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Tracer Test In Crude Oil Storage Cavern

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ABSTRACT

The primary object of this test is to identify the seepage locations within underground facility which is causing drawdown of ground water level by means of water level observations in monitoring well. The present paper discusses about a case study of an oil storage cavern located in Karnataka. This project area is comprised of banded granitic gneisses, with true intrusive granites and few mafic intrusions. Project consists of two storage units and two water curtain tunnels located over two legs of each unit. For this test, fluorescein sodium was selected as a dye to conduct tracer test. The tracer was injected through surface borehole. UV lamp is used to identify tracer material by minimizing the other lights, as the tracer is not easily visible by naked eye. Identified zone of leakages were grouted till the maximum reach and additional boreholes were drilled in water curtain tunnel (WCT) to stabilize the ground water till the grouting is completed.

Keywords: Tracer test; Water seepage; Underground oil storage; Borehole; Grouting.

1. INTRODUCTION

Tracer testing is a powerful method for characterization of sub-surface. In its simplest form, tracer testing can be defined as injecting one or more tracers – usually chemical compounds – into the subsurface water in order to estimate its flow and storage properties. A tracer test is an indirect method for characterizing aquifer properties.

The tracer should have negligible effect on the transport properties of the injected fluid (e.g., density and viscosity). Tracer tests take many forms, with different numbers of tracer and different well configurations, different means of introducing tracer and different method of sampling. Tracer test type can be grouped into the following general categories.

Conservative Tracer Test*:* A conservative tracer is one that stays entirely in the phase in which it is injected, therefore only the volume occupied by the phase is interrogated. Anions (e.g., chloride or bromide) are typically though not always conservative aqueous phase tracers. One or more conservative tracers are injected, and subsurface properties are inferred from the tracer behavior. Most frequently tracers are used as under single-phase conditions (e.g., below the water table), they are also used in multi-phase applications; for example, to estimate hydraulic conductivity in partially saturated column experiments. Whatever conditions conservative tracers are used under, they provide information relating to its reference phase, that is, the phase in which it is soluble.

Partitioning Tracer Test: Partitioning tracers are compounds that have some affinity for multiple phases, and therefore there is partition between two or more phases. Examples of partitioning tracers include heavier alcohols (e.g., hexanol), which partitions between the aqueous and non-aqueous phase liquid (NAPL) phases, and perfluorocarbons, which partition between the gaseous and NAPL phases. While adsorption can be regarded as partitioning between a mobile and solid phase, it is usually referred to explicitly as an adsorbing tracer because of its typically negative connotation.

Other Tracer Method: Tracer methods that defy categorization involve injecting a suite of tracers and observing differences in their residence times. For example, differences between conservative and adsorbing tracers' effluent history can be attributed to adsorption parameters in the subsurface. If two or more tracers with different diffusion coefficients are injected into fractured media, it is possible to estimate surface area for mass exchange and tortuosity of the rock matrix. These are two examples of inferring subsurface parameters from difference in tracer behaviour.

The most popular method of conducting tracer tests, however, involves one or more injection wells, multiple extraction wells and underground facility. Tracer histories from each extraction well provide information on the injection-extraction well pair. If more than one injection well is used, unique tracers should be used to provide unambiguous results. Tracer tests can likewise be conducted in a variety of flow conditions, including steady-state flow (either forced or ambient) and transient flow conditions.

This paper deals with the tracer test carried out in a crude oil storage cavern project. The test was designed and interpreted to estimate the location of seepage inside rock cavern due to which ground water level was continuously decreasing (observed through surface monitoring borehole) and compromising the integrity of hydro-confinement of storage caverns.

2. STUDY AREA

The Padur rock cavern project located in Karnataka state of India is one of the few underground rock oil storage caverns completed in the country. It is an unlined underground rock cavern excavated for storage of crude oil, the crude oil is kept confined within cavern by principle of hydrodynamic confinement (Amantini et al., 2005) wherein the natural ground water potential towards caverns is enhanced by artificial recharge. Two more similar projects are located in southern part of India.

