Gypsum Karst Problems along An Alpine Motorway Tunnel

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ABSTRACT

The 1271 m long cross-border Fuessen tunnel is the missing link of the German Freeway A7 and the Austrian Fernpass route B 314. In March 1996, during running excavation works, an unexpected ground water inburst of 400 l/sec occurred. Voluminous grouting measures were then required to stop the water inflow. To explain this unexpected inflow, the model of a collapse dolina has been forwarded. The dolina is believed to have developed due to heavy leaching of the gypsum bearing strata of the Raibl formation during glaciation, covering an area of app. 100 x 80 m at surface. The burried dolina is surrounded by collapse breccias, which provide a reference for the extremely steep walls of the sink hole. As a consequence, and in order to avoid further lowering of the ground water level in the Faulenbach valley, the tunnel had to be excavated within a protective shield of pre-grouted rock over a total length of 240 m. This paper gives a brief description of the geological conditions and the material in the dolina itself and the dolina margin.

GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

With a total length of 946 km, the Federal Freeway A7 is one of the most important transit routes in Germany. The 1.2 km long, border-passing tunnel of Fuessen at the very south of the A7 is the connection to the Austrian “Fernpass” route B 314 (Figure 1). Table 1 provides a listing of important project data of the Fuessen tunnel.

The project area is situated in the northern alps in the Falkenstein mountain range in a sedimentary sequence consisting of a dolomite formation (Hauptdolomit), a carbonatic, clastic and evaporitic formation in the “Faulenbach” valley (Raibl formation) and a solid limestone (Wettersteinkalk; see Zacher, 1966). For the first 500 meters, the tunnel cuts through heavily jointed and water-bearing Hauptdolomit with a maximum rock cover of 160 m (Figure 2; Thuro et al., 1997).

Under the “Faulenbach” valley, a 200 m section was drifted through the Raibl formation leaving a minimal rock cover of only 20 m (Baumgaertner, 1997). The Raibl formation consists of an interstratification of limestones, dolomites, sandstones, mudstones and - in the upper part - gypsum (formerly anhydrite). Through this section an approx. 40 m broad channel consisting of quarternary deposits had been prognosted. During the next 520 meters the tunnel was driven through jointed and partly karstified Wetterstein limestone (with some dolomite) under the Vilser hill with a maximum rock cover of 210 m. In addition, several meters of mudstones and limestones of the Partnach formation and limestones of the alpine Muschelkalk had to be excavated. Water seepage flowing through joints and karst cracks also had to be dealt with in the Wetterstein limestone.

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Figure 1: Situation of the Fuessen Tunnel in the federal transit route network.
Due to the suspected connection between the ground water level of the “Faulenbach” valley with the discharge of a nearby spring at the Bad Faulenbach medical resort (located 1.5 km east of the tunnel), restrictions were placed in the contract with respect to drawing down ground water levels during tunnelling. These include:

- The ground-water level in the Faulenbach valley had to be maintained within the natural fluctuation range and could not be adversely altered during construction. The total ground-water discharged from the tunnel was not to exceed 1.5 l/s.
- Larger ground-water inflows entering the tunnel had to be stopped by grouting measures.
- The implementation of 45 m long zones of pre-grouted rock ahead of the tunnel face was scheduled in the Faulenbach valley to seal the quaternary channel filled with soft ground.
- The tunnel had to include an impermeable tube over a distance of 276 m in the above mentioned quaternary channel.

During the investigation stage between the years 1990 to 1993, 16 of 60 boreholes and 4 surface water weirs were converted into automatic discharge sites to monitor and assume the hydrogeological-based contract stipulations in the Faulenbach valley.

**WATER INBURST AT CHAINAGE 480 M**

Over a short distance in the dolomite section, the required condition pertaining to the maximum water discharge could not be maintained. In this respect, large water inflows entering the tunnel diffusely at a number of small joints and cracks, could only (at best) be reduced through injection measures, even when...
carried out immediately after excavation. However, it was not possible to stop the water inflow completely. This experience repeated itself during excavation of the Wetterstein limestone. In contrast, the excavation works progressed with few other problems: daily drill and blast excavation rates reached 10 m / day, with support installation including some Swellex bolts and wire mesh with 15 cm of shotcrete.

On March 6th, 1996 the top heading reached the chainage 480 m in the Hauptdolomit. Water inflow at this point already exceeded 10 l/s. According to the geological longitudinal section, the Raibl formation was to be expected only at chainage 530 m. In the course of investigation drillings ahead of the tunnel face, ground-water under high pressure became evident with an even higher inflow of approx. 20 l/s. After a number of the installed flow gauges had reacted severely to this event (Figure 4), the tunnel excavation was stopped and horizontal core drilling was ordered by the client to investigate the adverse rock mass conditions. Three days later on March 9th, 1996 a sudden water inburst occurred in the course of the core drilling works. The initial water invasion was estimated to be as high as 400 l/s and was reflected in as series of dramatic drops in all installed piezometer gauges in the valley. As a consequence, a “red alert” had to be raised at the medicinal spring “Nothburga”.

