Bad Bergzabern Bypass Tunnel—NATM Tunneling Through Vineyards

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ABSTRACT

This paper presents the details of the Bad Bergzabern tunnel project. This tunnel is the main part of the B427 federal road bypass, intended to improve the regional traffic infrastructure and to reduce the traffic load in the historic city centre of the health resort Bad Bergzabern. Located in the south-western part of Germany, the project area is situated at the eastern margin of the so-called Palatinate Forest, a low mountain region of mainly triassic sediments with a complex and variable geological history.

The German federal government, represented by the office of mobility of Rhineland-Palatinate, awarded the contract to BeMo Tunnelling, a specialized Tunnelling company with a long history of innovation and success in NATM tunnelling. The contract includes the construction of two separate tubes with a length of approximately 1,44 km (0.9 mi)—the road (main) tunnel with a cross section of 101 m^2 (1,090 sq ft) and a parallel rescue tunnel with a cross section of ca. 23 m^2 (250 sq ft.) Both are connected by six cross passages. Tunnels and cross passages are excavated according to the principles of the New Austrian Tunnelling Method (NATM).

Due to BeMo Tunnelling's technical expertise and capabilities, the project team was able to engineer a speed-up concept that saves money and time for the construction team and client. This paper presents the innovative approach BeMo Tunnelling made to optimize the execution of the tunnelling works and the challenges the project team is facing with regard to a complicated geological situation, countermeasures against an increasing effect of climate change and volatile prices for construction materials.

PROJECT BACKGROUND

The project area is located near the city of Bad Bergzabern in the state of Rhineland-Palatinate, Germany. Bad Bergzabern, a medium sized town with approximately 8,500 inhabitants, is situated about 5.5 kilometers (3.5 mi) northeast of the French border and about 40 kilometers (25 mi) northwest of the city of Karlsruhe (Figure 1). Morphologically, the project is located at the eastern margin of the so-called Palatinate Forest, at the transition to the plain of the Rhine Valley. The Palatinate Forest features a multi-national hilly region with mountain ranges reaching up to 670 meters (2,200 ft). Due to occurrence of thermal water, that is brought to the surface by wells from a depth of approximately 450 meters (1,500 ft), Bad Bergzabern enjoys a high reputation in health tourism and was officially rewarded the prestigious title of a "health resort." This, and the high regional popularity of the Palatinate Forest as a recreation area in south-western Germany, lead to a high traffic volume on the federal road B427, which interferes with the interests of residents and guests. Therefore, the decision of constructing a local bypass tunnel was made by the federal ministry of traffic and digital infrastructure and the project was included in the federal transport infrastructure plan to be under traffic by 2030 at the latest.

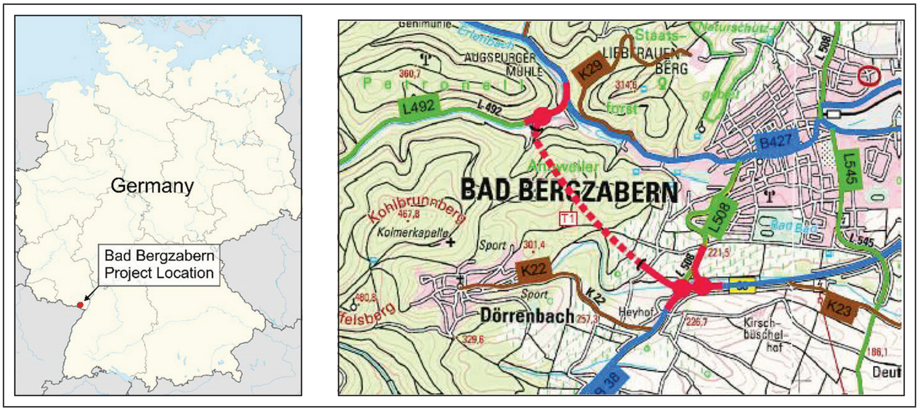

Figure 1. Location of Bad Bergzabern within Germany (left) and alignment of the Bergzabern tunnel (dotted red line) west of the city center (right)

In 2020 the tender procedure was started and the potential bidders were provided the necessary technical information. Two award criteria were defined, on the one hand dominantly the best price and on the other hand the optimization of the construction schedule. Thanks to careful processing and the implementation of innovative concepts, BeMo Tunnelling was able to convince in both categories and was awarded the construction contract of the Bad Bergzabern bypass in February 2021. The contract has a total value of 71 million euro (incl. VAT).

