Analysis and Design Approach for Treatment of Weak Geological Features in Underground Caverns

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ABSTRACT

Buffer storage of crude oil in large underground unlined rock caverns is one of the economical alternatives to ensure energy security of import dependent countries. Principle of storage essentially employs ground water pressure for containing the product within an unlined rock cavern. Initial site investigation campaign carried out involving geological, geophysical, geo-technical and hydro-geological investigations, establishes competency of rock formations in conjunction with ground water conditions for construction of unlined rock caverns. In such projects, engineering geology forms an important aspect not only during the initial feasibility stage of the project, but also in subsequent execution phase, wherein unlined rock caverns are built by conventional drill and blast technique. Design of underground structures exhibit lot of uncertainties in their basic approach and require an active and dynamic design intervention during construction progress. In this context predictive geological model is developed based on initial investigation results, which is continuously updated as the excavation progresses through stages of heading and benches. As part of this modeling exercise, critical segments of the caverns are identified as geological hotspot which undergoes additional stability analysis before excavation in order to take necessary counteractive steps. This approach based on pro-active construction methodology, helps to ensure preparedness to address the rock mechanical aspects of the identified segments, thus results in a reduced risk exposure. The study outlines, the process of identification and approach adopted to treat geological hotspots encountered during excavation for large underground rock caverns.

KEYWORDS: Cavern, geology, hotspots, rocksupport, underground

INTRODUCTION

Stoarge of crude oil in underground unlined rock caverns is an established technology and successfully adopted in many countries. The principle of storage essentially employs hydrodynamic containment of product within an unlined rock cavern where the tightness of storage is ensured by directing ground water flow towards the storage caverns (Figure 1). In this process ground water table is always maintained above the caverns by uninterrupted artificial charging through water curtains so as to rejuvenate the ground water regime. The water curtains are constructed by drilling and charging horizontal as well as vertical boreholes from small dimension water curtain tunnels (6 X 6 m) encasing the storage caverns.

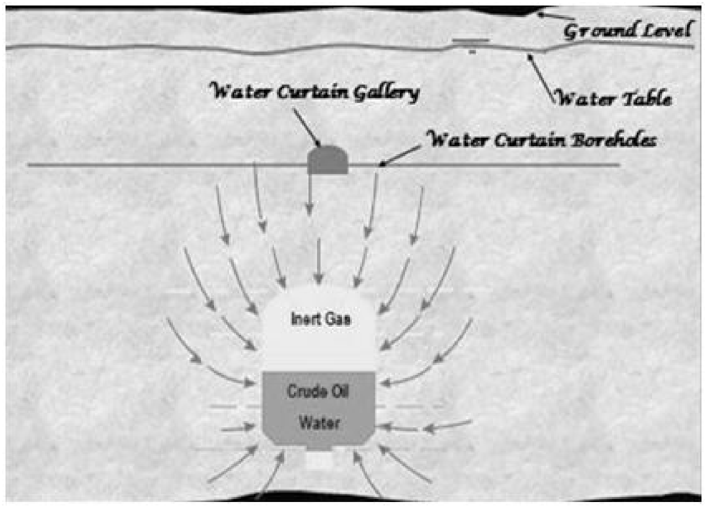

Figure 1: Pictorial representation of storage of crude oil in underground rock caverns

Large caverns (900 x 30 x 20 m) are constructed by conventional drill and blast technique wherein sequential excavation takes place through top heading and benches using the downward ramping method. For planning, design and construction of underground storage caverns, engineering geological assessment of the proposed site forms a key input. During feasibility stage, geological setting of a site is assessed. This initial information gathered during feasibility stage is converted into a two dimensional geological model showing the layout of the storage along with main geological features crossing the storage.as shown in Figure 2.

