Gas ground risks and geological investigations for TBM tunneling in Iran

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ABSTRACT

Natural gases are a potential hazard in construction of underground excavations. Encountering with gases usually result in costly delays. Gases occur in a wide variety of geological conditions, so predict the occurrence of potentially hazardous concentrations of gases needs a good understanding of geological conditions. Understanding gas grounds will enable investigators to assess the risk associated with gas prior to excavation. This article outlines the findings of post inundation desk study and specialized geological investigations carried out to verify the gas ground risks. Some practical mitigation measures and recommendations for gas ground investigation are also presented.

KEYWORDS

Gas ground, geological hazards, TBM tunneling, geological investigations

1. INTRODUCTION

Construction of underground excavations such as rock tunnels is among the most problematic civil engineering works. Rock masses (as a nature product) surrounding a tunnel show special behavior with any changes in geological conditions. According to Zhao, et. al (2007), suitability of a tunneling system to the encountered geological conditions is a key factor for a successful project construction. Gassy grounds as an adverse geological condition have always been the most hazardous environments in underground excavation projects and gas inflow can accordingly disrupt normal work activities. Gases from the ground may mix with air in the excavation to generate an explosive, toxic, or asphyxiating atmosphere. It can threaten personnel health and project safety as it detect, in excess of allowable limits, in an excavation atmosphere. Doyle, 2001, denoted that most accidents and financial losses attributed to gas are a consequence of errors made in developing and maintaining control measures, originating from a lack of awareness of the nature of gases underground. Therefore, understanding of the nature of gas is an essential task and enables to make excavations safer, by making control measures more reliable. Nowadays, more long tunnels are being driven in gassy grounds in mountain ranges of Iran which gas-related hazards have relatively reported in all of them. It has become the most important challenge in construction of long tunnels for Iranian participants. Table 1 presents some of recent tunneling projects in Iran in gassy grounds along with related hazards and selected mitigation measures. It shows that tunneling in gassy grounds is almost subjected to an increase in construction time and cost of every project. However, few case studies have been reported to describe gas-related hazards in these kinds of tunneling projects. Ghiasvand (2009), describe some problems related to gas emission in Long Zagros (Lot. 2) tunnel. Shahriar et.al. (2008), presents high gas emission accidents and practical mitigation measures in the construction of Zagros tunnel. Wenner and Wannenmacher (2009), have shown that gas emission is the main extraordinary difficulties encountered during the excavation of Alborz service tunnel. They discussed the possible source of methane, hydrogen sulfide and Carbon monoxide and presented effective countermeasure to reduce gas emission hazards.
According to the above researchers, it is recognized that tunneling in gassy grounds in Iran is not completely tackled for several reasons. (1) Few tunneling encounter gas hazards in Iran, so gases have not been a subject of interest in ground investigations. (2) Wide variety of gas origin and geological setting of the Mountain ranges in Iran, so experience from one tunnel might not be readily applied to the others. (3) In addition, there is no standard practice to characterize hazardous gas during design of tunnels. The aim of this study is to describe geologic environments that may contain all factors necessary to pose a gas risk to rock tunnel construction. For this purpose, some tunneling projects are selected as typical case study to explain the accidents based on geological setting. It is intended to describe the occurrence of potentially hazardous concentration of gases in main geological formation and engineering geological conditions of Iran and to provide a general understanding of gas hazards. It is also suggests essential investigations as a basis for eliminating gas-related hazards and design of atmosphere control measures during tunnel construction. It could be helpful for engineering geologist and civil engineers to assess the risk associated with gas prior to excavation and take proper countermeasures, to which little attention has been paid so far.

### 2. BACKGROUND

Tunneling in gassy ground is the most hazardous task due to the high risk of interference with high accumulated gases. Many of accidents are related to failure in understanding the nature of gassy ground and gas problems. Therefore, it is essential to have a good understanding of gas-related hazards before the excavation of a tunnel. Gases are usually dispersed in low concentrations, but under some geologic conditions are abundant. They can be discharged into excavations by geostatic, hydrostatic, and barometric pressure reductions associated with the excavation.