The permeability of the gneissic rock is very low of the order of 10^{-9} m/sec but some joints in the project showed permeability in the range from 10^{-8} to 10^{-6} m/sec and locally very high permeability of the order of 10^{-4} m/sec. The contacts of dolerite dykes (intrusive bodies) had permeability of the order of 10^{-6} to 10^{-7} m/sec. Permeability is inversely proportional to the rock mass quality.

Locating water bearing features ahead of cavern excavation face helps to plan judicious treatment like grouting. The process starts through geological and hydrogeological investigations in the feasibility stage and continuously updated through the construction stage.

The water curtain system is conceptualized and is normally orientated parallel to the orientation of the caverns and boreholes are drilled in the direction perpendicular to the major joint set so as to achieve maximum seepage flow towards the cavern. A water curtain system comprising series of boreholes with a regular pattern are drilled from water curtain gallery above the storage cavern.

The geological face mapping and observation during excavation of water curtain gallery enables to adopt the design considerations for detailed engineering of the water curtain system. Based on the result of the excavation mapping, through an active design process, details of the water curtain system such as length and orientation of the boreholes, spacing of the boreholes and inclination of boreholes has been designed.

Stringent monitoring of the ground water table is carried out during construction. Grouting in water curtain gallery is minimized and only employed where leaking water endangers works safety or creates unacceptable drawdown of the ground water table.

Water curtain system comprises a significant number of water curtain boreholes drilled from water curtain tunnel before start of the cavern excavation. The water curtain system is designed to extend so as to provide a cover of about 20m on all side of the U-shaped storage cavern.

3. GEOLOGICAL SETUP

The geological features of the survey region globally consist of migmatites gneiss complex and basic dyke intrusion. Migmatites gneiss complex of the survey region can be divided into banded Gneiss and granitic.

The project area comprises of banded and granitic gneisses, migmatites along with true intrusive granites and few mafic intrusions. The banded gneisses consist of white bands of quartz-feldspar (felsic bands) alternating with dark bands containing hornblende, biotite and minor accessory minerals (mafic bands). The granites are porphyritic to granular with typical quartz vein system and at times with intrusive properties. The mafic intrusives are in the form of doleritic dykes of varying thickness in the above parent rock.

Details of the structural discontinuities within the rock mass as determined from detailed mapping during excavation reveals three major discontinuities (sub-vertical) and one sub-horizontal discontinuity. The sub-vertical discontinuities are persistent and oriented in almost north-south and east-west direction with a dip of about 80-85° both sides. Major tectonic and geomorphic features are also aligned parallel to these discontinuities. Mafic dykes are also found roughly oriented parallel to these discontinuities indicating these intrusions are both syntectonic as well as post tectonic. Sub-horizontal joints are oriented east-west to N60°W and dipping about 5 - 15° both ways.

A and B are two storage units (Fig. 1), where A1 and A2 are cavern legs of cavern-A connected at one end and separated at another end like B1 and B2. Water curtain tunnel is located in between cavern legs i.e. A1-A2 and B1-B2, marked with dashed blue line. Structure with cyan colour represents access tunnel to storage cavern and water curtain tunnel. Four intrusive bodies have been encountered during excavation of water curtain gallery which were projected to cavern heading before its excavation (Fig. 5). Intrusive bodies represented by pink colour with shear zone (hatched green area) in Fig. 1. BH-1, BH-2 and BH-3 are surface monitoring boreholes through which monitoring of ground water has been carried out. Whenever seepage occur along TD1 (dolerite dyke) and FR3 (Fracture zone) structures during excavation phase, these three boreholes reflect the same with decrease in water level. Recovery in water level has been recorded after treatment by means of seepage grouting in the affected zones.