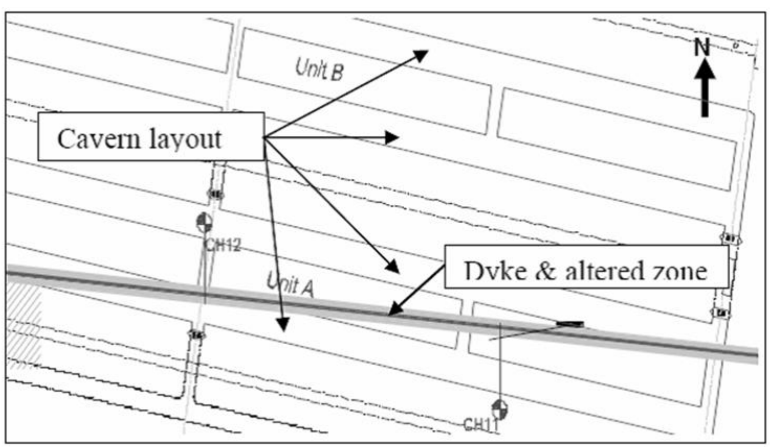

Figure 2: 2D Geological model of the storage area showing borehole and geological features

This derived interpretative geological model forms the basic design input and the storage layout is finalized such that major geological discontinuities are avoided. During excavation, smaller dimensioned water curtain tunnels and associated boreholes located above the caverns, are executed in advance. Thus revealed geology of water curtain tunnel system helps in the prediction of expected geological features though caverns and updating of 2D/3D geological model for the caverns. Further, adverse geological features that are predicted in advance are identified as “geological hotspots”; a terminology used to denote features with high risk levels, which are probed, assessed and supported by specific design supports. This geological model is further updated during excavation of cavern heading and helps prediction of likely scenarios during bench excavations, verification and possible optimization of rock support. This geological assessment of the site is made in a continuous process following an on-the-go engineering geological assessment. This paper discusses a case study of an underground storage project where adverse geological feature found out during the investigation stage, that was analyzed in detail for long term stability requirements.

CASE STUDY

The site considered in this study is a crude oil storage project located in the western coast of India under final construction stage. The project consists of two U shaped caverns of maximum 30 m height, 20 m width and about 900 m long which can store about 1.0 million tones of crude oil (Figure 3). Each U shaped cavern consists of a circular shaft located at one end of the cavern for transfer of crude oil through pipelines. The caverns are separated by 30m width of rock pillar. A water curtain system is developed above these caverns to contain oil and gas using hydro-geological confinement principle.

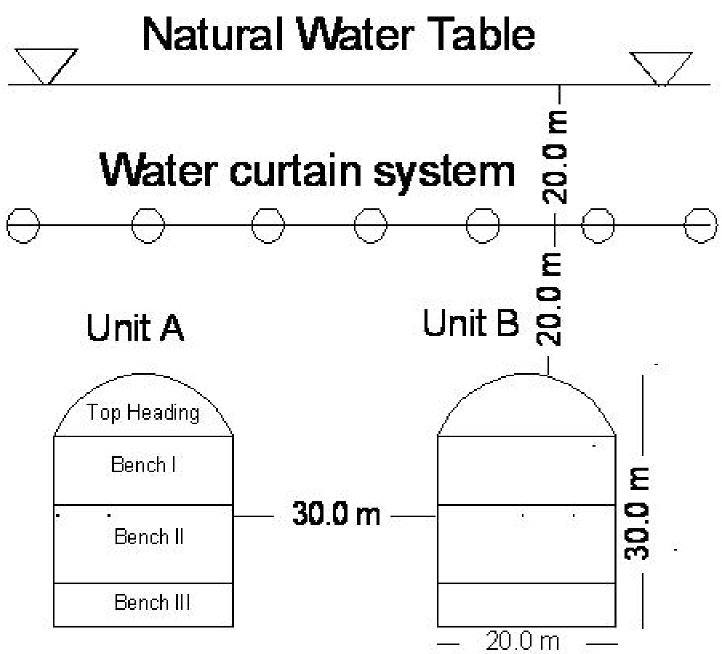

Figure 3: Cross-section of storage units along with water curtain system

The project area is topographically situated on a low lying plateau with valleys on both north and south. During preliminary site investigations of the cavern area that included geological, geo-physical, geo-technical and hydro-geological investigations it was established that rock formations in conjunction with ground water conditions are competent for construction of unlined rock caverns to store hydrocarbons. A number of coreholes and destructive holes were drilled along the caverns layout to investigate the underlying soil and rock properties. The coreholes examination revealed bedrock is mainly composed of granite gneiss which is covered with top soil that consists of landfill, laterite, residual soil and weathered rock with thickness varying from 5 to 20 ms. However as part of these investigations, in one of the drilled holes, a dolerite body was found to be intruding the parent rock formation in the form of a dyke with zones of hydrothermal alterations on each side along the contact. This was included in the geological model (Fig 3) as an intrusion within cavern alignment during the initial investigation stage. The orientation of the dyke with respect to cavern alignment could not be established initially based on the limited number of core holes and was later confirmed during additional site investigations carried out in the pre-construction stage. During additional site investigations in pre-construction stage, definitive inclined bore holes were drilled to ascertain the orientation of the inferred dyke with respect to the existing cavern alignment. The geological logging of the core holes revealed that the hydrothermally altered dyke is oriented N-S with a westerly dip transecting the caverns (oriented N100°E) across the alignment (Figure 4).

