1 Introduction

Slovenia lies at a crossroads of major traffic routes connecting Central Europe with the Mediterranean Area, the Mediterranean Area with the Pannonian Basin, and the Pannonian Basin with the Alps. Slovenian motorways entail an approx. 615 km long network of roads. The motorway network lies in the direction of two major European traffic corridors, i.e. the X. and the V. Pan-European corridors.

Almost a third (167 km) of motorway sections runs across the karst surface, particularly in the southern half of the country where they cross the Primorska, Notranjska, and Dolenjska karst area (Fig. 1.1). Connecting important parts of the country and opening them up to Europe, the construction of modern motorways is considered to be one of the biggest construction undertakings in Slovenia in the last two decades.

In the period from 1970–1972, the first Slovenian (then Yugoslavian) four-lane motorway from Vrhnika to Postojna was built; it was 30 km long and ran across the so-called Primorska motorway section. Two years later, an 11 km long motorway section from Postojna to Razdrto was built. The Primorska section which runs mostly on the karst surface was extended until the year 2004. At Gabrk near Divača, a 16 km long section branches off the Primorska section, it runs across the surface of the Classical Karst in the direction towards Sežana and Italy. It was built in the years 1994–1998. Below Mount Nanos, a motorway towards Vrtojba and Italy and completed in 2002 branches off and crosses the karstified areas. South of Ljubljana, there is the Dolenjska motorway section that branches off towards Dolenjska and Croatia. It was built progressively in the period between 1987 and 2007. Almost 70 km of its entire length runs across karstified surfaces. The entire motorway network encompasses 22 supply stations with all the required infrastructure (filling stations, restaurants, parking areas), fourteen rest areas (parking lots, benches, tables, sanitary fittings), and nine service stations with small parking lots (DARS 2015).

Almost half of Slovenia consists of karst and more than half of the country's water supply comes from karst aquifers. Slovenia is the country of the original Karst, which gave its name to a peculiar landscape on carbonate rocks in numerous languages, and is, in fact, the cradle of karstology. The delicate karst landform requires thorough knowledge of its characteristics, and concerted preservation efforts for it is an integral part of our natural and cultural heritage.

This volume is the result of years of experience which we have obtained from studying karst features in the course of motorway construction where we are still involved in the planning and monitoring of the construction works. In addition, it references some of the most recent findings made in karstology. It was established that some, otherwise well-familiar, karst features have been neglected in karst studies. Therefore, we have highlighted relevant examples from the original Karst, the low karst of the Dolenjska region and the karst in the breccias of the Vipava valley.

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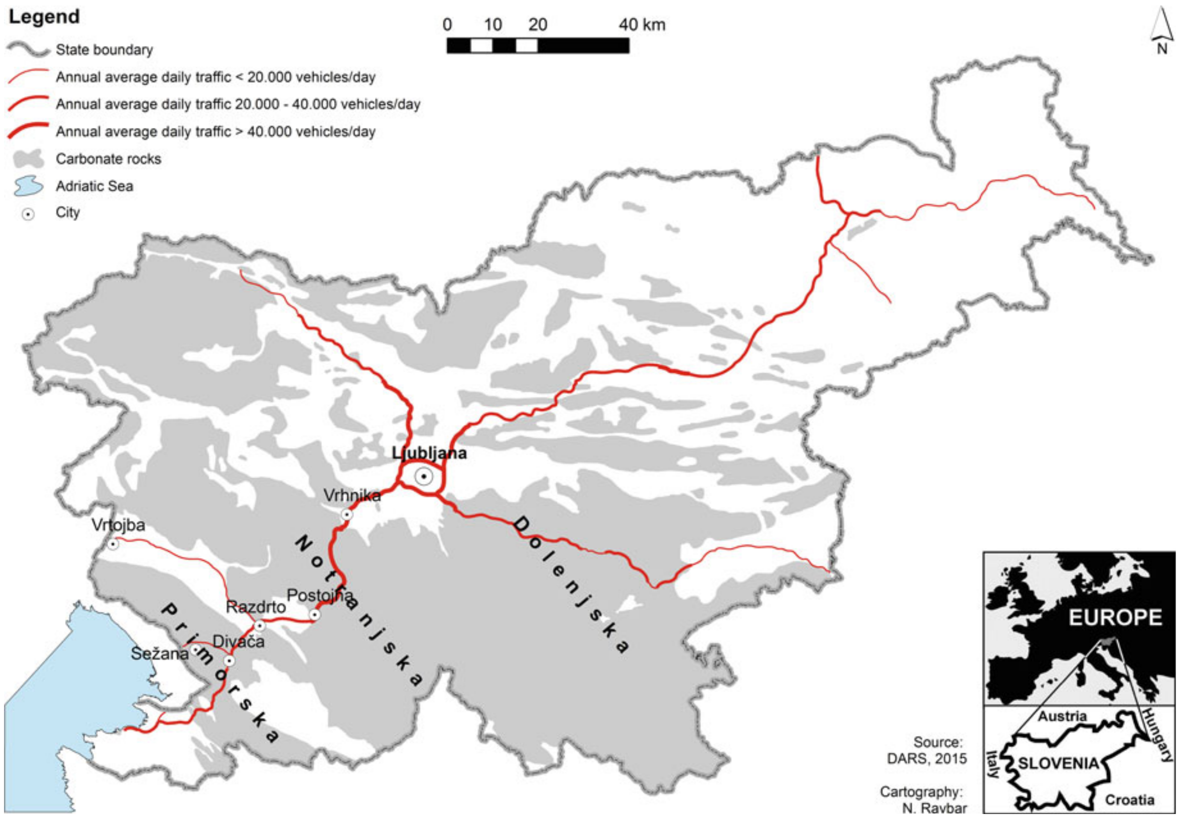