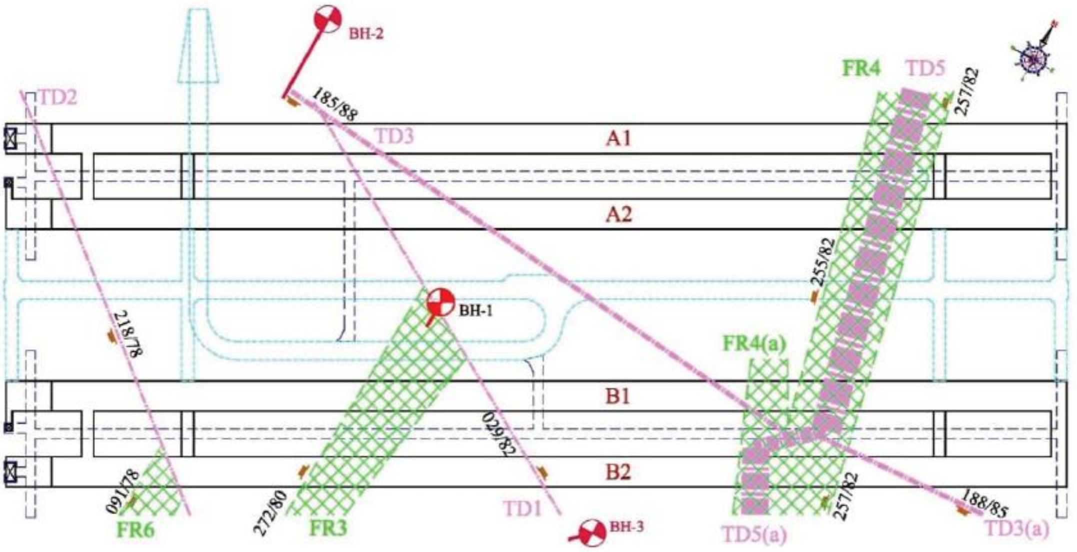

Fig. 1 - Location and extent of study area with major lineament

4. REQUIREMENT OF TEST

One of the principles for storing crude oil in mined rock caverns is the concept of hydrodynamic containment to ensure the oil/gas tightness. Water curtains are used in almost all storage facilities of this kind, which has been designed to meet the requirements for providing a continuous and fully saturated groundwater regime with sufficient water pressure. The rock conditions, such as jointing system, has been considered in the water curtain design.

The storage facility at Padur has been based on the principle of underground storage in unlined rock cavern with confinement by groundwater pressure. The concept of hydrodynamic confinement allows groundwater to flow into the cavern. However, sometimes small seepage represents the saturation of rock mass but high amount of water ingress needs to be controlled and minimized to reduce the operation cost which is caused by pumping of water from cavern and its treatment.

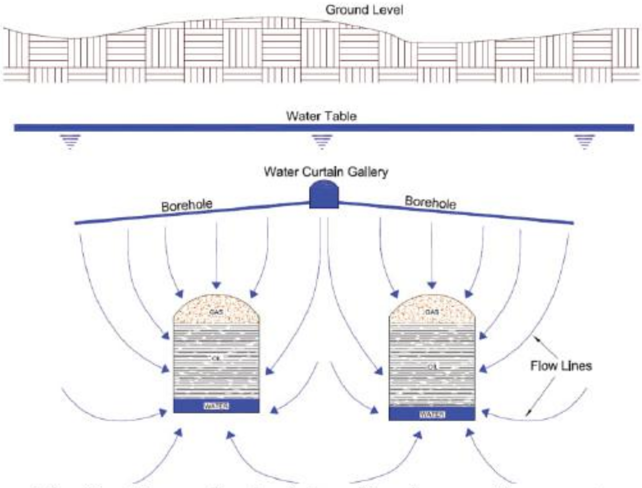

Fig. 2 - General principle of hydro-confinement

When the cavern is excavated below the surrounding ground water level, the oil is confined in the cavity. Due to natural fissures in the rock, water continuously percolates towards the cavern, thus preventing oil and vapour from leaking out (Fig.2). Water leakage into the cavern (seepage water) is drained to pump pit located in the deep end of the storage units and pumped out from the storage cavern on a regular basis.

During excavation, ground water level is continuously monitored through a number of surface monitoring wells distributed all over the site. Especially those boreholes which are directly connected to hydro-conductive lineaments. TD1 dyke shown in Fig. 1 is highly permeable zone, which require lots of pre-grouting and post grouting as well. Probe holes are made mandatory in this zone to locate ground water ahead of excavation face for pre-grouting to avoid water ingress during excavation and most importantly to maintain hydraulic confinement. Three monitoring boreholes (BH-1, BH-2 and BH-3) have been drilled along TD1 and all the drilled holes have intersected the intrusive bodies at deeper depth so that monitoring is not affected by surface runoff water or surficial percolation of rain water under unconfined conditions (Fig. 5).

