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ORIGINAL PAPER

Investigation of a methane flare during the excavation of the Silvan irrigation tunnel, Turkey

Mustafa Ayhan[1] · **Deniz Aydın**[1] · **M. Şefik İmamoğlu**[1] · **Mustafa Çoğalan**[2] · **Askeri Karakuş**[1]

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Abstract

Mechanized methods are being increasingly used in tunnel excavations to such an extent that to ensure safe construction and the economic viability of projects the need for design-stage geotechnical studies has considerably increased. However, unexpected problems, such as gas inflow, can be experienced during excavation when the geological conditions are insufficiently investigated. In fact, even if construction is taking place in a known oil–natural gas basin or coal-bearing strata, the possibility of methane flare/explosion events can be minimized if a suitable excavation method and equipment are used. However, little published literature is available on this topic, resulting in the potential problem of encounters with sources of methane during construction that have not been considered in the planning of the tunneling operations. We have studied a methane (natural gas) flare incident that occurred in 2015 during the excavation by full-face hard rock tunnel boring machine of the Silvan irrigation tunnel, south-eastern Turkey. During the planning and pre-construction stages no consideration was given to the fact that the tunnel passes through a natural gas basin and, consequently, the selection of excavation method and machine equipment was made without taking into account the high possibility of natural gas being present. During excavation a significant methane gas flare occurred, resulting in 13 workers being injured and abandonment of the project. Subsequent investigations revealed that the proposed route of the tunnel passed through a natural gas basin and that Turkish Petroleum Corporation (TPAO) had carried out natural gas exploration in the area. Here we provide details on the geological background and the flare incident itself and come to the conclusion that the pre-construction ground investigations for this project were grossly inadequate. We also suggest that in order to facilitate economical and safe tunnel construction, consideration should always be given to the possible presence of methane and other gases at the ground investigation stages of tunneling projects and that all previous geological and technical studies related to the study area should be taken into consideration during the pre-construction stage.

Keywords TBM tunneling · Gassy ground · Methane flare · Methane explosion · Geotechnical investigations

Introduction

While methane (CH_4) gas is usually associated with coal-bearing strata, it can also occur in organic-rich rocks, such as mudstone and shale, and in certain metal mines. Natural gases in these locations usually contain 70–90% methane together with ethane, butanes and hexanes. Methane can also be formed due to the decomposition of organic materials both in naturally accumulating organic-rich sediments or in waste dumps containing organic materials (Kissel 2006).

Kissel (2006) tells us that methane is explosive when it is present at between 4.5 and 14.5% in the air, with the easiest explosion occurring in the range of 7–8%, while the most severe explosion occurs at 9.5%. The presence of hydrogen, ethane and propane gases in natural gases reduces the lower explosion limit of the mixture, while the explosion interval increases in an high oxygen atmosphere.

Since methane gas is rarely encountered in tunneling works, planning is usually made without considering its presence. However many methane explosions have occurred in

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✉ Mustafa Ayhan
mayhan@dicle.edu.tr

[1] Department of Mining Engineering, Dicle University, Diyarbakır, Turkey

[2] Yertaş Construction, Ankara, Turkey

areas where either the presence of the gas was not expected or it was expected to be insignificant (Kissel 2006). It is thus necessary to carry out thorough studies aimed at determining whether the gas is likely to be present at the feasibility, route-planning and design stages of a tunnel project. There are many published cases of methane having been found to occur in tunnel excavations, including the following:

