

TBM Tunnelling in Hydrogen Sulfide Gas Bearing Ground and its Solutions

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Abstract In the late December of 2006 while Zagros tunnel project in western Iran was advancing according to the schedule, a sudden rush of groundwater accompanied by a nauseating odor similar to that of rotten egg intruded the tunnel. Some workers complained from eye and respiratory tract irritation. The presence of hydrogen sulfide (H_2S) gas as high as 200 ppm was soon tested positive by gas detectors and subsequently the ventilation fans (2×110 kW) speed were boosted to 1,450 rpm in order to dilute the gas concentration to safe levels (10 ppm). Nonetheless, the work continued at a rather moderate pace for another 11 days and 134 more meters excavated in the gas infested grounds before 4 men died during a damage assessment survey of the TBM after a power failure that had forced the tunnel ventilation system to temporarily shut down. This paper is to discuss hazards and geological sources of H_2S gas in of Zagros Water Conveyance Tunnel and to recommend practical solutions to prevent or mitigate the gas destructive effects on human and machinery, as well.

Keywords Zagros Mountains · TBM tunnelling · Water ingress · H_2S · Environmental impact · Mitigation measures

1 Introduction

Zagros water conveyance tunnel in Kermanshah province of Iran is aligned in $N210^\circ$ direction near the city of Pol-e Zahab. This section of the project is considered as the second lot of a more comprehensive water conveyance tunnel which is schemed approx. 26 km long and is 6.73 m in diameter. It has been under construction using a Herrenknecht hard rock double-shield TBM since March 2005. So far, 15 km (58 %) of the tunnel has been completed. The tunnel horizon is situated within the folded zone of Zagros Mountain Range, consisting of sedimentary rock formations at an average depth of 400 m ($H_{max} \sim 950$ m). In the course of tunneling, the machine encountered nearly many extraordinary situations related to continuous intrusion of hydrogen sulfide (H_2S) gas, all of which resulted in a significant reduction in TBM utilization rate and an increase in construction delays, as well as high cost.

This report will focus on the tunnel groundwater inflow which contains high concentration of dissolved H_2S gas, and the available technical provisions manipulated to ease the gas destructive effects on personnel health, equipments and environment.

The H_2S gas was first encountered at TM 3700 in water seepage (greater than 5 mg/l) and since then has reoccurred at several geological zones. The gas main hazards are related to its toxicity to human and corrosive effects on mechanical and electrical equipments. Presence of hydrogen cyanide (HCN) was also

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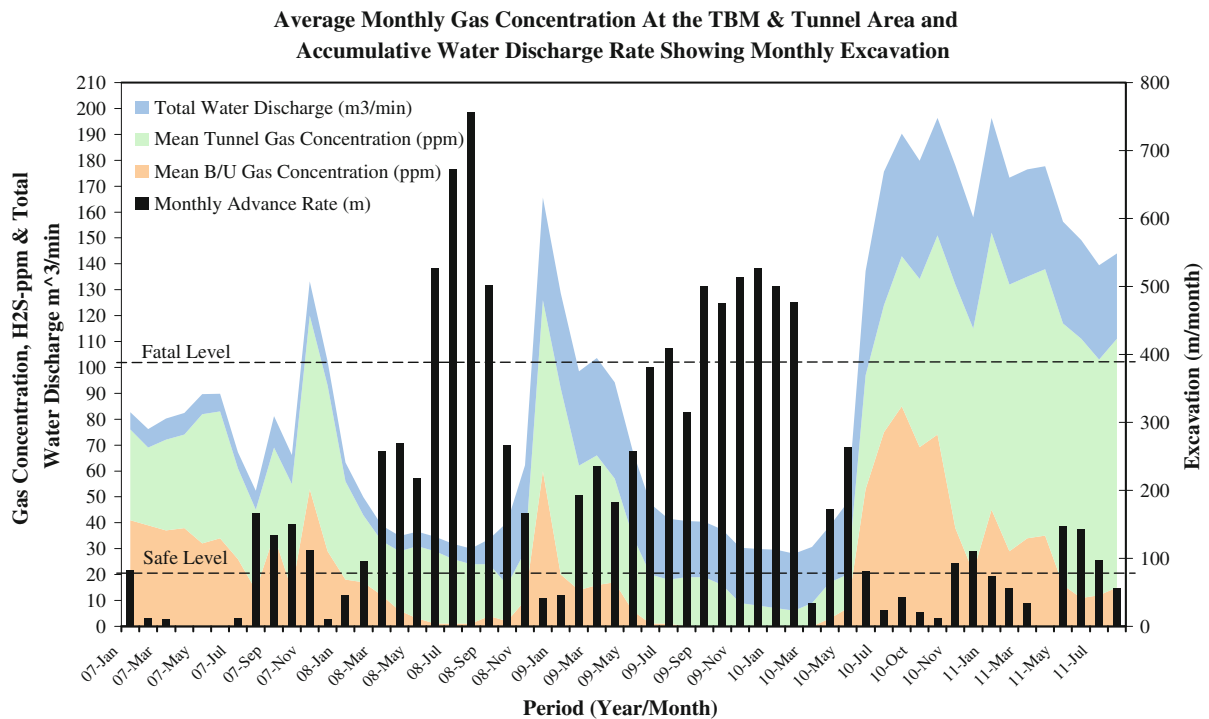


Fig. 1 Average monthly H_2S gas concentration at the TBM and tunnel area and accumulative water discharge rate showing monthly tunnel advancement

substantiated by field and laboratory tests at TM 4446 which resulted in a 3 week TBM shutdown. At TM 4157, a first significant water ingress was encountered ($Q > 110$ l/s), which gradually accumulated to $Q \sim 730$ l/s with further advancement to TM 8256. At TM 13846, 155 more liters of gas rich water intruded into the tunnel, totaling the tunnel accumulative discharge flow at the portal to 900 l/s. This amount of water released 700 ppm H_2S gas into atmosphere. In the past year, the aquifer water level has gradually subsided and the tunnel seepage rate has dropped to ~ 547 l/s. The tunnel average gas concentration has also decreased to around 125 ppm. Figure 1 illustrates the TBM monthly advance rate, total water discharge rate and the mean monthly gas concentration along the excavated tunnel.

Experience has proven that exposure to H_2S gas above 20 ppm for long periods of time can cause many health hazards for workers and damage machinery, due to its explosive-toxic and corrosive properties, respectively.

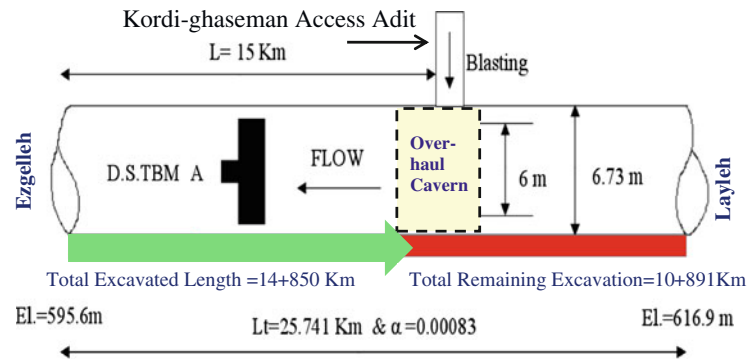
After tackling a number of gas mitigation options, the disciplines that proved in practice to be most

effective in safeguarding against the H_2S gas menacing effects were compiled as a report and are discussed in this paper. Currently, the TBM work has temporarily been suspended to carry out a comprehensive overhaul and machine option improvements. The overhaul is being conducted in a excavated cavern at the intersection with an existing access adit at the tunnel 14,850 marking. Figure 2 illustrates the general project layout and the approximate location of the overhaul cavern (13.5 m (W)*12.5 m (H)*50 m (L)) which is equipped with 2*15 ton overhead traveling cranes.

2 Geology

According to the structural geology zonations of Iran, Zagros tunnel is located in the core of the Zagros Mountain range. It is a wide Tertiary thrust and fold belt stretching across the entire western regions of Iran with a roughly aligned NW–SE strike. The Fold-Thrust belt of Zagros consisted of Flexural folds, Ramp & Flat, Detachment folds, Fault propagation

Fig. 2 Simplified sketch of project layout and current progress status



folds, Fault–bend folds, Klippen, Imbricate fans, Duplexes, Late stage strike-slip and normal faulting. The major principal stress of these structures is generally aligned in north-east to south-west direction (See Fig. 3).

