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# An electrical resistivity imaging-based strategy to enable site-scale planning over covered palaeokarst features in the Tournaisis area (Belgium)

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ABSTRACT

Since the beginning of the 20th century, more than 150 sinkhole occurrences, mainly dropout (or cover-collapse) sinkholes, have been reported in the Tournaisis area (south-eastern Belgium). Land-use planning in such a context has to take into account hazards linked with sinkhole subsidence and collapse. Management maps, drawn at a regional scale, point out zones where karstic risks have to be taken into account when dealing with infrastructure or building projects. However, karst hazard is highly variable in three dimensions at the local scale. Therefore, for such purposes, an accurate methodology is needed to detect and delineate covered karst features, especially when located in urbanized areas.

As geophysical investigations are sensitive to contrasts in physical properties of soils, these methods can be useful to detect such targets. The specific karstic context encountered in the Tournaisis area strongly guides the choice of investigation techniques. Electrical resistivity imaging (ERI) methods were tested on a well-known site where dropout sinkholes occurred formerly. This site was also studied using static cone penetration tests (CPT) and boreholes. A 3D inverted resistivity model was computed based on the 2D ERI models obtained after inversion. Resistivity profiles were extracted at each CPT location and compared to geotechnical results to determine an empirical and site-specific resistivity law that allows discrimination between weathered zones and sound limestone. Performance tests were conducted to evaluate the potential of the proposed methodology for two typical engineering problems based on two current hypotheses. Borehole data were used as ground truth. Similar performance tests were also computed using the CPT depth to bedrock model. The results of these performance tests are compared and discussed. Finally, an ERI-based investigation strategy is proposed to assess karst hazard in palaeokarstic context, such as encountered in the Tournaisis area, at the scale needed for building and infrastructure purposes.



## 1. Introduction

Land-use planning in covered karst terrains should take into account hazards linked with sinkhole activity. Covered karst areas are characterized by soluble rocks overlain by residual soils or allogenic sediments. Due to the presence of these cover materials, typical karstic landforms may be concealed. The presence of karst may remain unknown when sinkhole collapses do not reach the surface. When occurring in urbanized areas, these collapses can cause considerable damage on buildings and infrastructure ranging from temporary loss of serviceability during repair works to complete destruction and loss of human lives. Well-known cases of such damage have been reported all around the world. Examples of severe damage due to sinkhole activity can be found in: Sowers, 1996 (Winter Park, Florida, USA), Dougherty, 2005 (Allentown Corporate Plaza in Pennsylvania, USA), Buchignani et al., 2008 (Camaiore city in Tuscany, Italy), Buttrick and van Schalkwyk, 1998 (Gauteng Province in South Africa) and Yuan et al., 1998 (southern China).

At a regional scale, integrated methodologies have been developed to assess karst hazards (Edmonds et al., 1987; Kaufmann and Quinif, 2002; Benson et al., 2003; Waltham et al., 2005; Caramanna et al., 2008; Cooper, 2008; Galve et al., 2009). According to Waltham et al. (2005), the first step usually involves collecting records of sinkhole occurrences and other karst features and storing them in a database to produce a danger map which is an inventory map that shows the locations of mapped sinkholes and provide information on size, age and other relevant parameters. This danger map corresponds to the second level of hazard mapping in sinkhole terrains as defined by Waltham et al. (2005). To produce a hazard map, locations of recorded features are analyzed. Relevant background knowledge such as the geological and hydrogeological context should be taken into account in this analysis. Hazard levels are then defined and hazard maps are drawn. These maps may be computed within a GIS system (e.g. Kaufmann and Quinif, 2002; Cooper, 2008; Galve et al., 2009). Given the expected consequences of sinkholes, hazard maps can be combined with land-use maps to evaluate

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risks associated with different land uses. Finally, management maps may be derived from the risk maps to prevent and control development where needed.

However, these maps are usually drawn at a regional scale, typically tens of squared kilometers, while karstic hazard is highly variable in space at a local scale, typically from a few areas to a hectare. That is why local analysis for building purposes needs to be carried out at the local scale. When the presence of karst features cannot be predicted from surface evidence, as in covered karst areas, specific methodologies are needed to develop three dimensional engineering geological models of the near surface.

Geotechnical investigations, such as destructive boreholes or cone penetration tests have been shown to have limitations in the detection of such targets (Thomas and Roth, 1999). Indeed, the three dimensional geometry of karst features is often complex. Moreover, the depth of penetration could be limited by competent cover materials such as marls or chalk. Though these direct investigations are required to precisely determine the nature of the soils and to estimate soil resistance, they give only single point data. The number of boreholes and/or CPTs needed to reliably map buried karst features or detect sinkholes infilled to the surface rises quickly with the site dimension, as well as the cost of such investigations. Therefore, in practice, the number of geotechnical tests is limited and the reliability of interpretations based only on such investigations tends to be poor (Thomas and Roth, 1999).

