TBM Tunnelling for Alborz Service Tunnel, Iran: Difficult Ground Conditions and Solutions

D. Wenner¹, M. Rehbock-Sander¹
¹Amberg Engineering Ltd., Trockenloothstr. 21, 8105 Regensdorf, Switzerland

1. Introduction

The Tehran Shomal Freeway project in Iran is a new freeway to connect the capital Tehran with the city of Chalus at the Caspian Sea in the North. The total length is 121 km. Currently traffic runs on small roads passing the Alborz mountains and the journey takes 5 - 6 hours. Upon completion of the project the travelling time will reduce to less than 2 hours with an overall higher capacity. The freeway alignment has more than 30 twin tunnels for double lanes. The Alborz Tunnel will be the longest of these with a length of 6400 m at an altitude of 2400 m. This paper covers the TBM excavation of the service tunnel.

The service tunnel is located between the main tunnel tubes and is used for site investigation, drainage and as access for the main tunnel construction that will commence soon. Later it will be used for ventilation and as a service tunnel for the main tunnels during operation. The length of the service tunnel is 6387 m, including 314 m of drill and blast tunnel previously excavated from the south portal and 46 m for the TBM starting tube from the N-portal. An open gripper hard rock TBM from Wirth (5.2 m diameter) started excavation at TM 46 from north portal (= TM 0) with a constant positive gradient (~1%). The maximum overburden was in the range of 850 m.

TBM excavation started on 06.09.2004 during erection and commissioning of the TBM. Excavation proper started on 06.02.2005 at TM 122. On 03.02.2009, after some 48 months, break through into the S-portal heading was celebrated at TM 6073. During this time (1459 days), excavation took place during 919 days (63%), resulting in an overall average of 6.48 m/d during days with advance. The maximum advance was 30.47 m/day, 110.96 m/week and 389.43 m/month.

2. Site Investigation

Site investigation for the service tunnel included geological surface mapping, a geoelectric resistivity survey along the alignment from the surface and some index laboratory tests on rock samples. No boreholes were drilled. The service tunnel itself provided site investigation data for the main tunnels.

The predicted geological conditions were complex and overall heterogeneous. In the north, Triassic and Jurassic argillites with some sandstones and thin coal layers of Shemshak formation were expected, followed by a sandstone and then limestone formation. At TM ~3800, a 300 m thick fault zone was predicted, representing the Kandovan fault zone with a vertical displacement of some kms. No further information or details were available for this zone. Further south, Oligocene clastic sediments (Kandovan Shale) were predicted, including massive gypsum /
anhydrite bodies with a length up to 300 m at tunnel level. At the surface the gypsum shows massive karstic features to an unknown extent below the surface (overburden ~600 m above tunnel level). The remainder of the tunnel are Eocene tuffs, shales and other layered rocks of Karaj Formation.

The main hazards identified before excavation were the unknown behaviour of the fault zone, the influence of potentially karstic features in the anhydrite and the extent of water and material inrushes as a result of these features. Furthermore CH4 and H2S gases were predicted.

During construction further site investigation by core drilling from the surface was discussed and it was concluded that this would only be justified, if hazard scenarios predicted from general information available, could be excluded by these further investigations. This result could not be realistically anticipated. Consequently it was recommended to better invest the budget for the discussed additional site investigation into preparations for overcoming predicted difficult ground conditions and hazard scenarios. During TBM excavation, detailed geological mapping was performed. Some 145 percussive probe drills of diameter ~54 mm with totalling 3661.50 m were executed ahead of the cutter head with a drill unit mounted to the TBM. Between TM 3026 and 6074, 75% of the tunnel length was covered by them. The maximum length was 39.5 m. Additionally some 10 core drills up to 105.7 m length were executed ahead of the cutter head and above the shield (total length 437.7 m, diameter 56mm, core diameter 40mm, single core barrel) using a DIAMEG 252 drill sometimes installed in a small niche in the crown or when required from a bypass. Three tunnel seismic prediction tests (TSP system) were performed to investigate any structures ahead of the TBM.

3. Highlights of Technical Challenges

The designed rock support consisted of a variety of predefined rock support types. These ranged, from wire mesh in the crown for protection against small stones up to IPB 140 steel rings at 75cm centres with 4-5 x 240 cm Swellex rock bolts in the crown at 75 cm spacing plus wire mesh and 15 cm of shotcrete all round.