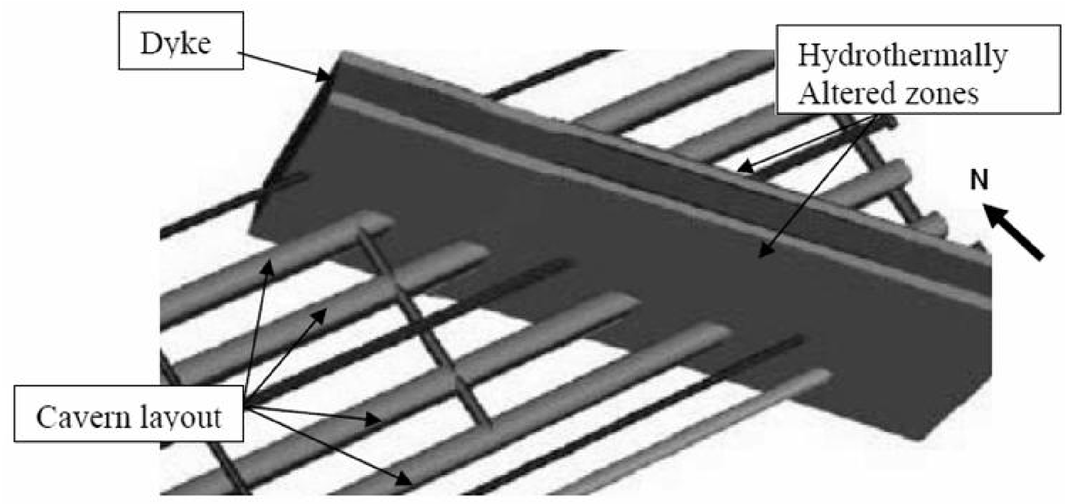

Figure 4: Dyke along with hydrothermal zones intruding storage caverns

Due to these additional boreholes, correct alignment of the dyke could be established, which otherwise was not known during initial investigations. Based on this information, critical segments of cavern with the likeliness of negotiating such features were identified and marked as “geological hotspots” as shown in Figure 5. On the basis of judgment of friable cores, very poor rock was foreseen to be negotiated during excavation of a cavern in the dyke section.

