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Post-Grouting in Unlined Underground Crude Oil Strategic Storage Cavern in India

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ABSTRACT

The containment of the stored hydrocarbon inside the unlined caverns is achieved by the hydrodynamic containment principle, which relies on the difference of pressure between the water in the rock mass and the stored hydrocarbon. This difference creates a flow gradient directed towards the caverns, thus preventing the stored hydrocarbon to penetrate the rock mass. The water flowing into the cavern, or seepage water, through permeable geological features is pumped out of the caverns during the whole life of the storage.

Nevertheless, the sealing of such discontinuities has to be planned with suitable grouting scheme as the same may cause (i) water impounding in caverns, (ii) loss of water head in access and water curtain tunnels, and (iii) lowering of groundwater table.

This paper discusses a case study on the performance of post-grouting for controlling huge seepage in caverns so as to maintain the water level in access and water curtain tunnel is presented.

Keywords: Hydraulic containment; Grouting; Storage caverns; Hydrogeological investigations

1. INTRODUCTION

With increase of oil and gas consumptions in India, the need of new import terminals with significant storage capacity was a critical aspect due to environmental constraints and, quite often, land restriction in the areas of interest. After the development of techniques to achieve hydrodynamic containment in unlined rock caverns, such caverns have been constructed in hard rock in many countries.

Government of India, taking into account the oil security concerns in India, had decided to set up strategic crude oil storages of 5.33 MMT at a total cost of Rs. 11,267 Crore (at Sept. 2005 prices) at three locations, namely:

- 1.33 MMT in in underground rock caverns at Vishakhapatnam in Andhra Pradesh, India;
- 1.50 MMT in underground rock caverns at Mangalore in Karnataka, India; and
- 2.50 MMT in underground rock caverns at Padur in Karnataka, India (2 packages).

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The containment of the stored hydrocarbon inside the unlined caverns is achieved by the hydrodynamic containment principle, which relies on the difference of pressure between the water in the rock mass around the caverns and the stored hydrocarbon in the caverns (Amantini et al., 2005). This difference creates a flow gradient directed towards the caverns, thus preventing the stored hydrocarbon to penetrate the rock mass. The water flowing into the cavern, or seepage water, through permeable geological features such as joints is pumped out of the caverns during the whole life of the storage.

Nevertheless, the sealing of such joints had to be planned with suitable grouting scheme as the same may cause (i) water impounding in caverns, (ii) loss of water head in access and water curtain tunnels, and (iii) lowering of groundwater table.

In the present study, a case study on the performance of post-grouting for controlling huge seepage in caverns so as to maintain the water level in access and water curtain tunnel is presented and the role of post-grouting in unlined storage caverns has been discussed.

2. PROJECT CONTEXT

The underground storage consisted of Storage A, comprising 3 U-shaped Storage Caverns namely Unit 1, 2 & 3 (700 x 20 x 30 m each), for storage of approximately 1.875 MMT high sulphur crude oil and Storage B, comprising 1 U-shaped Storage Cavern namely Unit 4 (656 x 20 x 30 m each), for storage of approximately 0.625 MMT of low sulphur crude oil i.e. with a proportion of 3:1. Each U-shaped cavern, with an approximate "D" shaped cross section, was designed to have a shaft with pump installations and pump pit, located at the end of one leg, a separate intake shaft shall also be provided at the end of the other leg. The cavern roof was horizontal along the full length and the invert is inclined from the intake to the pump pit to ensure a free flow (Fig. 1) (Mohanty et al., 2013).