Gases are common constituents of the underground environment, along with soils, rocks, and water. They occur in a vast variety of geological formations, generate from source rocks by complex biological and geochemical process, can migrate considerable distance through permeable geological features such as faults and fractures, and may accumulate at hazardous concentrations in special geological conditions. Storage of gas is only possible in suitable geological structures or formations, which are present in a limited number of locations (Evans and Chadwick, 2009). For a natural gas to reach hazardous concentrations there must be a medium in place, either at the source or along a migration route, that will receive the gas and an element which slow its dissipation into the surrounding environment. Organic materials in sediments are a potential source of hazardous gas through process of bacterial and thermal decomposition. Organic-rich rocks are the main source of bacterial and thermal gas, and gas or petroleum source rocks may retain gas in tunnel environment. Gases considered hazardous to underground construction are methane (CH4), hydrogen sulfide (H2S), and carbon dioxide (CO2), which are generated by natural biologic and geologic processes (Doyle, 2001). They may accumulate in pore and fractures (gaseous phase), in groundwater (solution phase) and in organic strata (adsorbed phase).

Conventional gas reservoirs are fractured rocks of high permeability which could hold potentially hazardous volumes of gas. In the near surface underground excavations they are rare, usually small and difficult to locate in a traditional geotechnical exploration. But if they release into an excavation could pose a serious risk to tunnel. Unconventional reservoirs are porous soils or rocks of low permeability that retain gas in gaseous phase in discrete, widely distributed stratigraphic traps and solution phase below the water table. Organic-rich unconventional reservoirs also retain an adsorbed phase. In general, the gas is relatively tightly held and widely distributed throughout the formation, in matrix porosity and fractures. Local permeability networks allow short-distance migration. Structural traps may form in moderately porous unconventional reservoirs, such as chalks and some sandstone, that have been heavily faulted and folded (Spencer 1985; Rice 1981). Groundwater aquifers are the most common reservoirs of hazardous gas in the near-surface underground. They hold gas
in solution, potentially in large amounts and in a mobile state. The amount of gas held in solution in an aquifer depends on its depth, temperature, porosity, and physical dimensions. Gas escapes the groundwater reservoir by ex-solution following a decrease in hydrostatic pressure, and by diffusion. Fold and faults can act as main structural traps to make gas reservoirs (Fig. 1). Faults may also put the conducting strata next to the impermeable rocks to provide other kinds of structural traps. Faults and folds in low permeable rocks can make unconventional gas reservoirs. Lithology and sedimentation process controls reservoir permeability which defines reservoir capability to storing the gas.

Current tunnel engineering and engineering geology lectures cannot provide enough information on the nature of underground gases or guidance toward basic investigations to avoiding potential hazards for tunnel construction. This paper presents information from the past gassy tunnels and solution of the gas problems in construction.

3. GEOLOGICAL SETTING OF IRAN

Iran is located at the western tip of Alpine-Himalayan orogenic system and geologically structurally an integral part of it. The Zagros and Alborz Mountains of Iran are the southern and northern part of Alpine-Himalayan orogenic system, respectively (Fig. 2). The Zagros Fold and Thrust belt is home to one of the largest petroleum producing reservoirs in the world (Fig 3). Several potential source rock units with different geological ages were deposited in this tectonically developed area making it as the most prolific region in the Middle East. The most important source rocks in this area are the Lower Paleocene-Eocene Pabdeh Formation, the Santonian-Masstrichtian Gurpi Formation, the Lower Cretaceous Garau Formation, Albian Kazhdumi Formation and the Neocomian-Aptian Gadvan Formation. These source rocks contain at least 70% carbonate and are best referred to as argillaceous limestone or as marls. These layers generated 99% of the onshore Iranian oil reserves, trapped into two main reservoirs, the Asmari (Early Miocene) and Bangestan (Cenomanian) limestones.

The Albian Kazhdumi Formation consists of 300m dark bituminous shale with a dark argillaceous limestone layer in the type section in the Khuzestan mountain front area. In north of Dezful and northeast of Lurestan, the Kazhdumi Formation laterally changes to carbonate unit. This Formation is substituted by the Garau Formation in the south and central part of Lurestan Province. The Kazhdumi is classifying as one of the richest source rocks. The organic matter contains up to 5 to 7% per weight of sulfur, this fact explains the high sulfur content of the oil generated (Bordenave, 2002).

150-250m argillaceous and fine grained dark grey marl sediments of the Eocene Pabdeh Formation were deposited under the euxinic condition, and are rich in planktonic fauna of Globorotalia and Globigerina. The Pabdeh Formation has a
high organic content in Lurestan. The Gadvan Formation, at the type locality, consists of about 107 m of dark gray, argillaceous, bioclastic limestone interbedded with gray, green, and brownish yellow marl. Laterally, the formation grades into dark shale and argillaceous limestone in the Khuzestan Province. It is located between the top of Fahlilyan limestone and base of the Dariyan Formation. Lateral facies changes occur; the formation in the Khuzestan province consists of dark shale and argillaceous limestone, whereas in the Lurestan province, the limestone passes to dark and black argillaceous limestone of the Garau Formation (Rabbani and Bagheri, 2010).