- Los Angeles, California, USA, 1971. An 8.85-km-long, 6.8-m-diameter water tunnel was being excavated using a hard rock tunnel boring machine (TBM). An explosion caused 17 fatalities. It was known that the tunnel passed through an oil field. Several months before the explosion a drill core was extracted from the tunnel face that smelled of hydrocarbons. One day before the fatal accident, a minor gas explosion occurred that resulted in four miners being injured (Proctor 2002).
- Akita Oil Field, Japan, 1978. An explosion in a tunnel being excavated using a hard rock TBM in mudstone caused the deaths of nine workers and injuries to an additional two workers. Methane had accumulated in an anticlinal fracture zone. A methane detector sounded the alarm, but the automatic power cut-off did not work (Çopur et al. 2012; Kitajima 2017a).
- Carsington, UK, 1982–1985. A number of methane incidents occurred during the construction of an 8.5 km long, 2.4 m diameter aqueduct tunnel through a sequence of Upper Carboniferous age sandstones and marine shales. All equipment and plant structures used in the tunnel were flameproof due to expectation that methane might be encountered during tunneling and no fatal accidents were recorded (Pearson et al. 1989).
- Abbeystead, UK, 1984. Methane gas dissolved in underground water that accumulated in voids at the end of a completed water transfer tunnel. The concentration of methane gas led to an explosion that caused 16 deaths and injuries to a further 28 people (Lockyer and Howcroft 1997).
- Rochester, New York, USA. Detailed test borings for a 34-km-long tunnel for the Jay–Arnett combined sewer overflow abatement project revealed the presence of methane in nearly all holes. Natural gas deposits were known in the sequence of Paleozoic sedimentary rock formations, including dolomite, limestone, sandstone and shale, and test borings were drilled at an average spacing of 225 m. A hard rock TBM was used for excavation. Explosion-proof electrical equipment was successful at preventing fatal accidents (Peters et al. 1985; Çopur et al. 2012).
- Tokyo, Japan, 1993. During the pre-construction geological explorations for a tunnel excavated by earth pressure balanced (EPB)-TBM, methane was not expected, but gas monitoring equipment was in place. Despite this precaution, an explosion occurred after which it was realized that a warning was not given because the methane sensor was placed 90 cm below the crown of the tunnel. After the explosion, the ventilation system was revised, flameproof electrical equipment was used and an automatic alarm system was installed (Çopur et al. 2012; Kitajima 2017b).
- Abdalajis, Spain, 2002–2007. A 10-m-diameter high-speed train tunnel was excavated by a double-shield TBM. In the first 2.5 km of the tunnel a very unstable argillite formation was encountered in which there was rapid convergence of the tunnel walls and frequent face collapses. Large gas inflows with pressures up to 1100 kPa were measured in this section (Grandori 2006).
- Mill Creek Tunnel, Cleveland, Ohio, USA, 2007. A 4.65-km-long was being excavated through the Devonian Chagrin Shale formation using a 7.8-m-diameter shielded TBM. Natural gas was being extracted by shallow gas wells for domestic consumption along the tunnel line. During excavation several unusually large plumes of methane gas were detected entering the tunnel, resulting in tunneling operations being suspended for 8 months until various precautions were in place. These included increased ventilation capacity, drilling of degassing wells and upgrading of the gas monitoring system (Schafer et al. 2007).
- Zagros, Iran, 2007. A 26-km-long, 6.73-m-diameter tunnel was excavated by a double shield TBM through the Pabdeh and Gurpi formations, characterized by sulfide mineralization, where major oil and gas bearing basins were present. High levels of hydrogen sulfide (H_2S) and methane gas discharges were experienced, leading to the cessation of excavation work for 4 months (Shahriar et al. 2009).
- Hong Kong, China, 2004. A 4.5-m-diameter TBM was being used to excavate tunnels through reclaimed fill and pre-Quaternary marine deposits and alluvium in order to install electricity cables. The concentrations of methane, carbon dioxide (CO_2), hydrogen sulfide, oxygen and carbon monoxide (CO) were measured in pre-construction in situ tests that included gas monitoring by lowering a monitoring tube down to the water surface in each borehole. As a result, necessary precautions were taken, and no fatal accidents were reported for this tunnel (Wightman and Mackay 2008; Çopur et al. 2012).
- Variante de Pajares, Spain, 2005. Methane was detected during the excavation of different segments of these tunnels by means of single shield TBM. Further study linked the presence of methane to a coal mine in the Carboniferous San Emiliano formation. The methane emission rate and average methane flow rate were computed from measurements of TBM advance rate, air flow quantity and methane concentration during tunnel excavation. The results were very similar to those observed in coal mines and,

consequently, mining experience could be used to predict the methane inflow into a tunnel excavation. This information was used to design the ventilation system (Rodriguez and Lombardia 2010).

- Istanbul-Selimpaşa, Turkey, 2010. A methane gas explosion occurred in a waste-water tunnel which was excavated by EPB-TBM through the Oligocene deltaic Gurpinar Formation of mostly sandstone and shale deposits. Methane from a fault zone accumulated in the excavation chamber, resulting in an explosion. The EPB excavation chamber would usually be full of spoil and foam, and it was considered likely that the amount of air necessary for methane explosion came from the foam (Çopur et al. 2012).
- Queensland, Australia, 2014. An EPB-TBM was used in the development of an 813-m-long conveyor drift in a coal mine. This was safely completed by the injection of nitrogen which also assisted with spoil management and temperature control. Continuous monitoring and maintenance was carried out for gas regime and ventilation control (Belle and Foulstone 2015).
- Sparvo, Italy, 2014. An EPB-TBM that was specifically designed to prevent the risk of explosive gas–air mixtures and ignition sources was used in the construction of twin tunnels between Bologna and Florence. The methane gas concentration was maintained below the lower explosive limit, and an integrated and structured system of safety precautions was adopted, including an gas monitoring and alarm system coupled with forced ventilation and the use of explosion-proof plants and equipment. In addition TBM compartmentalization was used to ensure safe excavation in the gas-bearing rock (Bandini et al. 2017).

