A Study on Grout Estimate for Crude Oil Storage in Rock Caverns

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ABSTRACT

Underground mined-unlined rock cavern is one of the economical alternative for buffer storage of crude oil to ensure energy security of import dependent countries. The principle of such storage employs hydrodynamic containment of the product. As the large rock caverns are excavated by conventional drill and blast method, the groundwater management is of utmost importance to conserve ground water and avoid inadvertent de-saturation of rock mass. This is added to the constraints due to inflow of water during excavation of rock mass like other underground projects. Consequently, grouting forms an important aspect during planning, investigation and subsequent construction stages and estimate of grout intake during project planning is a significant component of project cost.

The present paper focuses on grouting during construction for a storage cavern excavated in West Coast of India. In the process it highlights early identification of permeable structural features, the adopted grouting philosophy with case specific treatment of permeable geological features and an attempt to estimate design correlation of grout intake based on seepage inflow of the permeable features identified during investigation stage.

Keywords: Hydrodynamic containment; Water curtain; Water carrier; Grout fan; Grout intake

1. INTRODUCTION

The principle of storage of crude oil in large unlined-mined rock cavern ensures tightness of product by directing ground water gradients towards the storage caverns (Amantini et al., 2005). This is known as hydrodynamic containment. Water, incoming through permeable rock joints, prevents crude from escaping through the joints. The unlined storage caverns are constructed below natural ground water table. The ground water level during construction and operation stage of the cavern is maintained by uninterrupted artificial charging of water curtains so as to rejuvenate the ground water regime. The water curtains comprise of water curtain galleries (WCG) and horizontal & vertical water curtain boreholes (WCBH) drilled from these galleries. These WCBH are charged with water and encases the storage caverns. The project under discussion comprises of four large caverns (900m L x 20m W x 30m H), three (6.5 x 6.5m) water curtain galleries, two circular shafts (8.2m diameter) for pumping of crude & seepage water and access tunnel (12m x 8m) for facilitating construction (Fig. 1).

Ground water ingress during excavation is one of the major uncertainties. In the aquifer of jointed hard rocks, the permeability varies over wide range (10-9m/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).
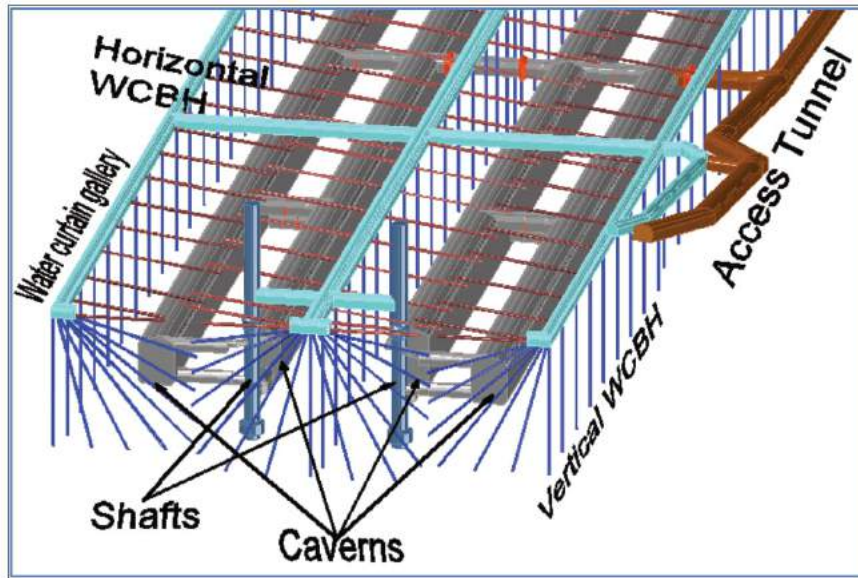

Figure 1: Layout of the project

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

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

For storage cavern, water loss through excavated areas, hinders the groundwater table conservation and threatens the de-saturation of rock mass - a condition where rock mass is depleted of water.
Such condition has to be prevented to maintain the safe storage principle.
Hence depending on the type of construction, the main improvement of rock mass that is expected from grouting in storage caverns, is reducing the permeability of the rock mass.

2. HYDRO-GEOLOGICAL MODEL OF PROJECT

During excavation, a minimum hydraulic head equivalent to 20 m of water above the horizontal water curtain level to be maintained in order to ensure hydraulic gradient >1 (Aberg, 1977). This is to prevent de-saturation of rock mass surrounding the cavern. A

hydro-geological model of the project is prepared based on the project geological model and various explorations during investigation and pre-construction stage.

