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PROBLEMS OF MECHANIZED TUNNELING IN GASSY GROUND CONDITIONS A CASE STUDY: NOUSOUD WATER TRANSMISSION TUNNEL

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ABSTRACT

Current advances in science, followed by development of excavation equipments technology resulted in growth of tunnelling projects for different purposes. In spite of conducting exploratory studies prior to these projects, in some cases due to of impassable paths, the studies are limited to certain areas. Hence, during geotechnical studies, it is possible that all problems facing tunnelling not be detected. Therefore, lack of awareness of these conditions can result in a lack of proper planning and consequently lead to problems during the projects. Due to the lack of knowledge and consequently not predicting and planning the projects, drilling of the second sector of Nousoud water transmission tunnel, -26 km long- has been faced with many problems including emission of hydrogen sulfide and methane gas and drainage of high volumes of water containing dissolved gas into the tunnel, which has led to the loss of life, loss of working efficiency, as well as increased project costs. In this study, problems occurred in this project, reasons behind them will be addressed; and the solutions to these problems will be mentioned. The results of the study have shown that oil-bearing formations of the region and the immigration of gases coming from these formations have let the gas entered into the tunnel. In addition, due to the high solubility of hydrogen sulfide and methane gas in water on one hand, and hydrated formations with high permeability on the other hand, caused the influx of large quantities of water and therefore the concentration of these gases in the tunnel.

Keywords: Nousoud tunnel, Methane gas, Hydrogen sulfide, Mechanized tunnelling, Gassy ground.

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Contribution/ Originality

This study focuses on tunnelling in difficult conditions. The study documents the case histories all over the world, and then discusses the different measures in order to over comes the difficult ground conditions. The paper's primary contribution is finding that the baseline reports have a vital importance before tunnelling in vicinity of oil fields and according to these studies – probability of gases emissions- the tunnelling excavation must be designed and accurate measures should be considered.

1. INTRODUCTION

Exploratory studies conducted on long tunnels are of significant importance in engineering projects. In case of pointed projects, due to an appropriate distribution of identification locations, there is usually no significant difference between identified and real characteristics. Yet, as for linear projects such as long tunnels, due to their long length, tough topography and difficulties in accessing the locations, the studied points are limited to some certain areas; therefore, during the operation more unpredicted situations might be arisen which might result in irreparable injuries and great economic losses in the projects.

Some geological formations contain various gases such as methane, hydrogen sulfide, sulfur dioxide, and so on. In this case, the tunnelling operation is considered as difficult ground conditions and special precautionary measures should be taken according to local regulations. Thus the geotechnical baseline reports should contain information about possibility of gas emission along tunnel routes, and adequate surface boring should be carried out to identify and quantify hydrocarbons (Hanifi *et al.*, 2012).

Gas emissions during tunnelling are a phenomenon that happens occasionally but it is not as frequent as the water inflow or the face collapse. Among gases, the methane is more general, and there are few reports on emission of other gases. There are two problems related to presence of methane: first, methane is an inflammable gas which increases the fire risk; second, when this gas is mixed with air in a proportion of approximately 5–15% in volume, it is explosive (Rodriguez and Lombardia, 2010). Mine Safety and Health Administration (MSHA) of USA specifies that concentration of methane at working faces of coal mines should be kept below 1%, which is only one fifth of Lower Explosive Limit (Hanifi *et al.*, 2012). The presence of methane and the occurrence of accidents in coal mines and/or along with Carboniferous layers have been pointed out by some researchers. An example of such incidents is an explosion inside a tunnelling machine chamber of EPB-TBM type during the excavation of Siliveri - Guzelce swage tunnel in Istanbul. Subsequently, Bentonite injection for filling void spaces, installation of methane gas monitoring systems, and reduced drilling rates have been used in order to decrease the methane emission (Hanifi *et al.*, 2012).

Among other cases we can point to methane gas explosion (in spite of safety measures) during drilling of limestone rocks by drilling and blasting of Lotschberg pilot tunnel. Consequently, a methane warning system had been installed on all of the drill rigs. One rig was equipped with a 'Rod Adding System' to simplify the drilling of up to 40 m-long probe-holes for gas detection (Vogel and Rast, 2000).

