Interventions for highly permeable tunnel parallel joints in underground storage caverns

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Abstract

Underground rock caverns created for storage of crude oil adopts the hydro-geologic containment principle. Containment of the stored product viz. crude oil is ensured by artificial recharge of ground water above the storage caverns by water curtain boreholes drilled from water curtain gallery. In one such storage project, completed in western coast of India, excavation of the water curtain gallery itself was challenged by presence of highly permeable joints striking sub parallel to the tunnel alignment and leading to water ingress of the order 300 to 400 litres/min. The handling of this joint system involved three aspects: excavation and rock support under flowing condition, monitoring of ground water table and predictive geological modelling of the feature for excavations of caverns or access tunnels at lower level of elevations. The excavation of the area was conducted by continuous systematic pre-grouting through directional grout holes. The rock support involved packer + rock bolts which served dual purpose of rock support and pressure grouting of rock mass. Monitoring of area was performed by installation of manometer in upward directed hole. The joints were modelled with help of data from water curtain boreholes, specially, by interpolation of traces of joints from the position of water leaks recorded during drilling of holes. The present paper outlines intervention of the excavation, rock support, monitoring and predictive geological model in course of negotiating the highly permeable joints and successfully overcoming the encountered geological challenge during construction of the underground storage caverns.

Keywords: underground storage caverns, water curtain boreholes, directional grout holes, predictive geological model.

1. Introduction:

Storage of crude oil in large mined rock caverns is one of the economical alternatives to secure energy security of import dependent countries.

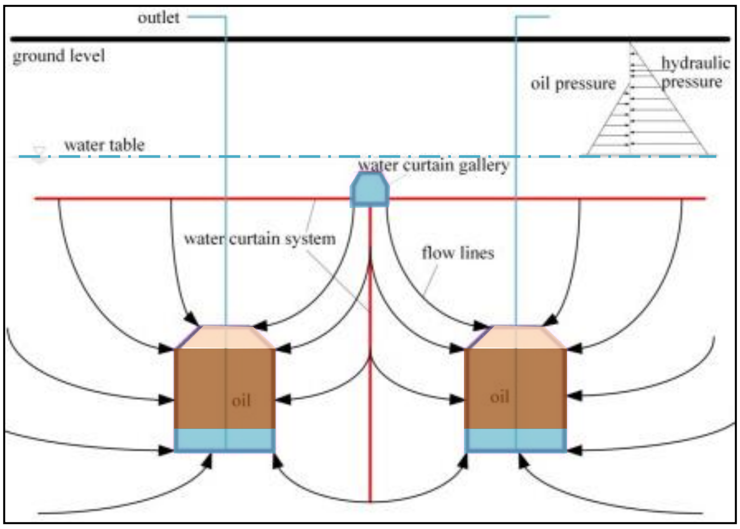

Figure 1 Schematic principle for unlined storage cavern

The principle of storage essentially employs hydrodynamic containment (Amantini et. al., 2005) of product within an unlined rock cavern where the tightness of storage is ensured by directing ground water gradients towards the storage caverns (Fig.1). In the process ground water table is maintained by uninterrupted artificial charging through water curtains so as to rejuvenate the ground water regime. As a part of design requirement, the saturation of rock mass is ensured during construction stage by charging water curtain boreholes (WCBH) 40-50m in advance of the cavern excavation. The construction sequence being excavation of water curtain gallery, drilling water curtain boreholes, charge them with water heads and then excavation of cavern. Thus, hindrance in excavation of water curtain gallery is indeed a critical path in the project completion schedule.

Large caverns (900m x 30m x 20m) are constructed by conventional drill and blast technique wherein sequential excavation takes place through top heading and different benches. The water curtains are constructed by drilling and charging horizontal as well as vertical boreholes encasing the storage caverns from small dimension water curtain tunnels above the storage caverns. In the present project inverts of water curtain galleries are designed to be 20m above the crown of the caverns. The caverns were housed in peninsular gneiss of west coast of India. The rock mass in general had low permeability of 10^{-9} m/sec or less. However, few joints and pervasive features had permeability as high as 10^{-4} m/sec.