The rock type in the project area is granitic gneiss belonging to the Peninsular Gneissic complex of India of Archaean age. The project is seated in a hilly terrain with thick laterite and lateritic soil at the top followed by weathered and fresh granitic gneiss, with 2-3 sets of sub vertical and a set sub-horizontal joint. The host rock has been intruded by dolerite dykes of variable orientation and thickness. The permeability of the soil and lateritic portion is high of the order of 10^{-5} to 10^{-6} m/sec whereas the permeability of the massive gneissic rock is very low of the order of 10^{-9} m/sec. However, 3-4 sets of prominent discontinuities were observed including a sub-horizontal joint which shows permeability in the range from 10^{-8} to 10^{-6} m/sec (some horizontal joints show very high permeability of the order of 10^{-4} m/sec locally). Sub-vertical and sub-horizontal dolerite dykes are also encountered with the permeability of the order of 10^{-6} to 10^{-7} m/sec. These permeable joints having aperture of 5mm to greater than 10mm, acted as water carrier during underground excavation (Fig. 2). The hydro-geological model also includes groundwater level contouring and residual seepage evaluation apart from the permeability distribution.

During excavation, the hydro-geological model was constantly updated by (i) structural projections of permeable features, (ii) updating probing and grouting detail, (iii) updating the seepage points, (iv) updating permeability values of all WCBH and manometer holes drilled from underground, and (v) correlating all above data.

Figure 1: Water ingress during excavation

3. GROUTING PHILOSOPHY

For all seeping probe holes, depth, rate and pressure of water inflow were recorded to take decision on grouting, magnitude of grouting and parameters of grouting. The hydro-

geological model was updated by significant features identified during excavation of small tunnels and were confirmed during top heading excavation.

Pre-excavation grouting was preferred and carried out from top heading by modifying the grout fan as suited to disposition of feature. In case of persistent features overlapping grout fans were constructed from alternate faces.

Once the disposition of major hydrogeological features were finalized on the basis of excavation data, the probing were optimized for subsequent bench levels and grouting were concentrated in the zones where the features are anticipated to be negotiated in the respective elevations (Figs.3a & 3b). Accordingly, pre-grouting plan of all benches was made. Side wall pre-grouting from higher bench was carried out in the identified zone with sub vertical grout holes directed to intersect the feature and constitute grout curtain to cutoff wall seepage. Invert pre-grouting from last bench was carried out with target to cutoff seepage up to depth of 5m from invert (Pal et al., 2014).
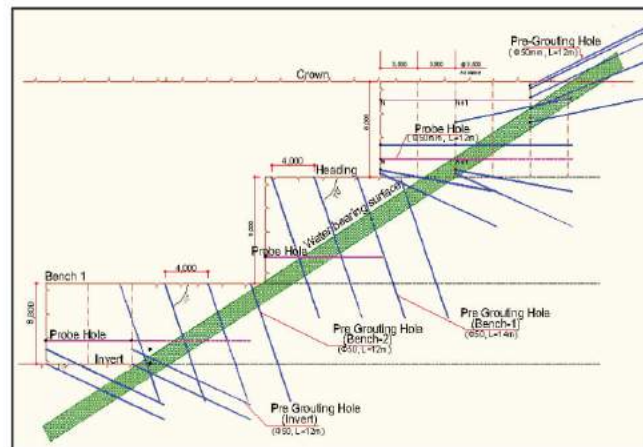

Figure 3a: L-section showing typical scheme for stage grouting
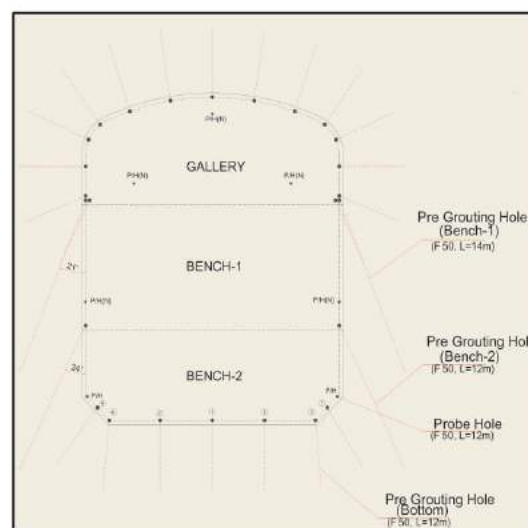