The Shemshak Formation has been long known as a source of commercial coal in several parts of Alborz structural geological unit. This Formation including Upper Triassic and Lower Jurassic sediments consists of coal-bearing shales interbedded with sandstone. Recent geochemical studies in the Central Alborz indicated that the Shemshak Formation is rich in organic matter and has potential to generate oil and chiefly gas (Zamani, 1999). This formation has a thickness of 1500 to 2000m and extends laterally for hundreds of kilometers in the Central Alborz.

### 4. TYPICAL PROBLEMS IN GASSY GROUNDS

Major problems encountered during TBM tunneling in gassy grounds are hazardous gas inflow, explosion and toxic atmosphere and corrosion of TBM components and electrical equipments. The consequences are a hazardous working environment, tunneling suspension, personal unhealthy, and the need to dilute incoming gas in excavation atmosphere. Hazardous gases typically refer to the gas concentration in excess of allowable limits in an excavation atmosphere, which disrupts normal work activities and designed operational modes. Hazardous gas inflow will lead to long downtime and cost overrun.

The particular hazard or hazards posed by any gas depends on its chemical properties. A combustible gas in an enclosed space can explode; a physiologically inert gas can displace oxygen, causing asphyxiation; a toxic gas absorbed into body tissues can disrupt normal physical processes. The hazards of methane, hydrogen sulfide, and carbon dioxide are summarized in Table 2.

<table>
<thead>
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<th>Nature of hazard</th>
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<td>Gas</td>
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<td>Combustion / explosion</td>
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<td>Simple asphyxiates</td>
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<td>Toxic</td>
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<td>Methane</td>
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<td>Hydrogen sulfide</td>
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<td>Carbon dioxide</td>
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Methane (CH4) is a common hazardous gas, and the most destructive. Methane is generated underground by bacterial decomposition of organic matter in anaerobic environments, and by thermal decomposition of organic matter during coalification and petroleum generation. It is an inflammable gas which makes the fire risk increase and when mixed with air in a proportion of approximately 5 – 15% in volume, it is explosive (Rodriguez and Lombardia, 2010). Methane also acts as a simple asphyxiates. It can cause an oxygen-deficient atmosphere in an unventilated, enclosed space by displacing normal air and reducing the oxygen concentration of the CH4-air mixture (Doyle, 2001).

Hydrogen sulfide (H2S) in the near-surface underground usually originates from bacterial decomposition of organic matter in anaerobic environments. It can also occur in geothermal systems, where it originates from magma degassing and thermal metamorphism. Sulfate in groundwater may originate from oxidation of small amounts of pyrite in shale and/or anhydrite dissolution. Hydrogen sulfide is heavier than air and with strong smell of rotten eggs. The main hazards are related to its toxicology and corrosive property to metals.

Carbon dioxide (CO2) is generated underground by bacterial decomposition of organic matter in aerobic environments. It also occurs in geothermal systems, where it originates from magma degassing, from thermal decomposition of carbonates, and from dissolution reactions between acid waters and carbonates. Carbon dioxide is classified as a simple asphyxiates in occupational medicine literature; it can displace normal air and reduce the oxygen concentration of the CO2-air mixture (Doyle, 2001).

### 5. PROBLEMS ENCOUNTERED DURING TBM TUNNELING IN IRAN

The Zagros orogenic belt is one of the richest oil provinces in the world. Nowadays, long water conveyance tunnels such as Long Zagros tunnels (Lot1a, Lot 1b and Lot 2), Sabzkuh tunnel and Golab tunnel are under construction in this area. Gas inflow with different incidents has frequently been occurred during the construction of these tunnels especially, Long Zagros tunnels. These tunnels are under construction in a variety of geological Formations, including Pabdeh, Gurpi, Ilam and Garau which contain the main source rocks. Extension of the time schedule and high construction cost beside technical problems has been the most important hazards of tunneling in the gassy grounds.

The Long Zagros tunnels in the Zagros Mountains and Alborz tunnel in the Alborz Mountains are the main tunnels, in Iran encounter hazardous gas emission during construction. Hazardous gas emission into tunnels caused serious problems such as personal healthy and TBM operation. Figure 4 shows the use of breathing apparatus for work in such difficult conditions. Hydrogen sulfide in solution in groundwater and methane are the main hazardous gas recorded in these tunnels. They are often accompanied by high groundwater inflow. Based on geological and hydro-geological reports, spoil material recorded from TBM excavation and observations of the rock mass from the invert opening of shield and from the face during maintenance, the geological condition and rock mass characteristics has been investigated along the tunnel routes. Geological formations containing coal and petroleum
source rocks are frequent materials intersected the tunnel excavation. The presence of these formations caused the huge and serious gas inflow during tunnel excavation and generated hazardous atmosphere, especially when poorly ventilating system was applied.