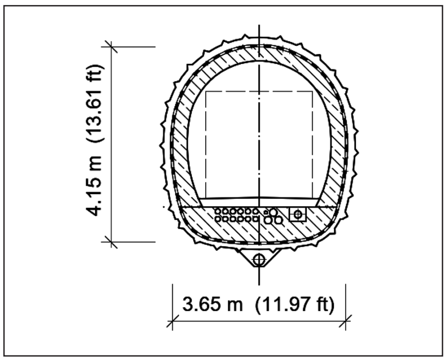

Figure 2. Cross section rescue tunnel

THE BAD BERGZABERN TUNNEL

The tunneling part of the project consist of two tunnels, a 1.44-km-long (0.9 mi) main tunnel and a parallel rescue tunnel of smaller diameter. Both tubes are connected by six cross passages. The maximum overburden above the tunnel is around 120 m (400 ft). In addition, the contract includes the construction of two km (1.25 mi) of road, water tanks for fire defense and two electrical and mechanical equipment buildings (see Figure 1).

The main tunnel has a length of 1.44 km and is designed as a two-way traffic tunnel with a break out cross section of 101 m^2 (1,090 sq ft) (see Figure 3).

Breakdown bays are located 0.4 km (0.25 mi) in the tunnel from both portals. For these the tunnel section is widened up to 193 m^2 (2,080 sq ft). The rescue tunnel with an originally planned section of 15–30 m^2 (160–320 sq ft) is connected to the main tunnel by 6 cross passages with an excavated cross section of 13 m^2 (140 sq ft). The maximum distance between the main tunnel and the rescue tunnel is 12 meter (40 ft).