Figure 3b: Cross-section of storage cavern showing the details of grout holes

The each round of fan grouting at heading was carried out as follows:

- 15 to 20 boreholes each 12 m long and inclined outwards at angle of about 25° with the periphery of the cavern. The spacing of hole was to be such that the distance between two adjacent holes was 3m at end of grout fan. However, case specific variations both in terms of length and number of holes were very much present depending on the feature to be grouted.
- Borehole diameter 50mm
- The grout mix was usually OPC with water-cement ratio of 2:1 to 0.5:1, bentonite and fluidizer.
- Refusal pressure of 15 bar above groundwater pressure.
- Minimum grout flow 2.0 l/min.
- Grouting started with thinner grout and continued until 3000 l/hole, if refusal based on the pressure or flow criterion was not obtained. The limit might be exceeded in case of connectivity of holes. After this, grout mix changed to thicker grout and up to additional quantity of 500 litre were grouted before refusal/stoppage of grout.
- Grouting was normally carried out in descending order.

Following the above methodology, grouting was targeted to create a low permeable zone around cavern periphery at the zone of intersection with the high permeable features.
Seepage was measured through small weirs constructed across the cavern at every stage to assess the grouting performed.

4.   WATER CARRIERS

The grouting map of the project after excavation of top heading emphasized that grouting in this rockmass regime is solely guided by the permeable features or the water carriers, irrespective of rock class negotiated during excavation. The five major water carriers shown in the project model (Fig 4) are described below:
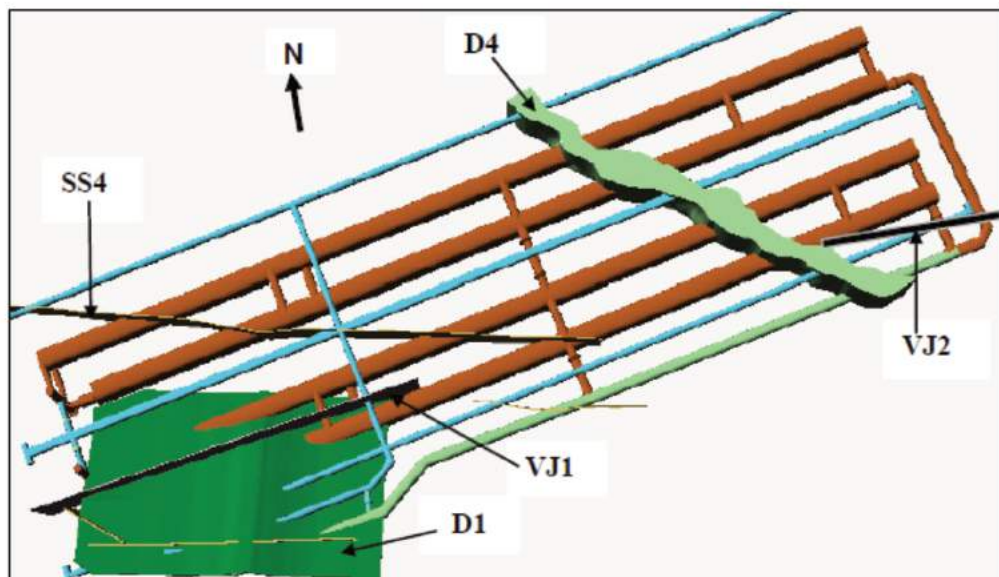

Figure 4: Water bearing features of project

4.1 Dolerite Dyke D4

The dyke is mesocratic, and fine grained. The sub vertical (80° to 88°) dyke body extends over a length of more than 400m making an angle of 50° with the cavern alignment. It has intersected the water curtain tunnels, access tunnel and all the cavern legs. Certain dip reversals are also observed with the dyke body dipping towards south-west in southern part and towards east of north east near northern part. The thickness of dyke ranges from 24 to 31m. The body is closely jointed with at least 5 sets of joints. The contact is smooth undulating with alterations in form of weathered materials.

At places the dyke is traversed by calcite veinlets as secondary infillings. The western contact is with hydrothermal alteration zone varying from 3-4m only. The eastern contact is widely affected by hydrothermal alteration, the width varying from 30 to 45m. The maximum permeability of the contacts of this feature is evaluated as 1×10^{-7} m/sec.