Fig. 4. Severe working condition for gassy ground tunneling in Iran. The use of breathing apparatus restricted the ability to work to a great extend.

6. KEY INVESTIGATIONS REQUIRED IN GASSY GROUNDS

It is essential to focus investigations in gassy grounds on hazard assessment for gas emission. The investigation consists of (1) geological investigations to identify geological factors controlling gas generation, migration, accumulation and emission into tunnel, and (2) site investigation to understand the nature of gas for a particular site. Main investigation target is assessment of the apparent source of hazardous gas, strata or structures along the tunnel route that generate and retain gas, phases of gas in the ground and mechanism of gas inflow to the tunnel.

The objective of the geological investigation is to explain the general nature of gas on a particular site, that is, how and where it is generated, how it migrated to the site if generated elsewhere, how it is distributed and retained on site, and how accumulations of gas may respond to excavation. Geological and hydrogeological models are the ongoing of the geological investigation. Geological features capable of discharging gas into excavation at hazardous rates are of main interests. The objective of site investigation is to define the presences of gas, and quantify gas concentration and mixture composition, through sampling and analysis. This is in addition to those efforts normally performed to characterize soil, rock, and groundwater.

Most gas in the tunnels is retained in solution in groundwater. Therefore, evaluation of groundwater inflow is necessary to estimate gas inflow rate and its concentration. Any aquifer within the zone of hydrostatic pressure reduction surrounding an excavation can contribute inflows of solution phase gas to the excavation. The significance of an aquifer with respect to gas inflow depends on the rate and duration of groundwater it can produce, and on its solution gas concentration.

7. DISCUSSION

Almost all the oil and gas field of Iran is concentrated in the Zagros orogenic belt and Alborz region. The Cretaceous/Tertiary Formations includes 6 source rock layer of unequal importance. The basal part of the Garau Formation, the Gadvan, the Kazhdumi, the Amadi, the Gurpi and Pabdeh are significant source rock in the Zagros region. The impact of these source rocks is extremely variable. Among Cretaceous rocks, the Neocomian Garau Formation deposited over Lurestan, NE Khuzestan and the northeastern part of the Persian Gulf, and the Albian Kazhdumi Formation, deposited in the central part of Zagros Mountains, have excellent characteristics with initial organic materials. Their organic matter is mainly algal with high sulfur content.

In High Zagros, rich Garau potential source rocks are seldom associated with valid traps. The Asmari reservoir is breached in the structures as the results of uplift during Pliocene. Therefore only few small fields are related to Garau source rocks, accumulated in the Sarvak and Ilam.

In the central part of simple fold belt of Zagros, very prolific thick mature Kazhdumi source rocks associated with excellent Asmari reservoirs. The Lower-Middle Jurassic Shemshak Formation is a significant source rock in the Eastern Alborz region and is considered as the most probable source for the main gas fields in the region. This Formation is an immature source rock.

8. CONCLUSION

Geological setting of Iran consists of geological environments that may contain all the factors necessary to pose the gas risk in underground constructions. The encounter of petroleum and gas fields with the presences of main source rocks in depths of tunnel excavation in Iran has a strongly accidental character and will accompany by permanently significant gas inflow during the excavation.

The Zagros and Alborz Mountain ranges have a potential for gas-related hazards to develop into accidents, if they are not recognized during planning and construction and if appropriate preparations are not made. It can be threatened the tunnel projects by delay the construction time and impose huge costs besides, subjected the personnel and equipment to danger. The impact of these environments on tunneling performance is variable in response to the factors required for gas generation, migration and accumulation. So it is necessary to provide a thorough understanding of gas origin, migration and accumulation to identifying potential zones of hazardous gases prior to tunnel excavation.

Geological and hydro-geological investigations, in addition to those efforts normally performed to characterize rock and groundwater, are essential to identify the presence of gas
source rocks, potential conventional and unconventional reservoirs and suitable conductive features connect to the tunnel for assessment of gas-related hazards. Groundwater inflow predictions make it possible to have a reliable evaluation of gas emission along the tunnel at different geological conditions.

Site specific investigations include groundwater and gas sampling from springs and boreholes, hydro-chemical studies and subsurface explorations (geophysical and geotechnical) is necessary to characterize the occurrence and distribution of gas and to quantify gas concentration and chemical composition for design of effective countermeasures.

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