Urban site investigation in the Belgian karst belt

ROBRECHT SCHMITZ[1] & CHRISTIAN SCHROEDER[2]

[1] *Université de Liège. (e-mail: rm.Schmitz@ulg.ac.be)*
[2] *Université de Liège. (e-mail: Christian.Schroeder@ulg.ac.be)*

Abstract: Karst in Belgium affects predominantly Palaeozoic carbonate rocks. The karst encountered developed during different geological eras: Palaeozoic, Mesozoic and Caenozoic karst can be found. Palaeozoic karst is encountered at any depth where the Visean meets the Namurian; this contact is infamous amongst tunnel engineers. Mesozoic karst is found e.g. in Tournaissian rocks, were the karst holes are filled by Tertiary sediments up to 100m deep. Caenozoic karst, affects nearly all carbonate formations. It was developed during the ongoing uplift of the region thereby allowing the rivers to erode into the riverbeds, lowering the regional water table and continue with the karst formation at a lower level. Several cases of urban development in the Belgian karst belt are discussed. During all of these cases, problems related to karst were encountered. It is shown that with a mix of geophysical methods, analysis of geological maps, information provided by locals and speleologists and analysis of aerial photographs, one is able to indicate if there is karst but neither its size, geometry, depth or extent can be determined with an accuracy that is precise enough to satisfy engineering design. It is, however, important that this engineering geological investigation is performed as early as possible during the project. Then the construction firm knows that not a 100% detailed planning is required but flexibility. In all these cases there is a double task for the engineering geologist very early, less detailed, to change the philopsophy of the construction approach and then later on during construction on a day to day basis directly on the construction site. It is shown that this approach, where applied, was successful to deal with the unpredictability of karst during urban development.

Résumé: En Belgique, le karst se rencontre principalement dans les roches carbonatées paléozoïques. Selon l'époque de formation, on distingue le Paléokarst, le karst mésozoïque et le karst cénozoïque. Le Paléokarst se rencontre à n'importe quelle profondeur, là où le Namurien est en contact avec le Viséen. Ce contact est source de nombreux problèmes lors de constructions, entre autres de tunnels. Le karst mésozoïque est situé, par exemple, dans les roches tournaisiennes où des cheminées karstiques peuvent être remplies de sable sur une profondeur. d'une centaine de mètres. Le karst cénozoïque affecte pratiquement toutes les formations carbonatées. Il s'est développé durant la surrection, toujours en cours, du sud du pays, qui a encaissé progressivement les rivières et entraîné l'évolution du karst en suivant celle du niveau de la nappe alluviale. L'article présente différents cas de développement urbain dans la "ceinture karstique belge" au cours desquels des problèmes liés aux karst ont du être résolus. Il s'avère qu'en utilisant simultanément différentes approches (géophysique, cartes géologiques et géomorphologiques, photos aériennes, informations des spéléologues…), l'existence d'un karst peut être affirmée mais jamais sa dimension, sa géométrie et son extension ne peuvent être déterminés avec une précision suffisante pour les besoins du dimensionnement du projet. Il est toutefois indispensable que les investigations soient réalisées le plus tôt possible, ce qui permet à l'entreprise de prendre en compte les impératifs d'adaptation du budget et du planning en fonction des phénomènes réellement rencontrés. L'ingénieur géologue se voit ainsi confronté à une tâche en deux phases: dans un premier temps, déterminer la présence du karst et modifier le cas échéant la conception de l'ouvrage puis, en cours de construction, intervenir au jour le jour sur base des reconnaissances continues. Cette approche se révèle fructueuse face à l'imprédictibilité du karst en développement urbain.

Keywords: site investigation, desk study, foundations, tunnels, karst, cavities

INTRODUCTION

A site investigation is needed prior to any civil engineering construction. The results of this site investigation must lead to recognition of problems related to geology. If the problems related to the geology-structure interaction cannot be handled economically, the structure has to be relocated into a more suitable location. In some cases this relocation is not always possible. In these cases the problems related to the implementation of the structure into the geology have to be overcome. In this light, karstified areas belong to the most difficult engineering terrains. Although the presence of karst in a certain region can be identified during a site investigation, the exact location of karst voids cannot be predicted with a precision accurate enough for construction. In this contribution, an inventory is made of the possible presence of karst in Belgium. Then two case studies are presented.

ENGINEERING GEOLOGICAL DEFINITION OF KARST

For engineering geologists the importance of karst is: any dissolution void in rock mass that represents a hydraulic or mechanical discontinuity. This is close to the definition by Richter (1989): karst involves all recent and fossil leaching and dissolution processes and the resulting surface or subsurface features (e.g. cavities or cave-ins) present in rocks prone to dissolution or leaching as well as in the overburden. Note that unlike other weathering phenomena, which show a gradual transition, karstified and sound bedrock can coexist next to each other (Höwig et al. 2003).

WHERE CAN WE FIND KARST IN GENERAL

In contrast with the surface water the geological work of the subsurface water is chiefly chemical in character (Ford & Williams 1989; Waltham et al. 2005) and chemical weathering is not restricted to easily soluble rocks but attacks all rock types. The most easily weathered are limestones. Of greater resistance are sandstones and shales. Igneous rocks (excluding certain volcanic rocks that weather rapidly) and quartzites are also resistant, but karst landforms can develop on highly siliceous rocks (Selby 1993). The karst landforms developed on limestone and gypsum are only the most widespread and best documented.