Another case that shows high concentration and dangerous consequences of gas appearance in a tunnel is the incident of Los Angeles water tunnel. A fatal gas explosion occurred in the tunnel on June 24th in 1971. Seventeen workers were died. Several factors and events came together before the accident and provided suitable environment for a gas explosion. For example, there were oilfields in the region under production. Also, several months before the explosion a drill core with "kerosene or diesel smell" was extracted from the excavation front. One day before the fatal accident, a minor gas explosion occurred and four miners were injured. Gas detector was malfunctioning. Spark preventive safeguards were lacking on TBM. After this explosion, higher safety standards were prepared by the State Division of Industrial Safety (SDIS) and OSHA to prevent similar disasters (Noack, 1998; Proctor, 2002).

Among other gases rarely be encountered during tunnelling is hydrogen sulfide gas which is less common than methane. Hydrogen sulfide is a colorless gas with rotten egg odor, is highly water - soluble and often flows into the underground spaces along with water. Prolonged exposure to the gas makes the scent to the nose to be lost within 2–15 minutes and causes its dangerous concentrations not to be detected. Hydrogen sulfide gas is considered explosive between the concentrations of 4.3% (LEL) and 45% (UEL) by volume (Naeemi *et al.*, 2000). Hydrogen sulfide in high concentrations (up to 200 mg/l) has been encountered in the groundwater of Kuwait City and its suburbs at relatively shallow depths (Mukhopadhyay *et al.*, 2007). Various tunnelling projects in the United States have had to address issues related to encountering hydrogen sulfide gas during construction and/or operation (Naeemi *et al.*, 2000). This gas with concentrations of more than 100 ppm, released from water and dry rock, has been encountered in Alborz Service Tunnel, the longest tunnel (6.4 km) along Tehran - Shomal Freeway (Wenner and Wannenmacher, 2009). Among other hazards that frequently occur during tunnelling and reduce the rate of tunnel excavation is the groundwater inflow through discontinuities and faulted zones (Li *et al.*, 2009; Moon and Jeong, 2011). The risk of this phenomenon can be increased if the groundwater inflow carries some soluble gases. The dissolved gas is released due to lack of pressure. Consequently, fast and effective drainage is of significant importance in these cases (Mirmehrabi *et al.*, 2012).

2. MATERIALS AND METHODS

2.1. Project Specification

The project under study is the second part of Nousoud water transmission tunnel. This tunnel is part of a plan to transmit water to the western tropical areas of the country. The whole tunnel is more than 48 km long (Figure 1)(Iran Water and Power Resources Development Co, 2004).

The project is divided into first and second parts so that the first part ranges from Hirvi to Lile River and the second part from Lile to Azglah. The second part is about 26 km long and its construction is being done by a mechanized tunneling method using double shield (D.S.) TBM. The tunnel excavation diameter is 6.73 m and finished diameter will be 6 m following segment installation. Immediately after each drilling cycle, precast concrete lining of tunnel is embedded (Ghiasvand, 2008).

2.2. Geology

According to structural-sedimentary classification of Iran, the second part of Nousoud water transmission tunnel is extended in the zone of folded and high Zagros that is quite different in terms of morphological features. In the beginning of this part (from Azglah to vicinity of Negarah village) there are medium altitudes consisting of low resistance stratigraphic units (shale, limy shale and shaly lime) and has U-shaped valleys. Among the most important of these valleys, Kordi Qaseman Valley can be mentioned. However, after Negarah village through the end of the second part, rough topography, deep valleys, deep cliffs and recumbent tight folds can be seen that consist of limestone and dolomite formations. The most important valleys in this part are those where Zimakan River flows (Iran Water and Power Resources Development Co, 2004).