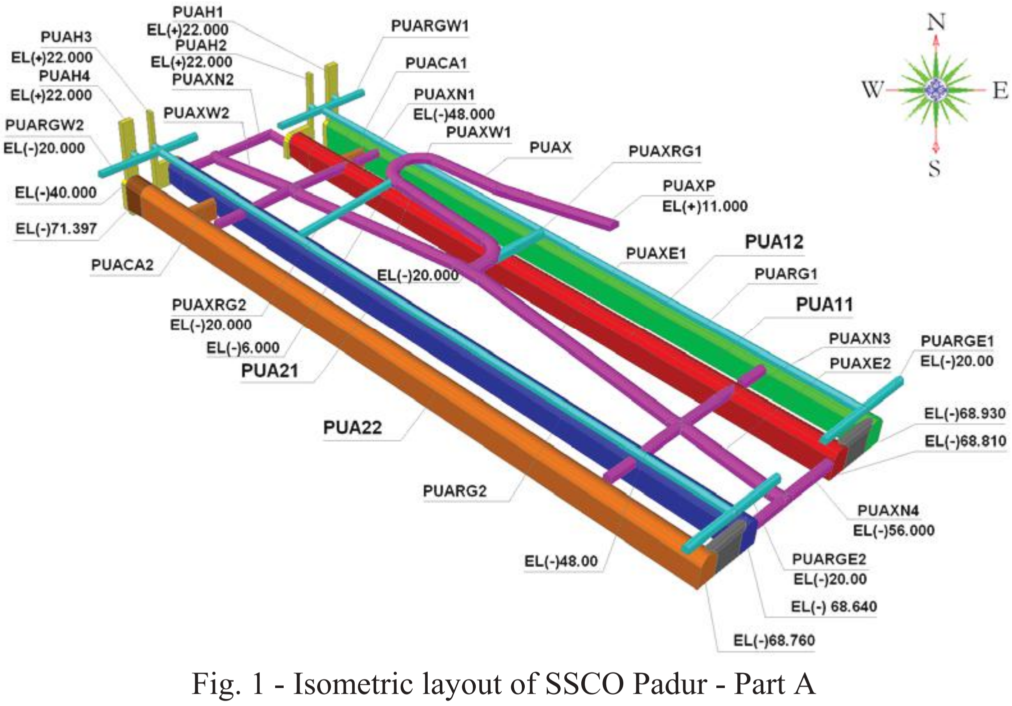

Fig. 1 - Isometric layout of SSCO Padur - Part A

3. GENERAL GEOLOGY

The project area lies within Dharwar craton and is composed of various types of rocks. Granitic Gneiss, in other words Peninsular Gneisses, belonging to this region are the most widespread group of rocks in Karnataka and many parts of southern India. They include granites, granodiorites, gneissic granites and banded or composite gneisses, the granitic constituents of which show distinct signs of intrusion. The banded gneisses consist of light bands composed of quartz, feldspar (felsic bands) alternating with dark bands composed of hornblende, biotite and minor accessories (mafic bands). Based on Barton's Q-system, rock mass classes were assessed, and based on rock support categories, as mentioned in basic engineering design, permanent rock supports were recommended (Fig. 2) (Sigl et al., 2014).