WHERE CAN WE FIND KARST IN BELGIUM?

One method to analyse the extent of karst in a region consists in mapping outcrops of the lithologies prone to dissolution. In Belgium the area that could be affected by karst is restricted predominantly to Wallonia, where it occurs on Palaeozoic rocks (karst features outside Wallonia can be found in the Cretaceous rocks north-west of Liège). In these Palaeozoic rocks the karst is restricted to those that consist of limestone and dolomite but most karst can be found in the limestone (Ek 1996). The occurrence of the outcrops of these formations is shown in figure 1. This contribution will, on the basis of the karst features in Belgium, discuss only the carbonate karst.

Brussels, Antwerp and Liège, the largest cities in Belgium, lie north of the karst belt. This reaches from Tournai via Mons and Charleroi to the German border, then it turns north between Liège and the Netherlands border but here in the subsurface (therefore not indicated on the map). Routes from the Belgian cities to Germany and France unavoidably have to pass this karst belt.

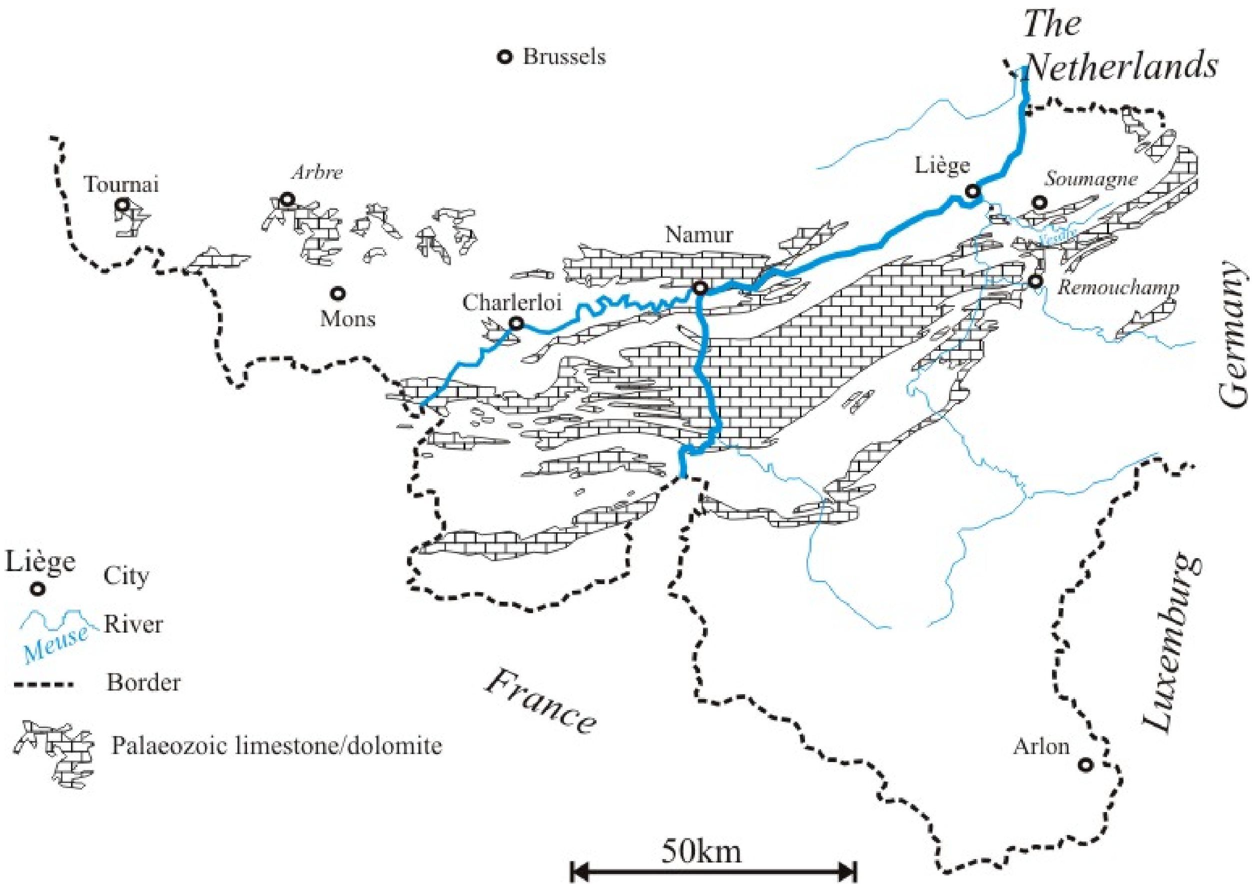

Figure 1. Palaeozoic limestone, which outcrops in Wallonia, contains most karst in Belgium (from: Schmitz and Schroeder 2003).

AT WHICH DEPTH CAN WE FIND KARST?

For engineering purposes it is of course important to know at or to which depth karst still can be encountered. Therefore we need to know when the karst was created.

During engineering construction?