These cases emphasize that many different factors can cause gas-related events that occur during the construction of tunnels and demonstrate the importance of taking the possibility of gas being present into consideration in all tunnel projects.

Here we provide details on geological studies carried out during the pre-construction stage of the Silvan irrigation tunnel, the occurrence and consequences of a significant methane gas flare due to the presence of gas and subsequent geological findings for the Silvan irrigation project in Turkey.

Tunnel geology and geological studies carried out at the pre-construction stage

The Silvan tunnel, which is the second part of the Silvan irrigation scheme delivery canal for the Silvan Dam, part of a project to construct tunnels and channels between the Silvan Dam and agricultural lands in Diyarbakir province, Turkey, is located in Silvan county, Diyarbakır province (Fig. 1). As shown in Fig. 2, it is located in the Hazro Anticline, the folded belt of the Southeastern Anatolia thrust belt. In this region, there are asymmetrical folds with reverse faults and later strike-slip faults. During planning stage 5 of the project, five ground investigation boreholes were drilled on the tunnel route (BAR-SU Engineering & Consultancy Inc. 2011), of which four were located on the axis of the tunnel and the fifth

Fig. 1 Site location map of the project

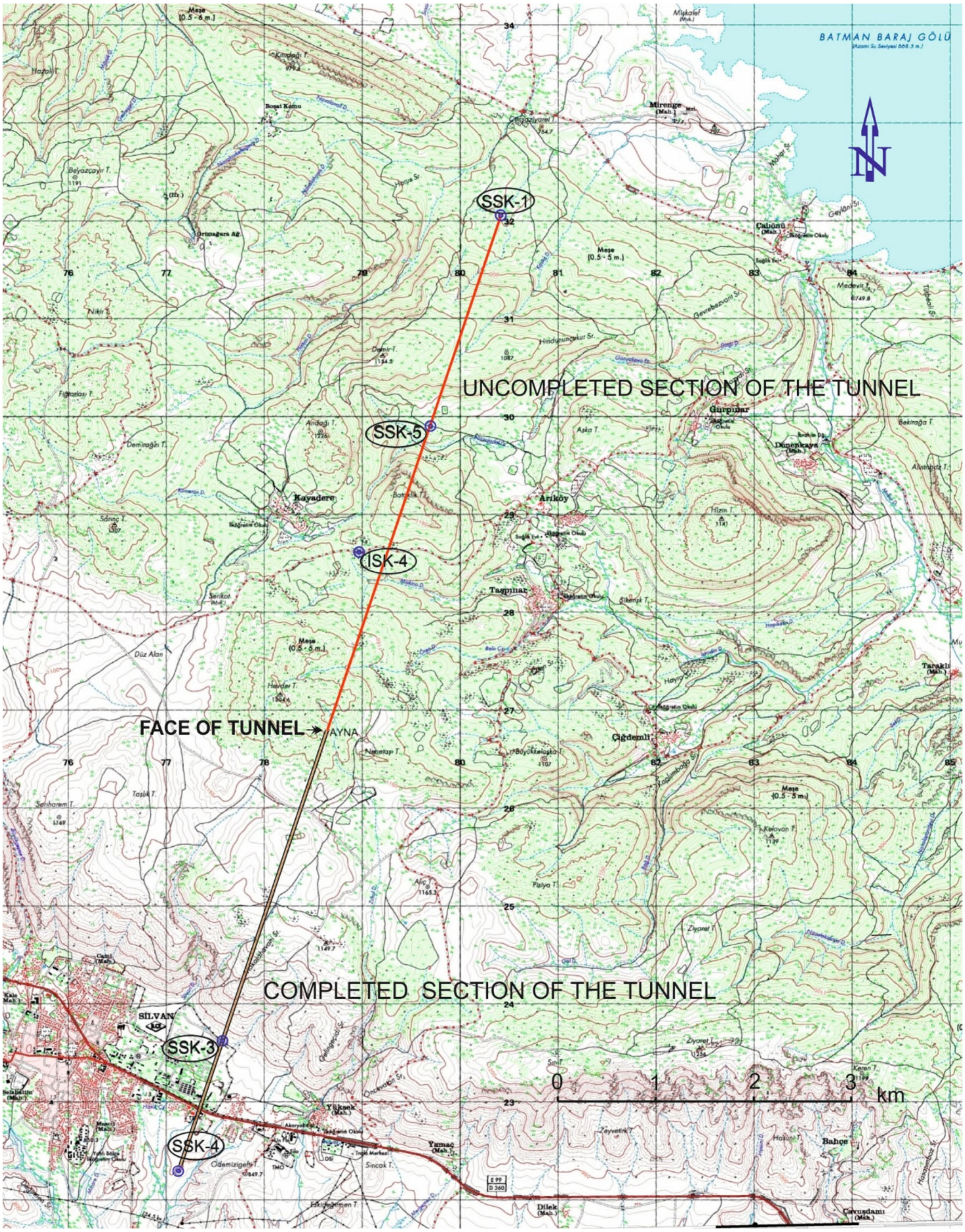

Fig. 2 Location of ground investigation boreholes drilled along tunnel route

was located 240 m to west of this line (Table 1). The formations to be passed through and their characteristics are summarized in Table 2.

