Handling ground water ingress in underground storage cavern

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ABSTRACT: Underground construction remains ever challenging job due to ground uncertainties. Ground water ingress during excavation is most uncertain factor owing to wide variation of ground permeability In case of underground storage caverns, working on principle of hydrodynamic containment, the most important impact of ground water ingress may be drawdown of ground water table which leads to desaturation of rockmass. Apart from this, the total seepage in cavern has to be restricted to threshold limit according to capacity of pumps installed for dewatering of seepage water. Probe holes, water curtain tunnels and water curtain boreholes are important prediction tools for storage cavern excavation. Effective probing helps in optimised design of grouting and reduces risk exposure. The efficiency of grouting can be evaluated by regular measurement of ground water levels as well as seepage measurement within caverns. The present paper outlines the approach of probing and grouting, with case specific treatment of permeable contacts of dolerite dyke, adopted for a large underground storage caverns recently excavated in West Coast of India.

KEYWORDS: *Probing, Water curtain boreholes, grouting design, seepage measurement.*

1. INTRODUCTION

In unlined underground rock caverns excavated for storage of crude oil, the product is kept confined within caverns by principle of hydrodynamic containment (*Amantini et al 2005*) wherein the natural ground water potential towards caverns is enhanced by artificial recharging. The recharging is done by making small dimension galleries above the cavern and water curtain boreholes (WCBH) drilled from gallery (Fig 1). This is known as water curtain system. In the field of underground space technology, continuous advancements are made with respect to ground prediction techniques, equipment and instrumentation. However, underground construction of tunnels and caverns are challenging job by virtue of uncertain ground conditions. Ground water ingress during excavation is one of the major uncertainties. In the aquifer of jointed hard rocks, the permeability varies over wide range (10^{-9}m/se to 10^{-4} m/sec). The water affects the stability and deformation of tunnel by reducing the effective stress and thereby resistance to shearing, generates seepage forces towards excavation boundary and may lead to draw down of water table *(Anagnostou 2006).*

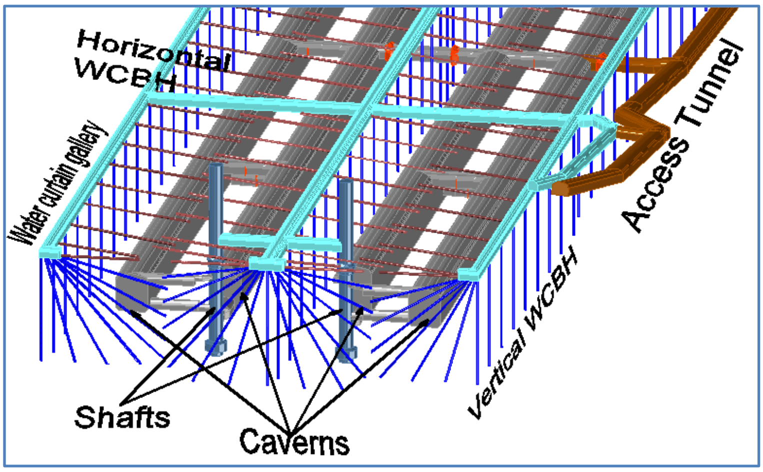


Fig 1 Layout of Project

In case of storage cavern, the effects of ground water ingress are:

- Instability of structures due to ground water: similar to all other forms of underground excavation
- Ineffective hydrodynamic containment: water loss through excavated areas, hinders the groundwater table conservation and threatens the de-saturation of rockmass.
- Increase in water curtain intake
- Increase in seepage quantity with respect to Design dewatering pump capacity

The two way approach of handling such adverse effects are:

1. Groundwater control by prediction through probing and reducing rockmass permeability through pregrouting.
2. Artificial, pressurised water injection or infiltration through “water curtains”, in the ground adjacent to the cavern openings.

The present paper is limited to first method of ground water control.

2. PROJECT HYDRO-GEOLOGICAL MODEL

A hydro-geological model of the project was prepared based on the project geological model and various explorations during investigation and pre-construction stage (Usmani A. et. al. 2010).

The project is one of the storage caverns, excavated in western coast of India. It is located in granitic gneiss belonging to the Peninsular Gneissic complex of Archaean age and is seated in a hilly terrain with thick laterite and lateritic soil at the top followed by weathered and fresh granitic gneiss. The permeability of the soil and lateritic portion is high of the order of 10^{-5} to 10^{-6} m/sec. The rock is strong granitic gneiss with 2-3 sets of sub vertical and a set sub-horizontal joint. The parent rock has been intruded by dolerite dykes of variable orientation and thickness. The permeability of the gneissic rock is very low of the order of 10^{-9} m/sec but some joints 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 had permeability of the order of 10^{-6} to 10^{-7} m/sec.