The solution of limestone is a relatively rapid process in a geological sense but very slow with respect to the durability of an engineered structure. A dam site is not endangered by solution of limestone in a valley floor or flanks since concrete is generally more soluble than most limestone. Cavities filled with clayey material may let through only a little water, but its amount may increase progressively as filling is washed out from the cavities. In some cases this phenomenon has been explained erroneously as being due to rapid enlargement of caverns by the solution of limestone (Zaruba & Mencl 1976). The fact that karst cavities encountered during tunnelling are often stable and old in engineering terms can be appreciated when stalactites and stalagmites are present (John and Strappler 2003). Although karst formation continues even today it is too slow to develop during construction. The sudden development of voids during construction is related to changes in the local hydrogeological system (e.g. caused due to construction activity). These may change the properties of fills in karst voids, and therefore allow premature failures; dissolution of carbonate rocks does not occur on a time-scale relevant to engineering. The karst that is encountered must be older, and dissolution commenced before engineering construction started on site.

Karst formed during three different geological eras

Karst encountered in Belgium was formed either during the Palaeozoic (Visean), Mesozoic (Lias) or during the Caenozoic. What is the engineering geological significance contained in this information? Karst formed during the Palaeozoic can be found at virtually any depth in the subsurface - due to various mountain forming processes and accompanying faulting and folding which occurred since then - and at any inclination and orientation. Mesozoic karst can extend hundreds of meters below the present hydraulic base level and Caenozoic karst can be found in a zone +/- tens of meters below and above the present drainage system given by the large rivers in the vicinity. This shows that information about the age when the karst was formed can be used to estimate the location and extent of karst. In more detail:

Palaeokarst

Palaeozoic paleokarst in Belgium is common in the Palaeozoic limestone. The contact between the Visean and the Namurian, stratigraphically a normal contact, corresponds on the regional scale to an old erosional surface with important karstification of the limestone of the Visean. The karst is filled with Namurian sediments. The geotechnical properties of the infill material of the Palaeozoic karst on the contact Visean - Namurian is very heterogeneous: silt, sand, weathered shale, clays, breccias etc can be found (Calembert 1975). These formations were extensively folded and faulted during the Variscan/Hercynian orogeny. The Palaeozoic limestone and dolomite were karstified during the erosion of the Variscan/Hercynian mountain range (Calembert & Monjoie 1970). Just south of Visé (north of Liège), an outcrop can be found: the type locality of the Visean (next to the quarry of Souvre-Argenteau). It was Professor Dumont who gave this formation its name in 1832 (Murawski and Meyer 2004). This outcrop (figure 2) is famous not only famous for its Visean deposits, but also for its palaeokarst. The quarry of Souvre-Argenteau offers an interesting outcrop of the top of the Carboniferous in a zone located northeast of the Brabant massif. Following the nomenclature of the new geological map of Wallonia 1:25.000, N° 42-3-4 "Dalhem-Herve" (Barchy and Marion 2000), one distinguishes from top to bottom along the outcrop (figure 2):

- Quarternary: silts, alluvial gravels, river Maas terraces
- Cretaceous (Campanian): "Smectite de Herve" = "Vaalser Groenzand". In fact, this is not a smectite but a marl containing carbonate, quartz, smectite, illite, illite-chlorite mixed layers, pillared smectite and glauconite bands. This formation was deposited during the Campanian transgression on the Hercynian/Variscan peneplain. In an outcrop, the carbonates in the "Smectite de Herve" are dissolved. Thereby the originally very good rock mass (rock quality designation, RQD >90%) is transformed into a weak soil. This causes many problems if houses or roads are founded on this material.
- Carboniferous (Namurian): Souvré formation: siliceous shale and silicified limestone ("Phtanites").
- Carboniferous (Visean): sedimentary calcareous breccias, massive (dm to m) thick limestone banks, bioclastic massive limestone.

The following karst phenomena can be identified:

- Palaeokarst: provoked the formation of large cavities at the contact with the "Houiller" (= Namurian and Westphalian). The cavities have been filled with collapse breccias (Phtanite, shales and clays). Examples of this Palaeokarst can be found in an outcrop just north to the quarry (figure 2, left) and in the quarry itself (figure 2, middle).
- Reactivation of palaeokarst: the presence of discontinuities (filled with river terrace sediments) and the reactivation of palaeokarst result in progressive upwards failure (figure 2, right).

Mesozoic karst

Mesozoic paleokarst can also be found in the Palaeozoic carbonates in the south western part of Belgium. These carbonates are like the carbonates described above of Carboniferous age but a little older and were deposited during the Tournaissian. Tournaissian limestones were highly karstified during the Lias and are filled by Tertiary sediments (Schmitz 2004). This Mesozoic karst was encountered during the construction of the Arbre railroad viaduct (discussed by Schmitz and Schroeder 2003).

Active karst of the Caenozoic

The Ardennes massif is currently uplifting. This means that rivers are incising into their beds. Thereby steep valleys are formed and the regional groundwater level is lowered. Thereby karst proceeds downwards too, leaving caves located at higher altitudes dry. Karst can be found at depths of 60m below the actual riverbeds (Fetter 1994). This Caenozoic karst was encountered during the construction of the Remouchamp highway viaduct (discussed by Schmitz and Schroeder 2003), and at the foundation work at Mont Godinne discussed later on.