The geological conditions anticipated along the tunnel route before construction began are shown in Fig. 3 (BARSU Engineering & Consultancy Inc. 2011). However, during construction problems with higher than expected water ingress occurred together with unpredicted flammable/explosive gas inflow. An ignited gas flare occurred at chainage of 4668.70 m at which point approximately 45% of the tunnel construction had been completed. During the construction the ground conditions were found to be different from those anticipated from the pre-construction investigations (Table 3).

Table 1 Locations and depths of ground investigation boreholes along the tunnel route drilled before the flare incident

Boreholes	Year	Project kilometer	Distance to start of excavation (m)	Altitude (m)	Depth (m)	Formations
		23+115	0			
SSK-4	2010	22+720	395	798,50	39,50	0,00-39,50 m Şelmo Formation
SSK-3	2010	21+720	1395	888,00	123,00	0,00-107,50 m Silvan Formation
		18+447	4668 (Methane flare point)			
İSK-4	2000	16+342	6773	1084,20	315,00	0,00-70,00 m Midyat Formation 70,00-315 m Gercüş Formation
SSK-5	2010	15+185	7930	975,00	213,00	0,00-150,70 m Midyat Formation 150,70-213,00 m Gercüş Formation
SSK-1	2010	13+355	9760	873,50	107,50	0,00-107,50 m Silvan Formation

Excavation method

Many tunnels are excavated by machine, and fast and safe excavation can be performed using full face TBMs that excavate the whole excavation face at once. However excavation with a TBM, which requires a very high initial investment cost, is only viable if the formation properties are well-defined (Ateş et al. 2014; Paltrinieri et al. 2016). In more risky environments where there are water inflows and poor or faulted ground or where gas inflows are likely, TBMs can perform poorly. In some cases, it has been necessary to halt the excavation or leave the machine in the ground (Price 2009; İlci et al. 2014). Therefore, the advantages and disadvantages of different tunneling excavation methods, including with the New Australian Tunneling Method (NATM), drill and blast, hand excavation and TBM should be carefully analyzed for each section of the proposed tunnel.

The double shield machine shown in Fig. 4 was used in the Silvan irrigation tunnel. Using gripper and shielding techniques, it can be applied in a wide range of geological conditions. The double shield TBM consists of a front shield with cutterhead, main bearing and drive as well as a gripper shield with gripper shoes, tail shield and auxiliary thrust cylinders. Both shield parts are connected by a section called the telescopic shield where the telescopic thrust cylinders operate as the main thrust cylinders (Herrenknecht 2018). The principle is based on the machine being anchored to the tunnel wall during excavation activities and installation of the segments. Once the ground is supported, the cutterhead and front shield are pushed forward by the telescopic cylinders. The auxiliary thrust cylinders in the tail shield serve only as support for the segments. When the telescopic cylinders reach full stroke, the tension of the gripper shoes is released and the gripper shield is pulled forward towards the front shield. The auxiliary thrust cylinders are extended accordingly in order to maintain the positioning of the last set segment ring. The support during the re-gripping procedure of the gripper shield is provided by the vertical support shoes, the shield of the front shield and the auxiliary thrust cylinders (Herrenknecht 2018).

As Fig. 5 shows, the Herrenknecht S-794 machine used in the Silvan irrigation tunnel was equipped with six gas sensors, of which three were methane detectors and positioned at 4, 19 and 66 m from the cutterhead, respectively. The purpose of the other three sensors was to detect hydrocarbon compounds ©$_n$H$_m$), located 20 m from cutterhead, and carbon monoxide and carbon dioxide, located at 66 m from cutterhead, respectively.

Methane flare occurrence

The generally adverse geology, including karstic features and high water ingress, resulted in difficult tunneling conditions. In addition, a gas incident occurred on 21 April 2015 at distance of 4668.70 m from the right (west) portal. Fortunately, there were no fatalities but 13 workers suffered injuries of varying degrees and the tunneling activity was stopped due to concerns that gas emission would become even more intense and there would be a loss of life and property if the tunnel progressed on the planned alignment. The TBM, with the exception of the cutterhead, was dismantled, and geotechnical investigations into alternative ways of completing the tunnel were carried out.