2.2.1. Geological Profile of the Tunnel Route

The study area is located in the North West part of Lorestan, including the folded-trusted Zagros zone. In this zone, the general process of structures is from northwest to southeast. In order to evaluate the environmental and geological potential hazards, it is necessary to have an accurate understanding of the lithology of geological units. The oldest rock units in the study area are Jurassic units of shale, limestone and gypsum (J formation). Above the Jurassic rock units, there are mainly cretaceous limestone units. These rock units are called K_l and K_i formations. Gurpi (K_{Gu}) formation located on the Ilam Formation consists of limestone and shale strata. Pabdeh (PE_{pd}) formation is composed of alternating purple to dark shale and thin limes of post - Paleocene to Eocene age that is located beneath the Quaternary deposits (Figure 2).

2.3. Problems Created During Excavation of Nousoud Tunnel

As it mentioned before, 48-km Nousoud water transmission tunnel is currently being drilled to transmit water to tropical western areas of Iran. Tunneling of the last second part consisting of 26 km is being done using Double Shield TBM. Since March 2006, the tunneling has started from outlet and there have always been problems of methane emission, hydrogen sulfide and inflow of underground water containing soluble gas into the tunnel. As a result, tunneling has faced with some problems such as personnel's endangered health and life, decreased efficiency, and/or halted and prolonged tunneling which result in huge financial losses. In the following sections we will explain these problems.

2.4. Methane Gas Emission

During excavation of underground spaces, methane is more common and causes more deaths and injuries than the other gases (Hanifi *et al.*, 2012). Despite of the technological developments in recent decades, methane hazards have not yet been fully eliminated (Diaz and Gonzalez, 2007). Today, in spite of using advanced drilling machines that are equipped with gas detectors, we witness incidents in tunneling due to detectors damage, the lack of proper ventilation systems in workplace and drilling machines that are not equipped with anti-fire systems (Hanifi *et al.*, 2012).

Two major risks of methane presence are that it is highly flammable and explosive. When methane concentration is within the ranges of 5 – 15% in the presence of ignition source such as flame or spark there will be an explosion. For this reason scientists have tried for years to diminish the hazards in underground spaces (Rodriguez *et al.*, 2012). Methane density proportion to air is at about 0.55 and it is characterized based on some physical properties such as having no smell and no taste. Its allowable concentration is 1% (10000 ppm). Methane is not toxic, but if its amount increases, it reduces the percentage of oxygen in air then it can be considered dangerous. The Russian standard for this gas is always less than 10000 ppm and it is 700 ppm for that of Switzerland. Methane is lighter than air and in the stagnant air it tends to accumulate in air traps in the workplace (Naeemi *et al.*, 2000). Therefore, tunnel air quality monitoring to determine the composition of the air in order to prevent the losses of life and property is very important. In Nousoud tunnel also there was a permanent presence of methane gas during tunneling, but the concentration of this gas was changing based on the type of rocks, their permeability coefficient and geological structures. Due to methane detectors on drilling machine and elevated concentrations of the gas, tunneling operations on Gurpi and Pabdeh formations automatically stopped at least at five steps.

Figure 3 shows longitudinal section of second part of the tunnel length along with methane concentrations. As it is clear from Figure 3, throughout most of tunnel route the concentration of methane has reached less than 5% of LEL and in some cases it reached less than 88% of LEL. In these cases, the machine is automatically switched off and the tunnel is evacuated. Methane emission has a good relationship with contact layers on geologic profile. That is, due to the different permeability of the various rocks in different formations or different units into a formation, methane migration takes place in permeable layers. Once encountering with impermeable layers, methane accommodates at that zone and it released in high volumes during tunneling. During tunneling if initially the cap rocks (impermeable unit) are tunneled and then we suddenly enter into reservoir rocks (units with high permeability), the amount of methane emitted will be high. But, in a case where tunneling starts from the reservoir rock, especially when drilling rate is slow, because of the gradual release of gas, by encountering of tunnel excavation with site of contact units with different permeability, the amount of gas released will be less than previous case. Hence it is recommended that in gassy grounds drilling is not allowed in a record-breaking rate. Or tunneling rate should be planned in such a way that the amount of gas released be in the allowed range.

