight along the cave passages, etc. At each station only distances to walls are recovered left, right, up and down (LRUD). The numerical treatment of these data leads to a discretization that represents the conduits with elliptical or rectangular section shapes (Fig. 1). Dealing with both categories of data, the 3D reconstruction remains a problem that is currently solved in common speleological programs with a linear interpolation between the various two-dimensional sections leading to more or less realistic shapes (e.g., Survex,[1] VisualTopo[2] or GHTopo[3]).

In both contexts, few works have been conducted on modelling more realistic 3D karstic conduit shapes (e.g., Labourdette et al., 2007; Henrion et al., 2010; Boggus & Crawfis, 2009). The object-distance simulation method (ODSIM) proposed by (Henrion et al., 2010) generates an envelope along a curve skeleton whose shape is irregular at fine scale but globally cylindrical at the first order. To integrate a geological constraint on the shape, e.g., for the development of hydrothermal dolomites around fractures, they use plane skeletons instead of curves. But the resulting envelope retains a round aspect at the plane extremities. Contrary to geometries generated with this simple approach, karstic shapes are more elongated along given inception features (e.g., Jameson, 1985; Filipponi, 2009) that favour karst conduit development. Thus, depending on the local geological context, the cross-section geometry of karstic conduits varies from circle to lens or "keyhole" (Section 2). These particular shapes are not reproduced by ODSIM (Section 3). In this paper, we propose a new methodology to integrate various geological features influencing conduit shapes by using a custom distance field generated with a fast marching method instead of a Euclidean distance field (Section 4). This involves the creation of a

[1] http://survex.com/.
[2] http://vtopo.free.fr/.
[3] http://siliconcavings.chez-alice.fr/.