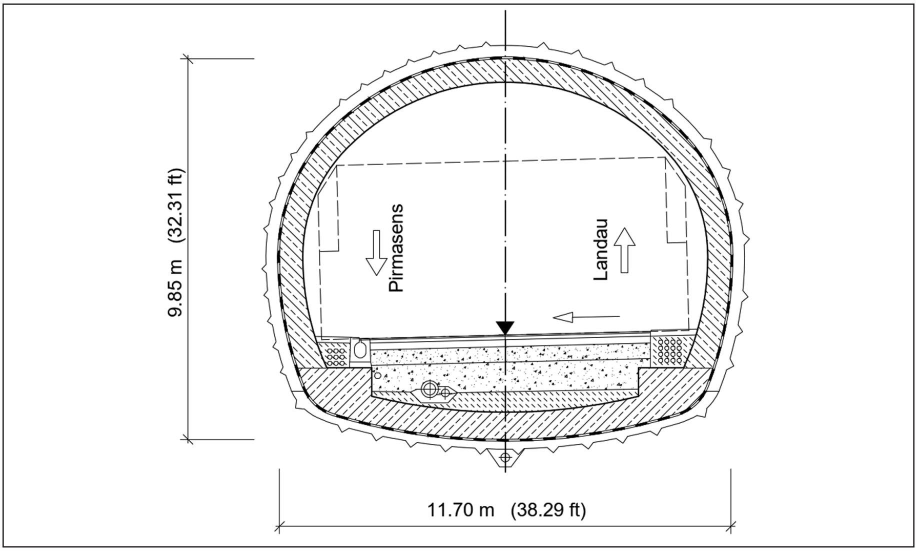

Figure 3. Cross section main tunnel

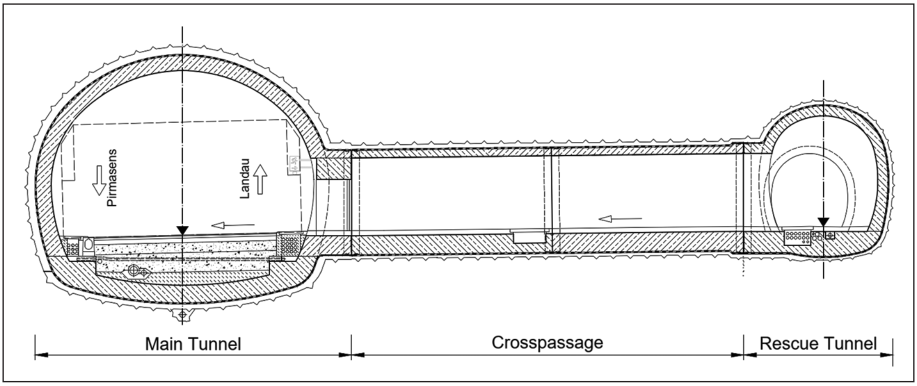

Figure 4. Longitudinal section through the crosspassage

GEOLOGICAL OVERVIEW AND GEOTECHNICAL PROBLEMS

As a result of the complex regional geological history, the geological and geotechnical conditions in the Bad Bergzabern tunnel are highly heterogeneous and variable (Figure 5). In the portal areas, younger quaternary soil deposits (mainly silt, sand, gravel) are encountered, which feature isolated horizons of ground water.

After a short section of marl and limestones of the so-called “Muschelkalk” Formation, the two tubes encounter sandstones and siltstones of the so-called “Buntsandstein” Formation. These sediments have been deposited in a braided river system in the Triassic age, about 250 Mio. years ago. Later, during the opening of the nearby Upper Rhine Graben valley in the tertiary age, the formation was tilted, shifted by numerous faults and partly decomposed by migrating hot fluids. Recent weathering processes have further contributed to the alteration and deterioration of the rock mass.

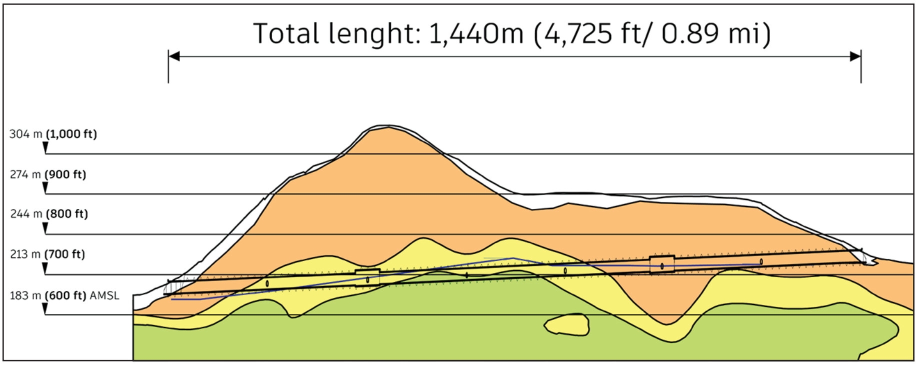

Figure 5. Schematic geotechnical longitudinal section of the Bad Bergzabern tunnel, showing the different rock quality of decomposed sand (orange), intermediate sandstone and sand formations (yellow) and hard sandstone (green)

The highly variable, small-scale changes in the degree of decomposition and strength represents one of the main challenges for tunnel excavation. When highly weathered or decomposed, the sandstone shows no or little strength and cohesion and provides only very limited unsupported standup-time. To make things worse, the key properties of the rock mass are structurally not at all linked to decisive elements, like bedding or discrete faults, so that the succession of softer and harder rock within the tunnel advance is more or less unpredictable. This requires a close observation and documentation of the rock mass conditions and frequent changes of excavation method and support classes.

Within the bedrock formation and partially above the gradient of the tunnel, a consistent ground water level exists, which is influenced by precipitation and climate and thus can rise and fall temporary within some feet in height. During excavation, a combination of decomposed sandstone with soil-like behavior and water inflows bears the potential risk of loose sand flowing into the opening. Regarding the long-term operation of the final tunnel, a full waterproofing of the tunnel is necessary as a result of the ground water level and the potential of the water to sinter the drainage.

In order to project-specifically classify different types of rock and rock mass, a system of homogeneous "Ground Units" (German term: "Homogenbereiche") has been established according to the actual German Standards for Subsurface Works. These Ground Units consider the specific properties of soil and rock and are intended to characterize larger volumes of rock with similar technical behavior, regarding for instance excavation, transport, and finally treatment and deposal. During the tunnelling works, the actual Ground Unit is jointly determined and documented by the Engineering Geologists employed on site on behalf of the client and contractor.

The following sections give a concise overview over the different Ground Units encountered at the Bad Bergzabern project.