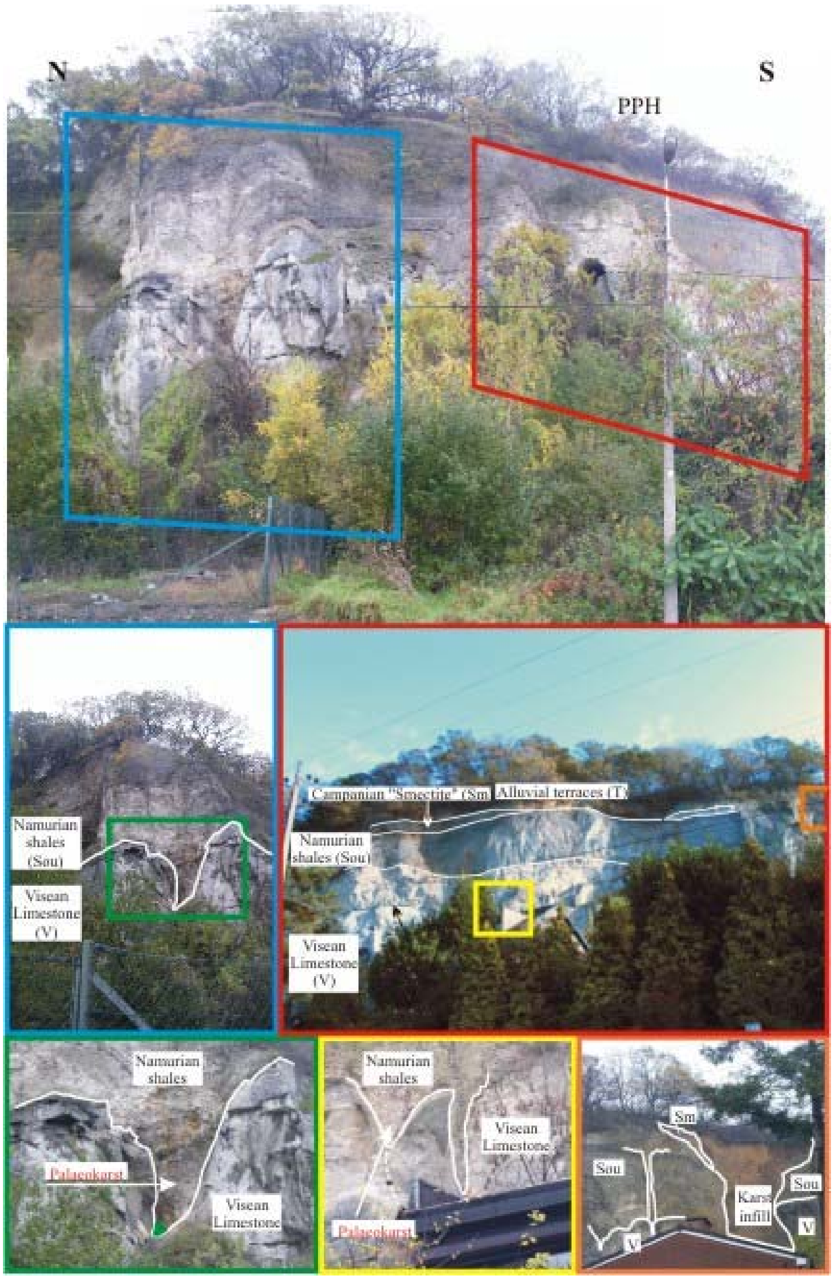

Figure 2. Outcrop showing the Palaeokarst on the Namurian-Visean interface. The outcrop is located just south of Visé (Schmitz, Schroeder & Polo-Chiapolini 2005). PPH = Post hercynian peneplain.

CASE STUDY I: PALAEOKARST IN THE TUNNEL DE SOUMAGNE

A large project for the Belgian railway in recent years was the construction of a new high-speed railroad from Brussels via Liège and Aachen to Cologne. To be able to maintain high velocity, the path of the previous, rather curved railroad, was not followed. Unavoidably, a tunnel was needed to pass through some hills on the way from Liège to the plateau de Herve. This tunnel is the Soumagne tunnel (the breakthrough occurred October 2004). From the geological maps it was known that the Soumagne tunnel had to cross the Namurian, Visean and Westphalian rocks.

Site investigation

Because outcrops like the one in Visé were known, the presence of Palaeokarst was predicted before tunnel construction started. The Visean limestone outcropping near the central shaft of the tunnel can be classified as very good rock according to the RMR (rock mass rating). The UCS (unconfined compressive strength) of the intact rock is far above 100MPa (figure 3), but the UCS of the infill can have any value down to 0.

In the Soumagne tunnel the Visean-Namurian contact was crossed, moreover, due to the local tectonic setting the tunnel remained close to this interface (figure 4); a detailed geological description can be found in Monjoie et al. 1994 or Couchard et al. 1994.

Figure 3. Karst in the Visean at the surface, directly above the tunnel construction site. This formation dips into the subsurface to intersect the tunnel axis.