Water levels of these boreholes were always showing similar trends with different but stable levels. Ground water level of these boreholes are directly affected by TD1 and FR3 zone.

BH1: Water level of this borehole is repeatedly fluctuating in observation range of EL -12.0 to -23.5m due to seepage during excavation and grouting to counter it. In month of March and April 2012, water level suddenly fell up to EL -36.3m due to encountering of TD1 dyke in excavation of bench 1 in cavern B1. Groundwater recovered back to its normal level after pre and post grouting (Fig. 3).

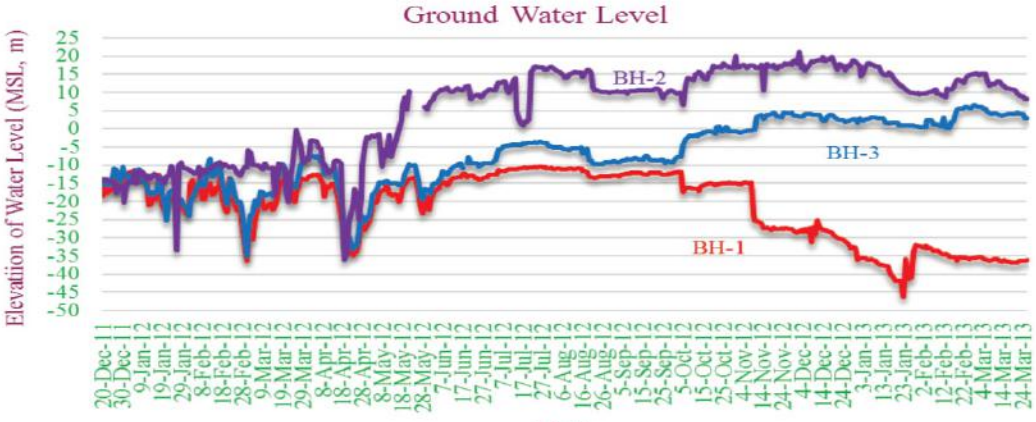

Fig. 3 - Drawdown of ground water level before test

BH-2: This borehole lies almost at the intersection of two intrusive bodies i.e. dykes TD1 and TD3 as shown in Fig. 1. Overall water level is affected by TD1 and surrounded fracture zone; TD3 is tight and completely dry. Other than major drawdown, local fluctuation in water level (mid of July, 2012) caused by scarcity of water for pressurization through water curtain boreholes due to local strike.

BH-3: Groundwater level of BH-3 is directly affected by TD1 dyke. Water level of this borehole was in observation range in between EL -5 to -10m. Fluctuations in water level were due to seepage and grouting activity within storage cavern. In the mid of April 2012, sudden drawdown was observed in water level due to loss of water during pre and post-grouting drilling at bench 2 level in A2 cavern (Fig. 4). Grouting drilling involves big loss of water which is expected because of longer drilling length and extension of drilling rod to encounter and cross TD1. Pre and post grouting for the same has helped in recovery of ground water to its normal level.

Fig. 4 - Pre-grouting for TD1 (left), post grouting for TD1 (right)

Till September 2012, fluctuation in groundwater level in all the three boreholes were similar but in October BH1 has shown a drastic drawdown different from the other two. Excavation status in all the cavern were way far from TD1, therefore such behaviour was not expected. To retain water level back again, several measures were taken like drilling of additional boreholes in water curtain gallery as well as from access tunnel to penetrate TD1 and pressurize with more water. Still no improvement was found and neither the seepage in caverns were visible.