Ground Units B1 to B4—Gravel and Hillside Debris

In the portal areas quaternary soils such as sandy gravel or slope debris occur. These soil deposits vary in grain size from gravel to clay. The ground is unstable and needs additional support in order to remain stable. Without immediate support of the face with shotcrete, rock bolts, and grout injection, the face, and thereby the tunnel itself, would immediately collapse.

Figure 6. Typical appearance of decomposed triassic sandstone/sand of Ground Unit X1. Left image: Sequential and partial mechanical excavation in the crown section of the main tunnel. Right image: Although originally gained in form of a hand specimen, the decomposed sandstone can easily be crushed by hand

Under these conditions the face has to be stabilized with shotcrete and bolts to prevent a local failure and a pipe roof to prevent a global failure has to be installed. The pipe roof consists of 50 feet self-drilling pipes with a diameter of 140 mm (5.5 in). To create a supporting arch (canopy), the pipes have to be grouted with a cementitious grout mixture. In addition, the side and top have to be supported by systematically installed rock bolts. The excavation starts with the top heading, which is divided in two parts, followed by the bench and the invert A temporary invert of shotcrete has to be installed to ensure distribution of the vertical and horizontal forces by a completed ring. Due to these efforts, the heading in the unstable ground proceeds slowly with an advance length of only three feet per excavation round.

Ground Unit X1—Loose Sandstone and Sand

Ground Unit X1 describes a type of completely decomposed sandstone / sand with soil-like behavior and non-existent Unconfined Compressive Strength. However, the quartz sand still has a relatively high density and is still highly abrasive. The behavior of the ground is similar to Ground Units B1 to B4. The face needs immediate support with shotcrete and rock bolts to avoid a collapse.

The face has to be stabilized with shotcrete and rock bolts in the face. Additionally, an umbrella of spiles has to be applied. The excavation then starts with the top, while the supportive wedge has to be spared, and continues afterwards with the bench and the invert. In the larger cross-section of the main tunnel, stability issues require excavation in smaller sections of only some square-feet and immediate sealing with shotcrete. As in Ground Units B1 to B4, after each stage of excavation a temporary shotcrete invert has to be installed to create a resistant support ring.

Ground Unit X2—Weak and Loosened Sandstone

Ground Unit X2 describes weak sandstone series with an Unconfined Compressive Strength of below 15 MPa. The face usually consists of weaker and harder parts, representing a mixed face condition. This results in a more complicated excavation workflow, since some parts of the face are weak enough to be excavated by use of a ripper bucket, while other parts have to be excavated by use of a roadheader or jackhammer. However, the high quartz content of the sandstone implies the risk to generate harmful respirable dust which limits the use of roadheaders in these rock conditions.

Depending on the actual conditions on the face, the stability measures vary significantly. If the face shows a high amount of decomposed rock, the same procedure as in Ground Unit X1 is applied, which means rock bolts in the face, a spile umbrella and construction of a temporary invert. If the face shows more homogeneous rock conditions, less effort has to be put in stabilizing the face. The rock bolts then can be substituted by a supportive wedge of loose rock in the centre part of the face. Also, the length of advance naturally increases with the occurrence of more solid rock to around four feet .

Ground Unit X3—Alternating horizons of Weak and Hard Sandstone

Ground Unit X3 consists of alternating horizons of weak and hard sandstone. The horizons are strongly bonded together and the rock is generally speaking of a better quality than in Ground Unit X2. As a result of mixed face conditions, both excavation by drill-and-blast and mechanical excavation is applied. As in Ground Unit X2, the stabilization measures are dependent on the actual composition of the face.

Ground Unit X4—Hard Sandstone

This Ground Unit contains fresh, high strength sandstone, where the only suitable excavation method is drill and blast. Since this Ground Unit includes only rock of high strength and good rock mass quality, the stabilization measures can be divided in “must” and “can” measures. “Must” measures contain shotcrete covering of the walls and rock bolts in the side and top walls. Sealing the face with shotcrete and piling an umbrella of spiles are “can” measures that have to be coordinated with the engineering geologist and geotechnical engineer of the client.

