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Delineating subterranean water conduits using hydraulic testing and machine performance parameters in TBM tunnel post-grouting

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ABSTRACT

Zagros Water Conveyance tunnel in western Iran crosses a vast unconfined aquifer. This TBM burrowed tunnel has long drained the region's groundwater which is unusually rich in hydrogen sulfide (H_2S) gas. The gas reacts with the tunnel humidity and produces an acidic fume that penetrates the tunnel lining and causes its decay. The exact locations of the discharging conduits and their morphology are not known, since they are concealed by TBM segmental lining. An elaborate post-grouting plan is on the drawing board to reclaim the aquifer, but the cost of a systematic grouting is particularly high and at best this scenario not conclusive. The scope of this paper is to discuss a series of carefully controlled field experiments in a 100 m pilot study area along the tunnel. The scheme manipulates the TBM performance parameters recorded during the tunnel excavation. Based on this information, suitable field models are established that may be interpreted as being associated with either water or air-filled solution channels.

1. Introduction

Zagros water conveyance tunnel in Kermanshah province of Iran is near the town of Pol-e Zahab. This part of the tunnel (~26 km long) is regarded as the second lot of a broader plan, which is schemed approximately 48 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, 16 km (61%) of this tunnel has been completed.

In the course of tunneling, the machine encountered nearly many extraordinary situations related to continuous intrusion of 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. The encountered circumstances contradicted the pre-construction subsurface investigation results, which had forecasted low to moderate amount of fresh water seepage at a maximum rate of 5–10 l/s/km [1].

One of the major factors affecting the performance of tunnel boring machines is the degree of fracturing of the rock [2]. During excavation, machine performance parameters are continuously displayed and recorded on the control cabin monitors. Fig. 1 shows the TBM display screens. The screens display TBM performance parameters and register TBM mechanical behavior against the excavated material [3]. These screens disclose an assorted set of data; e.g. penetration rate, boring time, total thrust, torque power, cutter speed and etc. Based on the careful analysis of these parameters, uniform patterns were established as a model to identify concealed joints and to delineate water-carrying conduits along the tunnel path. The objective is to improvise a model to pinpoint water conduits and fill in their leaks and cracks by post-curtain-grouting. This is in contrast to a systematic grouting approach where grouting is done in a continuum fan pattern regardless of water points of entries [4].

2. Geologic setting

According to the structural geology zonations of Iran, Zagros tunnel is located in the core of the Zagros Mountain Range. This region includes simple structures of reverse faulting and symmetrical anticlines and synclines known as Folded Zagros province. 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}~950 m) [1].

The geological unit along the Zagros tunnel in the pilot study area consists of brownish gray limestone of Garou Formation. Overlaying this unit is Gurpi Formation, which is comprised of alternating thin to thick-bedded shale and argillaceous limestone. Some layers of Gurpi Formation are rich in pyrites in the form of nodules [5]. The assembled rock strata changed frequently from hard rock to soft, dry to wet, stable to instable, stick to nonsticky ground (and vice versa), more often than anticipated. Essentially,

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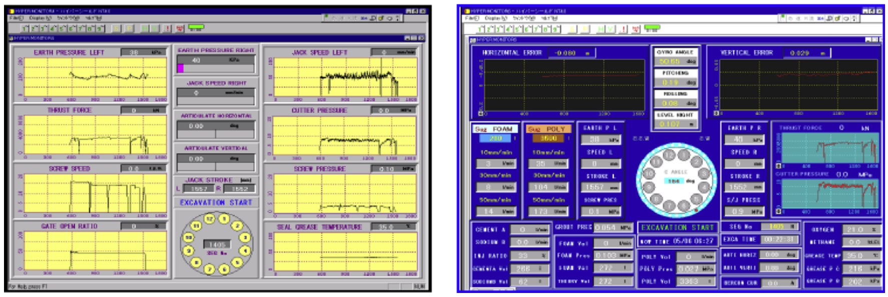

Fig. 1. TBM control cabin main display screens showing excavation data and machine mechanical behaviour against the excavated material.