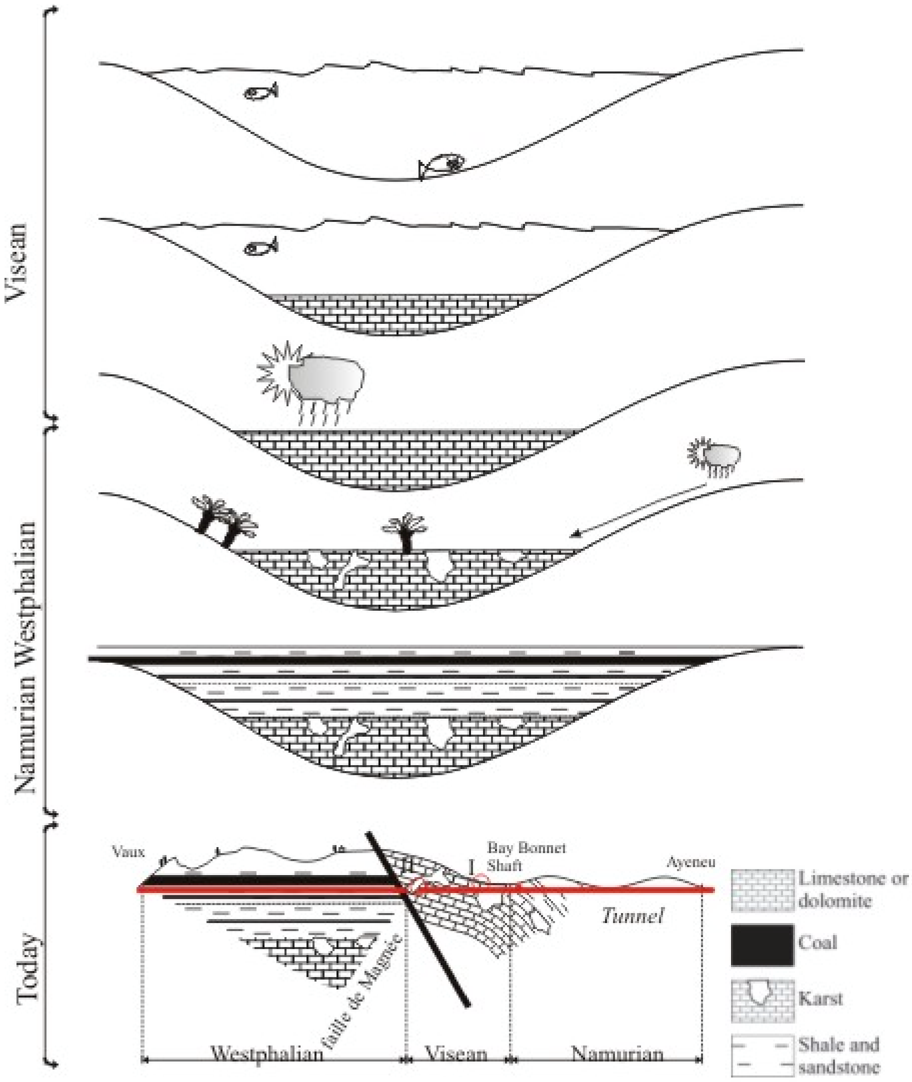

Figure 4. A simplified draft of the geology of the Soumagne tunnel. Due to tectonic disturbance the tunnel remains close to the Visean-Namurian interface thus within the palaeokarst. Not indicated in this section is the faulting and folding of the coal and schist layers of the Westphalian (from: Schmitz and Schroeder 2003).

The site investigation consisted of:

- 105 boreholes (total length 8km) geophysical, geotechnical and geohydrological measurements
- the construction of a pilot gallery
- the application of microgravimetry measurements (Monjoie et al. 1994) to determine the location of karst voids.
- drilling in advance of the tunnel front.

Results of the site investigation

Especially in the proximity of the future shaft a large anomaly indicated that karst could occur. It was verified during the tunnelling, that this anomaly was indeed related to palaeokarst in the contact Visean - Namurian and in the Visean self.

Was the site investigation appropriate?

Karst phenomena were encountered during tunnel construction (figure 5). Based on geological knowledge of the area and the site investigation it was known that karst occurred and in which stretches of the tunnel karst phenomena could be expected. The site investigation did not provide the exact location of all different karst voids. Therefore in Soumagne a flexible approach was followed. Different support methods (steel arches, swellex, shotcrete) were applied depending on the geomechanical requirements. Different excavation tools (blasting, roadheaders) were available on site to deal with hard and soft rock. Difficult stretches were mastered using support in advance of the tunnel front, including forepoling and spiling, methods commonly used in Europe to pass difficult zones in karst, *e.g.* the Irlahüll tunnel in Germany.