The most important feature that distinguishes a methane explosion incident from a methane flare (rapid combustion) incident is the formation of a large pressure and vacuum wave in an explosion incident. The shock effect caused by a sudden change in pressure can result in damage to the machine, scattering of the excavated materials and injury to and/or death of personnel. These pressure and shock effects are much lower in a flare incident. Investigators concluded that this was a flare incident, rather than an explosion, as there was no shock-related damage to the cutterhead or to the machine tail, and even the lightest materials in the tunnel, such as plastic bottles, carton cups, gloves and helmets, were not displaced. Furthermore, the workers did not suffer injuries attributable to a shock effect.

Prior to the methane flare incident it had been noted that the TBM had entered a weak zone and its driving forces had been

Table 2 Formations through which the tunnel passes and their characteristics

Characteristics	Formation						
	Silvan	Germik	Midyat	Gercüş	Midyat	Silvan	Şelmo
Identity	Limestone marn	Claystone, marn, argillageous limestone	Limestone, chalky and argillageous limestone	Claystone, mudstone, conglomerate sandstone	Limestone, chalky and argillageous limestone	Limestone marn	Claystone, sandstone, siltstone, peplestone
Characteristic	Pretty hard, fragmented in places, fractured and karstic permeable–very permeable good strength	Medium hard, partially fractured, jointed, Less permeable-permeable	Jointed, fractured dissolution voids, Less permeable–permeable Middle-durable	Medium hard and soft in places	Jointed, fractured dissolution voids Less permeable–permeable Middle-durable	Pretty hard, fragmented in places, fractured and karstic permeable–very permeable	Soft to medium–hard, low-strength, poorly cemented
Dip	North–northeast	North–northeast	North–northeast	North–northeast South–southwest	South–southwest	South–southwest	South–southwest
Number of fractures (fracture/m)	> 50	1–3	3–10	3–10		Massive-Fragmented	Silvan fault
Rock Mass Rating (RMR)	37–24	46–37	54–49	61–56	62–57	57–40	37–22
Rock quality designation (RQD) (%)	0–25	50–75 75–90	90–100	25–50 50–75 90–100		0–25	0–25
Expected Problem	Water inflow	Water inflow	Water inflow	Water inflow	Breakage at week zone, Karstic	Water inflow	Mucking

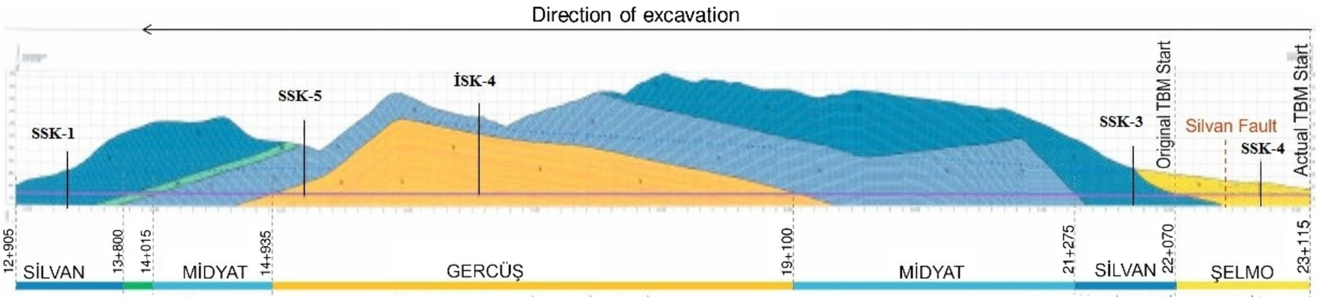

Fig. 3 Predicted positions of formations along the tunnel route. *TBM* Tunnel boring machine

reduced. One possibility is that this zone was unforeseen faulted ground in which high-pressure methane gas had accumulated. The gas probably entered the space between the bunker span and the telescopic shield and was ignited. Due to damage caused by the flare it was not possible to determine whether the gas detection devices, which would have cut off the electricity supply to the machine, sensed the gas before this event. It was concluded that the gas entered the tunnel suddenly under high pressure where it rapidly exceeded the methane explosion limits before being ignited and then it moved into the ventilation system outlet which was supplying clean air into the excavations (Fig. 5).

The fact that the upper part of the machine was burned but the lower parts were not suggests that the flare originated in the middle of the tunnel and continued upwards. There were signs that successive flares occurred at different points until the oxygen was consumed, with the effects of high temperature and open flames causing damage during the first flare incident. The position of the thrust pistons (open) and the telescopic shield (closed) at the time of the flare and the presence of only a small amount of material on the conveyor leads to the conclusion that the machine had just begun excavating.

About 1 week after the methane flare incident, observations and gas measurements were performed in the tunnel by the rescue team from Zonguldak Turkish Hard Coal Institution. This team identified high-pressure degassing from fractures in the rock face based on the sounds and creation of bubbles (Fig. 6). Measurements indicated that this ingress to the excavation face contained an high ratio of methane (28.6%) and that the ratio of oxygen in the air was also high (17.30%), indicating that conditions for the occurrence of a new flare/explosion incident were ongoing.