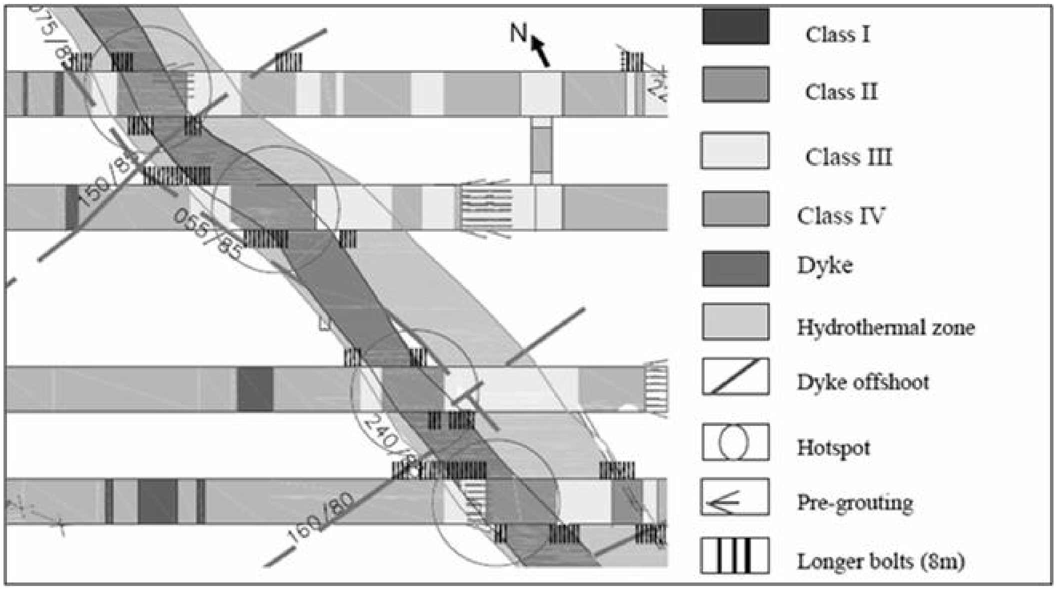

Figure 5: Hot spot location and rock mass classification

During excavation of the water curtain gallery through the likely zone of negotiating dyke body; thin dyke bands were reported which was sub parallel to the alignment of galleries as well as the caverns. In order to confirm the disposition of the dyke as well as to assess the geological conditions associated with dyke in tunnel grade, a horizontal investigation hole of 69 m was cored along tunnel alignment. The results confirmed the oblique alignment of the dyke body as shown in the geological model (Figure 5). However the condition of the dyke revealed through investigation hole was observed to be better than design stage with a sharp contact on the west and altered wider contact on the east. The thickness of dyke along cavern was inferred to be 32 m. No water seepage condition was observed along the contacts. This investigation hole data and ongoing excavation mapping of the water curtain gallery helped to conceive a reasonably accurate geological model. Further information gathered about the presence of dyke offshoots and more severity of altered zones during excavation of the cavern heading resulted in having a definitive model and taking necessary precautions during during the subsequent bench excavations.

NATURE OF THE GEOLOGICAL FEATURE

Based on the information gathered so far, the dyke was reported as mesocratic, and fine grained. The sub vertical (80° to 88°) tabular body extended over a length of more than 300 m making an angle of 50°with the cavern alignment. The thickness of dyke ranges from 24 to 31m. The contact is smooth undulating with alterations in the form of weathered materials. The body is closely jointed with at least 5 sets of joints resulting in brittle behavior of the dyke. At places the dyke is traversed by calcite veins as secondary infillings. The Q values of dyke were found to be in the range of 2.1 to 3.9. The western contact is relatively sharp with a width of the hydrothermal alteration zone varying from 3-4 m only while in the northern part it is about 12 m wide. The eastern contact is widely affected by hydrothermal alteration, width varying from 30 to 45 m.

DESIGN METHODOLOGY FOR HOTSPOT AREAS

Rock support for different rock classes were determined using rock bolts and shotcrete as per Barton's (2002) Q classification system. However for very poor rock conditions (Q<0.1) provisions for other rock support measures like spilling, steel rib installation (Tilak & Nanda, 2006) along with option of reduction of section were also kept in the contract. On the basis of rock mass characterization of geological logging of investigation hole as well as rock-mass classifications from water curtain galleries (Figure 5**)**, the model of dyke evolved to be persistent across all the caverns with altered zone on east along with some seepage on eastern contact. Specific excavation planning consisting of (a) pre-grouting before the contact zone of the host rock and the dyke (b) Controlled blasting pattern (pilot blast, if required) with contour holes, alternately charged along with dummy holes was adopted. Two probe holes of 12 m long were carried out from the face of the dyke effected chainage in successive heading and benching stages. Selective pre-grouting was performed once the hydrogeological condition was affirmed based on the probe holes analysis. Sealing of the excavated face immediately after the blast with 50 mm shotcrete first followed with application of full rock support consisting of balance 150 mm shotcrete and 6 m longer rock bolts at a spacing of 1.3 m were adopted for the dyke effected region.

Since large cavern excavations (heights of about 30 m) were involved in this project, which was executed through sequential stages (heading & benching) of excavation, it was difficult to revert back to earlier excavated benches in case of any stability issues because of the time and cost overruns. Hence, it was an absolute necessity to recheck and confirm the completeness of rock mass treatment of the dyke affected region at the heading stage itself before initiating the next lower benches. Therefore a set clearances of clearances was planned for the contractor before proceeding for lower benches based on analysis and assurance of the following. This included (a) verification of the applied support for largest wedges formed based on the joint sets encountered from the face map of the affected region, (b) check against the adequacy of treatment of water bearing joints by measuring actual seepage values and (c) continuous recording of movement of rock mass using optical targets.In order to analyze the potential wedges formed along the contact, wedge analyses (Figure 6) were undertaken using Unwedge software (Rocscsinec, 2007) with input cohesion c = 0.20 MPa and frictional angle of the joints ϕ = 33° and minimum factor of safety of 1.5.