Stratigraphically, the tunnel is driven in a variety of formations, including Mesozoic to Cenozoic age rocks. The youngest geologic unit along the tunnel course is alternative thick greenish-gray shale and thin bedded siltstone, sandstone and argillaceous limestone of Amiran Formation (chainage 11 + 800–12 + 100) which locates in the core of Baneh-dar syncline

(see Fig. 4). Underlying this unit is the Gurpi Formation which spreads out throughout most of the tunnel path. It consists of combination of limy shale and argillaceous limestone. Some layers of Gurpi Formation are rich in pyrites in the form of nodules. Garou Fm. underlies the Gurpi Fm. which is comprised of alternating thin to thick bedded shale and argillaceous limestone. The oldest unit along the tunnel path is the Gotnia Formation (chainage 19 + 500–21 + 500) which is consisting of anhydrite, gypsum and evaporate cast. This formation intersects the tunnel at several sections in Zimkan structure. The rockmass

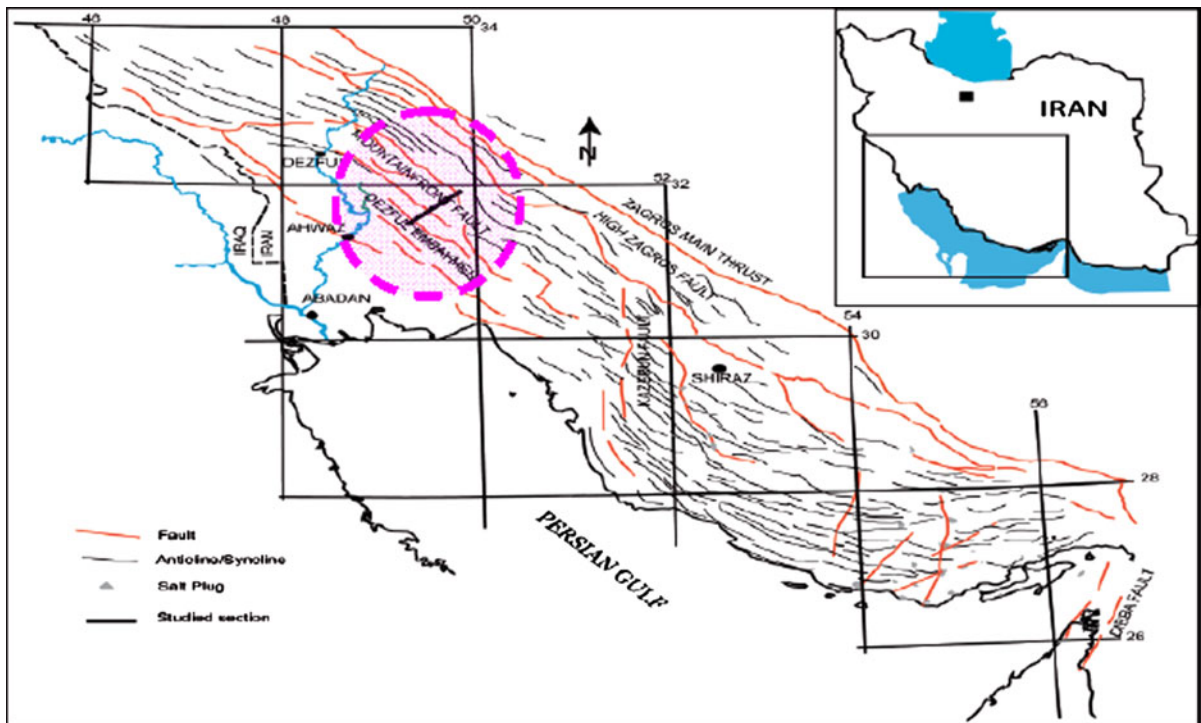


Fig. 3 Tectonic map of the Zagros fold-and-thrust belt. The Zagros tunnel is located in 30–32° & 48–50° coordinates

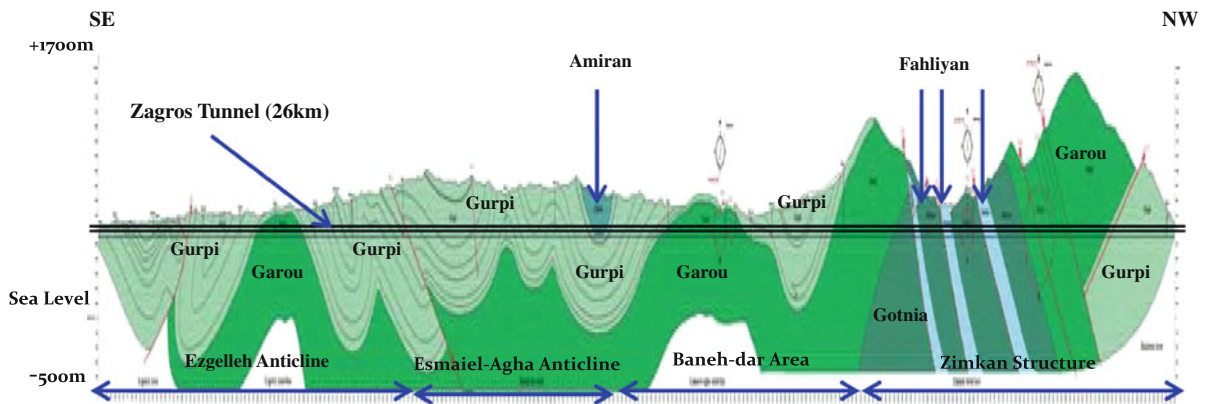


Fig. 4 Longitudinal geological profile of lot 2 Zagros Tunnel. (After Pars Kaneh Kish Consulting Engineering Co. 2010)

geomechanical quality along tunnel alignment varies from poor to good. The groundwater level varies from 30 to 340 m above the tunnel crown. The assembled rock strata changed frequently from hard rock to soft, dry to wet, stable to unstable, stick to nonsticky ground (and vice versa), more often than anticipated. The geological profile of the project line is illustrated in Fig. 4.

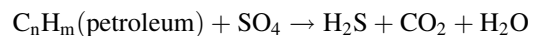
3 Occurrence of Hydrogen Sulfide

H₂S is a naturally occurring component of crude oil and natural gas reservoirs. It has a nauseating smell of rotten egg at low concentration and a sweetish odor at higher concentrations. The odor is a poor warning property because exposure to H₂S quickly deadens the sense of smell. Both H₂S and sulfur dioxide may occur in fractures of any rock type which contains iron sulfides. When exposed to air, these sulfide minerals and in particular pyrite, oxidize and produce H₂S gas. The gas is 18 % heavier than air ($d = 1.393 \text{ g/l}$), therefore, may collect in low areas of tunnel, ditches and collection sumps. This gas is quiet lethal, about five times as toxic as carbon monoxide and almost as toxic as HCN. According to OSHA standards, a level of H₂S gas at or above 100 ppm is immediately dangerous to life and health. H₂S dissolves in water to make a solution that is moderately acidic.

Lot 2 Zagros tunnel is surrounded by Garou Formation which is known to be as the host rock in many major oil (gas) bearing basins further down in the south provinces of Iran. In this project area, the

formed hydrocarbons may have migrated or leached out during uplift movements, due to lack of a suitable cap rock and a favorable geological structure to trap the hydrocarbons. Therefore, only traces of hydrocarbons have remained in the rock formation in the form of black tarry liquids. These liquids have been frequently observed along the tunnel path, seeping through holes and gaps of the tunnel segmental lining.

As mentioned before, H₂S may have various sources or most likely is an associated component of gas and oil reservoirs in the form of SBR (sulfate reducing bacteria), TSR (thermo-chemical sulfate reduction), thermal, pyrite dissolution; reduction and oxidation reaction and H₂S migration are known sources. It is impossible to reject each of these sources completely. However, TSR source has more probability than others (Mirmehrabi et al. 2008) as shown in equation below:



To verify the source of gases and determine the type, chemical analysis on seepage water was carried out both in the field and laboratory. The relative ratios of gases in the air of tunnel were also measured. The results are presented in Table 1 and 2.

The upper threshold which H₂S gas can be measured by field testing is 5 mg/l. With respect to fundamental differences between field tests and laboratory analysis, both results confirm each other. Table 1, implies that maximum gas liberation takes place at or near the infiltration source and then it decreases considerably with increasing distance from

Table 1 Summary of chemical analysis of tunnel water seepage in mg/l (Sahel Consulting Engineers 2007)

Sampling location	H ₂ S gas content (field measurements)	H ₂ S gas content (lab measurements)
Cutter head	>5	15
03 + 000	1	3.7
02 + 000	1	0.8
01 + 000	0.5	–
Portal	0.5	–

Table 2 Summary of chemical analysis of tunnel air in mol% (Sahel Consulting Engineers 2007)

Parameters	N ₂	H ₂ S	O ₂
Cutter head	79.48	0.16	20.36
Segment erector	78.27	0.84	20.87
Control cabin	78.74	0.25	21.01

the source (and so by increasing elapsed time). As it may be stipulated from the above data, volume of the gas for different amounts of water inflow can be estimated and based on these concepts, an efficient ventilation capacity can be determined. For example, if the water inflow is equal to 100 l/s and with the given data for H₂S (after Mirmehrabi et al. 2008):

Molecular mass = 34 g/l.