2.5. Hydrogen Sulfide Gas Emission

Among other gases that are rarely encountered during the drilling of underground spaces is hydrogen sulfide gas. Hydrogen sulfide is also a product of organic decay that often can be seen with other natural gases and liquid hydrocarbons. It also exists in swamps, near sewers, landfills sites and refineries. So sometimes it is called sewer gas, swamp gas, and sour gas. Sometimes do to the reaction of acidic waters with Pyrite or Marcasite, hydrogen sulfide is produced and is generally accompanied with volcanic eruptions and geothermal waters (Ghiasvand, 2008). This gas is absorbed well by the human lungs and skin absorption is very rare. Continuous exposure to this gas might create some systemic side effects. Hydrogen sulfide is known as a multi-spectral poison gas because it has different effects on different body systems. However, it has more effect on the nervous system. Toxic effects of hydrogen sulfide can be compared with cyanide. Safety threshold for exposure to the gas is 8 hours for 10 ppm. More concentrations can stimulate smell sense and in more than 700 ppm survival would not be possible. Just like the methane, this gas is flammable and explosive in the concentration ranges of 4.3 - 45.5% of the air (Naeemi *et al.*, 2000). After the start of Nousoud tunnelling from the outlet, the working efficiency of TBM increased day to day. Furthermore working efficiency had reached to about 600 m long per month. During this period we encountered with small amounts of hydrogen sulfide gas. Up to 3+720 km of the tunnel composed of Gurpi and Pabdeh formations mainly containing low-permeability shaly rocks; small amounts of this gas (less than 10 ppm) was reported. But then everything has suddenly changed due to changing in geological formations and entering into Ilam formation containing limestone with high permeability. With increased discharge of water and then emitted soluble gas, concentrations of hydrogen sulfide gas went up increasingly. The gas concentration got to more than 50 ppm so that its physiological effects become visible on the tunnel workers and a number of them were sent to the hospital. Through new conditions of water and gas, tunneling rate diminished to high extend (Figure 4). As TBM entered into Ilam formation; the volume of water inflow into the tunnel increased. Then four people lost their lives as a result of high concentration of hydrogen sulfide gas.

This gas due to its acidic property caused gradual destruction of electronic boards of TBM. With increased concentration of this gas during Ilam formation tunneling, the TBM had to be stopped for about 6 months to be repaired. Hence we had to make accurate decisions and necessary preparations in order to continue tunneling (Figure 4).

This corrosive gas is a mixture of cation H^+ and HS^-anion. When H_2S is emitted as a gas in the air reacts with copper that can damage the electronic boards and reacts with steel alloys that can cause sulfating which results in higher destruction of rail system and create problems such as derailing of the wagons during locomotives traffic.

Figure 5 shows a direct relationship between the discharge of water off the tunnel and the rate of released hydrogen sulfide gas.

As noted before, H_2S gas is water-soluble and each liter of water at a temperature of 15°C and at atmospheric pressure is capable of dissolving 3.2 liters of H_2S gas. Therefore, Traffic in these waters should be done with caution because turbulence in water can release large volumes of H_2S gas that can cause injury or death. As a result of encounter with permeable formations (such as Ilam Formation) or with the fault zones where we encounter the high volumes of water, the risk of this gas concentration is increased. Based on studies conducted by Mirmehrabi *et al.* (2012), the H_2S concentration dissolved into the water has been determined 15 mg/l, 3.7 mg/l and 0.8 mg/l around cutter head (3+750 km), at 2 +000 km and at the tunnel outlet respectively. As a result, the water drainage systems are very important for continuing the activities.

Figure 6 shows hydrogen sulfide gas concentration at different time periods. Apparently, with the progress of tunneling throughout Pabdeh and Gurpi formations and entering into a high-permeable formation (Ilam), the concentration of the gas increases. Due to problems created by this gas the efficiency of tunneling decreases.

According to the Russian standard H_2S allowable limit during mining is 6.6 ppm, the USA standard is 20 ppm and the Swiss one is always less than 10 ppm and at most 40 minutes for 20 ppm (Mc Pherson, 1993). Based on safety regulations, this standard is less than 10 ppm, and at most 15 ppm for short term in Iran's mines (Madani, 2003).

2.6. Fall in Groundwater Level and Springs Drying Up Around the Tunnel

One of the consequences of tunneling is underground water drainage and thus by underground water drainage the subsurface water flow directions change. Consequently the springs and surface water resources fall or are dried up.