Fig. 1.1 National motorway routes and the distribution of carbonate rocks in Slovenia

In particular, our research focused on the Karst region in Slovenia, rising above the north-easternmost part of the Adriatic Sea and lined by an extensive flysch area in the southeast with altitudes of over 600 m. On a broader scale, this plateau with a total surface of 440 km^2 and altitudes ranging from 200 to 500 m is part of the Outer Dinarides. In terms of the plate tectonics theory, it is located on the northern deformed margin of the Adriatic plate and emerged as the result of thrust tectonics. Here we find only Cretaceous and Palaeogene rocks. They are characterized by a great variety of limestones which were mostly formed in relatively shallow sedimentation basins featuring diverse fauna and lush flora. In the Karst region, there is no trace of surface streams which were the go-to theory to explain the plateau development in the past. Initially, the region was surrounded and covered by flysch and therefore subject to floods. Vertical percolation was held at a minimal level. Later, the soil water dropped several hundred metres down into the karst. At the contact between carbonates and flysch, surface watercourses created a typical and vast contact karst. Today, it is typical for karst rivers to sink underground as soon as they reach underlying limestone beds instead of flysch beds. Underground, the water runs towards the Timavo Springs in Italy. The largest watercourse is the Reka River that sinks into the Škocjanske jame Caves (Škocjan Caves), with 65 % of the water percolating dispersedly from the surface. In terms of ecology, Karst is one of the most vulnerable ecosystems in the country.

The low karst of the Dolenjska region is mostly covered with various sediments over a distinct karst surface with very prominent stone forests (Knez et al. 2003). Underground water is often found shallowly beneath the surface, while the valley systems are occasionally flooded.

Karst also developed in breccias consisting of the rubble from the slopes of the Nanos plateau. Breccias lie on more or less impermeable flysch. The water running over the contact area has carved out the biggest caves around.

For a number of years now, karstologists have been involved in the planning and construction of motorways in the Karst (Bosák et al. 2000a, b; Knez and Slabe 1999b, 2000, 2001c, 2002a, 2004a, b, 2005, 2006a, b, 2007, 2008, 2009a, b, c, d, 2010a, b, c, d, e, f, 2011a, b, 2012a, b, c, d, 2014; Knez and Šebela 1994; Knez et al. 1994, 2003, 2004a, b; Kogovšek 1993, 1995a, b, c; Kogovšek et al. 1997; Mihevc 1996, 1999a; Mihevc and Zupan Hajna 1996; Mihevc et al. 1998; Slabe 1996, 1997a, b, 1998a; Šebela and Mihevc 1995; Šebela et al. 1999). When outlining the route of the motorways and railway lines, we make an effort to not interfere with the integrity of the karst landscape, and to bypass the more important surface karst features (i.e. dolines, poljes, collapse dolines, karst walls) and the caves which have already been discovered. The impact of the construction process and the use of motorways on karst waters are examined in greater depth. Motorways are supposed to be impermeable, which is why waters from the roadway are first collected in oil separators and released into the karst in a purified state.