Table 3 Expected and actual lengths of geological formations in the completed section of tunnel

Formation	Expected distance (m)	Actual distance (m)
Şelmo	1050	1293
Silvan	805	447
Midyat	2175	661
Gercüş	4200	2187
Upper Sinan	–	80

Damage in the tunnel caused by methane flare

The main units of the TBM, such as telescopic shield pistons, hydraulic connections, cutterhead engines, the sensor camera close to the cutterhead and electrical wiring, were all badly damaged by the methane flare. The cutterhead unit was unusable and could not be repaired without the risk of igniting gas that continued to enter the excavations (Fig. 7). This unit was therefore left underground.

Superficial damage caused by the high temperature resulted in spalling to parts of the concrete segments as far as 48.50 m from the excavation face, revealing the reinforcement (Fig. 8). At this time the methane concentration was well above the acceptable limits and, therefore, a number of occupational health and safety measures were taken. These included uninterrupted 24-h air flow provided by three blower fans (90 kW, 20 m^3/s) located at the tunnel entrance. A generator system that would provide automatic back-up power in the case of a power cut was installed to ensure the uninterrupted operation of the fans. Due to the leakage and resistance, only

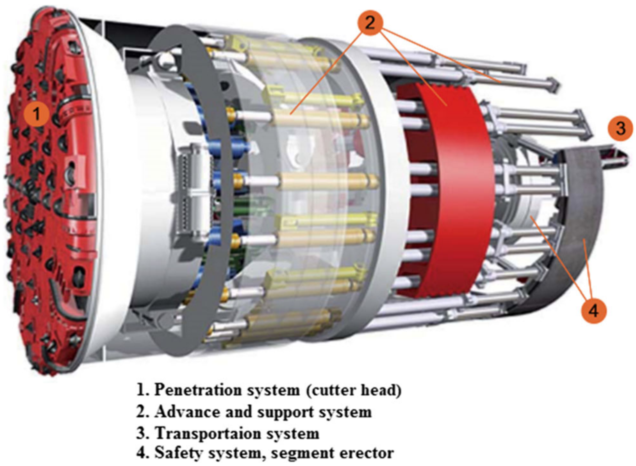

Fig. 4 Basic components of the double shield TBM

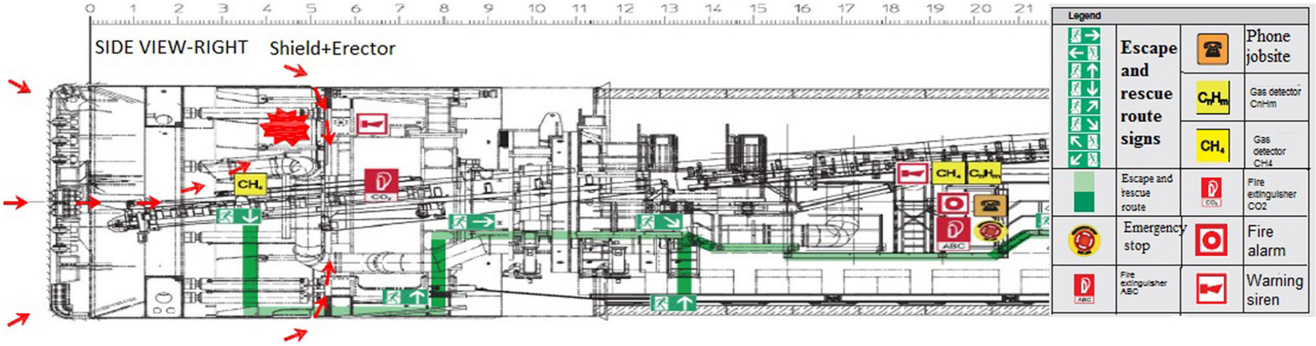

Fig. 5 Entry of methane into the tunnel and the possible first flare point. C_{Hnm} Hydrocarbon compounds, CH_4 methane, CO_2 carbon dioxide

approximately 50% of the air pumped from the fan tubes reached the excavation face. The air duct established in the tunnel reached 4500 m with the addition of 2-m diameter fan-tubes on flexible pipes. After the incident, this air duct was extended to the front of the cutterhead by use of two 800-mm-diameter branch fan-tubes.

Methane measurements were taken regularly for 2.5 years, during which time there was no significant change in values and the methane flow was 1.5 m^3/min.

Geological studies carried out after the gas problem

As indicated in Table 1, the combined length of the five ground investigation boreholes was 798 m; therefore, in terms of the length of tunnel being investigated the boring density was 0.039 m/m. This is a quite low value. The U.S. National Committee on Tunneling Technology (USNCTT) (1984) recommend that boring density values should generally range from 0.2 to 1.5 depending on the general properties of a project and the risk situation. Furthermore, this value should be at least about 1 in large projects. The USNCTT also stated that the ratio of the cost of geotechnical investigations to project budget should be around 1.6% on average and that increasing this to 3% provides better results. In fact, 15 units of gain can be achieved in project cost in return for a unit geotechnical research investment.