2.6.1. Region Springs and Their State of Water Discharge

The hydrological-geological state of the study area restricts underground water resources to some springs that are often discharged from Ilam formation, horizons of Gurpi formation, and Cretaceous limestone units or present –time alluvial deposits. Most springs have low discharge but relatively steady flows. The most important springs are drained out of Ilam Formation in Aspar anticline (Iran Water and Power Resources Development Co, 2007). Through field studies conducted around the second part of Nousoud tunnel and also via information provided by local people, all springs around the tunnel axis were identified and their general specifications were collected. The identified area around the tunnel axis was chosen based on geological -hydrological situation in the region so that it may affect on or be affected by the tunneling. Based on these studies, 53 springs were identified 60% of which holds a discharge range between 0.6-6.3 liters per second. A number of Identified springs are sulfuric and contain H_2S gas and the water is opalescent. These springs are usually discharged from between contacts of two formations -Ilam and Gurpi- with high and low permeability respectively. Hydrocarbon Traces are present in form of arc mode on the water in the margins of the hot springs. Consumptive water in the workshop has been provided by the springs of Aspar 1 and 2 (Iran Water and Power Resources Development Co, 2007). Despite of low discharge of these springs, but due to the supply of drinking and irrigation water to scattered villages in this area, they are of great importance.

Thus, changing in water discharge and drying of the springs can lead to social consequences. Therefore, during the tunnel excavation we also continued to monitor water discharge. Moreover in case of decreased springs discharge, rural water supply has been carried out through tankers or through water transmission from nearby springs.

3. DISCUSSION

3.1. The Source of Gases

Due to sulfurous springs in the area, smell of H_2S gas during the drilling of boreholes, pyrite mineralization in drill cores, and hydrocarbon traces on the water in the form of arc mode, the probability of encountering with H_2S during the tunneling has been reported (Iran Water and Power Resources Development Co, 2007). Based on previous studies, due to the location of the oil basin source rocks beneath Ilam Formation, hydrocarbon materials migrate upward through discontinuities and have entered into Ilam Formation. Then these materials in gaseous form or dissolved in water enter into the tunnel during tunneling (Mirmehrabi *et al.*, 2012).

3.2. Necessary Measures to Deal with Problems of Gas and Water

Different measures have been taken in order to overcome the problems of encountering with gas and water during tunneling. We will discuss these measures in the following paragraphs.

3.2.1. Reducing the Groundwater Volume Entering Into the Tunnel

As it is mentioned earlier, hydrogen sulfide gas is water -soluble and its concentration can be increased as drainage water grows in volume into the tunnel. Therefore, one of the most effective measures to reduce the H_2S concentration is to prevent water from entering into the tunnel. Among the measures taken we can mention: a) effective injection behind the segments b) careful sealing of segment joints c) chemical injection of high-drainage points (Tseng *et al.*, 2001; Wenner and Wannenmacher, 2009).

3.2.2. Proper Draining

During tunneling, due to encountering with groundwater aquifers, water flows into the tunnel. Each liter of water contains 15 mg of sulfur. Due to lack of pressure during water leakage into the tunnel, about 5 mg of dissolved sulfur is released. According to the previous studies only 0.8 mg of sulfur gas remains dissolved in the tunnel water outflow. Thus, approximately 95% of sulfur gas in water is released into the tunnel length, resulting in corrosion of TBM parts as well as labors' gassing inside the tunnel.

One of the options proposed to solve this problem is to eliminate the source of the gas. If we can prevent the entering of water in the tunnel, hence, gas is not released. In this method, drainage of gaseous water into the tunnel is unavoidable and it releases 5 mg of gas and this problem has been accepted. But the water flowing in the tunnel floor should be collected and pumped off as soon as possible. Thus, in this regard, three pumping stations have been built and two 16 and 20-inch pipelines installed along the tunnel to collect and pump water out of the tunnel.

3.2.3. Enhancing Ventilation Systems

Providing safe and adequate air in underground spaces, particularly in tunnels, is the most necessary and important issue. Any deficiency in the ventilation systems may have unpleasant consequences. Thus, tunnel ventilation systems should work even if its drilling is stopped.