4.2 Dolerite Dyke D1

The dyke band is mesocratic and fine grained. The dolerite dyke body with thickness of 0.5-1m, moderately dipping (30-40°NE) was negotiated during excavation of water curtain tunnel, access tunnel (Fig 5) and continued down to cavern level. It has intersected three legs of cavern barring the northernmost leg. The tabular body extends over a length of more than 350 m making an angle of 35°with the cavern alignment. Sympathetic fractures exist up to a distance of 1 m from upper and lower contact of the dyke. The contact is smooth undulating with alterations in form of weathered materials. The contact of the dyke with country rock was permeable. The maximum permeability of the contacts of this feature is evaluated as 3×10^{-6} m/sec.

Figure 5: Dolerite dyke in access tunnel

Figure 6: Shear seam SS4 on cavern walls

4.3 Shear Seam SS4

The shear seam is 50 cm to 1m thick, filled with crushed rock material and lensoidal strong rock. The contacts are smooth, undulating and sympathetic fractures exist for 1 to 2m on either contact (Fig. 6). It is sub-vertical (dipping (80 -88°) towards north-west having strike in south-east direction. It was negotiated during excavation of water curtain tunnel and all four legs of caverns. The seam extends over a length of more than 650 m making an angle of 30° with the cavern alignment. The maximum permeability of the feature is evaluated as 1 x 10^{-6} m/sec.

4.4 Vertical Fracture VJ1

The fracture zone is 1-3 m wide with open joints. It is sub-vertical dipping at 80 -88° with almost east –west strike direction sub-parallel to the cavern alignment. It was negotiated during excavation of one of the water curtain tunnels and partly on northern wall of the southernmost cavern leg. The zone extends over a length of more than 300 m. The maximum permeability of the feature is evaluated as 2 x 10^{-7} m/sec.

4.5 Vertical Fracture VJ2

The fracture zone is 2 to 4 m wide with sub-vertical open joints running sub parallel to tunnel axis for more than 150m. It was encountered mainly south eastern portion of water curtain gallery and adjacent parts of cavern leg. The maximum permeability of the feature is evaluated as 1 x 10^{-5} m/sec. Several episodes of grouting had to done from the water curtain gallery itself to enable excavation of the gallery. This reduced the water inflow considerably from the feature at caverns. The summary of salient features is tabulated in Table 1.

Table 1 - Summary of water bearing features

Feature	Nature	Geometry	Maximum permeability (m/sec)
Dyke D4	Fractured dyke with hydrothermal alteration at contact	Continuity >400m; Width 25-30m; Sub-vertical; Oblique at 50° to the caverns	1×10^{-7}
Dyke D 1	Dyke band with weathered contact	Continuity >350m;Width 1-3m; Dipping at 30-35°; Oblique at 35° to the caverns	3×10^{-6}
Shear seam SS4	Shear seam with fractured contact	Continuity >650m;Width 3-5m; Sub-vertical; Oblique at 30° to the caverns	1×10^{-6}
Vertical fracture VJ1	Fracture zone with open joints	Continuity >300m; Width 1-3m; sub vertical; Sub parallel to the caverns	2×10^{-7}
Vertical fracture VJ2	Fracture zone with open joints	Continuity >150m; Width 2-4m; sub vertical; Sub parallel to the caverns	1×10^{-5}

5. METHODOLOGY AND DATA ANALYSIS

A rational estimation of requirement of grout quantity at the time of initial hydrogeological modeling would be of great use for project management and cost engineering of cavern projects. However, any practical correlation in case of grouting is obviously very difficult as the results of grouting varies over geological properties of permeable joints like hydraulic aperture, connectivity etc., rheological properties of grout slurry like grain size, flow-ability, gel strength, stability etc., mechanical properties of grouting equipment like grout pump pressure, mixer capacity etc. and not to mention the efficiency of operator (s).

It is general temptation to set-up a relationship between the Lugeon values and the volume of grout intake to be expected at grouting stage which may guide to quite misleading interpretation. The frequent fine joints may give the same Lugeon value as an unique wide crack. In the latter case, the grout intake can be very high, while in the former one, no cement may enter into fine joints. In fact, the experience shows that water pressure tests may, at the best, give an approximate indication of the reduction of permeability obtained through grouting works. It is thus felt that water tests carried out at grouting stage do simply represent a waste of money without any beneficial effect. Even more they may cause damages in re-opening already grouted joints (Lombardi, 2003).

On the contrary, there exists some work using the further developed theory where prediction of grouting result was done based on inflow during drilling of the grouting holes (Kobayashi and Stille, 2007).