EXECUTION OF WORK

Muck-Out Concept

In the Bidding Process

To place an economical offer, BeMo Tunnelling had to plan and simulate the different stages of the tunnelling works beforehand in order to identify critical work stages and to value risks. Especially the small section of the rescue tunnel included some challenges . There was no possibility to work safely with more than one big machine in the tight space. For the loose rock heading, BeMo decided to use an ITC 120, a combined tunnel heading and loading machine. The ITC machine is equipped with an excavation bucket and a conveyor belt for high-speed mucking. The excavated material is directly loaded to a dumper via the conveyor belt. For the rescue tunnels sections where drilling and blasting is performed, the mucking shall be done with a standard wheel-loader, due to restrictions with the bolder size processable with an ITC machine. The loader then transports the material via the next cross passage to the main tunnel and dumps it there for the final muck-out with larger machines. This concept proceeds the works applying a so called “Rottenbetrieb.” That means a normal level of machine equipment with a higher than normal level of personal. The effect is a higher utilization of the machines and an increase in productivity in comparison with a standard level of personal and machinery. But in comparison to a work program with twice the machinery and twice the personal, the productivity of this concept is less than 100%.

In Execution

In the execution phase BeMo Tunnelling brought an acceleration concept to the attention of the client. This optimized concept included a slightly enlarged cross section of

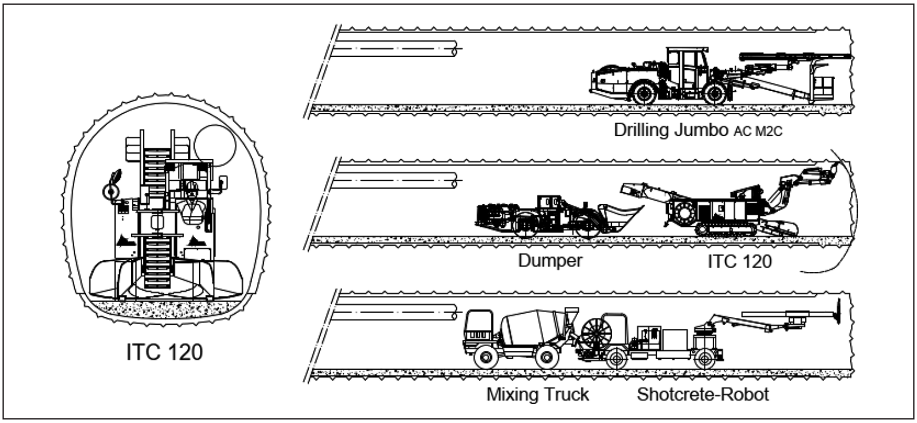

Figure 7. Tunnel works cross section for mucking and shotcrete logistics bidding process

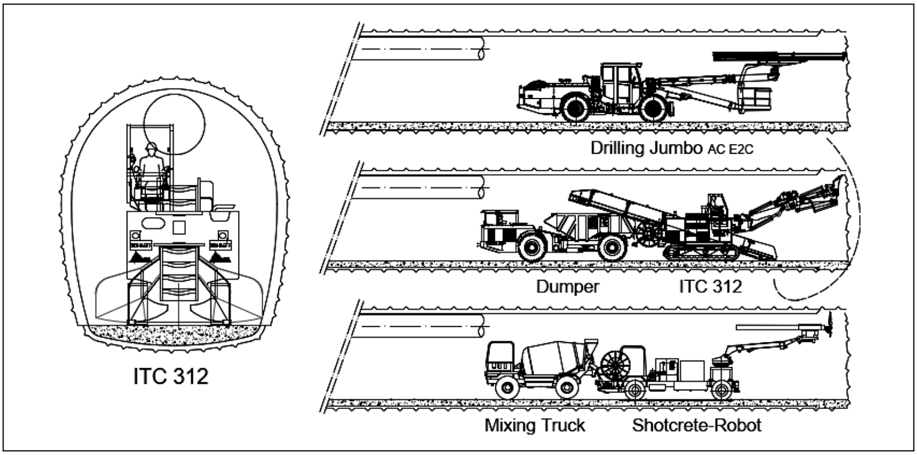

Figure 8. Tunnel works cross section for mucking and shotcrete logistics execution process

the rescue tunnel to make the use of larger machines technically possible. With the client's approval BeMo Tunnelling was now able to use a heavier and more powerful tunnel heading and loading machine, the ITC 312 tunnel excavator (Figure 9). Also, for the drill and blast sections an improvement of the performance given was possible.