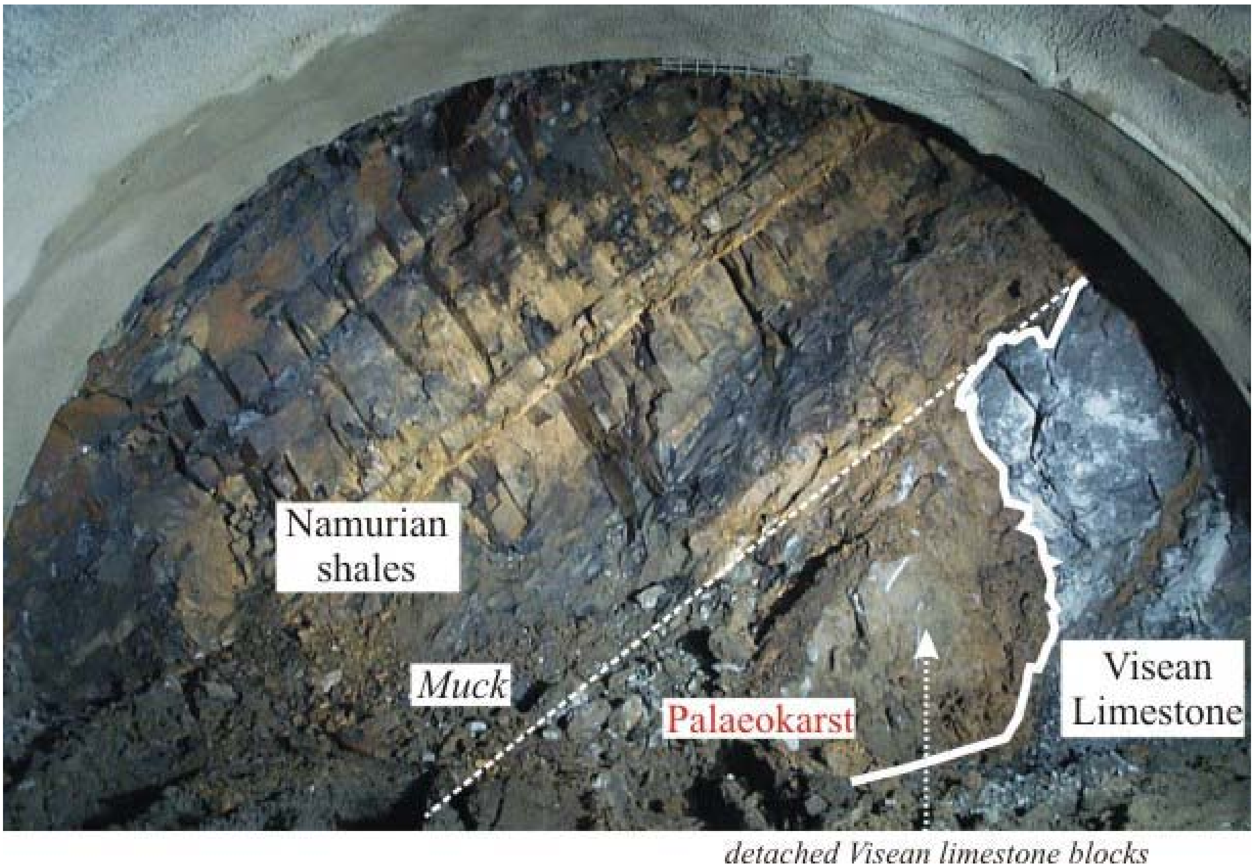

Figure 5. Tunnel front during the construction of the Soumagne tunnel (radius 5.5m) showing the palaeokarst on the Namurian-Visean interface (Photo: Courtesy of S.M. Soumagne Tunnel).

CASE STUDY II: CAENOZOIC KARST AT MONT GODINNE

Mont Godinne is located on a plateau east to the river Maas and south of Namur. At this location the construction of a large building was planned in the 1980s. Site investigation for the construction of another large building next to the existing one, started in 2004.

Site investigation

At the Mont Godinne site Devonian limestone formations of Frasnian and Givetian age surrounded by less permeable shales can be found (figure 6). The hydrological base level is set by the river Maas. As is known from the Liège region (e.g. Beauregard valley Amostrene) the contact between impermeable layers and limestone is especially prone to karstification. Karst features are often found a few meters down dip from the outcrop where a shale and a limestone meet. Karst decreases at depth from the outcrop, where the contact lies below the epikarst zone of high dissolutional acitivity. Within a syncline, water may accumulate in the axial zone. Above this axis karst features are known to develop *e.g.* the doline "effondrement de Amostrene" near the village of Esneux shown in figure 7.