2. The hindrance :

During excavation of the eastern part southern water curtain gallery, a zone of closely spaced open joints (VJ2 in Fig 2) was exposed from left (northern) wall of the gallery.

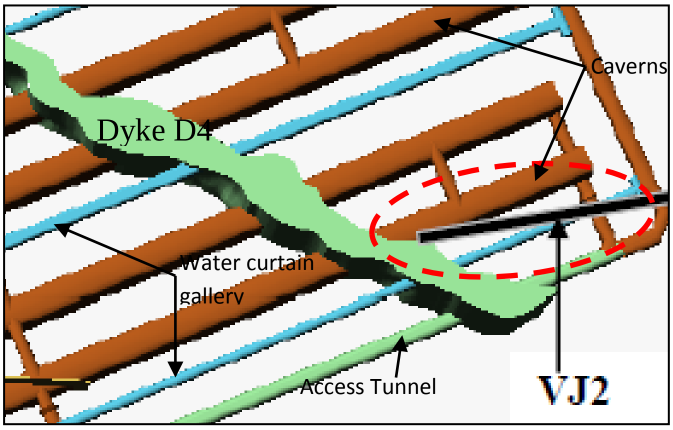

Figure 2 The permeable feature causing hindrance

The feature comprised of 6 to 10 m wide zone with sub-vertical open joints running sub-parallel to tunnel axis for more than 80m. It was observed the joints in the area were dipping in two virtually opposite directions forming a sort of conjugate joint set. The exact orientation of the flowing joints was difficult to differentiate due to close intricacy of the conjugate joints. Flow rates in the order of 300 to 400 l/min (under pressure of ~ 4 bar g) were met in several faces. The maximum permeability of the feature was evaluated as 1 x 10^{-5} m/sec.

The summary of salient features is tabulated in Table 1.

Table 1
Summary of Water Bearing Feature

Feature	Nature	Geometry	Permeability (m/sec)
Sub Vertical fracture	Fracture zone with open joints	Continuity >150m; Width 3-6 m; 200-210/75- 80° and 020-030/75-80°; Sub parallel to the water curtain and caverns-intersecting the tunnels at 10 to 20°.	1×10^{-5}

As a design principle, the water curtain galleries are to be flooded in the operation stage. Hence, grouting was to be limited to minimum possible in the water curtain gallery and was to be taken up only under following conditions (Pal et.al. 2015):

- Hindrance to carry out the excavation
- The inflow is affecting the water table.

In this case no immediate impact on local ground water table was revealed. However, the quantum of water obviously was difficult to handle for excavation and support works of tunnel. Hence, pre-grouting was necessitated in the area.

3. The excavation- grouting scheme :

The grouting of the area started with philosophy of drilling probe holes and check for criterion of grouting; full face fan grouting with grout holes of length equivalent to three rounds of blasting (10-12m); two rounds of excavation blasting followed by probing to check for further requirement of grouting (Pal et.al., 2014 & Kannan et.al., 2016).

This normal philosophy was however, not very effective in the study area. Apart from the high local inflow of water, the fracture being sub parallel to the tunnel alignment was difficult to carry out efficient grouting via the routine grout fans. The majority of grout holes were having probability of running parallel to fracture system. Often, grouting was necessitated before the stipulated third round of excavation, delaying the excavation works.

A grouting–excavation scheme was worked out specifically for the hindrance regime. It was planned to carry out the excavation of the span through systematic pregrouting of every face, without carrying out the routine probeholes. Also, to maximize the grouting efficiency, directional grout holes were considered to intersect the joints at high angle as much as possible. The grouting was made more focussed targeting the water bearing feature. This was done by:

- ✓ Reducing the length of grout holes from 12 to 5 m
- ✓ The grout holes are directed towards left with inclination of 15 to 30°with the tunnel axis (See fig 3.).
- ✓ Concentrating the fan to that half of the tunnel which contains the fracture zone

So, the sequence was Pre-grouting with modified grout fan, excavation of subsequent round, skip the check hole and start drilling the peripheral blast holes. If the water