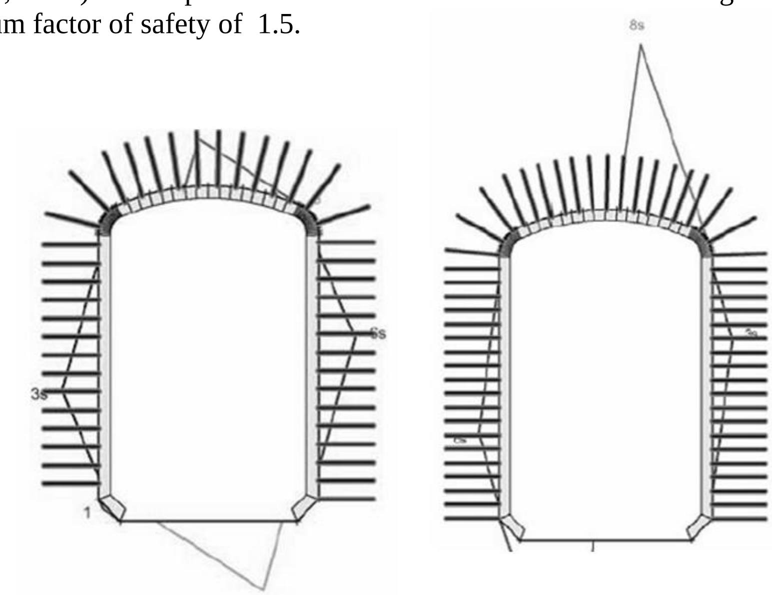

Figure 6: Unwedge analysis for caverns

Scaling of wedges was carried out as per trace lengths and persistence observed during mapping. The combination analyzer was used to find out wedges with least factor of safety. The wedges were found to be stable with installed support system. In order to ensure the stability of the walls, geometrical analyses were done for entire cavern sections considering the contacts of dyke to be the major detachment surface. Sections of full cavern were cut at the locations where dyke touches the invert. Considering dip of 80°, the maximum distance of the detachment surface was found to be 5.3 m. To counteract any such wedges longer bolts (8 m) were installed in the areas around inflection points of dyke body, identified as geological hotspots.

In these hotspot areas as part of the geotechnical monitoring program, optical targets were installed along the complete cavern section for convergence monitoring in order to verify the stability of the excavated structures under existing installed supports. Total twelve targets were installed along the periphery of the cavern; six in roof and balance six in walls in each section as shown in Figure 7.

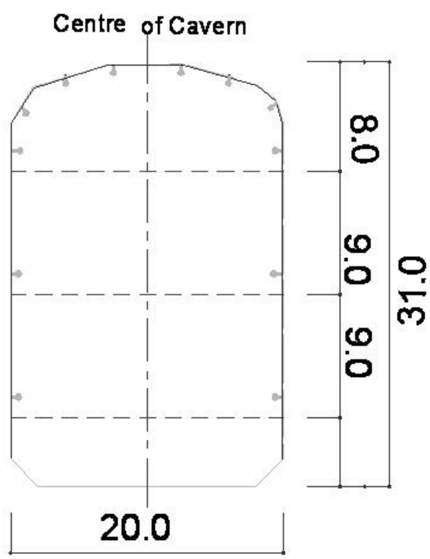

Figure 7: Optical targets located in caverns

The displacements of the targets were recorded daily until convergence of the readings. Maximum displacement values of 4 mm were recorded which was found to be within safe limits; less than the prescribed critical displacement values for the caverns taking in consideration the type of rock class.

CONCLUSION

Treatment of geological hotspots in large unlined rock caverns essentially comprise of identification of adverse features called “hot spots” in the geological model during investigation stages, establishing the identity of the feature with respect to its orientation and extent during progressive investigation stages. This information should be continuously updated as part of the active geological modeling. This constant evolution and updating of geological model aids to participate in dynamic modelling and active design of any underground straurure in tems of optimum support requirements as per actual encountered site conditions. This is coupled with continuous geotechnical monitoring to check and validate the installed support sysytem. The entire approach builds and adds to confidence in completing the underground construction on a safe note.

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