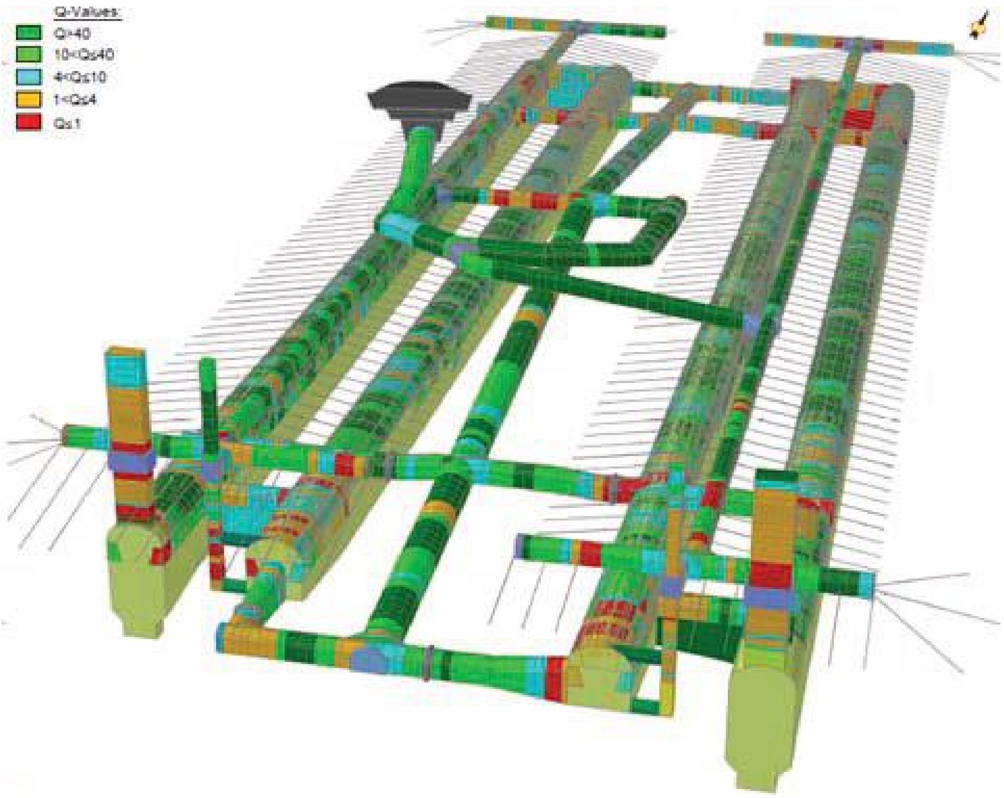

Fig. 2 - 3D model of the Q-value distribution in shafts, tunnels and caverns

4. HYDROGEOLOGY

During preliminary site investigations, the hydraulic conductivity studies (water pressure tests), short and long duration, were carried out for each rock formations, and the hydraulic conductivity profiles from all the water pressure tests were analyzed. The permeability of the soil and overburden were of the order of 10^{-5} to 10^{-6} m/s (low) whereas the permeability of the rock mass was of the order of 10^{-9} m/s (very low). However, rock mass with three plus random joint sets showed permeability of the order of 10^{-8} to 10^{-6} m/sec (low to very low), where-in a few horizontal joint sets showed permeability of the order of 10^{-4} m/s (medium). Sub-vertical and sub-horizontal mafic dykes showed permeability of the order of 10^{-4} m/s (medium) (Saikat et al., 2014). A very few geological features in the massive bedrock were actually water bearing and highly hydraulically conductive. Ground water table was ascertained to be at 10 m depth based on the monitoring of groundwater level throughout the year, especially in the dry season. This information formed the basis for design of water curtain system and finalizing the elevations of water curtain system and crown of the storage caverns.

A minimum hydraulic head equivalent to 20 m of water above the horizontal water curtain level was required to be maintained in order to ensure hydraulic gradient >1. The purpose was to prevent de-saturation of rock mass surrounding the cavern. Thus, impediment of uncontrolled inflow of groundwater in tunnels as well as conservation of the project were prepared based on the project geological model and various explorations during pre-investigation and construction stage.

5. WATER SEEPAGE ANALYSIS

The hydrogeological investigations (mainly, water pressure tests) included short duration, long duration and interference tests. The sub-horizontal joints were found rather difficult to grout and their residual permeability were in excess of the average bedrock permeability. In case of insufficient natural lateral supply for these joints, such situations could lead to insufficient containment during operation. It was, therefore, considered to introduce a vertical water curtain borehole system in between both storage units and also in between the storage units and surrounding access tunnel. Peripheral vertical water curtain system surrounding the storage units were also provided in order to maintain a continuous flow of water directed toward the caverns.

It was observed from the water pressure tests that while the overall bedrock covers 80% of the area, the final seepage values were mainly governed by the presence of dykes and horizontal joint sets. It was also inferred from the analysis that the permeability values considered for the horizontal joint set (5 x 10^{-7} m/s) were based on efficient grouting mechanism of the same during excavation, which otherwise could significantly change the final estimated values of seepage in caverns. The seepage estimation is shown in Table 1.

Table 1 - Seepage values for different rock formations (Kumar et al., 2015)

Rock formation	Seepage estimation (m^3/h)	
	During Construction (Atmospheric pressure)	During operation (Max. pressure, P_{max} = 1.6 bar)
Bed rock	24	16
Dykes and lineaments	67	45
Horizontal joint set	59	39

During construction, seepage encountered in different stages of excavation and the ingress quantity were classified into five categories as given in Table 2. It was observed that during excavation, there were 191 instances of seepage with magnitude less than 5 l/min. These observations revealed the intensity of seepage and efficacy of grouting which were conducted during excavation in Heading and Bench-1.