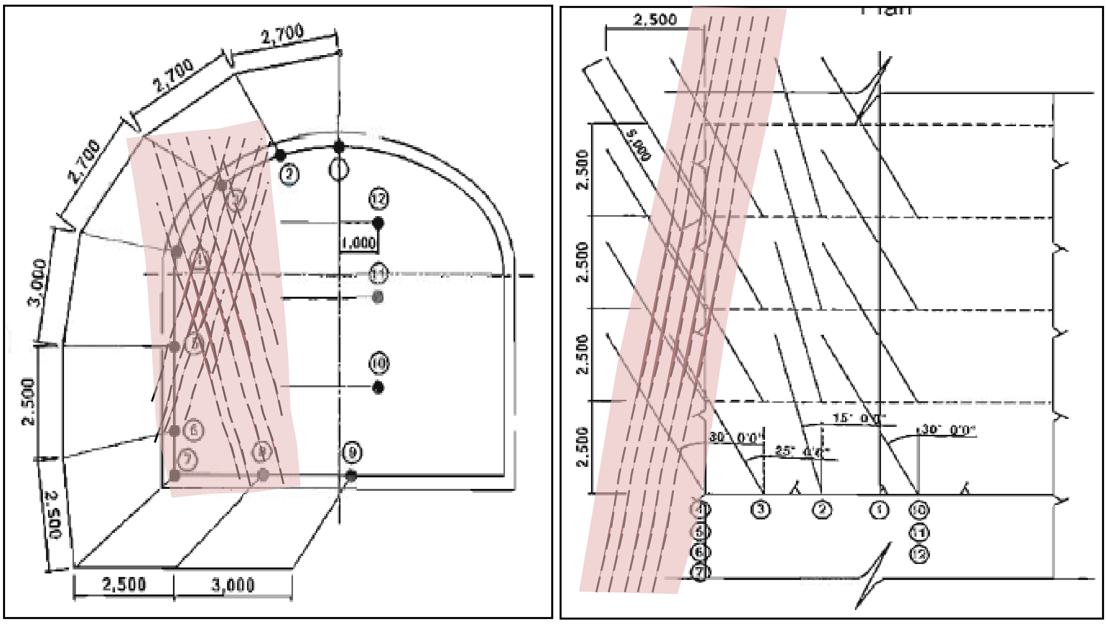

Figure 3 Sectional view of the grouting scheme

flow from the peripheral holes are within threshold limit (<1.5 l/min per hole), the drilling of other blast holes and subsequent blasting was taken up. In case the inflow was beyond the stipulated limit, re-grout to reduce inflow before blasting. The blasting was followed by next round of pre-grouting and so on. The work flow is given in the figure 4.

Total 30 rounds or sections of grouting had to be performed in the section. The grouting was done by OPC with Bentonite and fluidizer as additives. The water cement ratio varied from 2:1 to 0.5: 1 by weight. The maximum pressure of grouting was kept 15 to 20 bar g above the water pressure. The grouting was performed by Unigrout machine of Atlas Copco. The summary of grouting is given in Table 2.