We have studied the impact of traffic roads on karst water. Kogovšek (1993, 1995a) has examined the composition of the contamination of the daily runoff from the motorways. The stagnant waters, which were found in smaller quantities in the caves along traffic roads, contained traces of mineral oils (Knez et al. 1994).

In the scope of motorway construction, we carry out karstological supervision (Fig. 1.2). Additionally, we study newly-discovered karst features that make up an important part of our natural heritage, we provide advice on their preservation (as far as possible due to construction works), and help the construction team with new insights. We have made a series of new findings on the formation and development of the karst surface, epikarst, and the cavernosity of the aquifer.

Fig. 1.2 Exploring the cave with a collapsed roof due to the mining during construction of the motorway Klanec–Sermin

1.1 Researching the Karst Surface and New Caves in the Course of Construction

Surface landforms, epikarst and subsoil karst features were revealed following the removal of soil and vegetation from the karst surface and, of course, the large-scale earthmoving works during the digging of roadcuts and tunnels. Our task is to study these features in the context of natural heritage, to provide advice as to their preservation and, naturally, bring construction workers up to date with the new findings. These findings will be used to overcome obstacles arising during construction.

The karst surface is dissected by dolines (Fig. 1.3) and unroofed caves (Fig. 1.4). Today, dolines reflect the way the surface is shaped by precipitation water which percolates vertically through it, passing through the non-flooded part of the aquifer down to the groundwater. Dolines are filled up with soil, some more prominently than others. Doline floors feature shafts and crevices which drain away the water. First, the dolines must be cleared from the soil and next the floors must be reinforced with rocks stacked into arches (Fig. 1.5), since the mouths of shafts are often

Fig. 1.3 Dolines dissect karst surface

Fig. 1.4 Karst surface dissected by an unroofed cave

Fig. 1.5 Closing up a fissure cave

Fig. 1.6 Filling a doline (which now lies below the motorway) with rubble

smaller than the nearby cavities beneath them. Next, the dolines must be filled up with layers of rubble (Fig. 1.6). The unroofed caves are of similar shapes or more elongated. They are old caves that emerged to the surface due to the lowering of the karst surface, i.e. they no longer have the upper parts of the rim. In this case too, it is necessary to clear away the fine-grained fillings, which happen to be old cave sediments, and then fill up the caves with rocks and rubble. Otherwise, water could gradually carry away these sediments and subsidence could occur on the surface in response.

The epikarst is crisscrossed with crevices; the most prominent are found in the Cretaceous limestone and less so in the Palaeogene one. More crevices opened up at the bottoms and slopes of dolines. They are mostly filled with soil and their walls are covered with subsoil rock forms. Due to the lowering of the karst surface, many shafts are already immediately below the surface.

On a 75 km stretch of the motorway, which has been built in the Karst region in recent years, more than 350 caves had opened up (Fig. 1.7). In terms of aquifer development, caves can be divided into old caves through which water flowed when the karst aquifer was surrounded and covered with flysch higher up, and into shafts, through which water is percolating vertically from the permeable karst surface to the groundwater (Fig. 1.8). The deepest shaft measured 110 m. Old caves are either empty or filled with sediments, the latter accounting for almost two thirds of all the caves, while one third of the caves are already unroofed.

The caves opened up as a result of the removal of vegetation and soil from the surface, with an exceptionally large number having been opened up during roadcut digging (Fig. 1.9). When the rock was blasted, their roofs caved in, the cross-sections of the passages having been preserved in the banks. The majority of the shafts opened up on doline bottoms, after the soil and sediments had been removed.

We proceeded to examine all of the caves, map them out, define their shapes and rock relief, we took samples of the sediments for palaeomagnetic and pollen research and samples of flowstones for mineralogical research and dating. Based on the cave shapes and the geological features we have predicted their extension, which will be of particular use to the builders as the construction goes on.