In order to better ventilate the air inside the tunnel after encountering with H_2S gas, two 240-Kw jet fans were installed on the tunnel entrance and other jet fans were also enhanced along the tunnel route. A shaft construction project was performed in the middle of the tunnel to provide necessary electricity and air throughout the tunnel.

3.2.4. Using Compressed Air

In tunnels that are exposed to dangerous gases, compressed air is used for the dilution of hazardous gases entered into atmosphere of tunneling spaces. In this respect fresh air is blown by air compressor into the atmosphere of tunneling spaces and on sensitive devices and components, so that the negative effects of harmful pollutant gases decrease and their lifespan increases.

Hence, compressed air routes were set to the container of sensitive parts and the electronic boards to establish a consistent positive pressure.

3.2.5. Using Appropriate Safety Equipments

Installing warning systems throughout the tunnel, portable detectors, using the necessary equipments such as gas masks, air cylinders, etc are examples of appropriate measures for improving safety performance during tunneling.

3.2.6. Using Other Appropriate Measures

Other appropriate measures are: reduced working hours for each working shift, increased number of working shifts and personnel training.

4. CONCLUSIONS

As a result of methane and hydrogen sulfide gases emission into Nousoud tunnel, tunneling operations slow down and high costs are imposed on TBM services and maintenances. Because of the tunnel location in the petroleum basin and migration of these gases in porous and permeable formations from source beds, we witnessed the inflow of gases into the tunnel. Due to the high solubility of hydrogen sulfide and methane gases in water from one hand and high-permeable formations, and encountering with fault zones and discontinuities on the other hand, led to inflow of large volumes of water and therefore high concentrations of these gases into the tunnel. To cope with the presence of gases, different measures such as cement grouting, chemical injection, ventilation system enhancement, the pumping water out of the tunnel, shaft construction for air and power supply, using gas detector, using safety equipments, installing high pressure air route on sensitive equipments, reducing time of working shifts and increasing the number of working shifts, installing alarm systems etc were taken.

Therefore, it is recommended that in the rest of the tunnel route and in tunnels with probability of gas emission; structural, stratigraphical and hydrogeological studies are conducted carefully. According to these studies, calculations on gas emission rate and thus making decisions about drilling rates, air ventilation system design, draining systems, waterproofing methods and taking appropriate safety measures should be carried out. In addition, it is required in these tunnels to mount holes on the cutter head and shield of TBM in order to be used for slurry or foam injection. TBM should be equipped with detecting boreholes in order to be use in unit boundaries, shear zones and places where there are likely an accumulation of water and gases volumes.

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Figure-1. Location of Nousoud Tunnel