These values demonstrate the inadequacy of the pre-construction investigations carried out for the Silvan irrigation tunnel . In particular, there were no borehole data for the

Fig. 6 Gas ingress into the tunnel observed as continuous flow of bubbles

Fig. 7 The state of the cutterhead motor after the methane flare

5378 m section (52.7%) of the tunnel length, the section where the gas incident occurred.

Following the gas flare incident, the authors carried out a comprehensive geological study around the tunnel route to investigate the causes of the problem. This included investigation and examination of studies previously carried out in the region by different institutions and organizations. These investigations revealed the presence of a previously identified oil and natural gas basin and that the Turkish Petroleum Corporation (TPAO) had previously

Fig. 8 Spalling of concrete and exposed reinforcement due to heat damage in the roof of the tunnel

drilled a large number of boreholes to investigate this basin (Fig. 9). Four of these boreholes were 300–400 m distant from the tunnel alignment (Turkish Petroleum Organization 2015) and contained oil and natural gas. The Taşpınar no. 1 well, which is the closest to the tunnel alignment (approx. 300 m) had a natural gas production capacity of 24,000 m$^{3/}$/day at 4523 kPa pressure.

Data obtained during tunneling, new boreholes and the TPAO oil and natural gas boreholes are presented in Fig. 10. The main difference between this and the pre-construction predictions are that after the Gercüş Formation, the Upper Sinan Formation was present. The methane flare incident occurred after progressing some 80 m through this formation. The Lower Sinan Formation, which is the natural gas reservoir