These permeable joints acted as water carrier during underground excavation. During excavation, the hydro-geological model was constantly updated by:

- Structural projections of permeable features
- Updating probing and grouting detail
- Updating the seepage points
- Updating permeability values of all WCBH and manometer holes drilled from underground; and
- Correlating all above data.

3. PROBING: PREDICTING TOOL FOR GROUT DESIGN

Locating water bearing features ahead of cavern excavation face helps to plan judicious treatment. The process starts through geological and hydrogeological investigations in the feasibility stage and continuously updated through the construction stage. Probe holes play the role of important investigation tool while excavation.

Continuous systematic probing was envisaged during design and planning stage with provision of probing kept for each alternate faces. Probe holes, 10-12m long destructive drill holes, were drilled ahead of excavation faces. This was done by extension of 3.5 to 4m long drill rods. The distance covered each rod were treated as separate zones. The holes were 2 to 3 in numbers depending on the surface area of excavated face.

For underground rock caverns, water curtain boreholes have to be drilled from water curtain galleries at level above caverns. Once, excavation of water tunnels are done, the small dimension tunnels act as pilot and help to decipher the hotspots in terms of geology/hydrogeology. Also, array of boreholes drilled from sidewall and invert of water curtain tunnels provide valuable information particularly for features in vicinity to side wall of the caverns. The information from water curtain tunnel and water curtain boreholes are integrated to shape a nearly accurate hydro geological model with prediction of major permeable features before start of excavation of caverns. The probeholes done during excavation of main caverns were more for confirmation and/or precision of the predicted features and could be optimised limited around predicted features. So probe holes, done during the entire project, could be categorised to following types:

- **Predictive**: done ahead of the water curtain tunnels.
- **Confirmative:** done ahead of caverns

Effective probing depends on understanding of discontinuities relative to tunnel geometry. This helps to reorient the holes as well as to analyze the results properly. The orientations of probeholes were designed to be parallel to tunnel alignment. However, in areas with sub-horizontal permeable joints, the probeholes were inclined suitably to negotiate the features (**Fig 2**). The alignments of major sub vertical joints wrt to the cavern are shown in (**Fig 3**). It is evident from figure if water is found from all three or 2 probeholes, the permeable feature was likely along J1, whereas, if water is from any one hole towards one particular wall, the permeable feature was considered J2 or J3 accordingly. In case water was indicated from different depths from probe holes at different heights, the permeable joint was taken to be inclined towards or away from the face. However, probability for predicting unknown sub-horizontal joints were through probe holes was relatively lower.

The following parameters were recorded for all probeholes:

1. Rate of drilling (time of drilling)
2. Colour of sludge,
3. Water flow, if any.

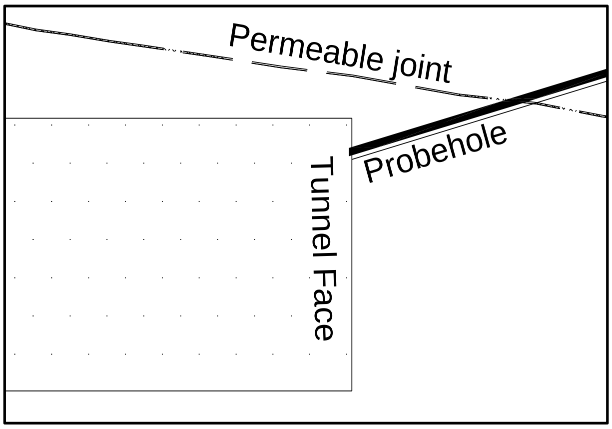


Fig 2 Probe hole oriented to encounter sub horizontal joints above crown

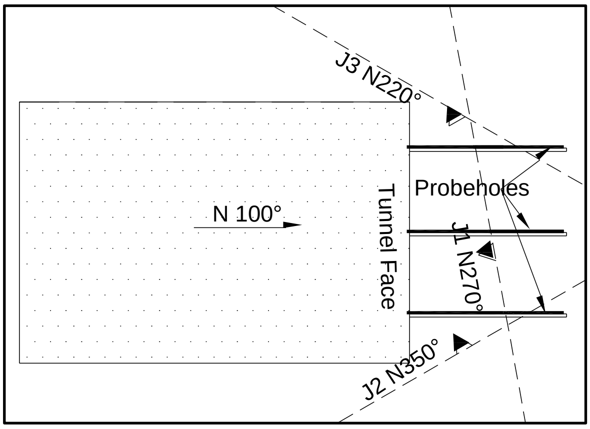


Fig 3 Plan of tunnel showing relative trends of major discontinuity and probeholes