During excavation of the service tunnel, an extraordinary variety of technical challenges related to adverse geological condition were faced. These include the presence of methane gas (CH4), high volumes of water ingress, inrush of running ground, squeezing conditions (resulting in blockage of the TBM shield and cutter head), a major karstic fault zone at the start of an anhydrite section and finally multiple gases in high concentrations (hydrogen sulphide (H2S), CH4 and carbon monoxide (CO)). To overcome the some of these adverse conditions various bypass tunnels were excavated to allow continuation of the excavation.

Some of the hazard types encountered and in particular the measures taken to negotiate these conditions are subsequently discussed.

4. Description and Measures
4.1. Bypass

The excavation of a bypass tunnel is one of the last remaining options required when a shield is stuck under severe squeezing conditions or the cutter head is blocked and the blockage can not be removed from inside the cutter head.

Blockage of the cutter head often occurred in collapsing voids, when large blocks squeezed or blocked the scraper openings, or where fault zone or karstic void material at the transition into anhydrite formations collapsed against the cutter head face and friction was increased
excessively. Collapsing voids were often created by too much mucking for too less advance. This created over excavation and progressive failure in the crown. When this mechanism was not detected in due time, the void increased until it collapsed.

All bypass excavations on the project were excavated mainly manually from directly behind the shield (length = 3.6 m) following the shield to the cutter head, either at one side (Fig 1a) or in the crown (Fig 1b).

Advantages of side wall bypass:
- Access to the bypass is easier, muck material can be dumped directly into the invert, and excavation is quicker.

Disadvantages of side wall bypass:
- Depending on initial stress state and rock strength, the side wall bypass might suffer from high vertical stress concentration and related failures.
- Face stabilization may be unsuccessful, because further advance upwards could interfere with spiles etc. In particular, if ahead of the cutter head further excavation upward is required, this might destroy previously installed support, which could make this operation not feasible.
- Backfilling of the bypass is required for resumption of the excavation with the open TBM because of gripper placement. Further with clockwise cutter head rotation during a further advance, the left hand side bypass would be filled with TBM mucking material, before this material could enter into the cutter head scraper openings at about the 10:30 rotation position on the face.

Advantages of crown bypass:
- In rather difficult conditions, the facilities and the feasibility of excavation and support is better in the crown. Steel frames could be welded onto the shield serving as a good foundation for support. The roof ahead of the cutter head can be stabilized in advance, before excavation proceeds downwards to free the complete cutter head.
- Crown bypass does not interfere with grippers. It could therefore be maintained in parallel with further TBM excavation for some sections, e.g. to cross a fault zone.
Disadvantages of crown bypass:

- Depending on initial stress state and rock strength, the crown bypass might suffer from too low horizontal stress and related failures.
- If excavation down in front of the cutter head is required, all mucking has to be lifted up to the crown bypass level, if it can not be done through the cutter head.

The advantages and disadvantages of side wall bypass and crown bypass experienced during the excavation are subsequently discussed for the 5.2 m diameter open TBM and may be found helpful for other projects.

There is no general rule, which location should be preferred for a bypass to the cutter head. The best solution always depends on local conditions and targets, which change from case to case.

The bypass can be used for installation of drainage holes, various probe and core drillings. These can be located outside the profile to be excavated by the TBM thus avoiding problems in case of a lost. The bypass can also be used for injections for ground improvement and water flow reduction.

4.2. Gases

CH4 was first encountered at TM 1884 and since then occurred occasionally. CH4 is an explosive gas, lighter than air and odourless. The lower explosive limit (LEL) is at 4.6 vol-% in the atmosphere, corresponding to 100% LEL. The source of CH4 is related to the coal layers in the northern part of the tunnel, which also exist in the central and southern part at greater depth to some extent. Since no major formations of permeable rocks exist in this area, the risk of quick inrushes of CH4 in large quantities was regarded low. Generally therefore CH4 could be controlled using sufficient quantity of ventilation, but particular hazards may develop in confined spaces such as over breaks or during and after temporary breakdown of the ventilation system. The installed capacity was increased and was then sufficient to generate 1.0 to 1.2 m/s air speed in the general body of air behind the TBM.

Alarm levels were set at 10% and 20% LEL in the general body of air. At 10% LEL, all measures were taken to reduce the gas such as local dilution of gas with compressed air or air movers, further increase of ventilation (if possible), suspension of works (probe drilling or TBM excavation) to reduce the release rate, detailed monitoring and reporting. When the concentration exceeded 20% LEL immediate and controlled evacuation of the complete tunnel was required. This included collection of all personnel including a head count, switching off the TBM main electrical power supply and starting an explosive proof ventilation system (when available).