1.2 Research Led to New Insights About Karst Development

A peculiar and common karst feature is the unroofed cave (Fig. 1.10). This surface karst feature, which bears relevance still today, is a rather familiar phenomenon, which, however, has not been subject to any comprehensive studies until now. In fact, it was pretty much neglected up until now when it turned out that the number of such surface features is much greater than originally presumed. The number of papers published on unroofed caves correlates with the construction of new motorway sections (Knez and Slabe 1999a, b, 2000, 2001c, 2002a, 2004a, b, 2005, 2006a, 2008, 2009b, d, 2010b, c, d, f, 2011, 2012b; Knez and Šebela 1994; Knez et al. 2012; Kogovšek et al. 1997; Mihevc 1996; Mihevc and Zupan Hajna 1996; Mihevc et al. 1998; Slabe 1996, 1997a, b, 1998a; Šebela and Mihevc 1995; Šebela et al. 1999). The shape of an unroofed cave is the result of the type and shape of the original cave and of the development of the karst aquifer and its surface under various geological, geomorphologic, climatic and hydrological conditions. The distinctiveness of the surface shape of an unroofed cave is dictated by the velocity with which the sediments

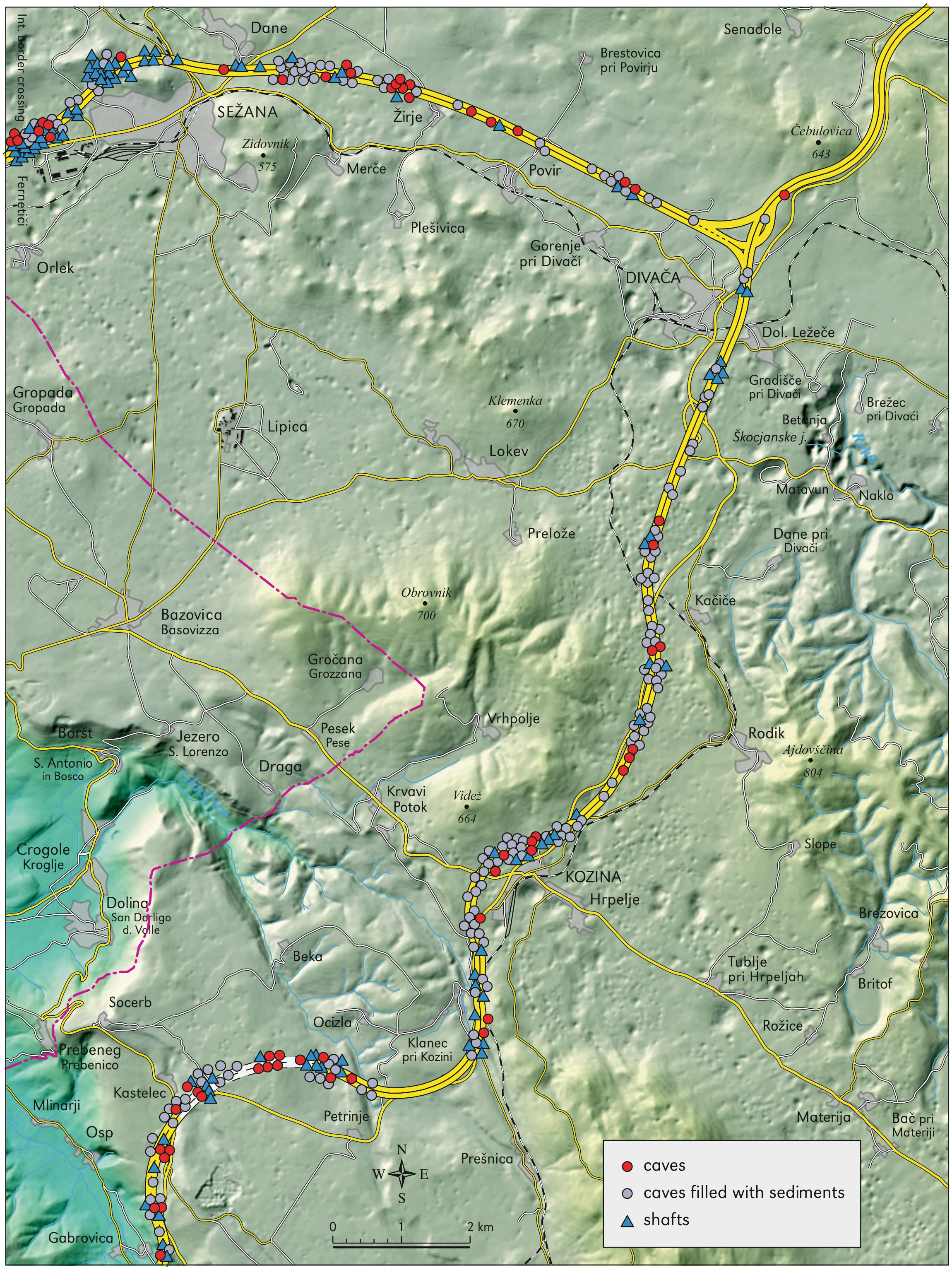

Fig. 1.7 Caves that have opened during construction works between Razdrto, Fernetiči, and Črni Kal (the motorway in the sketch is 15-times wider)

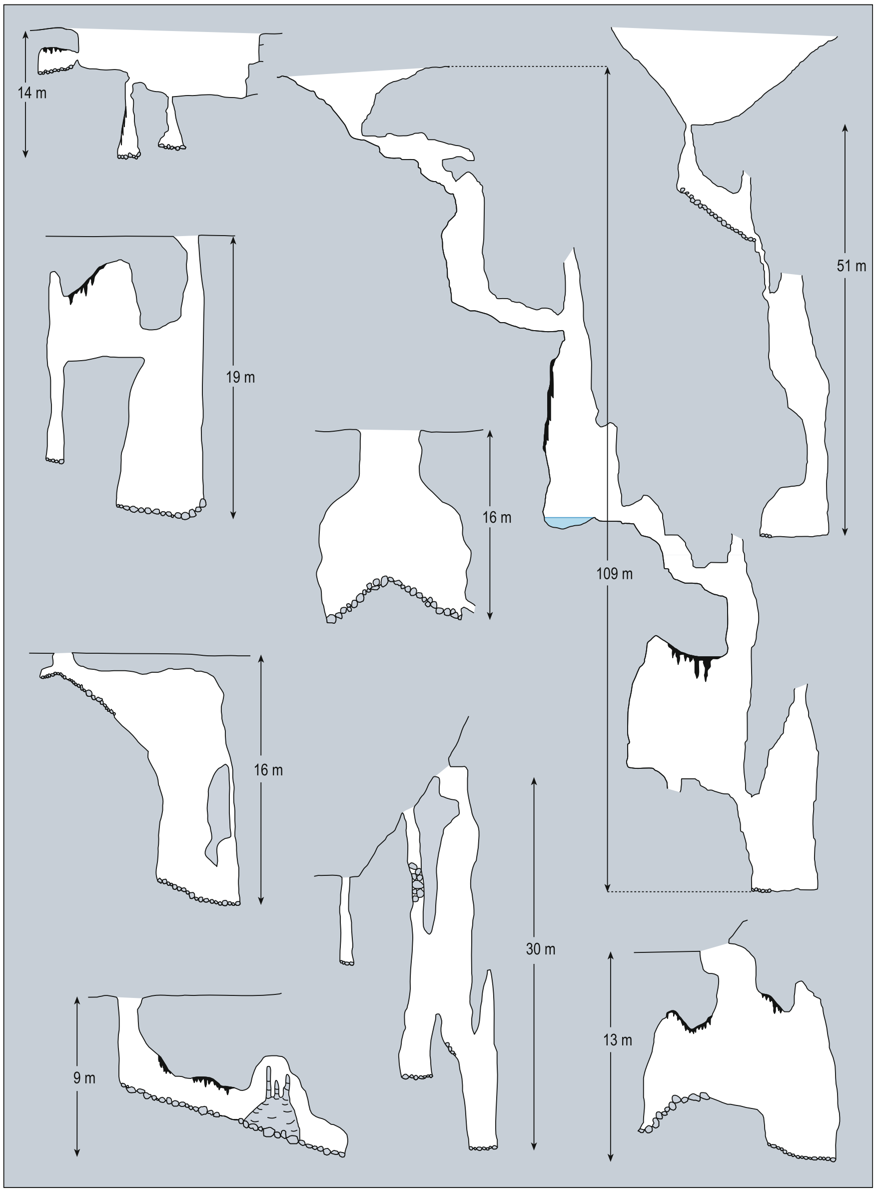

Fig. 1.8 Various caves that have opened during motorway construction

were carried off from the cave in comparison with the subsidence of the surrounding surface. If the process was slow, it is still possible to make out the soil and vegetation on the surface or zones of sediments and flowstone; if it was faster, the unroofed caves on the karst surface look more like dolines or strings of dolines or occur as elongated notches. They are often made up from a network of various old forms, i.e. caves, and of the present-day karst forms featuring dolines and shafts.