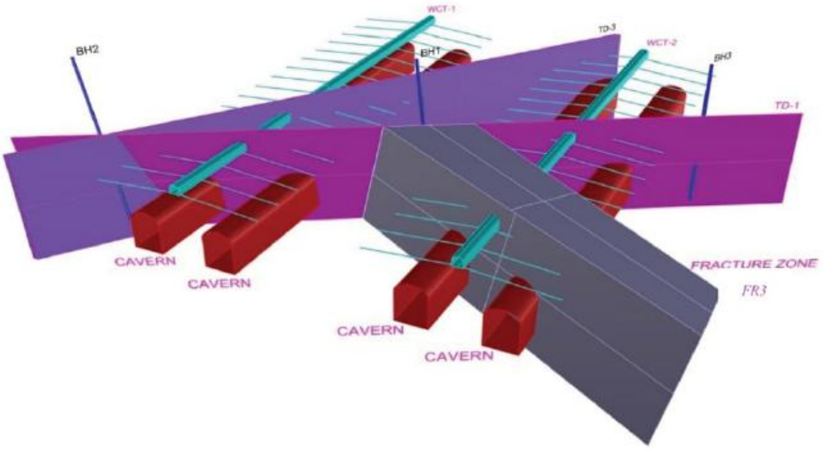

Fig. 5 – 3-D Geological model of project site

Tracer test (colour dye test) was one of the remedy measures to identify the seepage zone in cavern which is affecting the ground water level of BH-1. This test was of immense importance to prevent strata from desaturation and to identify the water bearing structure by visual inspection and to finally grout those seepage zones inside the storage cavern.

5. TRACER SELECTION AND TESTING

Before conducting tracer test, one important study was carried out at site to check the status of saturation, because desaturated areas cannot be covered with tracer test (as tracer test is water soluble) and then those critical areas might not get grouted. Those un-grouted zones will be problematic and are needed to find out to get desired results. To identify these zones, seepage map was prepared by visual inspection and measurement of water at every dripping locations. This new map was compared with the map developed earlier in September 2012 (when water level was at stable condition). Development of seepage map was a monthly exercise which includes each and every excavated tunnel and was available for analysis. By comparing these two maps, it is found that the quantity and locations of seepage is almost similar, therefore, drawdown of water level in BH1 has not affected the tunnels saturation status in a big way. A model developed based on the above observations is given below (Fig. 6).

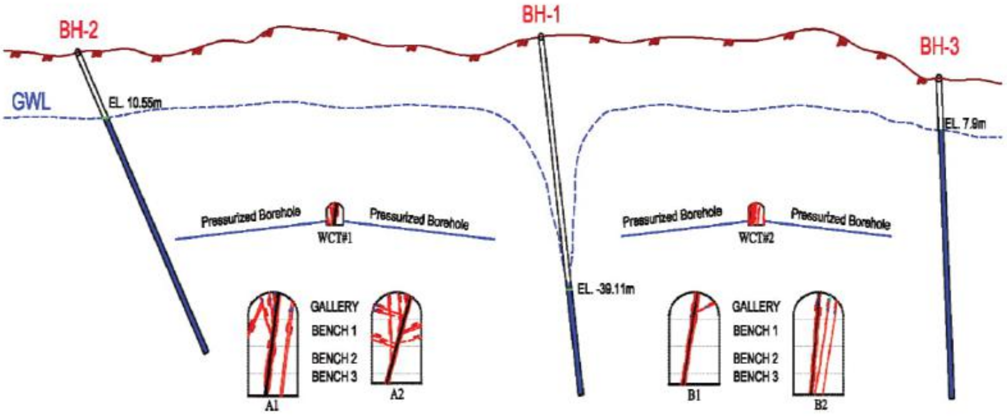

Fig. 6 - Typical geological cross section along TD1 dyke rock with ground water level

Hence, by seepage observation it is clear that the drawdown in surface monitoring borehole is not representing the whole zone but it is a result of few local joints which act as a passage for ground water to cavern. First appearance of tracer material was important to observe after injection, otherwise it will mix and spread everywhere and is impossible to find the source location (joint).

Many dyes are being used as hydrogeological tracers; the most prominent are probably fluorescein/ uranine and rhodamine WT. In most cases the tracer is used to track the movement of water. Consequently, an ideal water tracer has the following characteristics:

- The tracer is conservative in behaviour. The tracer moves in a manner similar to water, that is, (i) without sorption to soils, sediments, or rocks and (ii) without degradation during the time frame of interest.
- The tracer has low background concentration. The tracer is clearly discernible from the background of the system.
- The tracer is insensitive to changes in solution chemistry. The tracer's fate and transport behaviour are unaffected by changes in pH, alkalinity, or ionic strength of the aqueous solution.
- The tracers is detectable either by chemical analysis or by visualization.
- The tracer generates a low toxicological impact on the study environment.