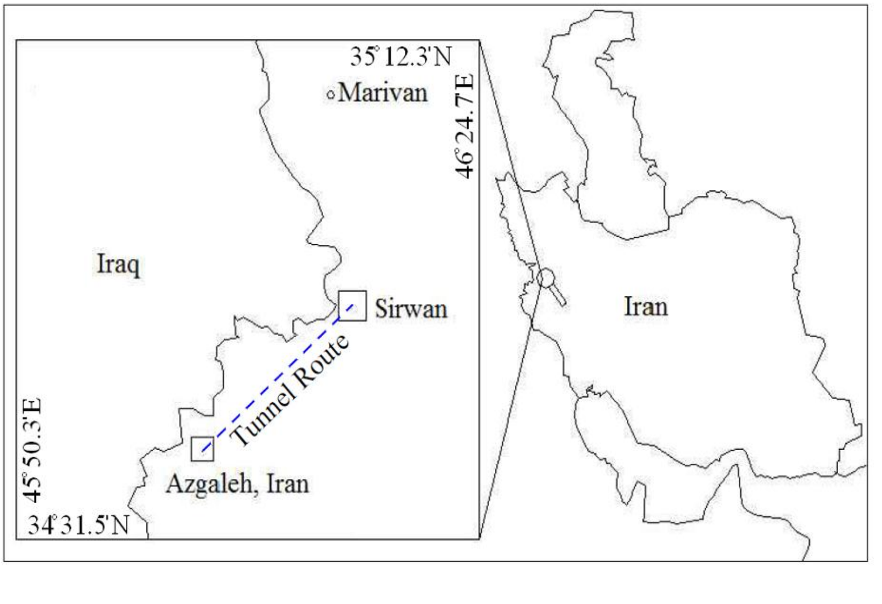

Figure-2. Geological profile of Nousoud tunnel route

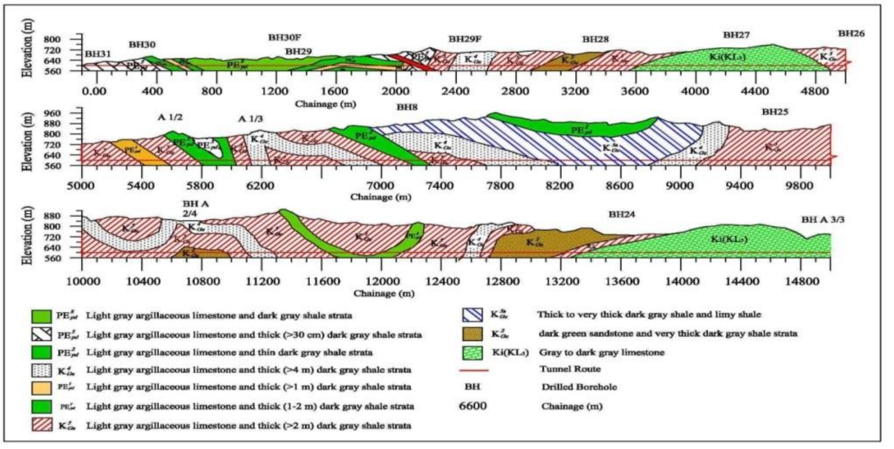

Figure-3. Status of methane emission along Nousoud tunnel

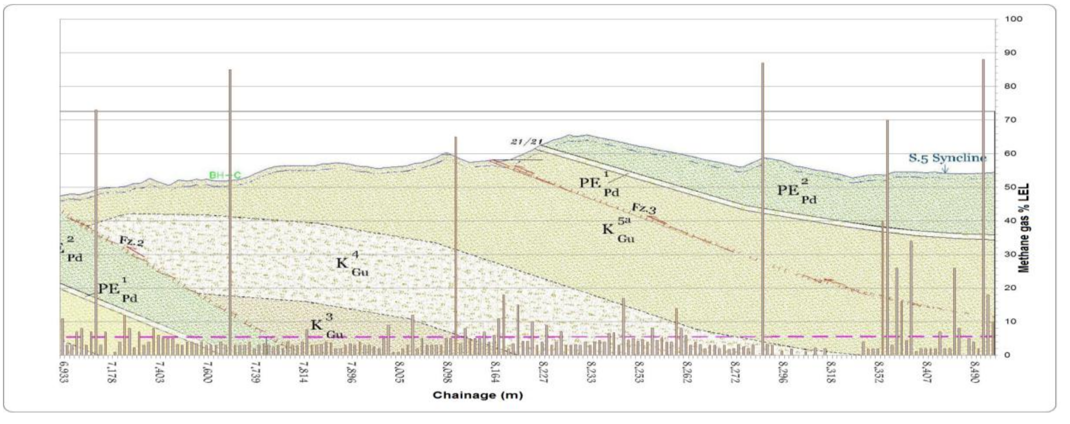

Figure-4. Monthly tunnelling advances in the second part of Nousoud tunnel