As a safety measure transport facilities must always be available at the TBM within potentially gas bearing ground. At times where this was not possible, e.g. when the mucking train was on the way out, no rock bolt or probe drilling works were allowed, because these could have initiated sudden gas ingress.

All hot works (welding, grinding) required special permission from the safety personnel, including a gas check. Evacuation training was executed at regular intervals.

Special procedures for reentering the tunnel after evacuation were defined and had to be strictly followed, e.g. tunnel ventilation for a specified time, entering with a gas detector (checking gas concentration at the front end of a train) and including confined spaces such as electrical cabinets. Depending on local gas concentrations further flushing by compressed air was required.
Only upon fulfilment of all the requirements and procedures was the main power supply allowed to be switched on and works continued. Further special procedures were required for entering the confined space, e.g. the cutter head.

Probe drills ahead of the cutter head and vertically into the crown were used to systematically check for gas and eventually drain it in a controlled way, before these gas bearing joints were intersected by the TBM excavation. Shotcreting of the rock surface helped to reduce the flow of gases into the tunnel.

**H2S** was first encountered at TM 2967 and since then occurred several more times. H2S is a gas heavier than air and with a strong smell of rotten eggs. The main hazards are related to its toxicology and corrosive effect on metals. It can be identified by smelling below 1 ppm. The 8 hours occupational exposure limit is 10 ppm. For short times (15 min), 15 ppm is acceptable. Above 15 ppm full face masks with filters were used. To a great extent this restricted the ability to work. In locations where there was water spray filters could not be used without further protection as, the filter was immediately blocked.

Above 100 ppm, H2S deadens the ability of a person to smell it. Above 100 ppm it is an immediate danger to life or health (IDLH). Therefore filters were only used up to 100 ppm. At higher concentrations, masks with positive pressure self supplying respirators were used. These were available with a compressed air capsule carried on the back or with central air supply from big bottles using a 50 m long hose (Fig. 2). Productive work became virtually impossible with this equipment and could only be used for inspections and remedial measures after tunnel evacuation. The maximum concentration recorded was in the range of 500 ppm in the general body of air (after tunnel ventilation had been non operational). Concentrations between 50 and 100 ppm had to be negotiated for longer periods of time. H2S also caused corrosion to metals, in particular to the electrical installations on the TBM. To reduce these effects, some electrical cabinets, the operator cabin and a rest cabin were connected to the fresh air supply. In spite of these precautions major electrical repair works were required.

![Fig. 2: Workers with positive pressure self supplying respirators in high H2S concentration environment, air supplied by tanks and hoses.](image)
H2S was encountered in two ways: the rock cutting process in dry anhydrite by TBM released H2S in some anhydrite sections, leading to concentrations up to 160 ppm. Directly after excavating a round of advance and TBM had stopped, the release of H2S also reduced significantly to values of between 10 - 20 ppm. In other locations, H2S, which has a high solubility in water, was released from ingressing water, in particular when water sprayed from the rock fissures under high pressure.

The source of H2S was not fully known. Most likely it was generated by bacterial sulphate reduction (of anhydrite with CH4), producing H2S, CaCO3 and water. Green oily liquid sometimes ran out at small fissures in the anhydrite in low quantities. This was suspected to be the remainder of the bacteria.

If H2S was only released locally at a high concentration, e.g. at a borehole mouth, it could be diluted by compressed air or drained into hoses. Ingressing contaminated water was drained as quickly as possible by pumps or directly from the rock mass into closed hoses and pipes and transferred to at least the end of the TBM, in order that it could no longer release the H2S into the tunnel atmosphere in the TBM section. Membranes were used to prevent spraying water and to guide the contaminated water into the tunnel invert. It was obvious that high concentrations could not be reduced by a realistic increase of ventilation capacity. The tunnel was regularly evacuated when the concentration exceeded 100 ppm.

Generally sufficient numbers of mobile gas detectors must be available, regularly calibrated and used, in particular during any drilling operation (TBM, rock bolts, probe drilling). Tunnel workers must be informed about the hazards, receive medical checks and approval to use masks, trained in the use of masks and other breathing equipment. Personal protective equipment (masks and filters) must be available in sufficient quantity and stock. Fresh air must be guided to typical working locations along the TBM, e.g. the operator's cabin and the invert section where rails are placed etc.