1 mol = 22.4 l.

For unit time (s) one can write:

$15 \text{ mg/l} * 100 \text{ l} = 1.5 \text{ g}$.

$(1.5 \text{ g}/34 \text{ g}) * 22.4 \text{ l/mol} = 0.9881 \sim 1$

Therefore, every second 1 l of gas will pollute the air of tunnel and 0.08 m³/s extra ventilation would be required to improve the air quality in the TBM area back to standard (10 ppm) level. Nevertheless, the manifestation should not imply that the gas concentration per volume of water is a constant criterion. For instance, the mean H₂S gas concentration in the first gaseous zone (3 + 582–4 + 523 km) was 69 ppm and the average water inflow was reported at 142 l/s. In the second zone (7 + 646–8 + 953 km) the added water was 420 l/s, but the mean gas concentration negotiated along the tunnel was around 39 ppm. During the third gas strike (13 + 420–14 + 312 km)

the tunnel mean gas concentration amounted to 218 ppm and the average water inflow was reported 289 l/s.

Most probably groundwater discharges through a system of open joints perpendicular to the tunnel axis. These conduits are impressed by 4 known major joint sets. Their common morphology is steep, undulating, smooth, fresh, $e < 0.1 \text{ mm}$, 15–35 cm spacing and $L < 1 \text{ m}$ length. Figure 5 shows the relationship between tunnel average gas concentration and water discharge rate monitored at the tunnel portal.

Water ingress accompanied by H₂S gas emission, imposed exuberating hardship to the tunnel crew and extensively damaged equipments, utility lines, TBM components and most important of all, the tunnel concrete lining, especially at the peak periods. The maximum gas accumulation ever recorded was in the range of 700 ppm (gas detector max. sensitivity limit). The problem was peaked when total water inflow reached to around 900 l/s and the flow of fresh air by the ventilation system was disrupted as a result of frequent line collapse due to increased wear and tear and its support system. Concentrations between 200 and 300 ppm had to be negotiated during these periods (see Fig. 5). Figure 6 shows the hardship in the tunnel and the tedious work condition for the crew.

Some of more recent underground projects that have encountered similar problem in the recent years and have successfully implemented various remedial measures to mitigate the harmful forces of H₂S gas during their construction stage are listed in Table 3. Among the argued projects, Zagros tunnel surpasses all the other cases both in severity of gas strength and its areal persistency. Base on these case studies, the H₂S gas in lot 2 Zagros tunnel project has more extensively deteriorated the TBM structure and its components than any other project. The rolling stock and the riling system were also devastated by the corrosive effect of H₂S gas since the rails were frequently submerged in the water and the maintenance crew could not attend the rails properly to carry out the necessary repair works.

As it can be determined from the given data in Table 3, there is a lack of compiled information about gas bearing tunnels in civil engineering literature, and much of the information available from mining literature is not directly applicable to construction. Hence, when gases are encountered in a tunnel, it is often an unexpected or poorly anticipated phenomenon. Even if

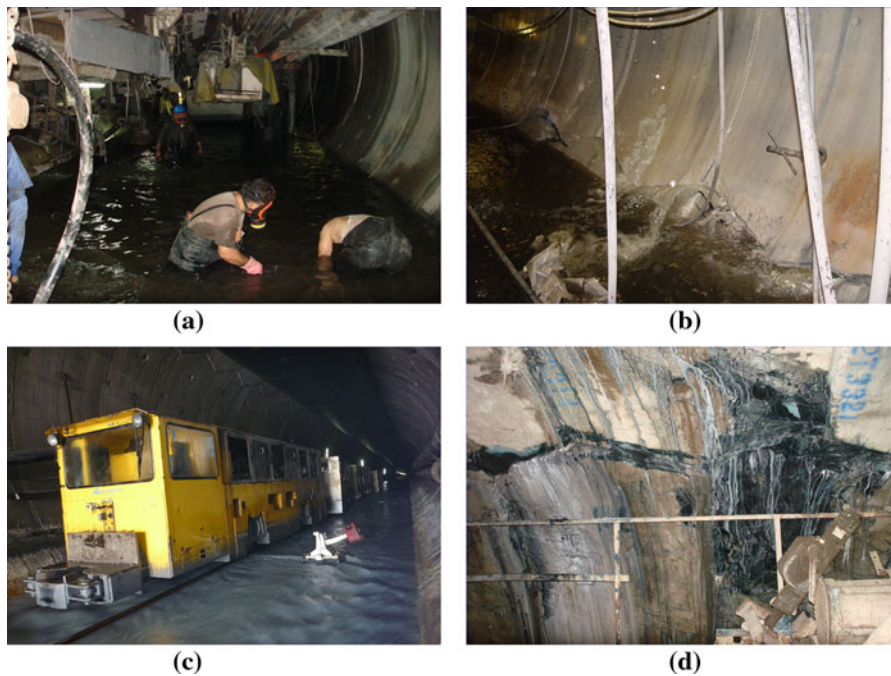
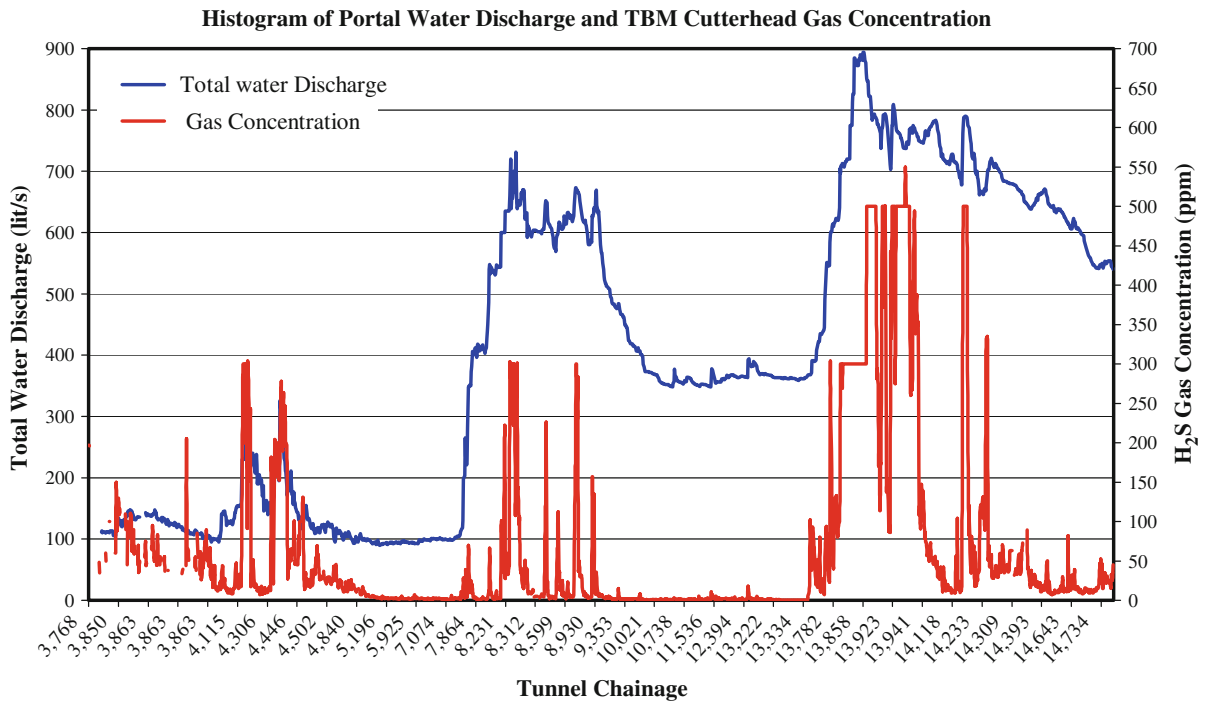


Fig. 6 Captured scenes of tunnel difficult work conditions. **a** Tedious work for the crew working with respiratory protection; **b** high water ingress from gaps and joints of tunnel's hexagonal segmental lining; **c** equipment failure due to

corrosion of electrical boards and interruption of railing system; **d** hydrocarbons seepage and damaged segmental lining by strong acidic properties of seeping water and formation of CaCO_3 on the concrete surface

Table 3 Comparison of some recent tunnels with gassy ground and water ingress

Tunnel	Location	L (km)	D (m)	Lithology	Tunnelling machine	Reference
Zagross	Iran	25.7	6.7	Shale, limestone, anhydrites	Double-shield TBM	Mirmehrabi et al. (2008)
Alborz	Iran	6.4	5.2	Shale, anhydrites	Open gripper TBM	Wenner and Wannemacher (2009)
Mill Creek	USA	4.0	7.2	Shale	Double-shield TBM	Schafer et al. (2007)
Los Angeles	USA	37.0	6.6	Alluvium, Sandstone, Siltstone, Shale	Open & Double-shield TBM	Stirbys et al. (1999)
Barnett Complex Mine	USA	–	–	Shale, gypsum	Drill & Blast Method	Ozark-Mahoning Co. (2006)

serious accidents are avoided, there is a likelihood that project costs rises abruptly as lengthy delays accumulate and equipments and man power impaired excessively.