The design of ground water ingress in the project included two basic objectives:

- To ensure hydrodynamic containment, the static head of groundwater present in rock mass discontinuities must exceed the internal storage pressure. The minimum groundwater pressure should be 20 m higher than the internal storage pressure as per the criteria set forth in contract.

- The leakage control was achieved by maintaining a specified low permeability of the rock mass. To ensure efficiency of seepage water pumping during operation - residual seepage to be kept within 30 l/min per 100 m (maximum allowable seepage). Permeability must be preserved by artificially creating an impermeable zone surrounding the rock caverns by sealing the most permeable discontinuities in the rock mass by grouting.

Table 2 - Frequencies of seepage encountered during construction

Excavation Sequences	Seepage (<5l/min)	Seepage (5-10 l/min)	Seepage (10-20 l/min)	Seepage (20-50 l/min)	Seepage (>50 l/min)
Heading	111	31	9	3	5
Bench-1	43	3	3	6	0
Bench-2	30	0	0	0	0
Bench-3	7	0	0	0	0
Total	191	34	12	9	5

6. CONSTRUCTION STAGE GROUTING

In the project, pre-grouting was invariably preferred over post-grouting in high seepage zones. Thus, a mandatory probing scheme was worked-out before every excavation round in order to plan suitable treatment. At the site, pre-grouting was performed when the seepage in probe holes exceeded certain seepage criteria decided based on the acceptable design seepage, i.e., 0.3 l/min/m/bar of static water pressure. Based on the geological and hydrogeological model, specific mandatory pre-grouting zones were established, where such high permeable zones intersected the caverns. Systematic pre-grouting was performed in these zones wherever the caverns intersect them during various stages of construction. The grout design was planned in such a way that the grout holes reach 5 m beyond all sides of caverns including roof, wall and invert. The probing parameters and grout design can be interrelated as shown in Table 3.

Table 3 - Interrelation of probing parameters and grout design (Sigl et al., 2014)

Parameters Recorded/Interpreted	Input for Grout Design
Disposition of permeable joints	The grout holes were orientated to cut across the permeable joints and concentrated to tackle interpreted zone. In case of sub-horizontal joints, grout holes were drilled along the joints and inclined suitably.
Depth of water inflow	Location of grout holes with respect to tunnel face were planned to cover zone of rock bolt length to be installed above crown. For water source near to face (zone 1), 12 m long grouting holes were drilled from about 4 m behind the face to cover 5m above crown.
Rate of inflow (Q)	Grouting was recommended if Q > 0.3 l/min/m/bar. If local inflow > 100 l/min, grout with water cement ratio (w/c) of 0.5:1 was used. Otherwise, w/c 2:1 was used.
Static pressure (P)	Refusal pressure of grouting, Pr was P+15 bar
Drilling pattern	51 mm diameter, 12 m long grout holes at an angle of 20º to the tunnel periphery in both side of selected geologic features were drilled (fan-drilling). At the tunnel periphery, grout holes were drilled at a spacing of 1.0-1.5 m with inter-fan distance of 2.0-3.5 m
Grout type	Cement based grout was used. Grouting started in the bottom holes, then in the walls and finally in the roof. Grouting started with a low w/c ratio to seal the main part of leakage, and in second stage, screens directed opposite to the first stage screen with high w/c ratio.