Once, water flow was observed from a probehole, further information was recorded to substantiate:

- Depth of water flow (from zone 1, zone 2 etc.)
- Rate of flow in litre/min
- Static pressure of water

The parameters help to assess rock condition in terms of the distance, nature and potential of water bearing feature ahead of the tunnel and the grouting could be planned accordingly. The interrelations have been explained in table below

Table 1 Interrelation of probing parameters and grout Design

Parameters recorded/interpreted	**Input for Grout Design**
Disposition of permeable joints	Orientation and quantity of grout holes: The grout holes orientated to cut across the permeable joints and grout holes are concentrated to tackle interpreted zone. In case of sub-horizontal joints, grout holes are done along the joints and inclined suitably (**Fig 4 & 5)**).
Depth of water inflow	Location of grout holes wrt tunnel face: planned to cover zone of rock bolt length to be installed above crown. For water source from near to face (zone 1), the 12m long grouting holes were drilled from about 4m behind the face to cover 5m above crown (**Fig 6**).
Rate of inflow (Q)	✓ To take decision for grouting: Grouting if Q>0.3l/min/m/bar ✓ To decide initial water cement ratio. If local inflow > 100l/min, thicker grout with 0.5 to 1 used. Otherwise, W/C 2:1 used
Static Pressure (P)	Refusal pressure of grouting- general guideline was P + 15bar

Fig 4 Water ingress along sub-horizontal joints

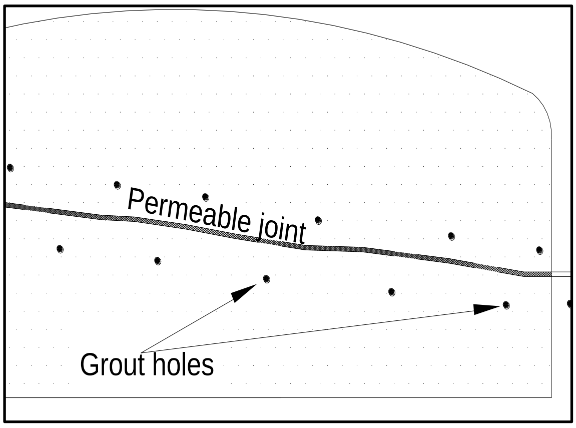


Fig 5 Grout holes along sub-horizontal joints

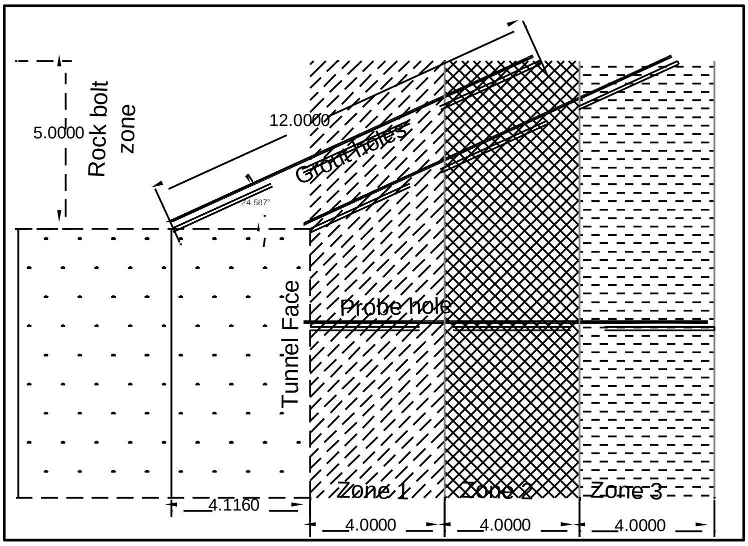


Fig 6 Grout holes according to zone of water inflow from probeholes

4. EFFICIENCY CHECK

The efficiency of handling ground water ingress in the project were designed to monitor the two basic objectives:

1. To ensure hydrodynamic containment
2. To ensure efficiency of seepage water pumping during operation- residual seepage to be kept within 30l/min per 100m (maximum allowable seepage).