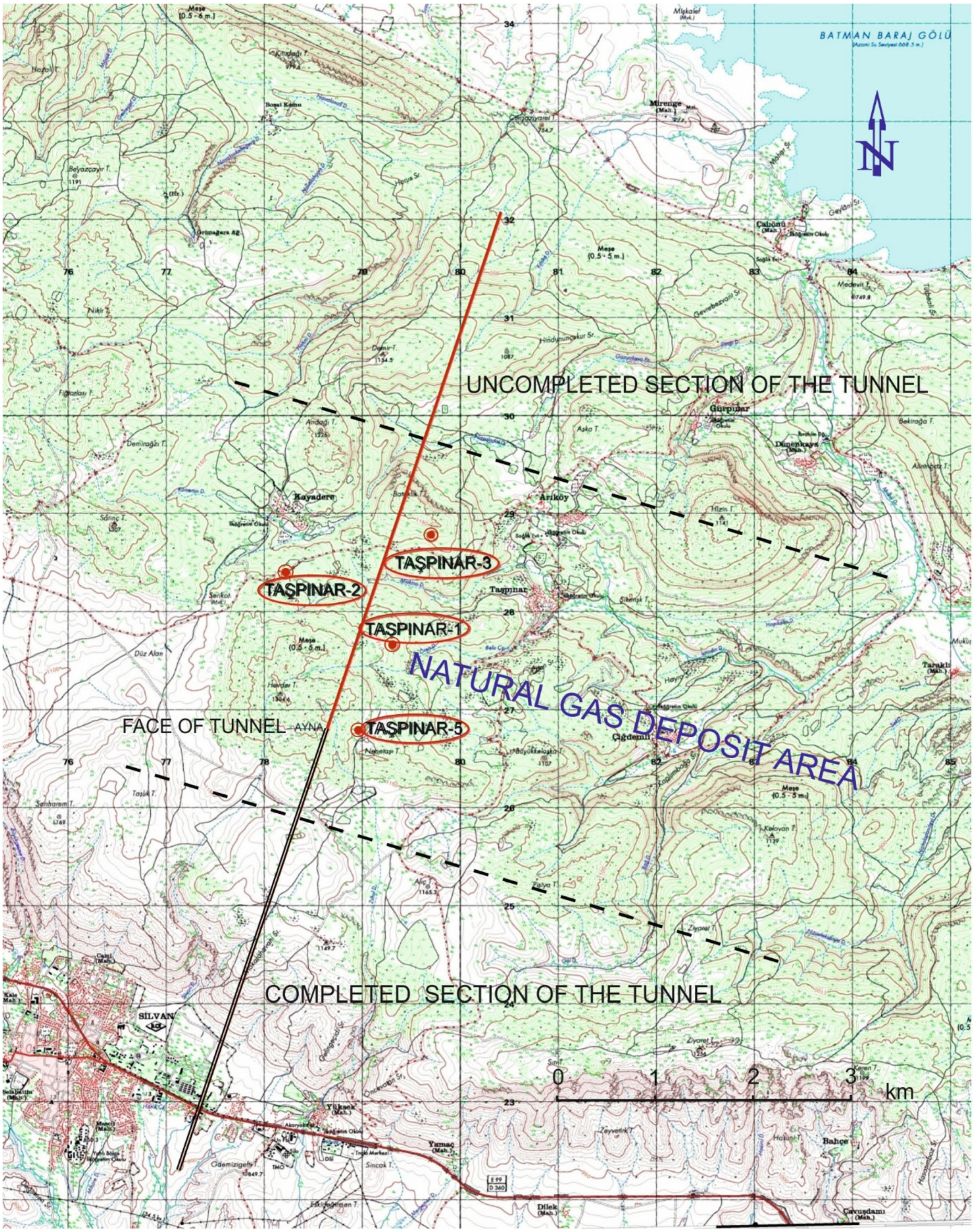

Fig. 9 Natural gas wells drilled near to the tunnel route

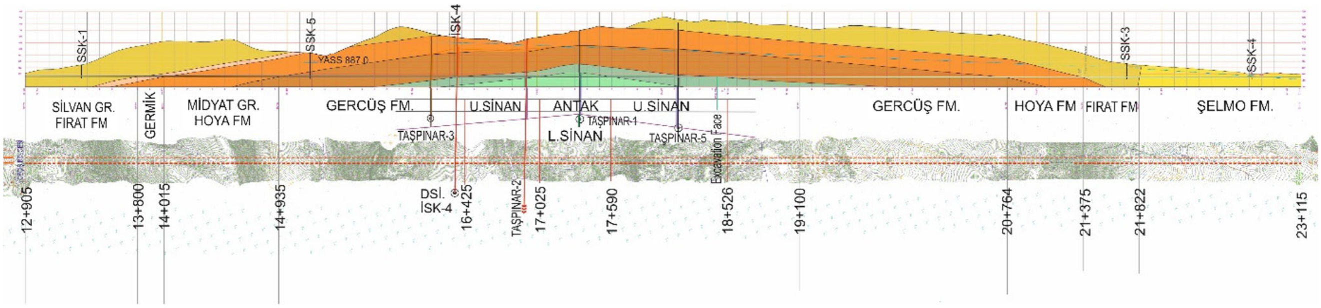

Fig. 10 Geological section for tunnel drawn with the data obtained from tunneling and new boreholes

rock, is located approximately 400 m below the point where the flare occurred. The impermeable—but likely to be fractured—Antak Formation lies between the Upper Sinan formation and the Lower Sinan formation. It is envisaged that the gas from the Lower Sinan formation seeped into the anticline traps via stress cracks in the otherwise impermeable and hard rock Antak Formation.

Conclusions

Although TBMs have been much more intensively preferred in terms of quick and safe excavation in recent years, serious problems have been experienced in those tunnels where geotechnical studies were insufficient and the geological structure not well-defined. The high initial investment costs of these machines and the fact that the excavation and final support are carried out together reduce the number of options for coping with poor ground conditions. The examples cited in the Introduction are those projects that have been abandoned or machines have been left underground with tunnels being completed using other methods.

The Silvan tunnel route passed through the natural gas–oil basin in the Lower Sinan Formation but this was not recognized during the project design stage. In this study, we investigated and analyzed the geological reasons underlying the methane flare incident experienced in the Silva Scheme tunnel in an oil–natural gas basin and how the incident occurred. The methane flare incident resulted in the abandonment of the tunnel, with the TBM cutterhead being left in the tunnel. Our study once again reveals the importance of geological surveys in the selection of tunneling method and equipment. Moreover, the gas risk should be taken into account not just in tunnels constructed in coal-bearing deposits but in all tunneling activities. All potential sources of ground gases must be taken into account, especially in faulted ground. The cost of a good-quality geotechnical investigation is small compared with the total cost of tunneling, and of whole projects, but tunneling in poorly characterized ground is liable to result in unacceptable risks to life and to the financial success of enterprises.

In addition to sufficient geological information being available, it is also important to equip the TBM with gas sensors to prevent such accidents and to have adequate ventilation that is sufficient to cope with likely gas ingress.

The methane flare experience described here clearly shows that the Silvan Tunnel was not properly planned. The budget for ground investigations was utterly inadequate, resulting in insufficient geotechnical investigation. Previous studies in the region had not been taken into account, and until the methane incident occurred they were not used in any analyses. The Silvan Tunnel Project was a large and high-cost project, and the problems with construction have resulted in a huge economic loss. This case history demonstrates the vital importance of carrying out adequate ground investigations so that a well-informed decision concerning the selection of the excavation and support methodology can be made. To ensure the safety of workers and the delivery of a successful project thorough and detailed monitoring of the as-found ground conditions should also be carried out together with an analysis of the implications of deviations from the anticipated conditions during construction.

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