The water pressure was eventually reduced by relief drillings at the tunnel face resulting in a continuous inflow of approx. 70 l/s. After establishing extensive injection and insulation measures during the following days, the inflows could be effectively stopped. The water levels subsequently stabilized themselves. Nevertheless, it wasn’t acceptable to proceed with the excavation works without implementing preventive measures like ahead-of-the-face-grouting.

Given the size of the water inburst, its location in the dolomite, the information derived from core drillings and the unexpectedly large area affected (as seen in the monitoring gauges, Figure 4) a decision was made to modify both the geological model and construction concept. The tunnel was then to proceed within a protective shield of pre-grouted rock over a length of 240 m. Before the excavation works could be continued, a broad investigation program (including 14C dating) had to be carried out to develop a new idea of the underground structure.

REVISED GEOLOGICAL MODEL: AN ALPINE GYPSUM DOLINA

The Faulenbach valley is lined by several lakes (one of which is the “Alat” lake), which originate from deep-reaching leaching of the gypsum bearing strata of the Raibl formation. Some of the former lakes are already silted up and only remain visible as turfy moulders. For this reason special attention was given to the

![Figure 3 : Detailed geological section through the Faulenbach valley.](image-url)
site investigations of the so-called quarternary channel (In the area of the Faulenbach valley more than 30 boreholes, partly drilled inclined, have been made during the last three decades). From these drillings, the channel was seen to be filled with cohesive soil of low permeability intermixed with lenses of highly permeable sandy gravels. It was therefore foreseen, that excavation through this structure would be one of the main problems encountered during the tunnelling works. The assumption was also made that the Hauptdolomite would be of low permeability and, to a great extent, free of opened fissures. After the water inburst at chainage 480 m, this model had to be thoroughly revised.

Repeatedly subsequent excavation workings had to be interrupted by injection works leaving time for deeper investigation into the causes of the water inburst. Two horizontal boreholes of up to 70 m in length, drilled from the tunnel face, and a 100 m deep vertical borehole drilled from the valley floor were driven into the suspected center of the quarternary channel. These measures resulted in a 9 month’s delay in the tunnelling works. Together with observations from additional tunnel workings and detailed geological mapping, a new model of the geological conditions along the tunnel alignment was derived (Figure 3).

This new model hypothesized that the heavy leaching of the original gypsum bearing strata, resulted in the development of a dolina in the Faulenbach valley during alpine glaciation. The leach hole, which was not discovered during preliminary site investigations, is filled with evaporite-solution residuals and moraine deposits. During subsidence of the dolina floor, the moraine and leaching residuals were subsequently compressed by the overflowing glaciers. The buried dolina is surrounded by collapse breccias, which relate to the extremely steep walls of the sink hole at that time. This hole caused the nearby dolomite rock mass to settle and to develop deep reaching, water bearing fractures. These fractures in the rigid rock mass (not in the dolina filling) are believed to be the primary cause of the water inflow into the tunnel. In addition, the dolina is located in the center of a fault zone striking NNW-SSE through the Hauptdolomit dolomite, the Raibl formation and the Wetterstein limestone. The outer limits of this fault zone and related faults could be observed during excavation.

Dolina Filling

The center of the dolina is filled with cohesive, highly consolidated soil, which contains scarred pebbles transported by glaciers (moraine till). The debris partly consists of host rock material (Raibl limstone and dolomite) and evaporite-solution residuals (cellular dolomite, clay and silt). The diameter of the dolina was approx. 40 m at tunnel level, the depth was believed to be at least 100 m. Organic material found between 49 and 66 m depth could be identified as humic soil with snail shells. The material was dated by ¹⁴C as older than 40,000 years which corresponds with the limit of the ¹⁴C-method. The preserved conditions of the snail shells and the humic soil suggest a dating to about 120,000 years.

It would be conceivable, that this former topsoil was already deposited in the warm period between the last two glaciation periods (so-called Wuerm-Riss-interglacial). If the topsoil was located on the former valley floor during its deposition, it is feasible, that the dolina could have been leached at an average rate of about 0.5 mm/year over a period of 120,000 years resulting in a depth of more than 100 m. Even if the collapse of the dolina was relatively fast during the initial phases or, in fact, instantaneous, settling movements today may still continue.