4 Environmental Impacts

The project is located in a semi-arid area and constant drainage of the main aquifer by the advancing tunnel has stressed out the regions hereditary delicate groundwater resources. In addition, the drought in recent years has stressed out the vulnerable groundwater regime and has depleted many active springs in the area. Figure 7 shows the typical behavior of groundwater as the tunnel passes underneath an index piezometer. As it is contemplated by the GWL behavior in the figure, groundwater level had dropped on the average 27 cm per every meter of TBM's advancement before it fell below the tunnel invert level. On a time scale, 62 days had elapsed since the well was first intercepted by the tunnel and the groundwater table had drawn down 132 m. Using Darcy's time-drawdown empirical equations, the country rock mass hydraulic conductivity is determined at $k = 2.46 \times 10^{-3}$ cm/s. This observation became a useful criterion to delineate the host rock conductivity characteristics and to estimate the groundwater seepage rate at any given location along the tunnel. As it was also revealed by regularly monitoring local active springs, the tunnel radius of influence is about 3.5 km.

5 Monitoring

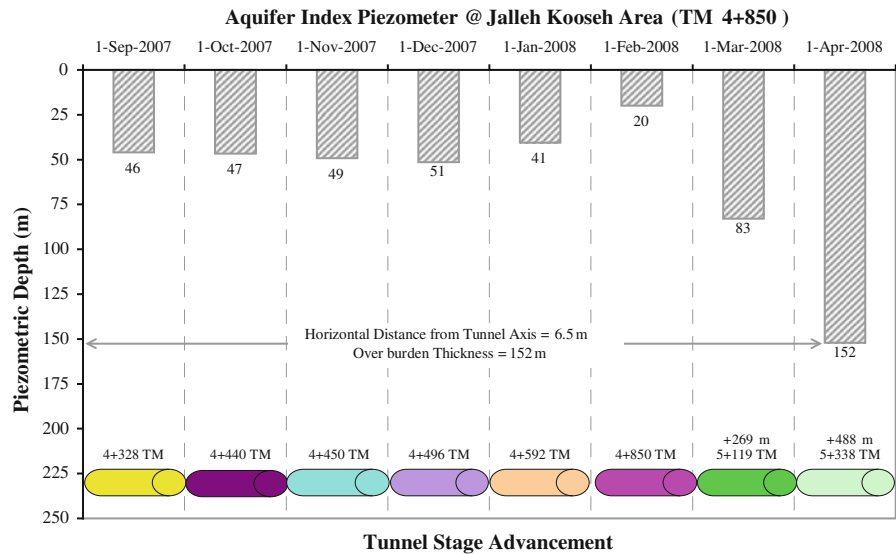
After encountering the first significant quantities of H₂S gas, some supplementary investigations were

carried out to determine the extent and the intensity of the gas bearing grounds along tunnel. An elaborated monitoring and data collection program was later stepped up both in the field and laboratory, as well. The volume of water has been measured daily at the tunnel portal and concentration of various gases has also been recorded by fixed stations on the TBM and by mobile sensors at the beginning, midpoint and end of each working shift. The results under various work circumstances is summarized in Fig. 8. Based on periodic measurements at different working circumstances, the tunnel average gas content determined at its lowest (53 ppm) when the dewatering system was in operation at its optimum capacity ($Q_t = 390$ l/s) and the speed of the ventilation fans (2*200 kW + 2*160 kW) were at 1,200 rpm. In the same critical zone and with a compatible water and gas amount, the tunnel mean gas concentration level reached to its highest (119 ppm) when the dewatering system was inoperative and the tunnel ventilation was partially immobilized and the fans were underutilized with a combined capacity of 2*200 kW (800 rpm) +2*160 kW (1,000 rpm).

6 TBM Failure Modes

Essentially, the presence of H₂S gas in the tunnel is due to the inflow of H₂S bearing water as it escapes into the atmosphere. Moreover, dry and wet cycles in the tunnel associated with inconsistencies of the ventilation and dewatering system output, coupled with mechanical agitation of gas bearing water during tunnel routine activities heightened the gas emission and changed the tunnel humidity to a compound with

Fig. 7 Groundwater behavior in response to tunnelling progress



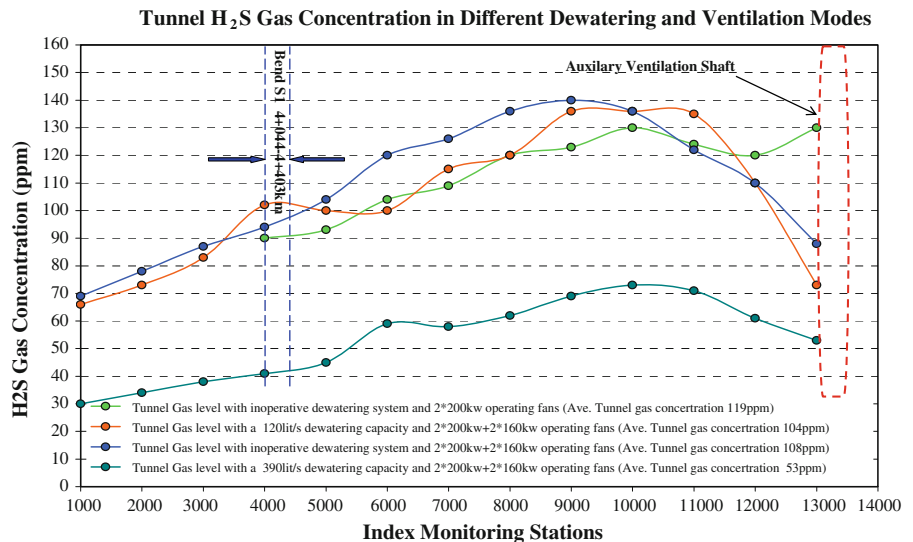
properties similar to sulfuric acid (H_2SO_4). This acidic fume with strong toxic and corrosive affects harmed workers health and damaged electronic boards and PLC systems of TBM as well as the backup components which in turn imposed equipment failure and unwanted downtimes (Fig. 9).

Frequent breakdown of the TBM rolling stock and the rail tracks was a menace for the crew since the rails were often submerged in the water and were not visible for maintenance and repair workers. As a result, locomotive and wagon derailment had become an almost daily event in the tunnel (see Fig. 10). Meanwhile, necessary remedial measures (TBM equipment

and components modification in addition to tunnel supply lines restoration), as well as decrease in durability of tools (e.g. pumps) and decline in shift times, forced complete stoppage of the machine operation in four different periods to perform necessary repair works.

Figure 11, illustrates the different work disciplines of TBM’s overhaul activities which took place in three different phases between December 2005 and March 2010. During this period, a total number of 83 potential failures modes were identified for the main systems (electrical, mechanical, hydraulic and pneumatic). The failure modes were frequently identified in TBM carriers such as segment erector, segment crane,

Fig. 8 H_2S concentration levels at fixed stations in different dewatering and ventilation conditions showing the least gas concentration when both ventilation and tunnel dewatering system are at their optimum performance