6.1 Grout Injection Pressure

Maximum grout injection pressure was calculated on a running basis and checked against local conditions in the tunnel or cavern. High hydrostatic water pressure and existing backflow in very poor rock conditions at the face was considered to be the indicator that maximum pressure must be limited. Excessively high injection pressure could lead to surface fractures and consequently heavy leakage and, when working across a weak rock zone, could lead to displacements. Therefore, injection pressure was maintained from 5 kg/cm^2 to 15 kg/cm^2 above the natural ground water pressure at EL -20.0 m. However, in grout injection, the maximum allowable said-pressure was used from the beginning or alternatively until one of the following occurs:

Injection pressure/volume for mandatory pre-grouting zones (Low water bearing zones):

- When no more grout was accepted by the rock mass at maximum allowable injection pressure (Refusal pressure: Pr = Static pressure + 15 kg/cm^2), and when Qr <=0.30 l/min, injection has to be stopped.
- Before reaching Pr, if the maximum specified grout quantity (V1 = 250 kg cement) per a hole has been reached, then the water cement ratio has to be changed from 1:1 to 0.6:1.
- Injection has to be started with water cement ratio of 1:1 up to V1 of 250 kg of cement, thickened to 0.8: 1 up to V2 of 250 kg of cement and further thickened to 0.6:1 up to V3 of 250 kg of cement. If grout intake is more than V3, then a new borehole has to be drilled between the actual grouted boreholes, and the injection has to be continued as mentioned above.

- If even after V1, V2 and V3 quantity of intake, Pr could not be attained, the injection has to be stopped for 0.5 to 2 hours, after which injection has to be repeated over again based on site hydro-geological condition.

Injection pressure mandatory pre-grouting zones (High water bearing zones):

- Pre-grouting was continuous within each mandatory pre-grouting zone, including wall & final invert. Gaps were avoided in pre-grouting fans. Spacing and length of boreholes were constant as per the pattern. Zone for the pre-grouting were extended approximately 10 m outside of the expected true water bearing feature for safety.

6.2 Pre-Grouting

Pre-grouting was carried out when the water leakage was expected in the unexcavated section or leakage was identified after drilling probe holes. Based on the test conducted in probe-hole, pre-grouting was adopted for leakage more than 0.51/m/min/bar.

Pre-grouting was carried out in the area where leakage exceeded the permissible value as a result of probe hole in all the tunnels (including shafts) and where leakage was expected before excavation. A jumbo drill was utilized for drilling grout holes, and the length, direction and angle were decided by the shape, leakage structure distribution and excavation area per blasting of tunnel. The details of grouting are provided in Table 4.

Table 4 - Grouting time and grout consumption

Seepage (l/min)	Approx. control time (h)	Approx. cement consumption (MT)
<5	10	1300
5-10	15	
10-20	24	
20-50	36	
>50	60	

6.3 Post-Grouting

Post-grouting was carried out in the areas where the water leakage quantity exceeded the permissible value or where the guaranteed effect of water tightness was lowered in the excavated area. Decision on post-grouting operation was made on the basis of leakage quantity. If the leakage quantity exceeded the permissible quantity i.e., 400 kl/day, post-grouting was carried out. As post-grouting was a last step in controlling leakage at behind the excavation face, the drilling plan was finalized after considering the geological conditions at the site.

The methodology for post grouting was similar to that for pre-grouting. The grout holes were drilled at least 3-4 m away from the leakage point and the drilling directions were decided so that the hole intersects the leakage deep inside the excavation face on the basis of interpretation from probe holes logs. Grouting was carried out in such a way that the drill holes do not become leakage point at later stages of excavation. Therefore, post-grouting was required to maintain the hydraulic containment, reduce the dewatering quantity from storage cavern and minimize requirement of water to maintain the ground water table.

7. POST CONSTRUCTION STAGE GROUTING

7.1 Water Seepage Observations

High water seepage was observed in storage cavern unit 1 & 2. Some possible locations of seepage through geological features in Access tunnel were identified and located in the structural map (Fig. 3). By lowering of water levels in Access tunnel (AT), these locations were further investigated. These geological features were required to be grouted from access tunnel after lowering the water levels.