With the improved concept dumping the material to the main tunnel by using a wheel-loader is no longer necessary, the material can directly be loaded on a dumper inside the rescue tunnel and transported to the surface without interfering with the operations in the main tunnel.

Further Advantages of the Enlarged Rescue Tunnel

The enlarged rescue tunnel makes parallel works in the main tunnel possible. Usually, the top heading is finished before starting the excavation of the bench and invert, since the invert of the top heading gets used as a temporary road to transport concrete and rebar to the face—and excavated rock off the face. With the enlarged section of the rescue tunnel it`s possible to supply the top heading through the rescue tunnel and

Figure 9. ITC 312 tunnel excavator in the Bad Bergzabern rescue tunnel

the cross passages. This allows for the invert and bench heading to be started with the top heading still being active, since there is no interruption in the supply chain for the top heading. The acceleration in construction is determined to be more than six months, saving the client substantial time-related costs, and taking pressure off the project schedule.

Sustainable Concrete Supply

The hydration of the cement content in the applied shotcrete is an exothermal reaction that sets free high amounts of thermal energy, what leads to an expansion of the hardening concrete. When the reaction slows down and the hardened concrete shrinks, cracks occur. Especially voluminous structural elements suffer from this effect, due to high temperature differences from the inside to the outside. The cracks can affect the functionality and stability of the applied concrete lining. To counteract this, the concrete gets cooled before installation ("Precooling"). Therefore, cooling down the components like water, cement, and aggregates can either be done individually before mixing or during mixing. Cooling down all components individually leads to high financial and logistical efforts; hence preference is given to cool down the mixture through the water itself and not all the components beforehand. A widespread technique is to add liquid nitrogen to the water. Liquid nitrogen is a by-product in the production of liquid air, that is widely spread used as a coolant across all industries. It has a temperature below –320 °F (77 K), is colorless and enables a low-threshold handling on site. Only an isolated tank is necessary for storage . The liquid nitrogen is then added to the uncooled water to cool it down to the needed, individually calculated temperature. This technique is wide-spread and there is a high level of application experience.

The increasing effects of climate change make the socio-ecologic responsibility of the construction industry obvious. BeMo Tunnelling has recognized this area of tension early and has been working towards a more sustainable approach on construction for a long time. To gain experience with eco-friendly and innovative technologies, the project team at the Bad Bergzabern tunnel project and BeMo's mechanical engineering department have chosen to put the current concrete cooling technique using

Figure 10. Aerial view of the construction side with the city of Bad Bergzabern behind. The plain visible in the background is the Rhine Valley Graben, the Palatinate Forest rises at the left margin of the photo

liquid nitrogen to the test. As a result, the decision was made to substitute the existing system by a new, fully electric, water-cooling system. For the new system, the periodic delivery of new liquid nitrogen by conventional diesel-powered trucks is made obsolete, thus benefiting the global climate and the local residents by reducing emissions. The experience and data so far look promising, although the final evaluation must be awaited to issue a recommendation for future projects.

CHALLENGES FACED

Dewatering

In February 2022 after approximately 0.42 km (0.26 mi) of excavation, the preceding rescue tunnel unexpectedly encountered decomposed sandstone with soil-like behavior in combination with significant water inflows and a ground water level above tunnel crown. In this situation, the potential risk of loose sand flowing into the tunnel had to be considered (Figure 11). Tunnelling works were immediately stopped in mutual consent of all project participants and additional measures were discussed and finally designed to be able to restart the excavation in a safe way.

With the support of the entire team at BeMo Tunneling, a suitable drainage system was quickly planned and implemented on site. Among others, the decisions included the specific experience, the company had gained during the construction of the 3.5 km-long Kramer tunnel (2.2 mi) near Garmisch-Partenkirchen, Germany, between 2019–2022.

The mechanical engineering department of BeMo Tunnelling provided the necessary machinery equipment on site in a timely manner, while the construction site team carried out immediate work preparation. The technical office, supported by the building maintenance department, was meanwhile able to elaborate a detailed design, which could be approved by the client within a few days. As a result tunnelling works were resumed after less than a week of downtime.