A great portion of the caves was filled up with sediments (Fig. 1.11). In most cases it is fine-grained flysch alluvium with interbedded gravel. We also took samples of sediments for palaeomagnetic research. It was

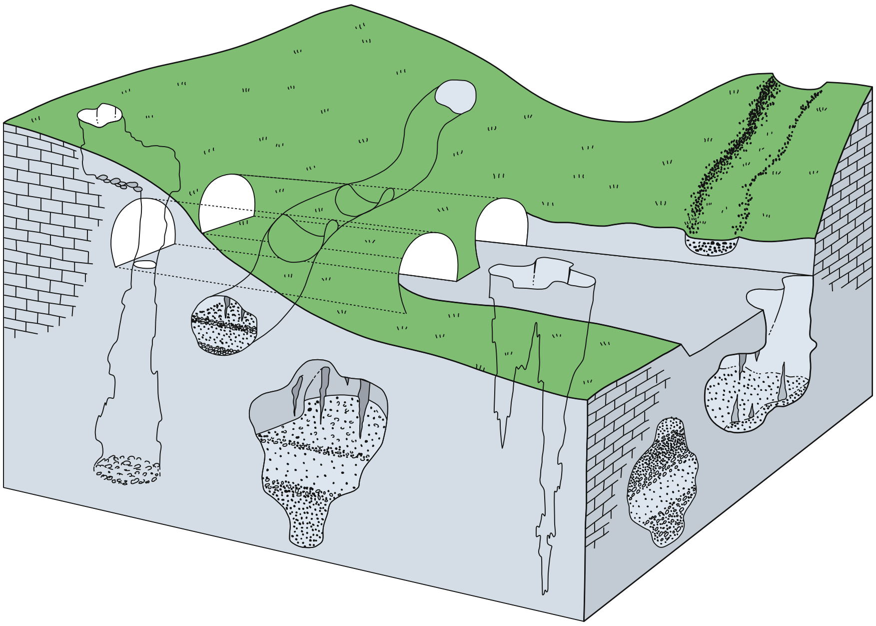

Fig. 1.9 Caves of various shapes and sizes opened during construction works which dictated all subsequent construction works

Fig. 1.10 Brezstropa jama unroofed cave near Povir

Fig. 1.11 A cave that revealed in a roadcut and has been completely filled with sediments

Fig. 1.12 Roof of a cave which collapsed during construction

established that the sediments in the caves near Kozina and Divača are of the older Olduvai period. This led to the conclusion that the caves must have been filled following the Messinian Salinity Crisis, i.e. approximately 5.2 million years ago (Bosák et al. 2000a, b).

Hence, unroofed caves are increasingly turning into a rather distinct feature of the karst surface, constituting an important part of epikarst and providing an intriguing clue to the development of the karst aquifer.

Dating the sediments gives us the chance to identify the oldest periods in the karstification, giving rise to conclusions that the oldest caves in the Karst region are much older than initially assumed by karstologists.

1.3 Road Planning

Before the construction works are to commence, an on-site check of the accuracy of the current cave data is carried out, supplementing it with any new measurements, and providing an interpretation as to their development. The existing knowledge on the cavernosity of the aquifer is presented to aid understanding, supported with prognostic subsurface maps with special emphasis on the anticipated lithological and tectonic changes in the rock. Karst cavernosity is to be demonstrated in detail prior to the actual construction works. The location of underground caves is determined by drilling. In this process, we also determine measuring indicators and the possible fill type (flowstone, alluvium). The shape, type and frequency of caves in the vicinity are predicted based on the existing knowledge from examined surface and subsoil features.

Motorway construction in the Karst region is heavily influenced by the cavernosity of this landscape (Fig. 1.12). In the Slovenian Karst region, which is strongly marked by very lively tectonics and lithostratigraphic diversity, coupled with diverse development, it is hard to predict where or when a cave will open. As a rule of thumb, they generally occur in places where flysch and limestone come in contact. In order to establish the extent of the karst aquifer cavernosity it is essential to possess solid and comprehensive knowledge of karst and be thoroughly and regularly involved in the road planning and construction process.