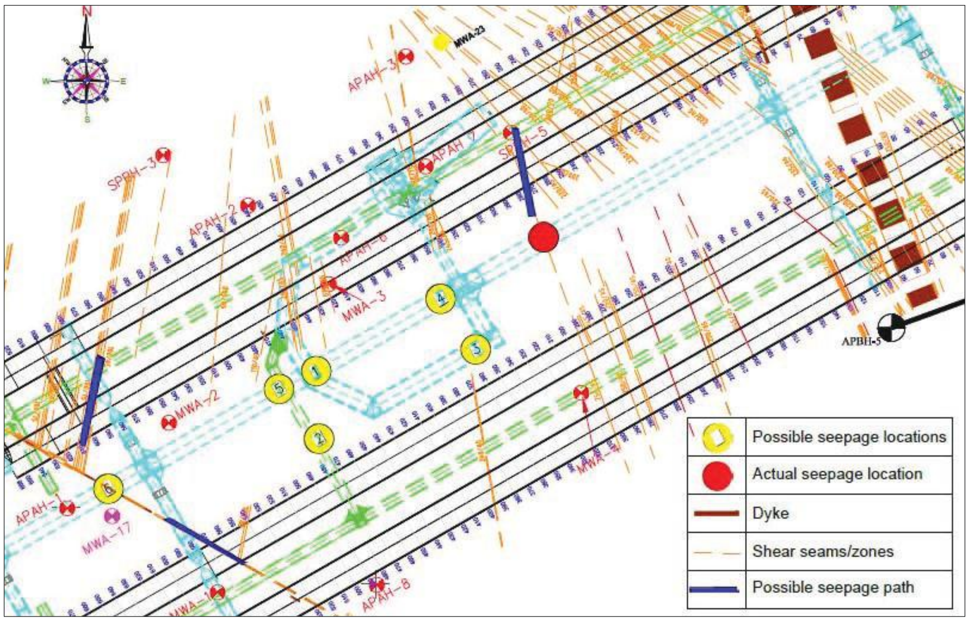

Fig. 3 - Possible locations of seepage during water level lowering

7.2 Water Pressure Test

Water pressure test was conducted at different elevations and locations of access tunnels and access of water curtain tunnel (Fig. 4). The result showed very low permeability in most locations, with exceptions in access tunnel EL -28 m, where it was difficult to build the required pressure.

7.3 Water Level Observations

In order to identify the location for seepage and subsequent grouting, water in access tunnel was pumped to specified levels and the following observations made during lowering:

1. Water in Access Tunnel (AT) was lowered till El. -7 m in both Water Curtain Tunnels 2 (WCT 2) and main AT, and the level was maintained at this level for 3-4 days by filing water on every alternate day during this period.
2. Further, water in WCT2 was lowered to El. -11 m and the level was maintained at this level by filling water on every alternate day.

3. Water in main AT was lowered to El. -21 m (both Access Tunnel East and Access Tunnel West) and the level was maintained at this level in AT west for 3-4 days. In AT east, water level was maintained at El. -21 m until lowering started in AT east.
4. However, water in WCT1 was lowered below El. -18 m. So, the existing wall was raised by another 2 m and the water level in WCT1 was raised & maintained at El. -16 m.
5. Water in AT west was lowered to El. -31 m and maintained at this level for 3-4 days.
6. Water in AT west was further lowered to El. -50 m and maintained at this level for 3-4 days.
7. Based on the observations, recommendations for grouting in AT west were evaluated.
8. Meanwhile after step 6 was finalized, water in AT east was lowered to El. -30m and water level was maintained at this level for 3-4 days.
9. Water level in AT east was lowered from El. -30 m to El. -50 m, but depending on the outcome of the above-mentioned study, water levels were kept constant at certain specified levels for 3-4 days.
10. Based on the observations, recommendations for grouting were evaluated for AT east.