These results suggest that a very old (possibly several hundred thousand years old) active dolina with deep reaching leaching of the evaporites of the steep dipping Raibl formation occur all along the Faulenbach valley. Subsequently during subsidence of the dolina floor, the moraine deposits and
leaching residuals must have been compressed by the overflowing glaciers. This nearly non-permeable filling would then act like a watertight “cork” with little contact to the surrounding rock mass which has a higher permeability. Observations during excavations confirm, that the dolina filling was generally consolidated, dry and stable. Under these conditions, expensive special measures could be reduced to a minimum and the quantity of solids injected by the ahead-of-the-face-groutings was low (Figure 6).

Collapse Breccias of The Dolina Margin

The loosened and fragmented Hauptdolomit is terminated by a steep dipping fault zone and followed by the bedrock of the Raibl formation. This bedrock – mainly dolomites and cellular dolomites – was fractured and dissected into large blocks. During excavation, the size of these blocks decreased from N to S and the material changed from a grain supported blocky type to a matrix supported type which behaved as a soft soil. A fluent transition to the material of the dolina filling could be observed. Of importance were the high permeabilities which made systematic injection measures necessary.

The strongly jointed nature of this rock mass can only be explained through the collapse of a large-scale dolina in the gypsum karst. Although certain components of the dolina consist of cellular dolomite, limestone and crumbly dolomite, the origin of these masses is much younger (of quaternary age). Therefore, this rock mass can be paraphrased as “collapse breccias” and they are part of the wider dolina margin. Also, the injected quantity of solids reflects the porosity of this material (Figure 5).

Causes of the water inburst

The water inburst at chainage 480 m seems also to be connected with a structure which is visible on the valley slope. This structure consists of several slope parallel cracks which can be tracked some 10s of meters along the slope. One of the parallel cracks forms two small caves – one of which is accessible for climbing. Due to the morphological situation, these cracks and caves cannot be explained through typical slope move-
movements. Instead, it seems, that the rigid Hauptdolomit is settling on the blocky Raibl material consisting of the soft clayey-sandy matrix. Accordingly, deep reaching, water bearing fractures may have developed in the vicinity of the fault zone. It thus seems, that these fractures in the rigid rock mass, not the dolina filling, caused the water inflow into the tunnel.

Conspicuous during the water inburst at chainage 480 m were the reactions of the water level gauges (Figure 4). While the gauges situated in the dolina filling showed no clear reaction to the inflows, gauge No. 7, situated in blocky material of the other side of the valley, significantly dropped over a 15 minute period. This suggests that water may be creeping around the dolina filling, through the blocky collapse breccias at the dolina margin.

CONSTRUCTION DELAY IN THE FAULENBACH VALLEY

After the water inburst at chainage 480 m, the tunnel had to be excavated within a protective shield of pre-grouted rock over a total length of approx. 240 m, which of course slowed down the excavation progress (Figure 5). The primary objective of any further excavation work was to avoid additional lowering of the ground-water level in the Faulenbach valley. This was accompanied by means of injection measures (Figures 6 – 8, Thuro et al., 1997).

To implement the injection treatment as quickly as possible, polyurethane foams were considered as the injection material. However, the responsible authorities rejected the use of these materials because of the potential dangers they generate to water system in the form of primary aromatic amines. The use of cement-bentonite suspensions was approved adding sodium-silicate up to a maximum of 15% of the cement weight.

The injection was carried out via fan drillings in sections isolated by packers. Drill hole pattern, length and direction were chosen to enable complete cover of the excavation cross-section from the top heading down to the final invert, over a tunnel length of 10 to 15 meters. Due to the resulting shape, the amorphous injection body became known simply as “onion” (Figures 7 and 8). Injections were carried out over a distance of 220 meters alternating with a “stop & go” excavation sequence. Altogether 26 “onions” with penetrations of 10 to 15 m had to be grouted making possible excavation segments of 6 to 10 m.

FINAL CONSIDERATIONS

The excavation works in the 240 m long Faulenbach valley section of the cross-border Fuessen tunnel have alone taken over one year’s time, with 70% of the working time being used for injection treatment. During this time, the total advance rate of the works was only 92 cm/working day.

What was the essential reason for these delays? Tunnelling through the dolina filling, for which special measures were originally intended, surprisingly few problems were encountered. However, the collapse breccias in the so-called dolina margin and the blocky and heavily fractured rock mass around the dolina center were unexpected, highly permeable and water bearing. The collapse structure was not recognized during the preliminary site investigations nor were the resulting consequences. The size of the water inburst and extent of the affected area has surprised those people involved in the tunnel’s construction and still today has not been fully understood despite the extensive geological and hydrogeological investigations performed.

REFERENCES