In view of the connection of surface and underground karst features, the road planning process must include a karstological evaluation of both the karst surface and the karst underground, the special features in their hydrology, and finally an assessment of the presented variants. It is safe to say that road construction in the Karst region will invariably lead to the uncovering of numerous karst features, i.e. dolines, filled or empty caverns and parts of old and present-day drainage paths dissecting the karst. Many karst caves have been denuded by the subsiding karst surface and are easily identifiable on the surface of the Karst region. Recently, unroofed caves, which came to light in the course of motorway construction, are attracting special attention. We are aware that an underlying thorough karstological study of the area envisaged to feature the road is a prerequisite for good route selection and that it is one of the basic starting points for construction planning amidst such a unique and delicate landscape.

We collect information on the surface karst features first by consulting literature published on this topic, archives and various collections; we make sure to particularly single out dolines, examples of collapse and other morphological forms. After the reconnaissance of the route, we lay down starting points to commence mapping along the selected route. We assess different rocks in terms of their karstological features. The known entrances to the underground areas are shown on thematic maps, and maps are supplemented with potential new entrances. Next, the branching of underground cavities is predicted based on the results of surface mapping and on the interpretation of the development of unroofed caves which are expressed in the morphology and can be made out in the relief. If necessary, we can predict the possibility of excess material deposits based on surface mapping.

We know from experience that underground cavities and parts of cave systems will invariably come up on every route that runs across karst. The shape and type of cavities can be partially predicted, drawing on the existing knowledge of surface and underground features. We determine the type of the caves found in the broader area surrounding the route, their position and role in the aquifer, as well as their form, rock relief, featured flood sediments and flowstone, and display them on relevant maps. For easier understanding, we present the insights on aquifer cavernosity obtained thus far and design a prognosis which highlights the anticipated litho-tectonic changes in the rock.

Due to the specific properties of carbonate rock, the karst waters, which sink down the examined area, easily pass into the underground (karst aquifer); they can pass through 100 m thick rocks in roughly an hour. Even though flysch rocks—in the Karst region they have constant direct contact with carbonates—are often presented as strictly impermeable strata, it should be pointed out that flysch (in many places in thinner layers) is merely an isolated lenticular bedding overlying permeable carbonate rock. It should also be noted that underground trunk conduits, though in smaller numbers, are also formed in flysch rocks and that the precipitation water accumulated on flysch runs off into the karst. To this end, we have to perform hydrogeological mapping of the site. This entails delineating and determining the underlying features of the hydrogeological units in the area next to the route, listing hydrological objects (captured and non-captured springs, surface flows, water caves, boreholes, measuring stations, and so on) and determining the physical and chemical properties of the springs. If necessary, we conduct two tracer tests at low and high water levels, mostly for determining the course and speed of the underground flow in the broader area surrounding the route. The results of the site mapping and the tracer tests help us design and update the existing hydrogeological maps, compile a database on the status of the environment and assess the impact of the construction on karst waters.

Fundamental guidelines applying to planning traffic roads can be summed up as such:

- route selection is based on an overall assessment of karst with emphasis on the local characteristics;
- the selected course of the route makes sure to bypass individual distinct karst features;
- one of the priority objectives in the course of planning is to preserve the karst aquifer.

1.4 Cave Preservation

The shafts were the easiest to preserve. Their smaller entrances were sealed with concrete slabs (Fig. 1.13). It was also possible to preserve old caves that had a firm rim. The caves located in crushed rock that opened as a result of the blasting had to be filled up. The caves that had been cut off by the roadcuts with entrances in their banks were covered with rock walls (Fig. 1.14). Their rim was too broken, rendering the caves unsuitable for further inspection, while from sediment-filled caves water might wash the clay out onto the roadway. We left one well-preserved cave open as a tourist attraction for passengers crossing the border with Italy (Fig. 1.15). The most interesting and well-preserved caves were, however, fully protected and left open to access even though they are located beneath the roadway or—as in the case of the Kastelec tunnel—wind around the tunnel tube. They can be accessed via concrete tubes, which end in a closed shaft next to the road (Fig. 1.16) and, in the tunnel, with a door (Fig. 1.13c).