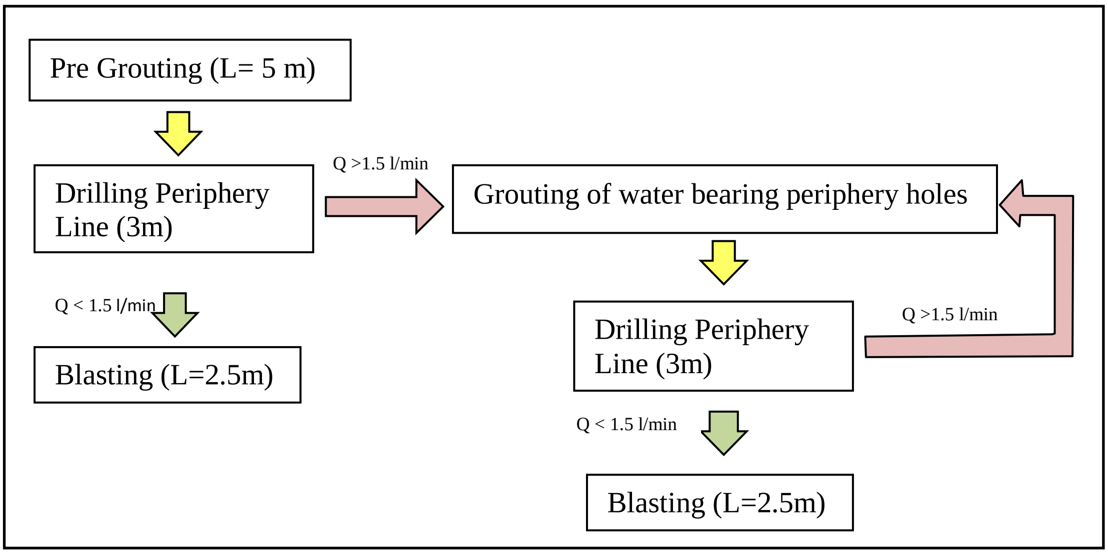

Figure 4 Work flow grouting-excavation scheme

Table 2
Summary of Grouting

Rounds of Grouting	Avg. Sectional Seepage (l/min)	Avg. Water Pressure (bar g)	Total Grout Volume (kl)	Total Dry mix (Tonne)
30	220 Max: 1100	3 Max: 5.2	43	26

4. Innovative Rock Support :

Followed by excavation, difficulties were faced during installation of rock support also. Many of the holes drilled for rock bolts were found with inflow of water. The initial scheme for rock support under such conditions were grouting the leaking hole, redrill a new hole in vicinity of the grout hole and install the rock bolt. The constraints observed following the method were:

- The leakage from multiple rock bolt holes lead to drawdown of ground water.
- The quantum of work increased as grouting of leaking hole had to be completed before rock bolt installation in new hole.
- The separate efforts for rock bolting and grouting involving manpower and equipment hampered progress.

In view of above, an alternative method for rock bolt installation in water seepage zones was conceived. The procedure named "Packer + bolt" was worked out with following schedule of activities (Pal et. al., 2016):

1. The bar to be inserted in hole and kept in place by using centralizers/slightly bending the bar.
2. Mechanical packer with gate valve to be installed at hole head.
3. Grout mix to be prepared with Water/Cement: 0.5 to 0.7 and added with fluidizer
4. Holes to be grouted, with pressure between 5 to 15 bar.
5. The valve of packer to be closed and allowed for curing.
6. Cutting projected packers.

The method of installation has been in illustrated below (Fig.5). The installations are shown in the photographs (Fig. 6).