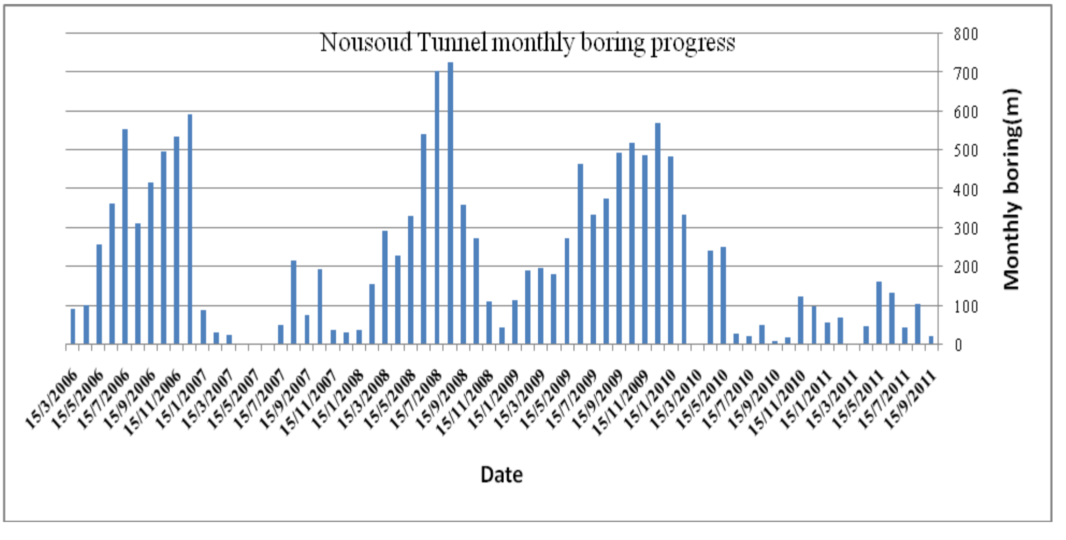

Figure-5. Comparison of the concentration of hydrogen sulfide gas and water drainage into the tunnel in the second part of Nousoud tunnel.

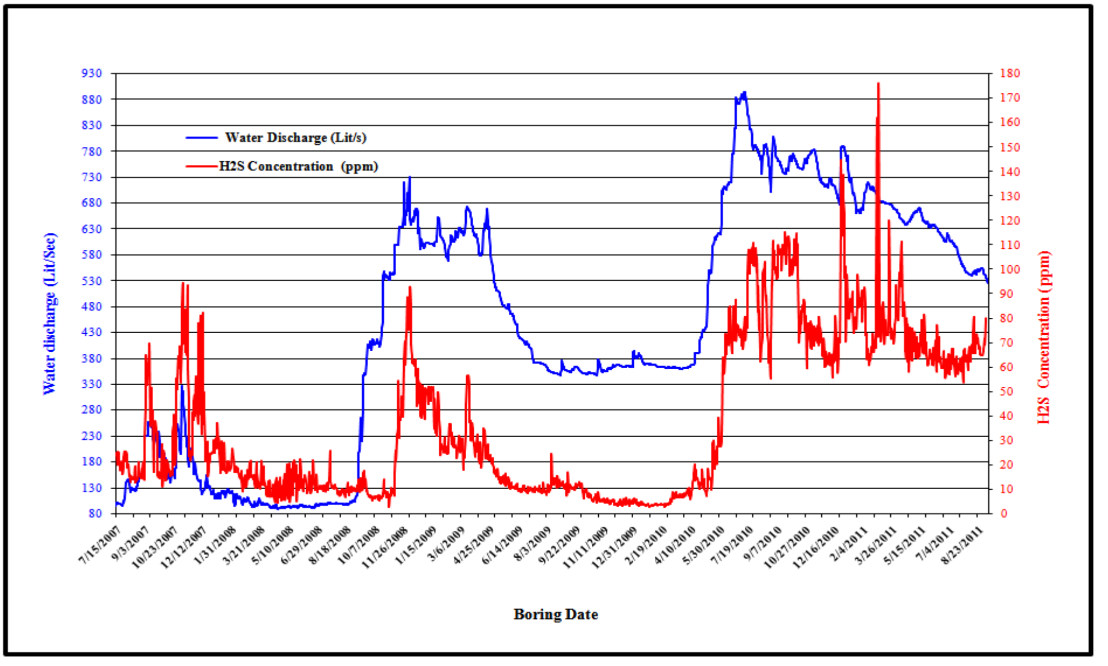

Figure-6. Comparison of the concentration of hydrogen sulfide gas and tunneling advances in the second part of Nousoud tunnel