The first objective was monitored through daily hydro-geological monitoring comprising of:

- Ground water level through surface piezometric wells
- Hydraulic potential measurement from underground WCG by manometer and pressure cells. These were installed adapted to monitor identified major water bearing features (**Fig 7)**.

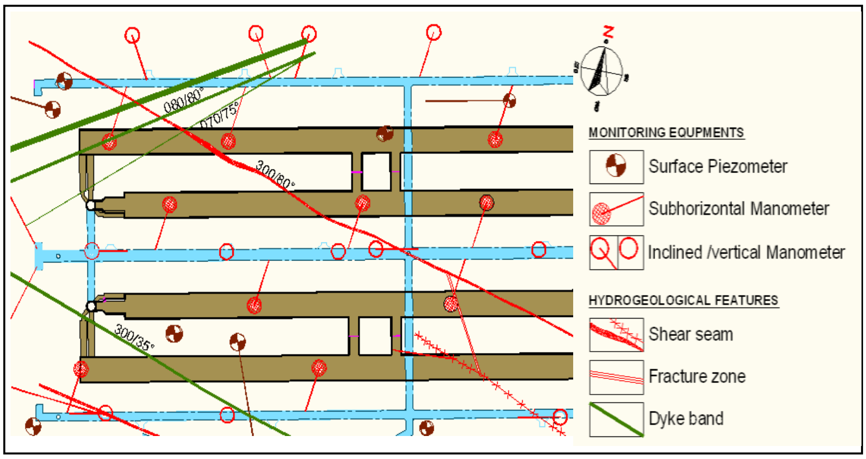


Fig 7. Hydro-geological monitoring plan of manometers and piezometers

- Pressure and water intake measurement of all WCBH to understand the groundwater balance of seepage versus recharge (natural and artificial).

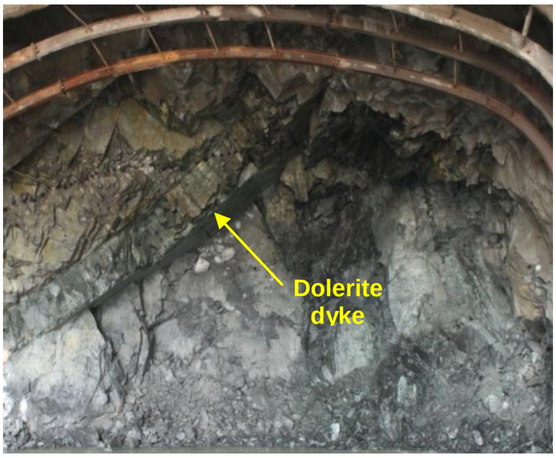
The second objective was monitored by seepage measurements through following methods:-

- ➢ Indirect seepage measurement- the daily difference of outgoing and incoming water assessed by using flow meters.

- Measurements from individual seepage points - the total seepage from individual seepage points on crown and walls were mapped and measured monthly to have an idea about change in locality as well as quantity of seepage.
- Direct seepage measurement_– the total seepage measurement in isolated sections. Isolation was done by constructing concrete/clay weirs across the gallery.

5. CASE SPECIFIC GROUTING STRATEGY

In the present project, a 0.5 to 1m thick, moderately dipping (30 -40°) dolerite dyke body with was negotiated during excavation of water curtain tunnel and access tunnel (**Fig 8**). The contact of the dyke with country rock was permeable of the order of 10^{-5} to 10^{-6} m/sec. This hydrogeological feature was projected along entire cavern section using 3-D Geological Model (**Fig 9**). Thus the expected chainages for the features could be known for each bench level. Provision for probing were kept ahead of excavating the expected chainages, with safety margin of some



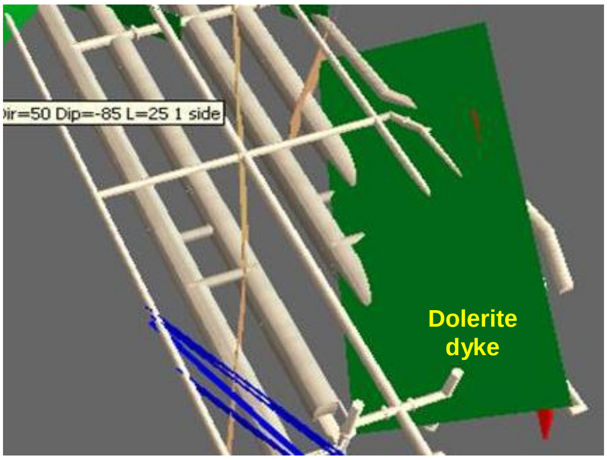


Fig 8. Dolerite dyke with permeable contact

Fig 9. 3-D Projection of feature

Once the disposition of major hydrogeological features was finalized, grouting was concentrated in the zones where the features are anticipated to be negotiated in the respective elevations (**Fig 10)**. Accordingly, pre-grouting plan of all benches was made. Side wall pre-grouting form higher bench were carried out in the identified zone with sub vertical grout holes directed to intersect the feature and constitute grout curtain to cut off wall seepage. Invert pre-grouting from last bench was carried out with target to cut off seepage up to depth of 5m below invert.