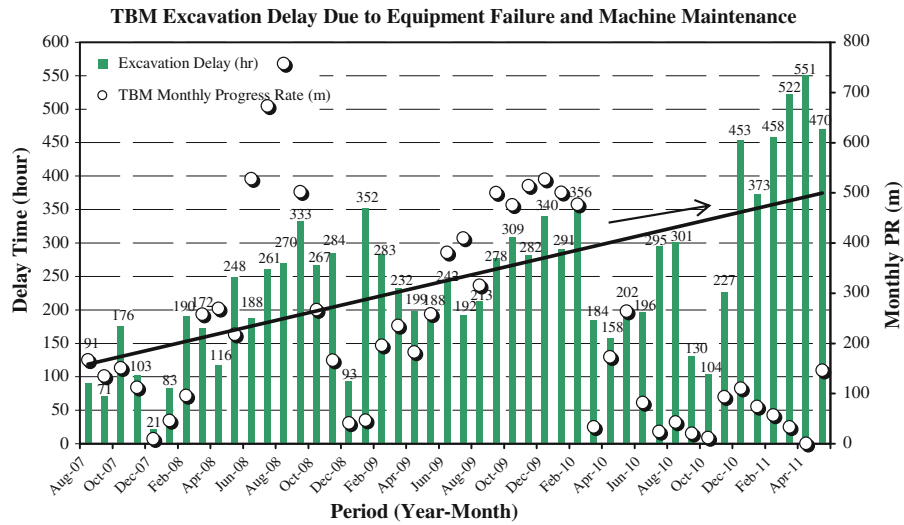


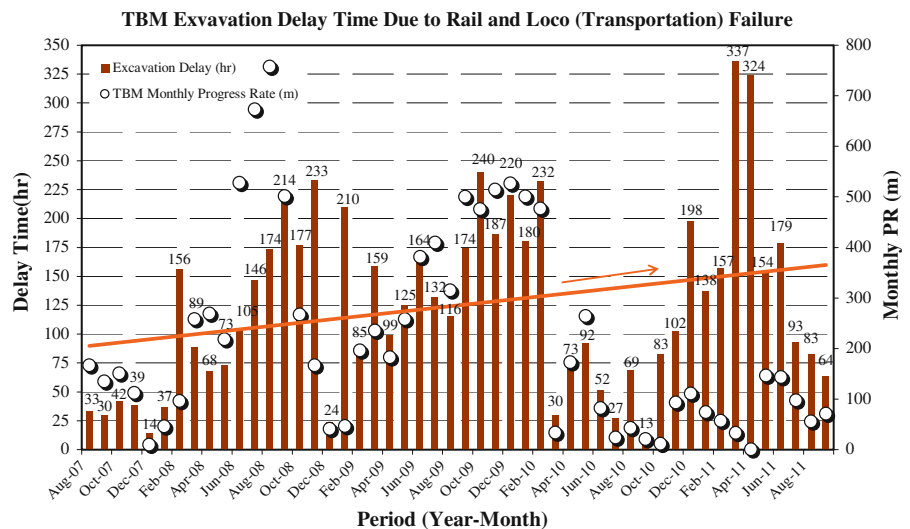
Fig. 9 Monthly TBM down times due to equipment failure and machine maintenance

and muck car mover and the conveyors. These operations intrigued an elaborate modification in such areas as the TBM electrical guiding (PLC) systems and to also improvise devices such as steel screens (mesh) at muck ring to collect wash outs, in addition to specially designed vacuum pumps to dredge sediments collected in the shield and segment erector areas. Overall, the failures categorically are outlined at 34 % as electrical, 17 % as hydraulic, 12 % as pneumatic and 20 % in mechanical systems. The remaining 17 % of TBM downtime was allocated to modifications of TBM control systems and improve its efficiency.

Addressing the failure modes of loco and the rail tracks of the rolling stock, the locomotive mechanical and electrical (PLC) components were at 32 %, wagon axial splitting due to excessive corrosion at 11 %, wagon derailling due to railroad defects 28 % and railroad repairs 29 %, respectively.

Cost of consumables and replaced spares to the gas pertaining areas (~ 3,129 m) is computed to be USD 19.2 per cubic meter of material excavated. This does not include labor costs for daily maintenance. Special safety equipments and gears including face masks and gas filters ran at a cost of USD 9.4/m³ excavated tunnel

Fig. 10 Monthly transportation system down times due to rolling stock and railroad failures



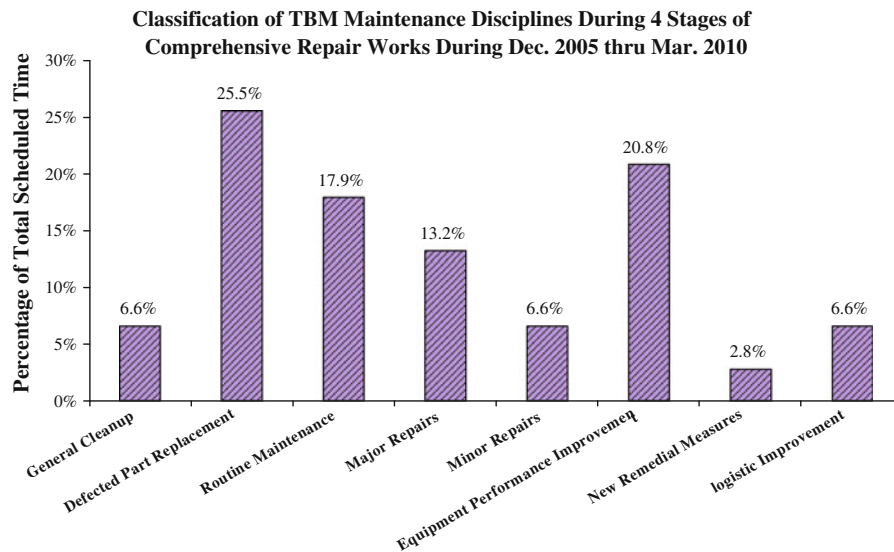


Fig. 11 Categorization of work disciplines carried out during TBM periodic repair works and maintenance schedules

and the supplementary ventilation equipments and dewatering system ($L = 13.3$ km) including electricity consumption and maintenance costs totaled USD $16.13/\text{m}^3$ of the excavated tunnel.

In terms of overhaul's life span, the periodic restorations (comprehensive repair works on main components) kept the machine running over the past 5.5 years. At the first scheduled overhaul, the repair works efficiency was 4,391 m (chainage 3 + 836–8 + 227) or equivalent to 2112 TBM working hours. At the second stage overhaul, the equipment efficiency was 5,073 m (chainage 8 + 227–13 + 300) or equivalent to 2108 TBM working hours; and finally at the third stage of TBM repair works the efficiencies of TBM overhaul was 1,550 m (chainage 13 + 300–14 + 850) or equivalent to 834 TBM working hours. The short life span of the latter overhaul was due to higher pace of equipment deterioration due to higher concentration of soluble H_2S gas in water. The 4th stage has now commissioned in a specially designed cavern (see Fig. 2) since February 19, 2012.

7 Description of Mitigation Measures

Depending on the contractor strategy and the concentration levels of the gas types, combinations of mitigation measures were considered to reduce gas level to safe standards. In Lot 2 Zagros tunnel, both

toxic and explosive gases, including H_2S and methane (CH_4) have been present in abundance. To deal with high gas emission and to minimize its impacts on the tunnel works, different provisional measures were implemented with varying degrees of success. Based on the author's first hand experiences, the solutions may be categorized into two preventive and controlling measures. The preventive measures (e.g. project realignment, consolidation grouting from surface, TBM replacement, ground freezing at tunnel face, dewatering by pumping wells from surface and so on) often were very time consuming and had appalling costs and at the best scenario not conclusive. Hence, controlling measures are more prevailing both economical and technical wise. Prudently, the controlling measures (remedial) are the main scope of this paper.

The first step is training the personnel and mobilizing a well experienced safety team (HSE) for search and rescue operations of gas poisoned victims. The safety team must be well informed of the gas hazards and must be equipped with sufficient numbers of mobile gas detectors. Other effective preventive techniques that were offered by the project design team and were implemented to reduce the impact of gas hazards are:

- Equipping the tunnel crew with approved breathing apparatus (face mask and filters) and supply them with personal protection equipments such as respirators and sealed clothing. Other safety

equipments such as rechargeable 6 and 9 l backpack compressed air capsules with capacity of 90 min of breathing oxygen as well as 50 l oxygen tankers on wheels (carts) with 10 h of life sustaining oxygen capacity stationed at several TBM gantries were utilized. In addition, twin oxygen capsules, similar to figure across, were essential for rescue team and should be stationed on all personnel carrying wagons.



- Mobile gas detectors are essential tools in monitoring gas levels along tunnel and the TBM work area. Installation of accurate gas detectors for the anticipated gas types are important part of advanced warning system in gas control. Moreover, fixed station gas detectors for simultaneous monitoring of four strings of natural gases including H₂S, CH₄, CO, and O₂ were installed inside the TBM Cutter head, shield, segment erector and several other areas in the back-up system such as segment crane, track laying area (interface area) and in the control cabin. The crews were also furnished with mobile gas detectors that were calibrated on regular bases.
- The presence of the gas is indisputably due to the inflow of H₂S bearing water and its escape into the air. Thus, special attention has to be paid on the quality and overall performance of tunnel lining during phases of production, transport, installation and tunnel operation. Taking the hexagonal geometry of the Zagros tunnel segmental lining into account, the importance of segment tolerances and imperfections demanded particular attention. Hence, the process of quality assurance that would control both the geometrical dimensions and fitting of segments into segmental lining rings had a crucial role to compensate for the inherent deficiency of hexagonal lining in blocking water intrusion. Furthermore, in hexagonal segmental lining low to moderate water seepages can be tackled to certain extent by means of conventional backfilling (pea-gravel + cement grout injection). It was initially preceded that seepage rate would be controlled within one finished diameter of the tunnel (6 m) in lit/s/km (6 l/s/km) by contact grouting, but the material was readily washed away by high pressure water intrusion in TBM rear shield and thru the segments joints and gaps. The alternative preventive measures were polyurethane based foam and resin injection, pre-drainage and plugging the segment joints with hydrophilic sealants (e.g. CEM SwellTM), which all proved time consuming and in particular costly. At the present overhaul stage, a cement-slurry injection system is being installed on TBM to backfill lining with in high water seepage areas for the remaining tunnel length. The success degree of the scheme and its ability to obstruct the ground water conduits remains to be seen. It is meticulously essential to provide a watertight (with gasket) segmental lining in H₂S gas bearing grounds and to avoid non-sealed flexible hexagonal segmental lining, all together.
- Successful grouting is considered crucial in subduing the gas emission. When water bearing zones were detected the water under pressure had to be tapped and transported through the pipes equipped with valve at the pipe end. This pipe should be connected with water bearing zone 1–3 m in the rock mass to avoid pipe plugging during grouting the space between segments and rock (see Fig. 13). If detection of discharge points is not possible the inclined tapping holes are necessary. Number of pipes and its diameter should be enough to transport at least 200 l/s. Subsequently, space between segments and rock, filled with Pea-gravel, had to be grouted to block the leakage between segments and to prevent grout mix leakage during the curtain grouting procedure of surrounding rock mass at a later stage. During the contact stage of