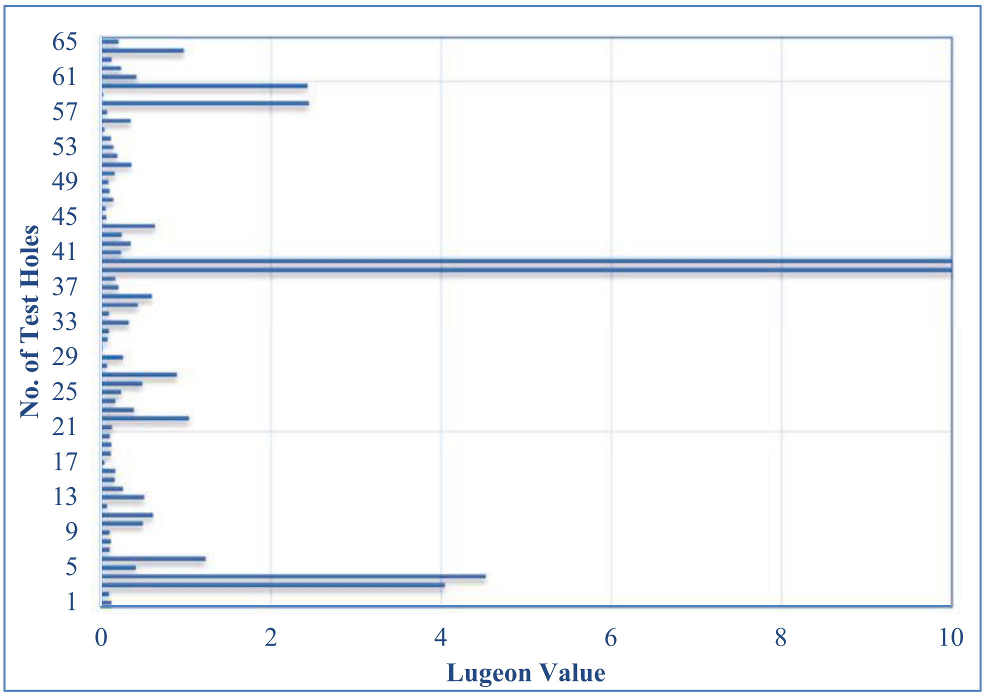

Fig. 4 - Water pressure test results in access tunnel before post-grouting

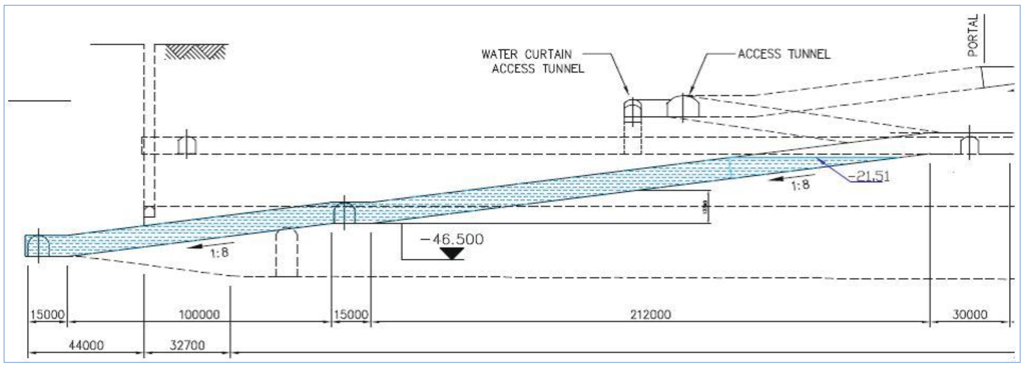

Fig. 5 - Typical sketch of water level lowering in access tunnels

7.4 Efficacious Performance of Post-Grouting

Since the hydrodynamic containment principle requires a permanent water flow arising from the rock mass toward the storage caverns, the risk of stored product migrating out of the caverns is higher than the risk of water flowing into caverns. But still, it is of the utmost importance to keep in mind that the amount of water flowing towards the cavern and ranging from several m^3/h to several tens of m^3/h. will have to be pumped out during the whole lifespan of the storage facility. For this reason, the risk of leakage at the plug area and all open and fractured joint was be properly managed and anticipated during both design stage and on-site works (Saikat et al., 2014).

After completion of cavern excavation, all temporary accesses were plugged by concrete barrier wall. The water curtain boreholes were sequentially dismantled and all access and water curtain tunnels were filled immediately by water to maintain hydraulic containment. The purpose was to maintain water level and water pressure which was build up by artificial pressurization system of water curtain boreholes. After filling of water in required level (El. +5.0 m), it was observed that drawdown of water level and the water volume of cavern unit 1 & 2 instantly increased with the same ratio as compared in access tunnel (Fig 6). Water seepage quantity was measured to be 255 kl/day in both the cavern units, which was permissible limit for dewatering during operation phase. Dewatering reduced the water in the cavern after which there was no loss in volume post-grouting operation. After water filling in access and water curtain tunnels at required level of El. +5 m, the water volume of storage cavern was increased as 2000 kl/day.