Figure 11. Small-scall flowing of non-cohesive sand (Ground Unit X1) in the face of the rescue tunnel in February 2022

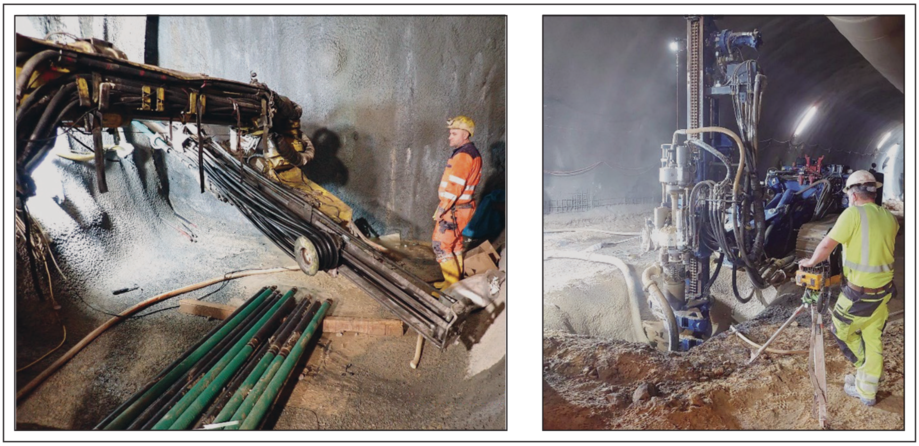

Figure 12. Impression of underground dewatering measures in the Bergzabern tunnel: Left image: Drilling of AT76 drainage boreholes by use of tunnel boomer and rotary percussive drilling equipment in the rescue tunnel. Right image: Drilling of larger diameter vertical drainage well from the crown section of the main tunnel using a HUETTE drill with cased rotary drilling method

The adapted execution plan for the rescue tunnel included an enlargement of the cross-section of four rounds (≈4 m/13 ft) with at least eight drainage boreholes, each approximately 12 m (40 ft) long, using the DSI AT76 3" pipe system, which could be drilled and installed by use of the tunnel boomers tophammer equipment (Figure 12, left image). In order to enable the groundwater level to be lowered below the invert, boreholes were partially drilled downwards and then connected to a vacuum pump system.

When similar conditions were encountered in the much larger main tube, the drainage measures were adapted and effective dewatering was successfully achieved by use of a system of one or more sub horizontal (inclined 30°) 12" drainage pipes, 24 m (80 ft) long ahead of the face and vertical 12" wells with a spacing of approximately 30.5 m (100 ft) and a depth of 14 m (46 ft), drilled from the invert of the crown section (Figure 12, right image). For these longer and larger diameter drillholes a HUETTE special drill rig for cased rotary drilling was employed. Additionally, the DSI AT76 3" pipe system is applied also in the main tunnel, where necessary.

By use of these drainage systems, rescue tunnel and main tunnel could successfully and safely be driven under the given groundwater conditions.

Material Prices and Availability

Since the beginning of the covid-crisis in 2020 prices for construction materials and for operating goods such as diesel fuel or electrical energy increased strongly. This leads to difficulties and uncertainty in the estimation and bidding process, as the development of prices in long terms can't be predicted. Being a contractor and having handed in fixed prices, makes taking the risk unforeseeable, drastic price developments after the submission of the bid a tough challenge. Public clients have recognized this problem area and implemented a compensation adjustment mechanism based on the development of prices published by the German Federal Office of Statistics.

For this project, the mechanism was also implemented, but is only limitedly effective, as it only covers the steel price and has some further disadvantageous restrictions regarding trigger limits or the difference between the theoretical official prices and the actual prices demanded by the suppliers. This, and the unforeseeable effects of the Russian attack on Ukraine in March of 2022 on the global markets, lead to a problematic situation.