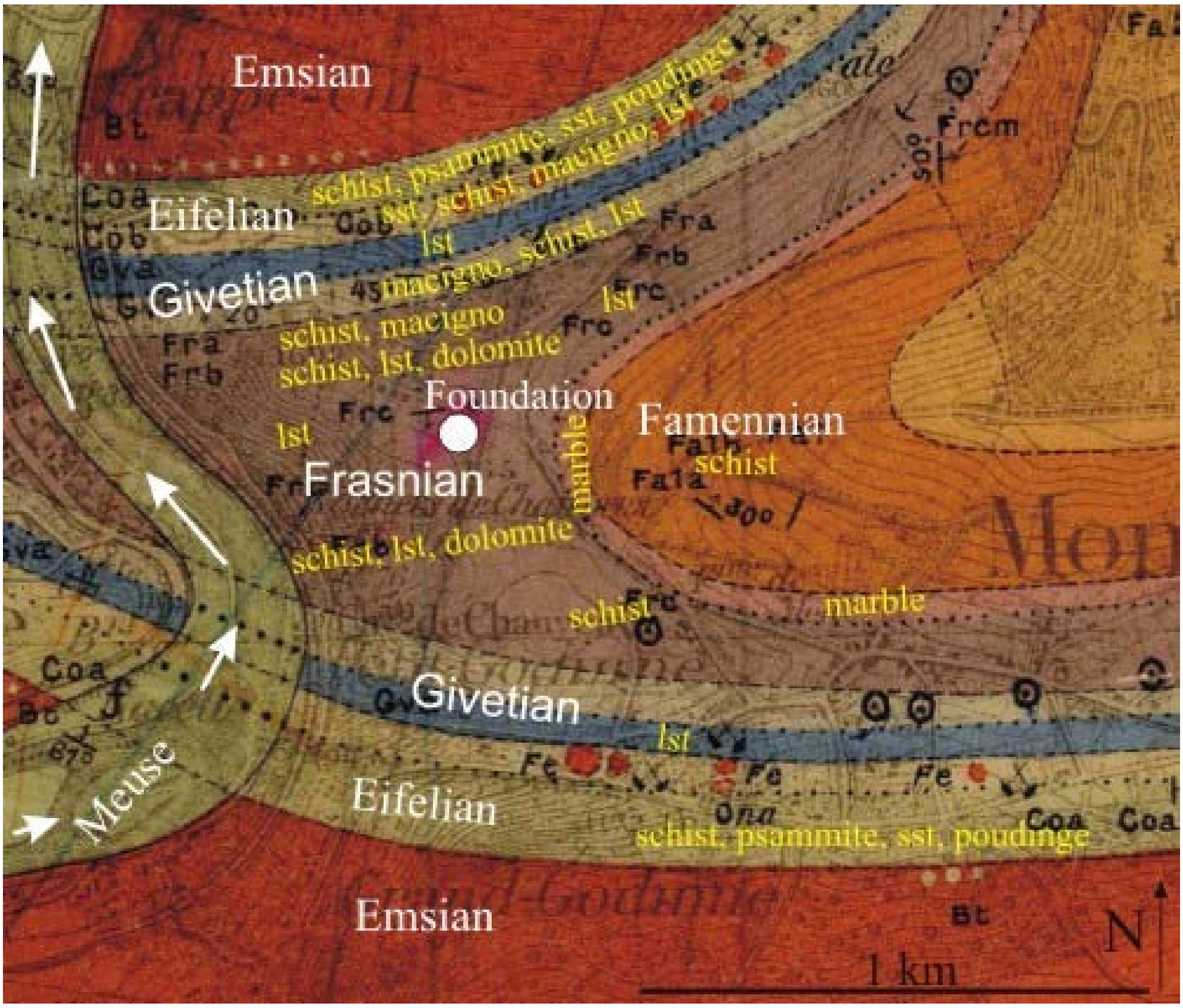

Figure 6. The geological map of the Mont Godinne site (marked by Foundation); lst = limestone. Source: Carte géologique de la Belgique au 1/40.000e (1890-1919).

Figure 7. The doline “effondrement de Amostrene” near the village of Esneux shown in this photograph (2004).

Site investigation

On the basis of the information, presumed to be provided by the geological map, the subsurface was interpreted as being composed of competent rock overlain by a soil cover. The site investigation concentrated therefore on finding the distance form the surface to the bedrock with a simple penetration system consisting of hammering a rod into the ground to determine the depth to the bedrock (figure 8).

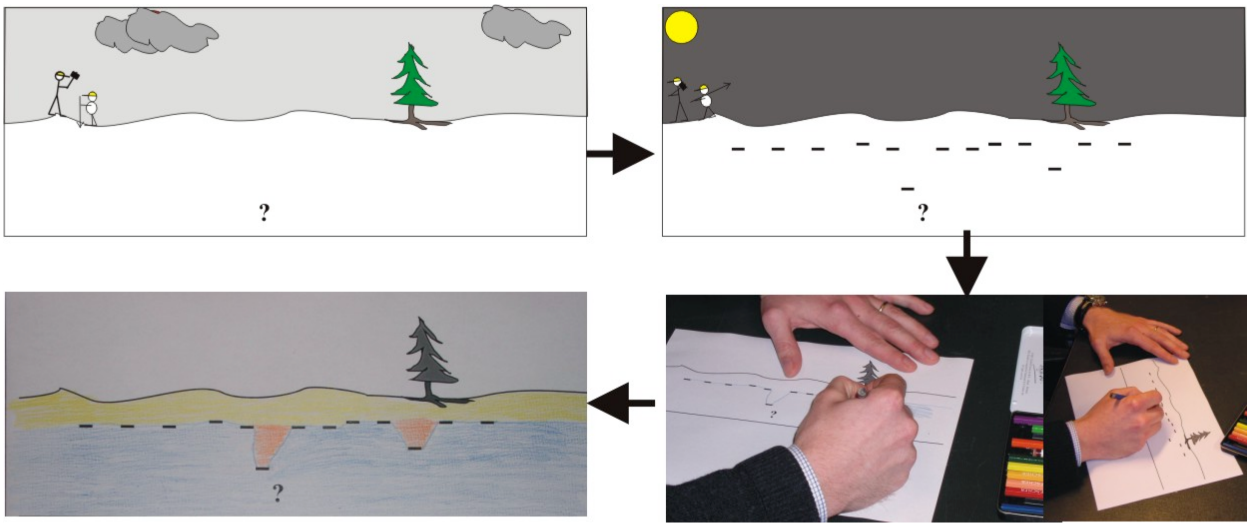

Figure 8. Reconstruction of the site investigation at the Mont-Godinne site in the 1980s. Upper left: a steel rod was hammered into the ground to find the depth to the bed rock. Upper right: the depth was measured along the extent of the future foundation. Lower right: this information was interpreted. Lower left: the interpretation used for design (some karst holes were identified).

On the basis of the site-investigation (figure 9) a quasi-continuous level of sound limestone with occasional karst voids was expected. This information was used to determine the type of foundation and to make all accompanying calculations.

Was the site investigation appropriate?