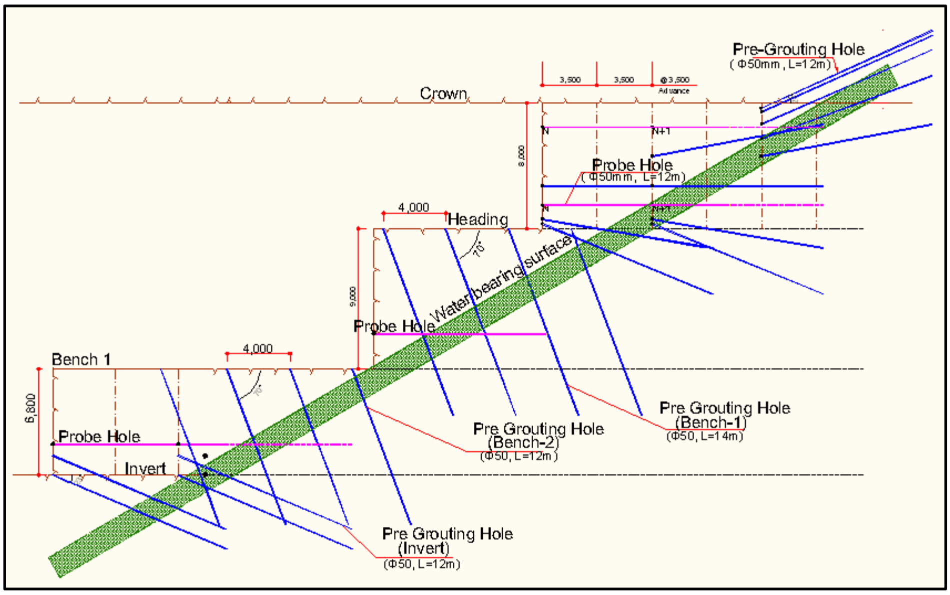


Fig 10 Schematic grouting in different stages of excavation wrt identified water bearing feature

Grouting following this principle was targeted to create a low permeable zone around cavern periphery at the zone of intersection with the high permeable features.

6. CONCLUSION

The dynamic approach of continuously updating hydro-geological model was of immense help in correct & timely anticipation of hydro-geological features. This aided to readiness of addressing situations. This also helped in expediting the work pace by optimization of activities like *probing*. The ground water ingresses during excavation of the project were handled by judicious combination of probing & *grouting*. The ground water level was in between 30m to 80m above horizontal water curtain level as against requirement of minimum 20m above water curtain level. The residual seepage measured in the storage caverns was between 20-25 litre/min/100m against requirement of 30 litre/min per 100m.. Thus the basic criterion of saturation of rock mass required for hydrodynamic containment was maintained and at the same time the overall seepage was controlled within the designed capacity.

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REFERENCES

1. Amantini E., Francois C., Anne M. (2005): Groundwater management during the construction of underground hydrocarbon storage in rock caverns, 9th International Mine Water Congress (IMWA 2005).
2. Anagnostou G.(2006):Tunnel stability and deformations in water-bearing ground- Keynote Lecture Eurock 06, ISRM Symposium, Belgium 2006.
3. Grøv E., *Blindheim T. & Trondheim AS,: “* Water control in Norwegian tunneling”, Proceedings of 2nd Brazilian Conference on tunnels and underground sturctures.
4. Pal Saikat, Kannan G, Shahri Vijay and Nanda. A. (2014): Ground water management for large underground storage caverns, Accepted for XII Congress, IAEG, Torino, Italy 2014.
5. Usmani A., Nanda A., Kannan G., and Jain S.K. (2010): “Hydraulic Confinement of Hydrocarbons in Unlined Rock Caverns”, ISRM 2010, Delhi, India.
6. Usmani, A., Kannan G., Nanda A. & Jain S.K., “Seepage assessment in tunnels under different field conditions”, Proceedings of Indian Geotechnical Conference”, Dec 13-15, 2012, New Delhi.