When CH4 or H2S was detected in joints in probe drills far ahead of the cutter head, these joints were attempted to be cement grouted in order to reduce the conductivity for the gas in the rock mass. In addition, approximately 6 m long gas drainage holes were drilled in the close vicinity of the cutter head in order to drain the gas.

Tests for the presence of hydrogen cyanide (HCN) were conducted and found not to be present. In another tunnel project in Iran, where high concentrations of H2S were also encountered, HCN had been detected in significant quantities. Carbon monoxide (CO) had also been detected in one section of the tunnel in concentrations above 500 ppm, where the 8 hours occupational exposure limit is 30 ppm. The tunnel was evacuated, since the available filters did not provide any protection against CO.

By implementing and strictly following the procedures described above, it was possible to execute the works without major accidents. But time delays and significantly reduced progress rates had to be accepted.

4.3 Water Ingress

The northern section of the tunnel had only low water flow. At TM 2582, the first significant ingress was encountered with >90 l/s, which increased to ~125 l/s during further advance. At TM 2967 a further water ingress had to be faced, adding ~110 l/s to the total flow rate and releasing H2S (up to 25 ppm).
At TM 3015, there was a rapid inflow of initially some 110 l/s into the tunnel together with an estimated 100 m3 of mud and stone material which also released H2S (up to 60 ppm). This represented a fault zone with karstic void fillings when entering into the first anhydrite section. Over the following two months, the total water quantity from the tunnel reduced from 290 to 50 l/s. The other end of this anhydrite contained no problems with respect to water ingress and did not cause any tunnelling problems.

The main water ingress occurred at TM 4524 in a fault zone: the total tunnel flow at the portal increased from 60 l/s to 690 l/s recorded initially (~800 l/s estimated, Fig. 3) with a high concentration of H2S (>100 ppm). After waiting period for water reduction, TBM excavation through the water bearing fault zone proceeded. The total water flow slowly reduced to 380 l/s over eight months. During the first 3 months, work could only be executed with masks. In mid August 2008, again a karstic fault zone was hit at the end of the southern anhydrite section. It initially added 220 l/s to make a total outflow of 600 l/s, which quickly reduced to 450 l/s within four weeks. Finally the total water flow continued to reduce to 270 l/s over a further 4.5 month until break through and reduction is expected to continue further.

The main hazards associated with these water ingresses and inrushes was the release of H2S and the collapse of washed out voids eventually leading to blockage of the cutter head. Working conditions for workers with cold water spraying everywhere were harsh, especially in winter times with temperatures down to -15 °C and the requirement to run the ventilation at full speed because of the gases. Neoprene wet and dry suits as used by divers were used for protection. Further hazards were related to the bad effect of water on various electrical installations and various high voltage cables submerged under water.

The inflow of water also affected the train transportation system. Sleepers for the rail tracks were placed directly on the bored invert or invert shotcrete. No invert segments had been used. Water drainage was by free flow in the invert to the portal. While an additional 400 mm drainage pipe has been installed on the tunnel wall, it was never possible to utilize it in a reasonable way, since no suitable high performance waste water pumps were available in the local market in Iran, because of overall political sanctions. One of the main problems was the sedimentation of fine
materials in the invert, blocking rails and causing derailments. This happened mainly in local depressions of the vertical alignment and at the upstream side of a California crossing, which effectively act like a sedimentation pond. Railway traffic on rails covered by water caused no significant problems. However more maintenance was required for the rolling stock.

Most water ingresses could be identified in advance by probe drillings. However attempts to grout these zones in advance to reduce the water flow were never successful. The reasons were mainly related to the high pressures and flow rates together with limited availability of equipment like preventers or packers and contractor’s personnel experienced in this type of work.

Due to these circumstances it was finally decided to always allow the water to drain especially as one of the main tasks of this service tunnel was to drain the rock mass in advance of the excavation of the main freeway tunnels.

Foam developing resins were also used to fill up the voids and for stabilizing the collapsed ground with running water inside.

5. Concluding Remarks

A series of extraordinary geological difficulties had to be technically mastered during the TBM excavation of the Alborz Service Tunnel in Iran. This had significant influence on the progress rates and the construction schedule as well as on the costs. The hazards and some of the methods to deal with them have been described in this paper.

However, and most importantly, all these hazards and difficulties were encountered without any major accident or even fatalities. Improvements could be achieved by better preparation for expected problems in advance, in contrast to solving problems “on the hoof”.