Once the excavation started the following situation (figure 10) was found. The actual situation showed that the interpreted "sound bedrock with occasional karst voids" was in fact an assemblage of detached blocks of limestone within the soil (sometimes known as "floaters").

Figure 9. Mont Godinne construction site: The dimensions of the karst can be appreciated by the scale of the full size ladder encircled in red used by the working team to descend into the karst. Each white cross marks the points identified by the site investigation using the simple penetration test.

What had happened? During the site investigation karst holes were identified but their size was underestimated. The design of the foundations had to be changed completely: The time-consuming solution, that was adopted to construct the building, consisted of laborious cleaning of the karst holes and filling them up with concrete.

With the same information obtained from the site investigation, and with a better understanding of karst ground conditions, the actual situation (figure 10) could have been predicted rather more closely.

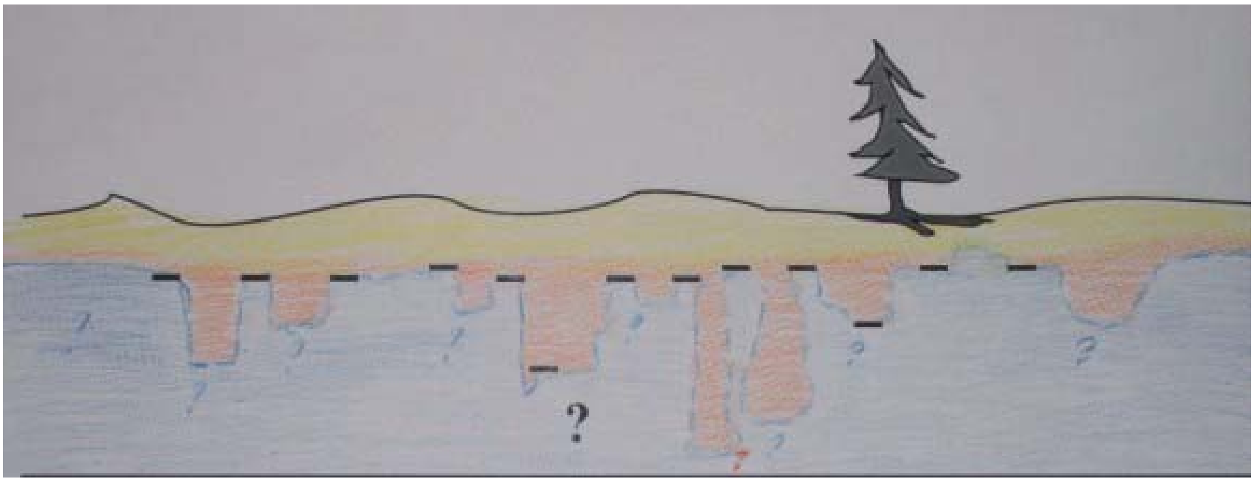

Figure 10. This should have been the correct interpretation of the engineering geologist. Could he have known this? Would you have known this?

The karst voids found in the 1980s were completely filled and the first building was constructed. When the second building has to be built next to the older one, the experience of the previous site investigation and construction were still vivid. Based on engineering geological advice, to consider a flexible foundation in this geological setting and continue with investigation during the project, the consultant is still studying the best solution. The foundation will probably be based on the use of micropiles (bored piles) along with reinforcement of the infill of the karst voids by jet-grouting.

CONCLUSION

Karst in Belgium affects predominantly Palaeozoic carbonate rocks, and karst will be encountered at many sites of urban development. The karst encountered is either palaeokarst or active karst. This palaeokarst karst can be found at any depth where the Visean meets the Namurian; this contact is infamous among rock and soil engineers. Mesozoic karst is found in Tournaisian rocks, where the karst holes are filled by Tertiary sediments up to a 100m depth. Active karst affects nearly all carbonate rocks. It was developed during the ongoing uplift of the Ardennes. As a consequence the rivers started to erode into their riverbeds, lowering the regional water table, thereby the karst formation continued at a lower level; abandoned, dry caves can be found above the present river levels. Good examples are the tourist sites at the Han-sur-Lesse and Remouchamp show caves.

Two cases have been discussed in which karst was encountered during urban development (tunnel and foundation engineering). Different types of site investigation were used. In one case (Soumagne tunnel) a very broad site investigation programme was started and in the second case (Mont Godinne), corresponding to the size of the project, a simpler site investigation was followed. In both cases the desk study phase of the site investigation was very important. Geological evidence of the occurrence of karst in both regions was available to the experienced engineering geologist. In case of the Soumagne tunnel the palaeokarst was identified well before construction. At Mont Godinne the possibility of karst was also identified. In the two cases, the information was used differently. In the first case the presence of karst was identified in an early stage of the project and led to the correct philosophy that not a 100% detailed design but flexibility and ongoing investigation during the project was needed. This same approach is followed for the present day construction at Mont Godinne.

In such cases there is double task for the engineering geologist. Very early during site investigation, he must develop an appropriate philosophy for the construction approach. Then during construction and on a day-to-day basis, he must gather information directly at the tunnel front or on the building site.

Corresponding author: Dr Robrecht Schmitz, Université de Liège, Chemin des Chevreuils 1 B52 Geomac, Liège, B4000, Belgium. Tel: +32 43669111. Email: Robrecht.Schmitz@rwe.com.

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