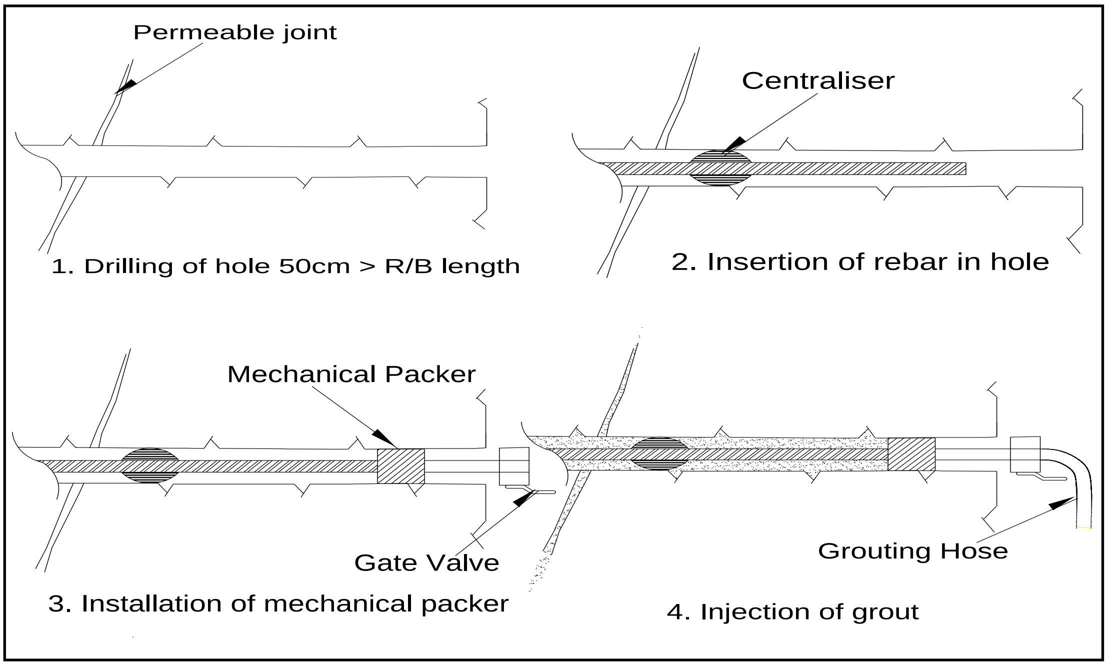

Figure 5 Procedure of installation of Packer + bolts

Figure 6 Installation of Packer + bolts at site

5. Monitoring :

Even though very high water loss was noticed during excavation of the gallery, ground water level of the surface piezometers, placed at 80-90 m above the gallery, in adjacent areas of the project was not reflecting any drawdown. It was therefore necessary to confirm the stability of ground water head immediately above the gallery in the water loss area.

In view of above, an underground manometer was proposed to be drilled in upward direction from the water curtain gallery in order to monitor the pressure drop consequent to drop in head. The 20m long manometer was drilled inclined at 50° in upward direction (Fig 7).

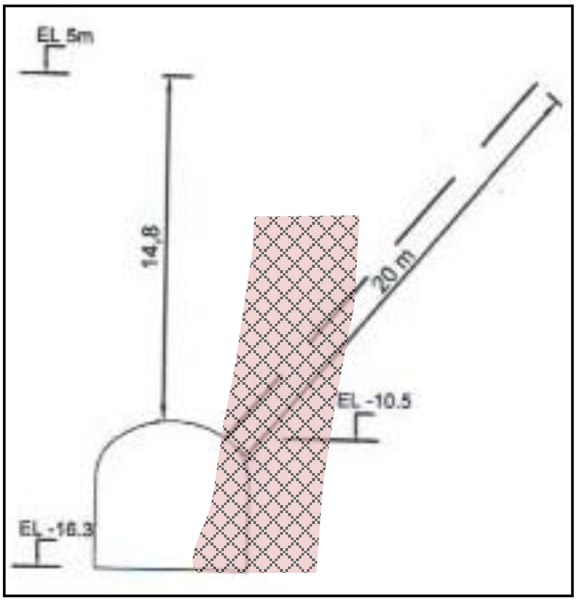

Figure 7 Upward manometer for monitoring drawdown

After installation, the pressure gauge of manometer showed a pressure of about 3 bar g and decreased gradually indicating a drop in equivalent water head as result water inflow episodes. This was recovered by grouting episodes. However, with increasing quantum of grouting in the area, the pressure gauge stopped showing any pressure as successive grout fans isolated it totally from the water table above.

6. Predictive Geology :

The predictive geological model, an absolute requirement for excavation planning of the project, was even more important in case of the above feature. If, the features were dipping towards north, they would be encountered while cavern excavation and thus necessitating pre excavation grouting to prevent excessive seepage in the cavern. Whereas, if the joints were dipping southward, they would be negotiated in the access tunnel on south of the gallery. As the access tunnel was to be flooded during the operation, the pre-excavation grouting requirement would be of much less quantum.

The exact orientations of the conductive joints were supposed to be inferred from the acoustic Borehole tele-viewer (BHTV) to be conducted in the vertical water curtain boreholes, drilled from the floor of the gallery, in that area. Unfortunately, due to heavy backflow of water from the holes, the BHTV probe could not be run inside the borehole.

Consequently, a more basic principle was adopted to interpret the dip direction of the flowing joints. The depth of water inflow recorded during drilling of the adjacent vertical water curtain boreholes in the area were plotted as per scale. Now, the inflow points were connected, keeping in mind the possible apparent dip trace of both set of conjugate joints in the vertical plane of water curtain boreholes (Table 3).

Table 3
Traces of conjugate set

Joint set	Avg. orientation	Angle of intersection with tunnel	Avg. Apparent dip in plane of vertical holes
1. S Dipping	200-210°/75-80°	10-20°	30-50° towards west
2. N Dipping	020-030°/75-80°	10-20°	30-50° towards east

The interpolated surfaces clearly indicated that the main water-conducive joints were dipping southwards (Fig 8). This prediction helped to confirm the plan of adjacent cavern excavation, without much requirement of pre-excavation grouting. The prediction was confirmed by negotiating the joints during excavation of the access tunnel.