grouting valves were open. This grouting included filling the overt area (area above the roof segment). After inflow between segments was blocked most of the discharging water flow through the tapping pipes. Before grouting started the valve at the end of tapping pipe were closed. It means turbulent flows along the open joints and conduits were blocked. In that circumstance (not flowing water along the open joints) grouting, with grout mix resistant to sulfates, started. A down-stage grouting procedure was utilized. The drilling was to be made for the grouting in stages of 6.5 m. The first stage (rock just behind segments) was grouted with a low pressure (5 bars) to avoid damage of segments and grout mix leakage into the tunnel. For deeper stages recommended pressure was 7.5 bars.

- Rapid dewatering systems via pumping and closed/covered water drainage pipelines will reduce the release of gas into the air. Other important benefits are; it lowers water level in the tunnel to facilitate the rolling stock mobility and also to facilitate the track repair works. Approximately, 150 l/s (25 %) of the average daily drained water ($Q_{ave.} = 600$ l/s) flows freely inside the invert ditches to the portal. While the 400 and 500 mm drainage pipe lines collectively transmitted 416 l of water per second in a closed circuit in a distance of 13.3 km. This scheme minimized the agitation of the drained water along the tunnel and thus limited the emission of H_2S gas. The tunnel dewatering system consisted of 3 separate pumping stations at TM 7,100, TM 10,000 and TM 13,300 each equipped with 5*90 kW submersible pumps (as shown in Fig. 12). It was never possible to utilize the system in an efficient way, since no suitable high

performance and corrosive resistance waste water pumps were readily available on the local market and the lingering dredging of the sumps and the ditches which severely reduced the systems original designed capacity of 750 l/s. It is therefore coherent that the tunnel dewatering system had in fact became partially ineffective when accumulative water seepage into tunnel exceeded the combined discharge capacity of both pipelines and ditches (see Fig. 5). Note that, considerable improvements may be accomplished by a more carefully planned maintenance schedule during system operation, in contrast to planning and designing a higher pumping capacity in advance.

- In addition to the described water drainage system, a supplementary dewatering system consist of 5*55 kW submersible pumps coupled to 8" PVC pipes (indirect pumping) or 12" pipes (direct pumping) that are individually attached by mechanical packers to the source of water infiltration, usually at the segment lifting socket. The system total drainage capacity is about 250 l/s and is extended roughly 500 m. It extends from the tunnel face to a primary mobile collector tank at the last backup gantry where sediment separation takes place and the cleansed water is then conveyed by 2*33 kW pumps through a 12" PVC pipeline to a secondary collector tank where directly drains water to the dewatering pipeline. The scheme helped to create a continuously closed circuit from the tunnel face to the tunnel portal. Thus, minimizing gas emission into the atmosphere. Figure 13, shows the layout plan of two different dewatering schemes that were successfully tried to complement the TBM existing dewatering system.

Fig. 12 Sketch of a typical tunnel dewatering pumping station showing the general layout and its various mechanical components

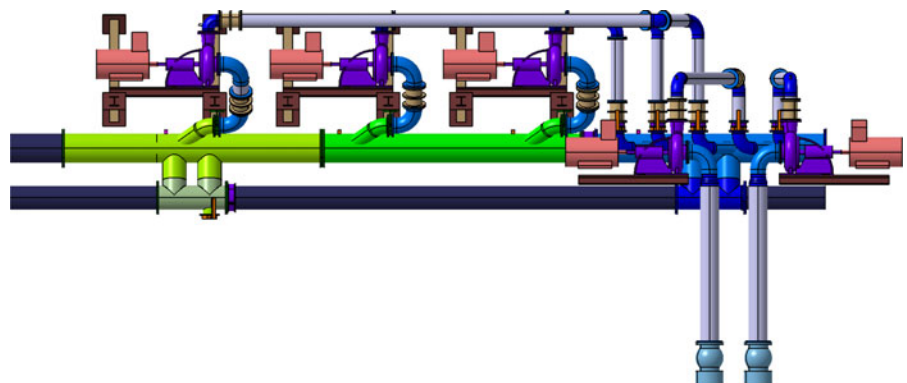


Fig. 13 The layout plans of two different supplementary dewatering systems used in the tunnel to collect gaseous waters at the source of penetration (Ieman-Sazan Consulting Engineers 2011)

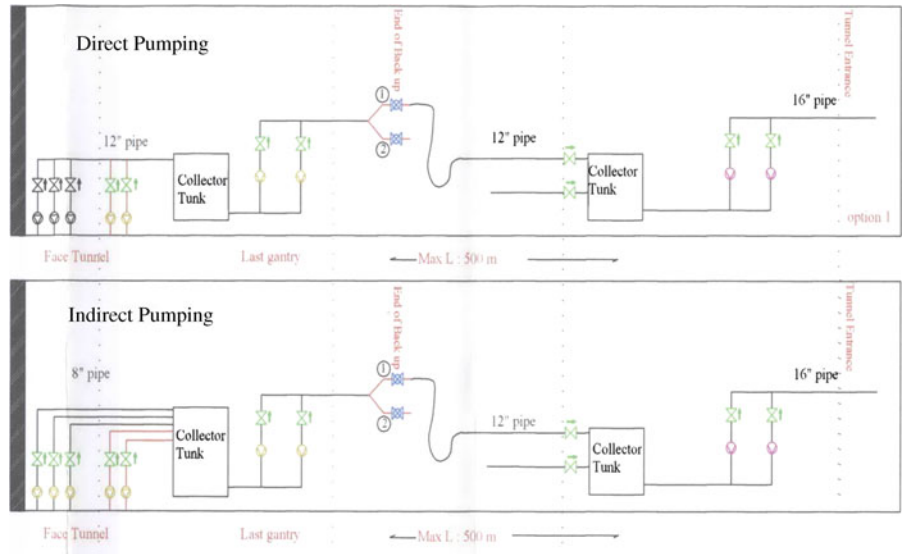
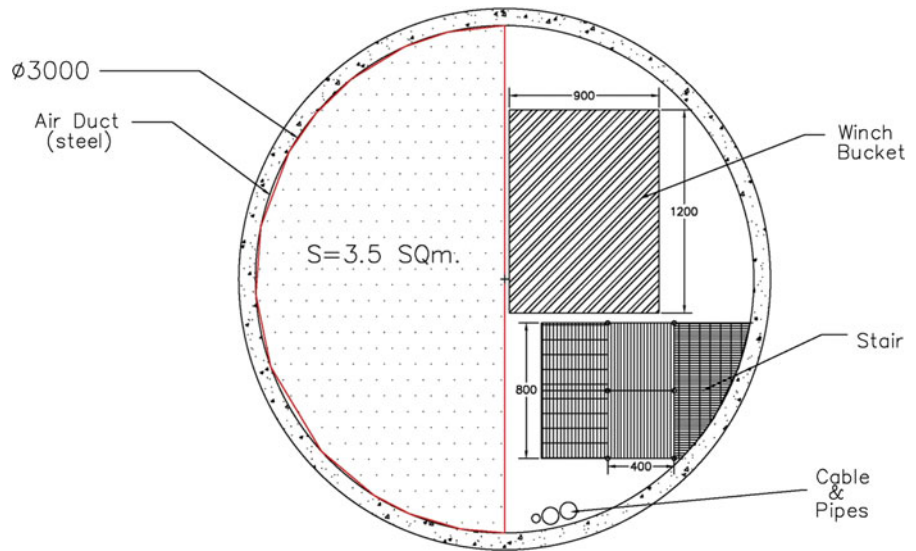


Fig. 14 Simplified sketch of tunnel auxiliary fan station via an excavated shaft (SV3) at the main tunnel 13,300 marker showing the general layout and the installed accessories to service tunnel in critical zones