It is more meaningful to establish a relation between grout intake and water flow of the features. An attempt has been made to correlate the grout intake with water flow negotiated from seeping grout holes. It will be handy to use data for grout estimate at the design stage when seepage inflow assessment in tunnels under different field conditions is done (Usmani et al., 2015).

In the present study, only the pre-excavation grouting conducted in top heading of cavern was considered. Data of all grouting episodes were tabulated face wise. With the help of geological map of the project, the grouting episodes were linked to the permeable features as described in section 4. The stray episodes of grouting which could not be linked with those features are left aside. The grouting data were then sorted feature wise. The summary is presented in Table 2.

Table 2 - Summary of feature wise grouting

Feature	No. of grouting sections (face)	Cumulative seepage (l/min)	Average Sectional seepage (l/min)	Total vol. of grout intake (litre)	Total weight of dry mix (kg)
Dyke D1	10	369	37	14188	8082
Dyke D4	04	150	38	7255	5123
Shear SS4	05	125	25	4813	2957
Vertical Fracture VJ 1	09	893	99	16097	13446
Vertical Fracture VJ 2	09	320	35	6362	3392

In order to do away with different water-cement ratio of grout mix used in the project, dry weight of mix has been used in the plot instead of liquid volume of grout.

The overall inflow from a permeable feature through probe holes and grout holes before the onset of grouting at a particular section was plotted along X-axis and respective total grout intake is plotted along Y-axis (Fig. 7).

Although, some minor differences in the linear trends for the different features are observed, the data are highly scattered. Hence no distinct relationship could be established from this plot of available data.
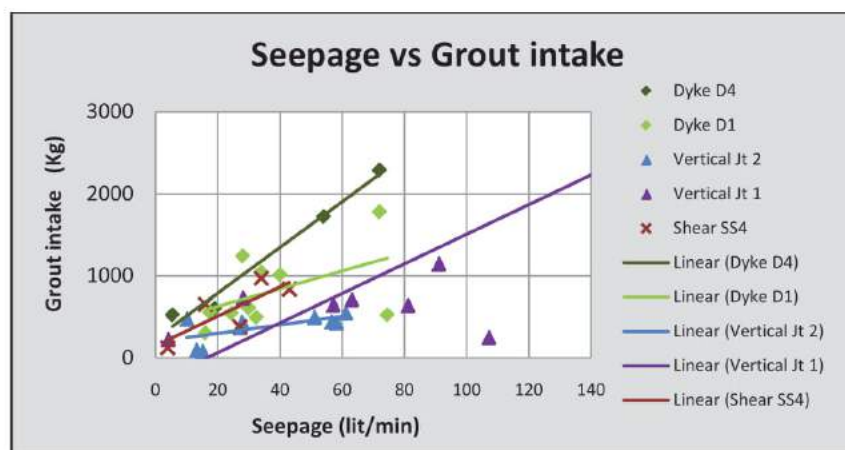

Figure 7: Seepage (inflow) rates versus total grout intake

It is obvious that total grout intake is governed by number and length of grout holes. To normalize the situation, the total weight of grout intake was converted to intake per drilling meter of grout holes by dividing the number and length of grout holes as follows:

$$Grout \text{ intake parameter} = \left(\frac{\text{Total grout intake in the section}}{\text{No. of grout holes } \times \text{ Length of grout holes}} \right) \quad (1)$$

The overall inflow from a permeable feature through probe holes and grout holes before the onset of grouting at a particular section was plotted along X-axis and respective grout intake per meter is plotted along Y-axis. (Fig. 8).
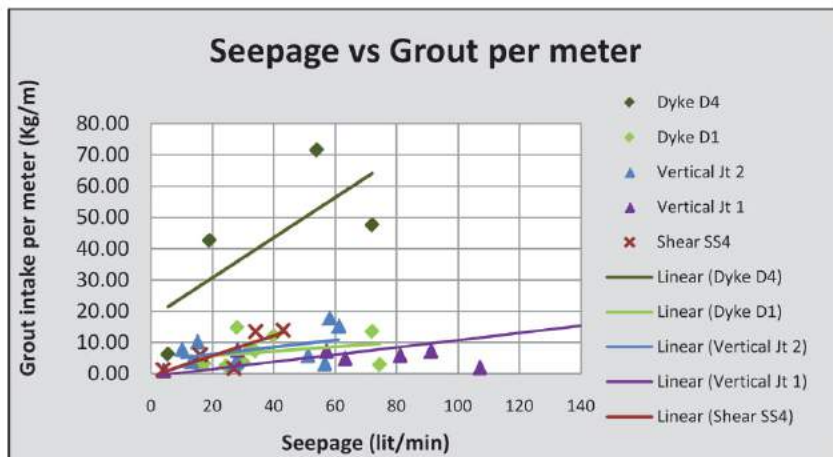