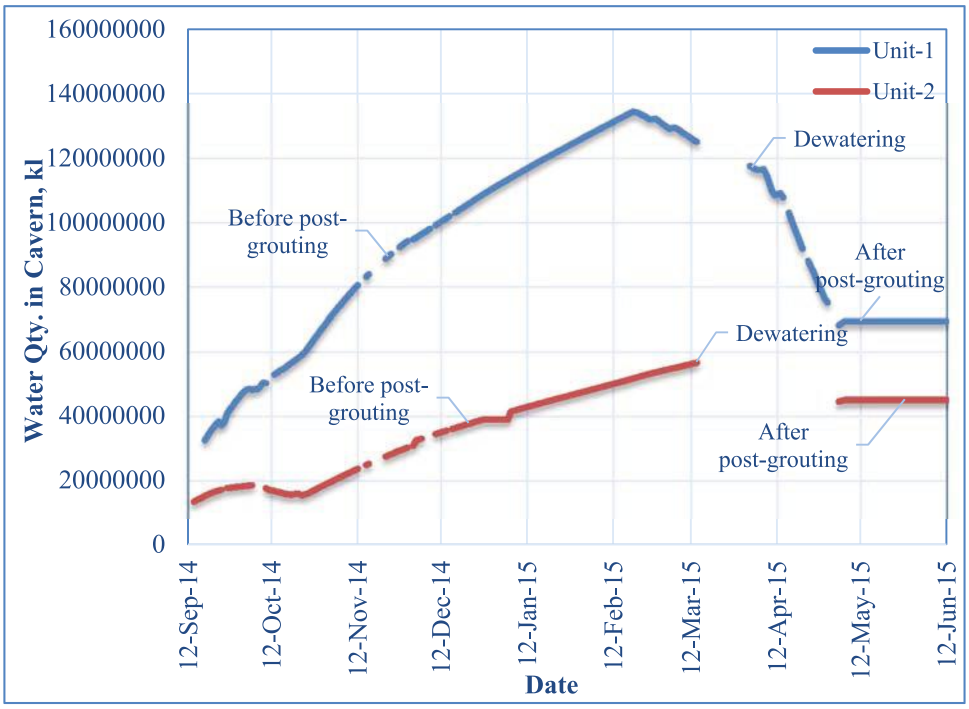

Fig. 6 - Seepage in storage caverns; before and after post-grouting

Dewatering pump installed in storage cavern was pre-designed to the capacity of 50 kl/h for the storage cavern unit. Final seepage was measured by weir gauge in both storage cavern unit. Final seepage maps and hydrogeological model updated before final closing the caverns and the result given in Table 5.

Table 5 - Final seepage in caverns

Seepage in cavern, l/min		
Unit-1	Unit-2	Total
115	62	177.00

8. CONCLUSIONS

In general, post-grouting works, which are significant part of underground structures like tunnels and caverns, are mainly performed to 1) reduce water inflows / permeability, and 2) improve groundmass stability.

The containment of the stored hydrocarbon inside the unlined caverns is achieved by the hydrodynamic containment principle, which relies on the difference of pressure between the water in the rock mass around the caverns and the stored hydrocarbon in the caverns. This difference creates a flow gradient directed towards the caverns, thus preventing the stored hydrocarbon to penetrate the rock mass. The water flowing into the cavern through permeable geological features is pumped out of the caverns during the whole life of the storage.

Nevertheless, the sealing of such discontinuities has to be planned with suitable post-grouting scheme as the same may cause 1) water impounding in caverns, 2) loss of water head in access and water curtain tunnels, and 3) lowering of groundwater table.

The case study in this paper revealed that the dynamic approach of continuously updating hydro-geological model was of immense help to plan post-grouting in an effective manner for controlling huge seepage in caverns so as to maintain the water level in access and water curtain tunnel.

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