Figure 13 shows the development of the mentioned official price index regarding diesel fuel and heating oil, reinforcement steel and electrical energy. Important milestones of the early project phase are marked on the timeline, as well as a general trend for the price development. In the binding offer BeMo Tunnelling made, prices of goods included in the calculation were as of September 2020. When the project was finally assigned in March 2021 and BeMo Tunnelling was able to close contracts with

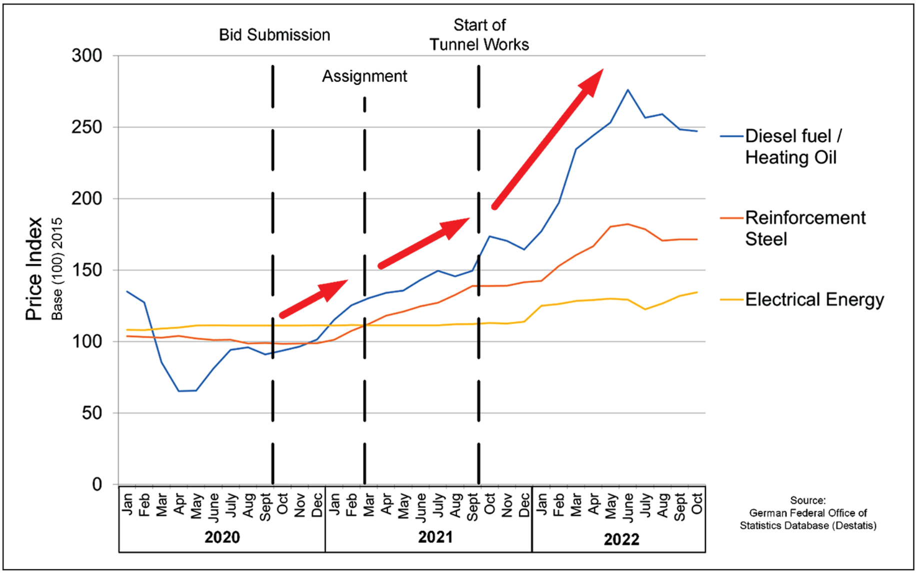

Figure 13. Development of the pricing versus time of selected goods

suppliers and subcontractors, prices for fuel, steel and other goods have increased drastically. Until the start of the tunnel works, and still ongoing today, Diesel and steel prices increased even more. In the European market, there are no fixed prices with fuel suppliers, prices for every filling are set in the moment of refuelling based on the market prices. This leaves the project team with the tough challenge of having uncertain, rising prices every day while still having mostly fixe*d billing prices to the client.

But not only the increasing prices are problematic, also the current availability of materials is concerning. As of June 2022, 45% of the German construction companies active in the field of infrastructure and civil engineering complain about shortages of critical and essential goods. This development began with the economic recovery phase after the COVID crisis in 2021, where international supply chains were still interrupted and production facilities weren't able to adjust their capacities to the again increasing demand. The situation was exacerbated by the impacts of the Russian attack on Ukraine, since a considerable share of raw materials used as construction materials such as steel or bitumen are imported from Ukraine or from, now sanctioned, Russia.

As a consequence, the project team takes action to absorb the effects of this development: supplier prices are renegotiated, the billing process and the stockkeeping are optimized. BeMo Tunnelling is confident, that handling the exceptional situation in an economical way is possible.

CONCLUSION

The construction of the Bad Bergzabern tunnel provides several significant challenges. Difficult and highly variable geological and hydrogeological conditions required a variety of measures to ensure a safe and economical tunnel heading. While in hard and stable rock mass conditions drill and blast tunnelling is possible with only few stabilization measures, tunnelling in loose soil deposits and decomposed sandstone require pipe roofing, combined with a sequential and partial mechanical excavation with additional rock-bolts, intense shotcrete stabilization of the face and eventually additional drainage measures ahead.

The variable rock conditions require permanent adaption and frequent changes between drill and blast and mechanical excavation. Mixed-face conditions generate the need for a combined heading, where only parts of the face can be blasted, while other parts need to be excavated mechanically. Besides the geological challenges the engineers of BeMo Tunnelling were able to speed up the construction by turning in a sophisticated speed-up concept that includes largening the rescue tunnel to move logistical boundaries and forcing points. This results in significant savings in time and money for the client. Out of awareness for climate protection a new electrical concrete cooling system does now substitute a high number of periodical truck rides bringing in liquid nitrogen to the construction site for concrete cooling. The exact savings and the effectiveness of the system is to be reviewed in the future, but the intermediate status is positive. Apart from environmental concerns, the project team faces the impacts of global crises like the rising material and goods prices, as well as a material shortage, due to problematic global supply chains.

Nevertheless, the project team and the involved departments at BeMo Tunnelling meet the challenges and do their best to successfully drive the project forward. The project will get handed over to the client in June 2025.