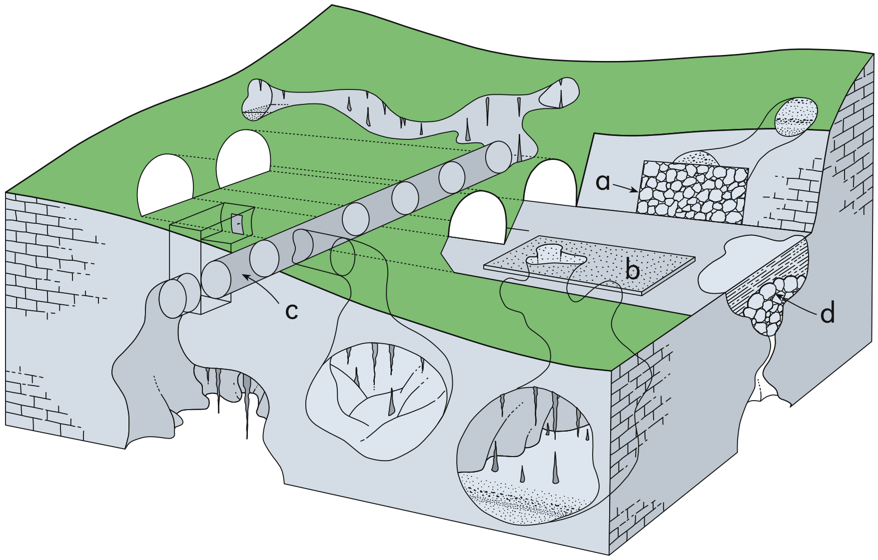

Fig. 1.13 Closing and preserving of caves. *Legend* **a** in road cuts the caves are hidden behind rocky scarps; **b** the caves lying below the road are covered by concrete lids; **c** entrance into the cave meandering around the tunnel; **d** bottom of karst fissures and tops of shafts are often closed by arches of rocks

Fig. 1.14 Closing a cave in the embankment of a roadcut

Fig. 1.15 A cave that has remained open before the Fernetiči border crossing

Fig. 1.16 Construction of a road-side artificial entrance

Fig. 1.17 Preparation works for laying pipes for road drainage

We have also studied the consequences of different blasting activities inside the caves, which will aid in further construction and in the preservation of karst features.

1.5 Karst Protection in Light of Motorway Construction and Usage

Our experience with tracing water and with accidental spills of different substances in karst, suggested that we must keep in mind the high degree of cavernosity of the karst aquifer. Numerous caverns that we found during the construction corroborated our assumption. Poor permeability characterizes only individual relatively small areas found either at doline floors which are covered with larger quantities of washed off soil (dolines on Palaeogenic limestone of the Divača lowland are dotted with puddles in the wet seasons) or yet even smaller areas of loam which fill old caves. This lends itself to the conclusion that road construction and road usage must be approached with circumspection. Daily traffic can leave many environmentally harmful substances on the road

Fig. 1.18 Drainage channels at the side of the road

Fig. 1.19 Construction of an oil separator

surface (Kogovšek 1993), and mineral oils were found in stagnant waters in caves next to the roads (Knez et al. 1994). As a result of these insights and our relentless efforts, motorway designs aim at providing impervious road surfaces. Pipes (Fig. 1.17) and drains (Fig. 1.18) are provided along the road, leading down to wastewater separators (Fig. 1.19). Ideally, untreated water does not reach the permeable karst surface. However, the technical aspect of the drainage system must be brought in line with our wishes. As it is, separators are often too small, and heavy rainfall can flush the sediments out.

1.6 Conclusion

It was established that the involvement of karstologists in the road construction process in the Karst region is useful. However, it is vital that we are involved both in the planning and construction process and, later on, in the monitoring of the impact that motorways have on the environment. Karstologists should therefore be involved in the full process of human intervention in the delicate karst landscape, from start to finish. Through meaningful collaboration we can preserve our cultural heritage and deepen our fundamental knowledge on the formation and development of karst and on the construction of motorways in a very distinct setting. Seeing as there are several different types of karst, each requiring a unique approach, the co-operation between the construction crew and karstologists should be permanent and regular. The co-operation between motorway engineers, constructors and karstologists produced new findings which are applicable in the planning process and realization of other human interventions in karst.