- Increased ventilation capacity to provide minimum required fresh air ($Q_{ave.} = 50 \text{ m}^3/\text{s}$) to the TBM face by using high powered fans and excavation of an auxiliary ventilation shaft ($D = 3 \text{ m}$, $L = 182.5 \text{ m}$) at the tunnel 13 + 300 chainage to supplement the tunnel existing 3*200 kW jet fans with an additional low resistance line equipped with 2*160 kW new powerful jet fans. Figure 14, illustrates the schematic drawing of the shaft that was analyzed from technical and economical point of view to achieve more efficient ventilation in a critically high gaseous zone at TM 13300-14850 and to also reduce gas

concentration to safe and standard level. Of course, as TBM advanced, the efficiency of ventilation system declined due to air leakage and related friction losses along the air ducts. Hence, ventilation shaft proved to be very beneficial to reduce gas and to relieve the existing overloaded and under-performed portal ventilation system by shortening the length of section. In addition, the ventilation shaft performed as a multipurpose scheme which provided a winch as an emergency rescue lift, stairs and a utility duct for cables and pipes for a vertical pumping station. Upon completion of the tunnel, the shaft can be converted to an exhaust

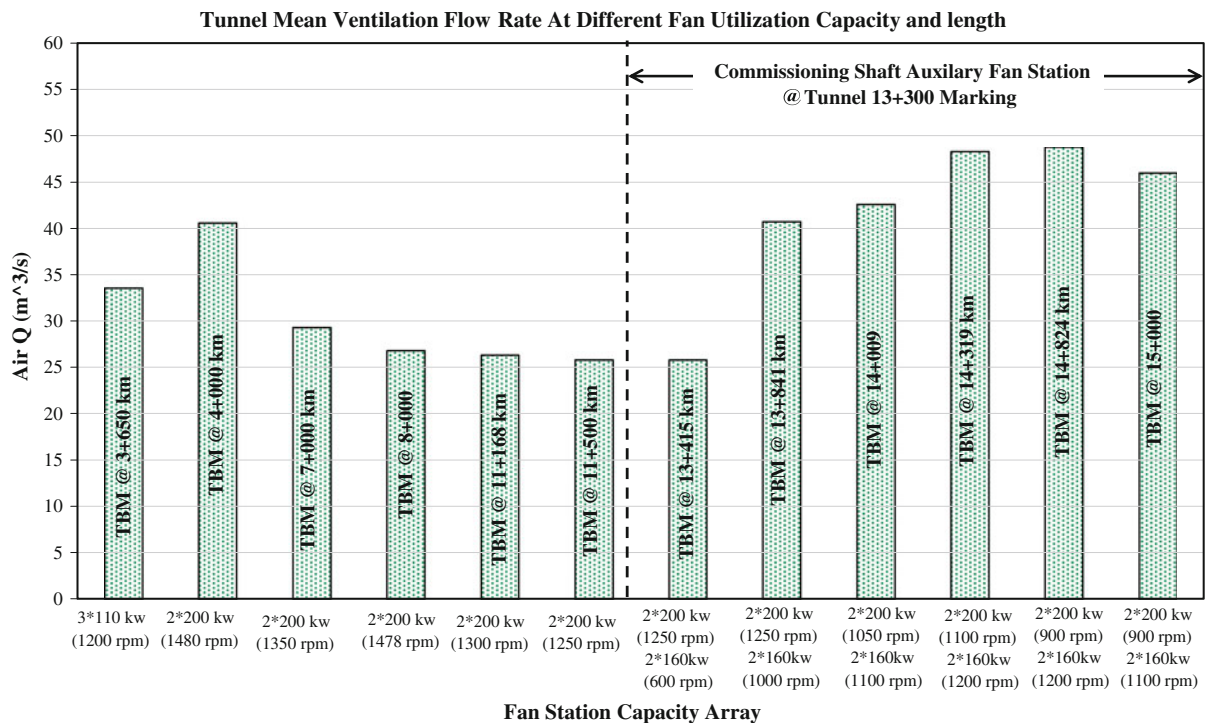


Fig. 15 Tunnel ventilation discharge rate at different fan utilization capacity indicating an increase in air flow as the SV3 auxiliary ventilation shaft is commissioned at different TBM face distance from the portal

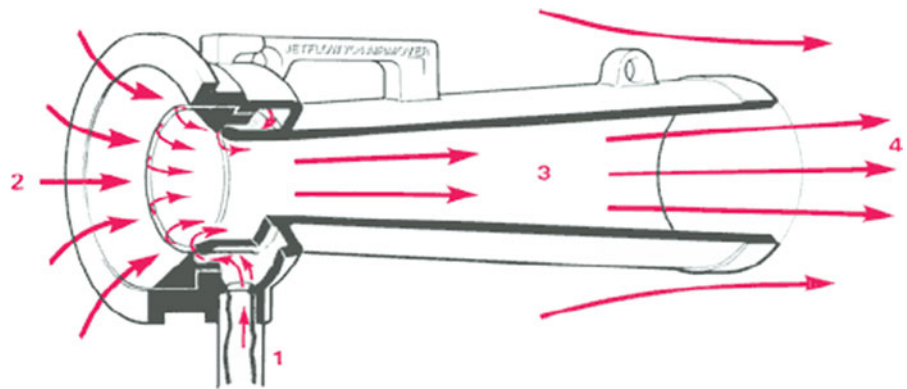
shaft to dilute the gas that may accumulate in a saturated acidic state in the tunnel crown. This phenomenon will eventually accelerate tunnel concrete lining decay. Figure 15 shows the average ventilation flow rate at different fan utilization capacity and the TBM distance from the fans which in depends on the duct length. As it is deduced by the data, the ventilation discharge rate has increased sharply after the SV3 ventilation shaft was commissioned and new fresh air was supplemented into the system.

- Fire extinguishers to control fires at the source of gas leakage were installed at locations that are easily accessible. Also, incidental ignition sources of explosion were eliminated by using anti-static ventilation lines and spark free exhaust jet fans and cigarette smoke prohibition by the crew.
- Basic literature research have established the explosive potential of CH_4 (5–15 %) and H_2S (4.3–4.5 %) by volume. The lot 2 Zagros project TBM is equipped with gas sensors that detect both methane and other explosive gases. The system is set up to activate the alarm at 42 LEL (2.1 % by

volume) and to automatically shut down the machine when the methane gas concentration exceeds 60 LEL. As CH_4 concentration increases above the safe threshold, it'll set off the alarm system and this inurn will provide a chance for tunnel crew to start emergency ventilation systems to disperse any trapped gas and if deemed necessary to evacuate the tunnel. The preferred solution to this problem was *Jet Flow Air Movers*TM. The Air Movers are mobile and can easily be carried off to the gas hot spots. The device is driven by a 900CFM compressor and projects jet air at a rate of $Q = 25.5 \text{ m}^3/\text{min}$. The jet air velocity is in the range of $V = 15\text{--}20 \text{ m/s}$. Figure 16 shows a sketched diagram of the air mover flow pattern and the operation mode in its manifold. Also, the tunnel face ventilation was amplified by a 90 kW booster fan (equipped with silencer) at the interface area with max. speed of 3,000 rpm.

- Proved to be efficient in dispersing gas were 6*2.5 kW installed exhaust fans each with a discharge rate of ($Q_{\text{max}} = 1.73 \text{ m}^3/\text{s}$) and max speed of 3,000 rpm equipped with silencer that

Fig. 16 Schematic drawing of the operational mechanism of an Air Mover



were set up in sequential at 25 m spans along the tunnel wall to flush the contaminated air from the tunnel face to the backup end.