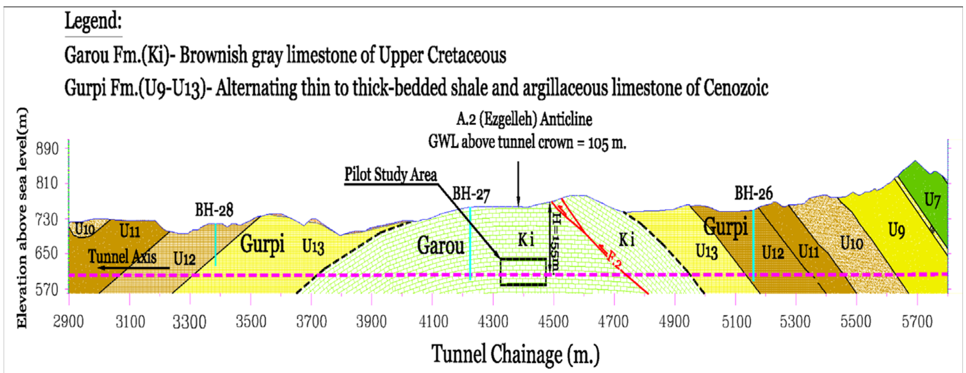

Fig. 2. Longitudinal geological profile of lot 2 Zagros tunnel along the study area showing the regional GWL. [after 8].

Gurpi sections are aquiclude layers, so there is no substantial groundwater accumulation in these parts of the tunnel. However, Garou sections in the form of anticline serve as an unconfined "water table" aquifer [1]. The geological profile of the project line is illustrated in Fig. 2.

The pilot study area is located in the core of a major geological structure known as Ezgelleh Anticline (chainage 04+359 to 04+458). The tunnel overburden thickness along this area is roughly 155 m. Generally, the phreatic zone is congruent to the areal topography and had stood 105 m above the tunnel crown before its excavation. It was later drained out and the water table plunged below the invert level after completion of the tunnel.

The water seepage in low amounts was first experienced at TM 3700. A significant water ingress in the range of $Q > 110$ l/s was later intruded at TM 4157, which rapidly accumulated to $Q \sim 315$ l/s with further advancement to TM 4435. Advancing deeper into the core of aquifer at TM 8256, the accumulative water seepage totaled $Q \sim 730$ l/s, with further advancement to TM 13846, 155 more liters of gas bearing water seeped into the tunnel, totaling the tunnel discharge flow at the portal outlet to 900 l/s. This amount of water released 700 ppm hydrogen sulfide gas into tunnel atmosphere. Fig. 3 shows the water discharge rate and the H_2S gas concentration at the pilot study area where is marked as Ezgelleh Anticline on the graph.

As is evident by the piezometric levels of boreholes 26 and 27 in Fig. 4, the groundwater level on the average has dropped 27 cm/m of TBM's advancement before it subsided below the tunnel invert level. This observation is roughly equivalent to the secondary permeability of the medium (hydraulic conductivity reaching up to 0.1–0.2 m/s), which is of similar value with most permeable rocks [6]. The conclusion became a useful criterion to predict the hydraulic characteristics of the aquifer and to estimate the host rock permeability at any given location along the tunnel.

Generally, Garou Formation is known to be as the host rock in many major oil (gas) bearing basins further down in the south provinces of Iran. As a result, some hydrocarbon materials may have migrated or leached out during uplift movements in this area, due to lack of a suitable cap rock and a favorable geological structure to trap the hydrocarbons. Therefore, only traces of residual hydrocarbons have remained in the rock formations in the form of black tarry liquids [7]. These liquids have been frequently observed along the tunnel path, seeping through holes and gaps of the tunnel lining. Hence, the hydrogen sulfide (H_2S) gas is most likely an associated component of the remaining gas and oil in existing traps.

Hydrogen sulfide liberates from the groundwater; so, its amount depends on the quantity of water inflow. The groundwater discharges through the open joints and solution channels. Obviously, part of water circulates along the space between segments and rock and the water source is difficult to track and handle properly.

Prior to this experiment, an elaborate joint survey was carried out from the surface to geometrically define the dominant discontinuities along the Ezgelleh Anticline and to produce a reliable model for the hydraulic characteristics of the rock mass. Overall, four major joint sets identified along the pilot study area (axis N215°). It was also determined that the prevailing joints dipped at an angle (α) of 30° to 80° with dip directions (β) varying from 44° to 264°. Their surface characteristics are undulating, moderately to highly weathered, e_{max}=25 mm, at 35–225 cm spacing, and are elongated 1–10 m.

Based on the information adopted from over 150 borehole water pressure tests (Lugeon Test) during pre-construction subsurface geotechnical investigation—interpolated most compatible with actual geological conditions (elevation, structural and lithological) along the bored tunnel, average permeability coefficient of the intact rock is calculated between 10^{-5} to 10^{-6} cm/s [1]. In general, 17% of the Lugeon tests were reported as impervious and 42% resulted in "laminar" flow. Turbulent flow that generally represents open joints and "washout" that refers to washing the joint filling were tallied at 21% and 12%, respectively. Dilation flow