Fig. 7 - Mixing and injection of tracer material into surface monitoring borehole BH1

The fluorescein dye 'Fluorescein Sodium' were selected for the dye tracer test and was injected at BH1 (Fig. 7). Fluorescein dye were used with concentration of 1500 ppm. The monitoring borehole was filled with about 650 litre of mix and was over filled with water to force it out into the fractured rock underground. Existing water in the borehole has been taken into consideration during calculation of concentration.

The dye were introduced on 20th March 2013 at 10 am. The injection wells were tested with potable water prior to dye introduction to measure the rate of intake. Mixing of dye was carried in grout injection machine for proper mixing and injected at zero bar pressure (i.e. gravity flow) (Fig. 7). Since piezometer (inner standpipe) is installed into the tested hole (BH1) therefore injection was carried out with inner tube of grouting packer. Prior to injection of dye, water was added first to wet the well casing/ pipe. This helped to prevent dye loss to inside surface of the well casing. The entire volume of colour dye was introduced in a single slug. The well was flushed further after completion of tracer injection. BH2 and BH3 have not been used as observation hole because inner diameter of these piezometers was too small to collect water sample through it.

6. OBSERVATIONS

Since the main purpose of this test is to identify the source of water leakage into cavern because of which ground water level near BH1 was gradually reducing, therefore, sampling or concentration calculation of tracer material was avoided because flow direction of water was not the concern. For identification of critical seepage zone, visual inspection was carried out on hourly basis after 12 hour of injection in all the caverns including water curtain tunnel (WCT). Main focus of inspection is around TD1 and FR3 (cavern B1 and B2). Due to fluorescent character of dye, UV lamp were used to identify tracer material by minimizing the other lights in concern areas. Logged water was observed carefully together with joints having dripping conditions.

Tracer material was first observed after 17:30 hour in cavern B1 (Fig. 8) followed by B2 at 21hour A2 at 26 hour and A1 at 32:30hour of injection along TD1 dyke. Figure 8 (left) shows the evidence of fluorescent material deposited at floor of the cavern and dripping water containing tracer material (right). As the time passes the concentration of tracer material was getting higher and after 2 days it was easily observed under normal lightning of tunnel.

Major appearance of colour dye was in B1 cavern followed by B2, A1 and A2 caverns had very minor concentration but still post grouting was done in all the caverns (Fig. 9) as precautionary measures. More than two rounds of post-grouting was carried out for TD1 in all the four caverns and FR3 was also grouted wherever tracer had appeared.

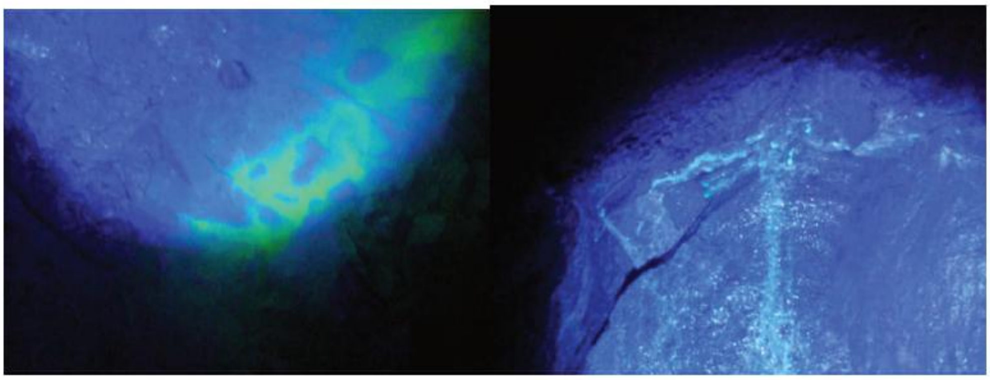

Fig. 8 -Appearance of fluorescent material in cavern B1

6. CONCLUSIONS

Identified lineaments were post grouted up to bench-1 because excavation status of all caverns were at bench-2 or bench-3, at that time therefore equipment limit had been reached. Cavern leg B1 had maximum concentration of tracer, therefore maximum post grouting was conducted in this cavern including bottom/ invert grouting for TD1 from bench 2 (Fig. 9). During grouting of FR3 zone, seepage water gets shifted from one joint to another, therefore grouting span as well as timing was increased (Fig. 9 & 10). Immediate response of ground water after each round of grouting was positive but during observation period of 20 days to one month it again started to decrease slowly (Fig. 12), so next round was planned accordingly.