- Establishment of a special line of fresh compressed air to create positive pressure inside the TBM main electrical units of machinery, control cabin, transformers and electronic boards and sensitive mechanical components by using a high power compressors at the tunnel portal to supply fresh air directly into TBM terminals and also to the utility posts along the tunnel line. The scheme's main purpose is to release pressurized air into the designated receptors and to prevent the infiltration of gassy air into the intended units and thus creating a clean environment for gas sensitive apparatus. The compressed air contains some moisture, oil residue and colloidal that should be filtered out. The system also must be provided with moisture traps to dry up the air. The filtering systems should at least have capacity of roughly $29 \text{ Nm}^3/\text{min}$ under the designed pressure not less than 13 atmospheric bars. The system has an 8 m^3 air tanker. The air is compressed at 11 bar pressure with a working discharge rate of ($Q = 29,000 \text{ m}^3/\text{h}$). The compressed air is transmitted to the TBM by a 150 mm high pressure polyethylene pipe where it bifurcates to several tributaries supplying fresh and positive pressure air into every gas sensitive terminals such as control cabin with ($Q = 100 \text{ m}^3/\text{h}$), cutter head and shield area with ($Q = 425 \text{ m}^3/\text{h}$), TBM transformers and the main electric boards with ($Q = 350 \text{ m}^3/\text{h}$). A separate valve with $75 \text{ m}^3/\text{h}$ discharge rate is allocated to the TBM's first aid (clinic) cabin. Another valve with equal discharge rate ($Q = 75 \text{ m}^3/\text{h}$) offshoots compressed air at the car mover area to disperse the released dust and gas from the muck shoot area.
- Individual valves also set up at 100 m spans along the tunnel line (i.e. for track repairs) and along the backup area at fixed stations with discharge capacity of $150 \text{ m}^3/\text{h}$ for protecting the equipment. In addition, eleven tributaries are designated for the tunnel's midway junction boxes with a capacity of $150 \text{ m}^3/\text{h}$.
- Use of rather innovative remedial measures such as sealing of TBM main electrical boards, control cabin and other vital electronic terminals by PVC gaskets to prevent gas infiltration. The corrosive properties of dissolved H_2S gas in tunnel humidity often caused rapid corrosion of electrical circuits.
- Installed devices to prevent inflow of fine size muck cuttings, carried into the shield and segment erector area by water ingress. Vacuum slurry (piston) pumps were occasionally utilized to collect accumulated sediments in the shield and in the track laying (Interface) area which often faltered due to clogging by sediments. Also Equipment congestion inside the TBM left little or no room for bulky pumps.
- Face stabilization was locally carried out in areas such as fault zones with water bearing gouge and often in unstable blocky grounds which imposed unproductive time and consequently low machine utilization. The main obstacle was the TBM probe-drilling system disability in fore-polling the unstable ground. Attempts will be made to refurbish and modify the TBM probe-drilling system in the present overhaul stage. If succeeded to upgrade the probe-driller, ground conduits (water carrying joints and curvatures) will be plugged off by pre-grouting before TBM approaches the future hazardous zone.
- Frequent and regular maintenance of sensitive parts by skilled personnel.

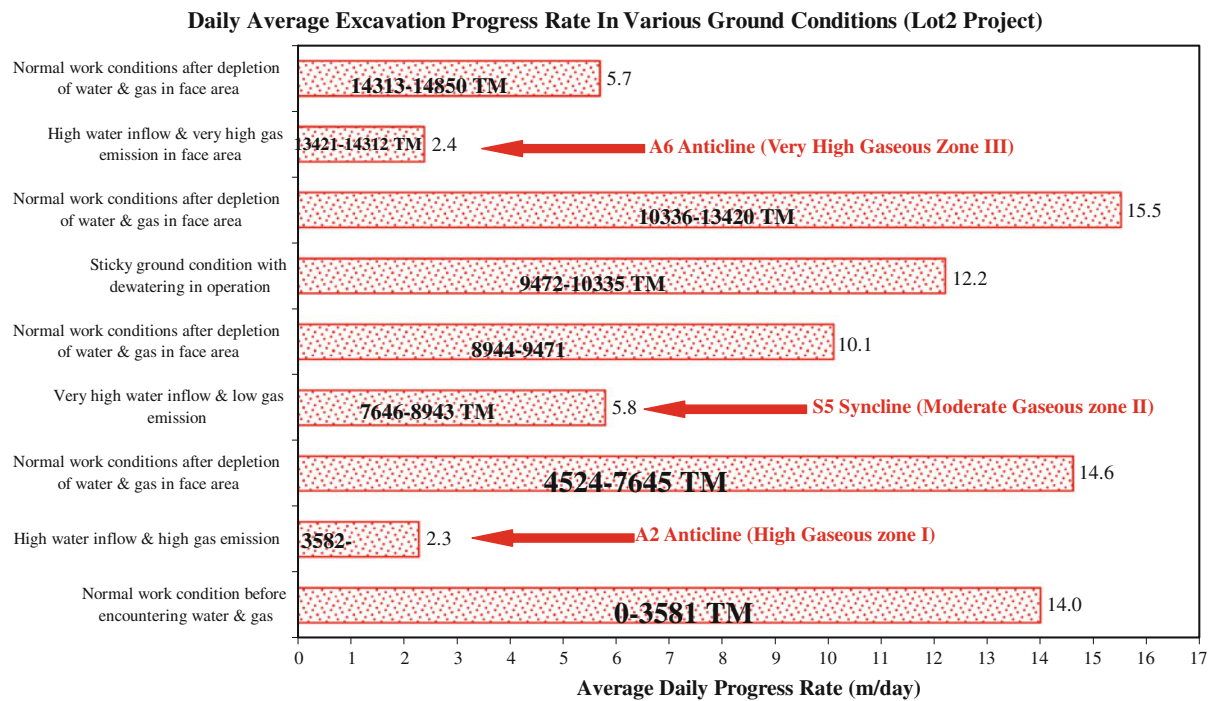
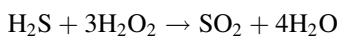


Fig. 17 Average daily TBM progress rate in various work circumstances

- In addition to the above mentioned mitigation measures, neutralization of the H_2S gas by chemical compounds such as hydrogen peroxide (H_2O_2) can oxidize H_2S to SO_2 based on the following chemical reaction:



H_2S gas may also be dissolved by salts such as ammonium bicarbonate, potassium bicarbonate and magnesium bicarbonate. However, sodium bicarbonate is recommended by many researchers as a better choice since it is stable and highly soluble in water. The Patent Storm website (2010) recommends from 0.01 to 0.25 grams of dissolved sodium bicarbonate per mole of gaseous water as an ideal dosage to cease gas emission process. However, the procedure was soon eliminated since it proved to be expensive and difficult to implement in a continuously recharging environment.

8 Conclusions

A series of extraordinary mitigating measures to combat high water ingress and H_2S gas intrusion

were implemented during the first 15 km of lot 2 Zagros tunnel. The lack of space and TBM inherent inflexibility was a handicap, whenever much work had to be performed in the TBM cutter head and shield area. Most of techniques were mastered during TBM excavation since tunnelling in H_2S infested grounds is not considered a routine tunnelling work. Experience gained from this case revealed that comprehensive geological study contemplated with advanced design methods will increase the capability to mitigate the hazards associated with H_2S gassy grounds and will significantly decrease the project risks, losses, down times and cost (Mirmehrabi et al. 2008).

As mentioned earlier, the main water inflow occurred near the cutter head. Exact points and characteristics of rockmass in discharging areas are not morphologically delineated since they are always covered by segments and water jets were registered along the contacts between segments (Fig. 6b). Most probably groundwater discharges through the open joints or cavities with limited apertures. Obviously, part of water circulates along the space between segments and rock. Considering all mitigation measures implemented in the project, a successful contact grouting and sealing segment joints with hydrophilic

mastics are the most reliable measure to prevent ground water and gas intrusion into the tunnel. However, water seepage from the tunnel face is always inevitable.

The first step of remedial works is to try to identify exact or approximate locations of high groundwater intrusion zones behind the segments or cutter head and redirect water into the pipelines. If the water can not be collected at the discharge points, using submersible pumps in the track laying (TBM Interface) area is the next step. Subsequently, contaminated water should be confined into the drainage pipelines and eventually discharged into the portal. A continuous probe drilling ahead of tunnel face 35–50 m and measuring water discharge and H₂S concentration are key prerequisite for a successful dewatering operation. Proper ventilation is another essential step to minimize the gas destructive forces and injecting compressed air into gas sensitive electrical terminals are unavoidable for longer life span. The additional measures included an expanded monitoring system, use of personal protection equipments and excavation of auxiliary ventilation shaft.

Using the discussed mitigation plans, as results a safer work environment and improved working conditions was provided. Thus, the tunnelling proceeded at a moderate utilization rates after the H₂S gas was relatively under control. Figure 17 shows the tunnel daily advance rate under different work circumstance.

The project average daily progress rate is 11 m/day (330 m/mo) for the first 15 km of the tunnel. This advance rate was achieved with the aid of discussed provisions and in spite of continuous seepage of gaseous water and experiencing numerous interruptions in supply line and the derailing of the rolling stock. Three individual zones are exemptions to the above statement. They are known as hot spots where the remedial measures did not succeeded to completely overcome H₂S hindrance affects. These areas are designated as A2 Ezgelleh Anticline (rated high gaseous-zone I) which expands over 941 m (TM 3582-4523) and A6 Kordi-ghaseman Anticline (rated very highly gaseous-zone III) from TM 13421 to TM 14312 that extends 891 m and finally to a lesser degree of intensity, S5 syncline (rated moderately gaseous-zone II) covering 1,297 m (TM 8953-7646) of the project path. These zones collectively add up to 3,129 m or roughly 21 % of the total 15 km tunnel,

excavated. The average advance rate in zone I and III are roughly 2.3 m/day which has more than doubled to 5.8 m/day advancement in zone II.

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