Even if karstic terrains remain a challenging context for geophysical investigations, continuous development of acquisition and processing techniques have significantly improved their imaging abilities (e.g., Aizebeokhai (2010), Loke and Barker (1996b)). Moreover, they are minimally intrusive and may prove cost-effective (Reynolds, 2011). That is why these imaging techniques are of increasing interest to improve the knowledge of ground conditions. Indeed, geophysical methods allow the detection of contrasts in physical properties of soils, such as density, magnetic susceptibility, dielectric constant or electrical resistivity. Geophysical surveys have been conducted in karst terrains to map karst hazards such as voids, conduits, sinkholes and weathered zones for several decades. Most of the techniques used were developed to detect water-, air- or sediment-filled cavities as some of their physical properties may be significantly different from those of the host bedrock. The methods tested include magnetometry (e.g. Gibson et al., 2004; Rybakov et al. , 2005; Mochales et al., 2007, 2008; Pueyo-Anchuela et al., 2010), ground penetrating radar (e.g. Beres et al., 2001; Al-fares et al., 2002; Mochales et al., 2008; Pueyo-Anchuela et al., 2010), seismic reflection (Cook, 1965), surface wave analysis (Thierry et al., 2005), micro-gravimetry (e.g. Bishop et al., 1997; Beres et al., 2001; Rybakov et al., 2001; Thierry et al., 2005; Mochales et al., 2008) and DC resistivity tomography (e.g. Guérin and Benderitter, 1995; Gautam et al., 2000; Kaufmann and Quinif, 2001, 2002; Sumanovac and Weisser, 2001; Roth et al., 2002; Van Schoor, 2002; Zhou et al., 2002; Gibson et al., 2004; Kaufmann and Deceuster, 2005; Deceuster et al., 2006; Abu-Shariah, 2009). Most of these methods were aimed at detecting voids or cavities filled with allochthonous sediments, sometimes in a covered karst context.

Only a few of these experiments were dealing with site-scale planning, especially in covered palaeokarst context, such as encountered in the Tournaisis area. However, accurate methodologies are needed to assess underground conditions in this specific karstic context as karst features are highly variable in three dimensions at the scale needed for building and infrastructure purposes. That is why, in this paper, the efficiency of a new strategy developed to discriminate between sound and weathered rocks based on ERI techniques is assessed.

## 2. Geological and hydrogeological setting

The Tournaisis area is located in the south-eastern part of Belgium near the French border (Fig. 1). In this region, the bedrock is mainly composed of argillaceous and siliceous Carboniferous limestone (Hennebert and Doremus, 1997) from the parautochthonous cover of the Brabant Massif (Mansy et al., 1999). This bedrock is overlain, in a non-uniform way, by a cover that mainly consists of Cretaceous marls and chalks and sandy or clayey Tertiary sediments. The thickness of this cover ranges from a few metres near Tournai to more than 100 m in the north-west.

In the Tournaisis area, the bedrock is marked by east to west dextral wrench faults that form part of the Melantois–Tournaisis faulted anticline structure (Fig. 1) dated as Tardi-Varsican. Later movements also affect Mesozoic and Cenozoic sediments (Hennebert, 1998).

The Palaeozoic bedrock elevations are linked with the structure even if the relief is fairly low in the area. Near the anticlinal axis, bedrock elevations range between 30 and 40 m above sea level. Away from the anticline axis, the bedrock plunges towards the northwest and the southwest and, consequently, the cover thickness increases. Cretaceous marls and chalks are mainly present in the western and southern parts of the Tournaisis area while Cenozoic sediments cover the whole area. The nature and thickness of the latter is mainly dependant on the actual relief, which results of their erosion.

The Carboniferous limestone aquifer of the Tournaisis area is a major water resource for Belgium and northern France. Aquifers of more limited extent are also encountered in the meso-Cenozoic sediments especially where marls or clays cover the limestone aquifer.

The structure delimits two hydrogeological domains in the Carboniferous aquifer: in the south, the Frasnes–Péruwelz–Seneffe free aquifer and, in the north, the confined aquifer of Pecq–Roubaix (Fig. 2). Since the beginning of the 20th century, intensive groundwater pumping has been carried out for deep quarry works or individual, municipal and industrial water supply. These operations resulted in differences in the way that the two hydrogeological domains developed.

In the Frasnes–Péruwelz–Seneffe aquifer, piezometric heads remained steady in most of the zone, while in the Pecq–Roubaix aquifer the piezometric heads dropped by at least 1 m per year between 1945 and 2000 due to a lower recharge given the presence of impermeable layers within the cover. More locally, dewatering for limestone quarries (east of Tournai) also has had a strong impact on the groundwater level. Lowering of piezometric heads has led to dewatering of the uppermost part of the limestone bedrock over broad areas.

## 3. Karstic context

Even if the fairly low relief of the Tournaisis area shows few landforms typical of karst terrains, quarry faces (Fig. 3) suggest that palaeokarst features are common in the underlying limestone. Fig. 4 shows a conceptual model of the different type of karst features found in limestone in the Tournaisis area (Kaufmann, 2000). These karst features formed prior to the deposition of the Tertiary sediments. Sinkholes occur when cover materials are washed away into the underlying bedrock voids.

### *3.1. Karst features*

Karst features mostly develop in association with discontinuity planes (joints) by progressive dissolution of the carbonates leaving a soft and porous weathering residue. A typical result of this weathering process is a profile with 1 to 10 m wide and 10 to 30 m deep enlarged weathered joints (Sowers, 1996) (also called grikes or cutters elsewhere) between blocks of intact rock. The main specificity of this profile is that these enlarged weathered joints mainly contain an isalterite, as defined by Delvigne, 1998, (a weathering product with slight or no change in rock volume and remnant rock structure) except at their top. As the host limestone is siliceous, this isalterite is also siliceous but a significant content of carbonate may remain in some of the intermediate weathering products and the porosity is commonly very high (up to 50% or more) as shown by Kaufmann et al. (1999) and Quinif