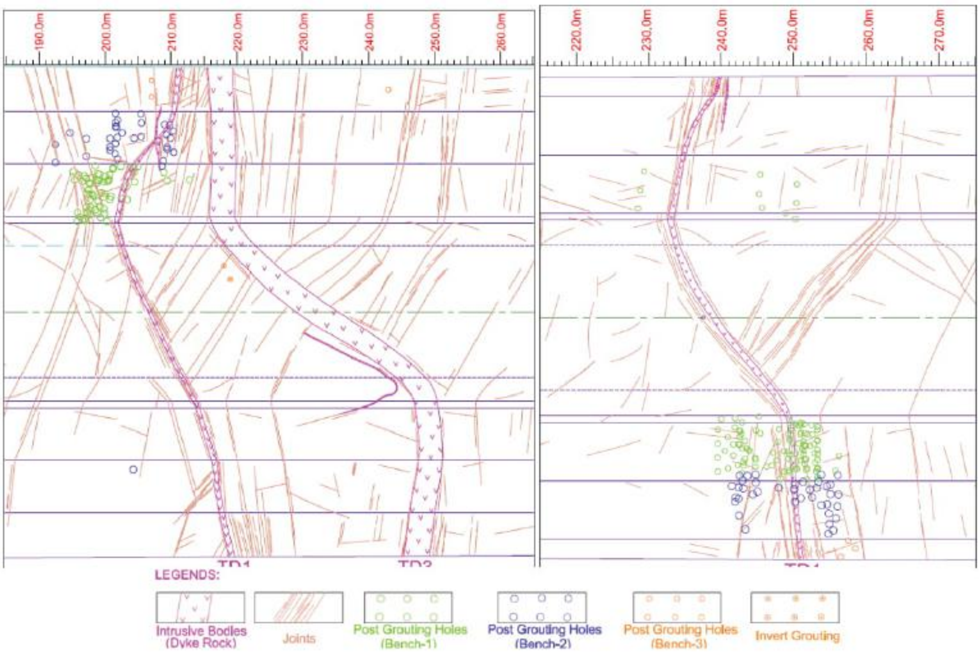

Fig. 9 - (a) post grouting locations in cavern A1 (b) post grouting location in cavern A2