Figure 8: Seepage (inflow) rates versus grout intake per meter

The entire set of features showed similar trend. Only the dyke D4 showed higher initial intake as well as high intake rate with respect to seepage. This may be accounted for by the intense fracturing of the feature leading to higher grout requirement at initial as well as at any point of seepage inflow.
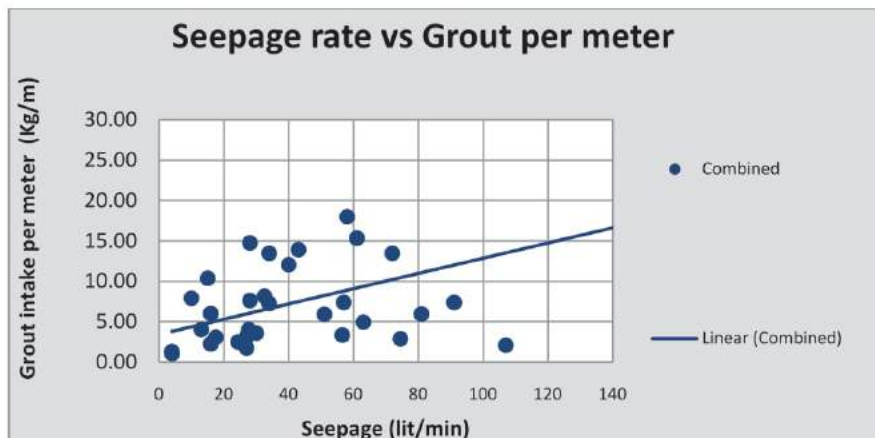

Figure 9: Combined Seepage (inflow) rates versus grout intake per meter

Looking at the similar trend, combined graphs of overall inflow versus grout intake per meter are plotted (Fig. 9), leaving aside D4 which exhibits totally different trend due to intense fracturing. This plot would help to have an idea of grout requirement for similar frame of parameters i.e., features with permeability of the order of 10^{-6} to 10^{-7} m/sec and seepage inflow of the order of 0 to 120 l/min.

6. CONCLUSIONS

The interdependency of grout intake on large number and wide range of parameters make it difficult to arrive to a full proof correlation. The present work has attempted towards somewhat rational estimate for design grout with respect to inflow of permeable features. This approach would be better than any arbitrary assumptions before start of project. The work may be carried forward with data from other projects and that would probably increase the linear regression of trend lines. This correlation will be different for different sizes of openings.

Acknowledgement

References

Aberg, B.(1977). Prevention of gas leakage from unlined reservoirs in rock, Proc. of the First Int. symp.,Storage in Excavated Rock Caverns: Rockstore 77, Elsevier, pp 399-413.

Amantini, E., Francois, C. and Anne, M. (2005). Groundwater management during the construction of underground hydrocarbon storage in rock caverns, 9th International Mine Water Congress (IMWA 2005), In: Mine Water 2005 – Mine Closure (ed. by J. Loredo & F. Pendás) (University of Oviedo), pp 311-315.

Anagnostou, G. (2006). Tunnel stability and deformations in water-bearing ground, In: Eurock'06, ISRM symp. on multiphysics coupling and long term behaviour in rock mechanics, Liège, pp 3–13.

Kobayashi, S. and Stille, H. (2007). Design for rock grouting based on analysis of grout penetration Verification using Äspö HRL data and parameter analysis, Rep. SKB R-07-13, ISSN 1402-3091, pp 1-73.

Lombardi, G. (2003). Grouting of rock masses, 3rd Int. Conf. Grouting and Ground Treatment, ASCE, pp 1-25.

Pal, Saikat, Kannan, G, Shahri, Vijay and Nanda, A. (2014), Ground water management for large underground storage caverns, Chap. 167, Engineering Geology for Society and Territory – Vol. 6 Applied Geology for Major Engineering Projects, Springer, pp 921-926.

Usmani, A., Kannan, G., Nanda, A. and Jain, S.K. (2015), Seepage behaviour and grouting effects for large rock caverns, Int. Jour. Geomechanics, 15 (3), ASCE, pp 1-7.