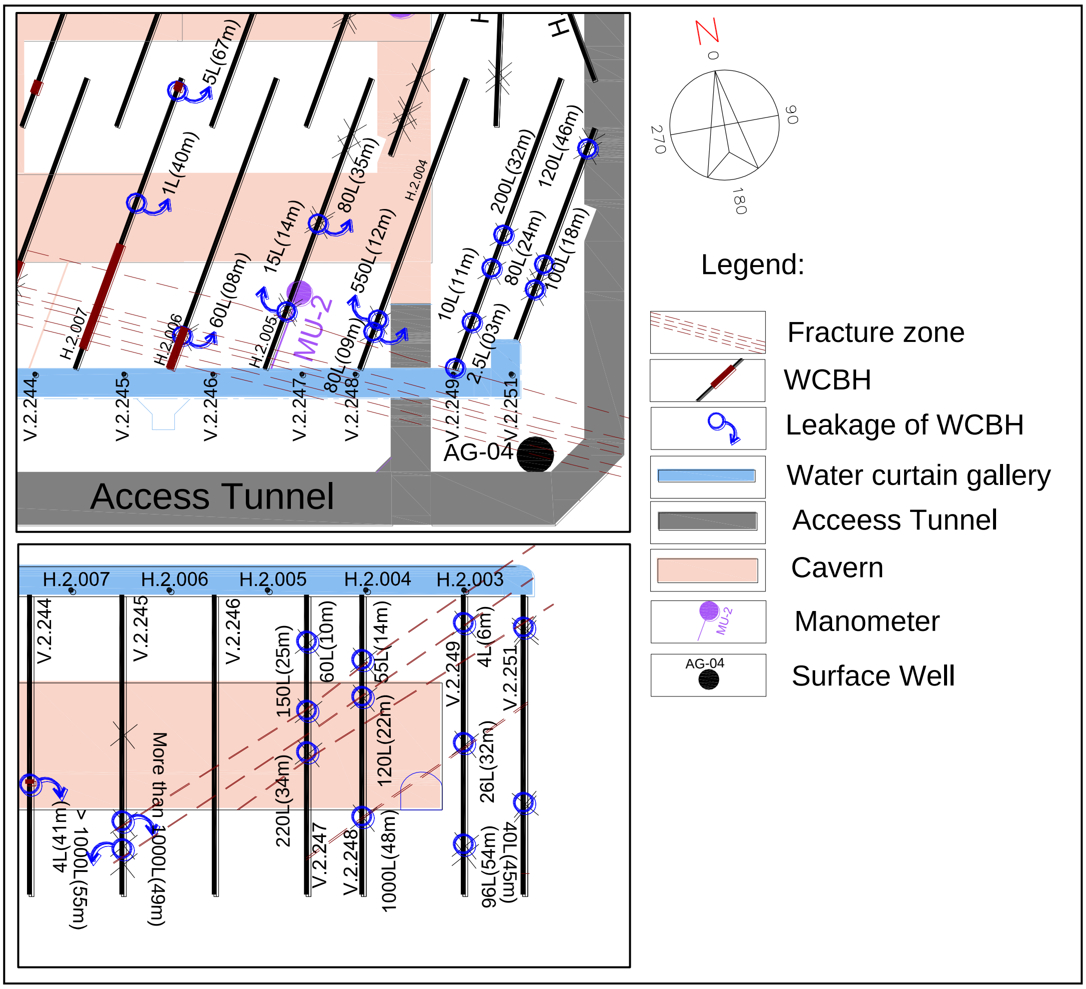

Figure 8 Plan and Section of fracture zone

7. Conclusions:

Tunnel parallel water bearing joints can pose serious challenge for successful excavation of tunnels more so when depletion of water table is undesirable. The intervention made in excavation, grouting, rock support, monitoring and predictions in case of the highly permeable and yielding tunnel parallel joints helped to minimize the time and cost overrun in the project. Documentation of the same is important to surmount similar impediment in future projects

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