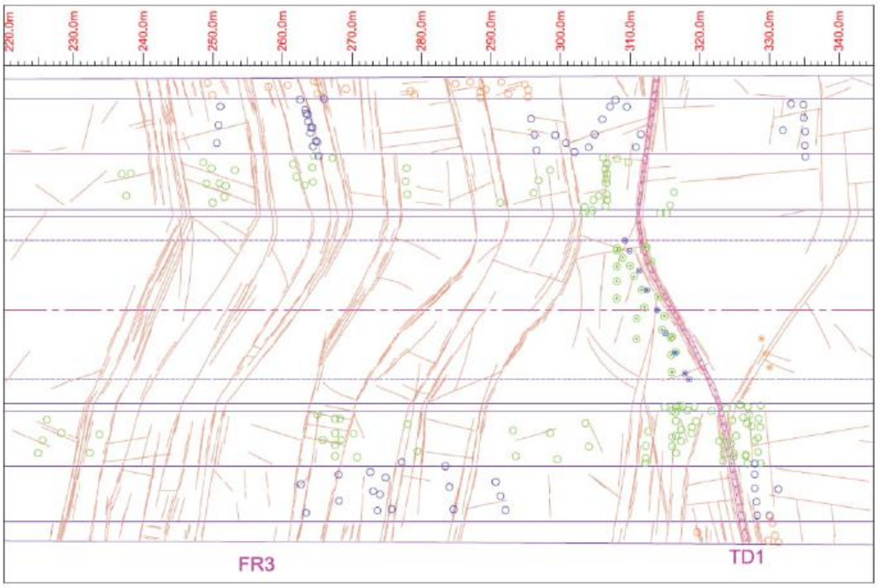

Fig. 10 - Post grouting locations (including FR3) in cavern B1

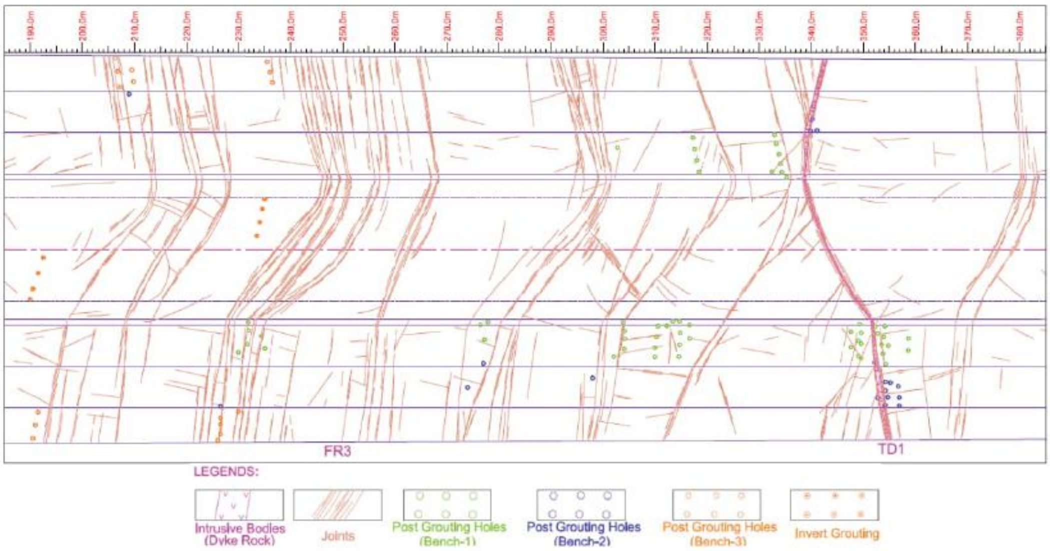

Fig. 11 - Post grouting locations (including FR3) in cavern B2

Parallel to post grouting, additional boreholes were drilled in WCT to stabilize the groundwater till the end of grouting. Effect of pressurization through additional boreholes was observed in ground water level as a quick rise. First set of boreholes (3 numbers to intersect TD1) was drilled in June 2013 in WCT 1 and second set of boreholes (10 numbers, to intersect TD1 and FR3 zone) was drilled in the month of august 2013 at WCT 2, which results in immediate rise in groundwater level (Fig. 12).

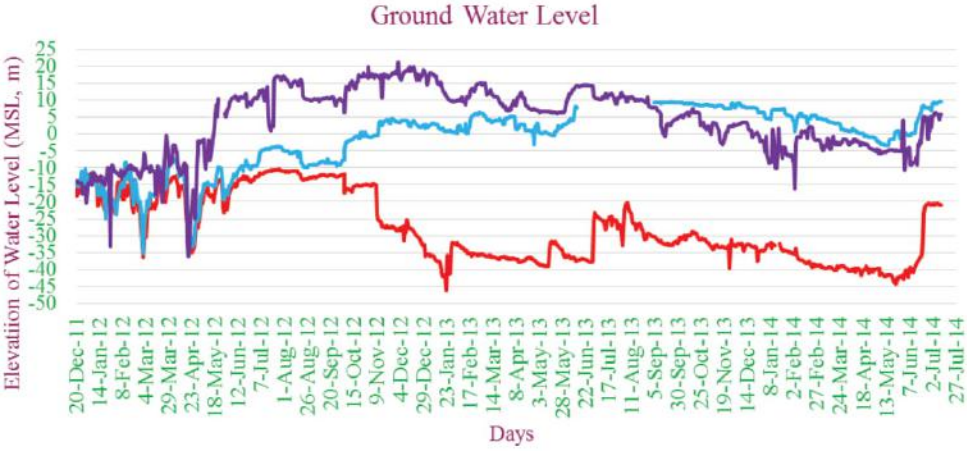

Fig. 12 - Recovered ground water level after grouting and additional borehole

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