Stress and seepage analysis of underground rock caverns

Le stress et l'infiltration analyze de cavernes sous-roche

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ABSTRACT

This paper discusses the design aspects of unlined rock caverns for storage of hydrocarbons including the investigations and analysis necessary to arrive at cavern elevation, layout and cross-section. The investigation and studies carried out for an underground cavern storage facility are presented. Results of numerical analysis for stress, stability and seepage which were carried out to establish the design of the underground storage facility are presented.

RÉSUMÉ

Ce document examine les aspects de la conception de Unlined rock des cavernes pour le stockage des hydrocarbures y compris les investigations et de l'analyze nécessaire pour parvenir à caverne d'altitude, la mise en page et de section. L'enquête et les études effectuées pour une caverne souterraine installation de stockage sont presents. Les résultats de calcul numérique pour le stress, la stabilité et l'infiltration qui ont été menées pour établir la conception préliminaire de l'installation de stockage souterrain sont présentés
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Keywords : stress, seepage, underground, caverns, hydrocarbons

1 INTRODUCTION

Storage of hydrocarbons in unlined rock caverns has been found to be one of the most economical solutions for storage of large volumes. The basic principle of storage in unlined rock caverns is the hydraulic confinement. Thus the rock caverns are planned at a depth such that there is sufficient hydrostatic pressure to counter the vapour pressure of the stored product and ensure that the water flow is directed into the cavern. In order to maintain required hydrostatic gradient a water curtain system is provided consisting of galleries located above the crown of the cavern. Boreholes are drilled from the water curtain tunnel to intersect the joints of rock mass. A saturated rock mass and ground water flowing into caverns ensure proper sealing of the stored product.

The engineering behaviour of rock formation, within which the principal underground structures are located, is of prime importance for the stability and reliability of the containment. A fundamental understanding of the rock mass geomechanical properties and their sensitivity and interaction with the proposed works is therefore essential for the safe and economic design of excavations and associated support elements. Therefore it is considered vital to evaluate the excavation stability on the basis of representative characterization and modeling of the rock mass to ensure reliable estimation of rock mass behavior. In addition the assessment of the hydro-geological conditions is also essential for the design of the water curtain system to ensure hydraulic containment of the stored product

This paper discusses the design aspects of unlined rock caverns for storage of hydrocarbons and the investigation necessary to arrive at design parameters. Results of investigations and preliminary stress-seepage analysis of an unlined underground rock cavern for the storage of crude oil are presented.

2 INVESTIGATION

The proposed storage site is located under a hill which has a maximum elevation of 130 m above mean sea level. The investigated area consists of landscape gently sloping down into two valleys. The elevation goes from +25 msl in the valley to +130 msl in the hill slope. The terrain of the area comprises of undulating, steep but short cliffs and rugged topography. The major rock type found in the area is Khondalite and leptyite with capping of laterite of variable thickness. Systematic and comprehensive investigations were planned during this study to minimize geological surprises during construction. Geotechnical investigations were carried out using vertical and inclined boreholes located suitably to detect geological profile. The depth of investigation was so planned to reach at least 5-10m below the invert of the cavern. Core Recovery, RQD, discontinuities spacing, joint condition, orientation, dip of strata, cavities and fissures are evaluated from the samples.

2.1 *Field investigations*

The bore hole drilling program was categorized into two groups with the one consisting of vertical holes which were drilled to investigate the rock mass in general and the other group of holes consists of those holes which were drilled to investigate specific weak zones which were drilled at an inclination of 30^o from vertical. From the bore hole data RQD values were recorded and rock mass was classified as good and fair quality rock mass. The RQD values ranged between 70-90 at the expected cavern roof level of -30 m with respect to mean sea level. Q system (Tunnel Quality Index) of classification was used for characterization of rock mass The Q value of rock mass in the cavern are based on the above data was found to be in the range of 2 to 25 which corresponds to fair to good rock conditions.

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The majority of the excavation work is expected to take place in a rock mass with an average Q value of over 10, corresponding to good rock. Stress measurements were carried out in vertical boreholes located on the valley side i.e. +25 msl, using the technique of hydro fracturing. Measurements were made at different levels corresponding to crown level of the caverns and within five meters above and below that level. Relatively high horizontal stress, with a maximum horizontal stress (S_H) of 9 MPa having a direction of NNE and minimum horizontal stress (S_h) of 4 MPa which is perpendicular to S_H were recorded. The high magnitude of stresses is attributed to the fact that these measurements were made in a valley and consequently the topography of site has contributed to these stress levels.

The investigation scheme also involves geophysical testing that includes seismic refraction test, electrical resistivity test and cross-hole seismic survey along with extensive laboratory testing to augment findings of other investigations. The detailed engineering geological map was prepared with the interpretation of the geotechnical and geological findings. This information later provides help to establish the layout of the rock caverns.

To establish the permeability profile and seepage water quantity assessment in the caverns, water pressure tests and pumping interference test were carried out. Water pressure tests were conducted in selected sections of the boreholes using either inflatable or mechanical packers. The test generally indicated moderate conductivity values, ranging between $3x10^{-7}$ m/s to $8x10^{-8}$ m/s at the cavern level.

2.2 *Laboratory Testing of Samples*

A total of 100 dry unconfined compression strength (UCS) tests and 45 tests for tensile strength have been carried out in all the six coreholes. The UCS values were found to vary from 70 to 90 MPa at cavern level. The tensile strength of the rock was in the range of 3 to 11 MPa. The average dry rock density over 18 tests was found to be 2.80 kN/m^3. The porosity of the set of samples was found to be 1.4%.

3 ENGINEERING AND DESIGN

The layout, cross-section and elevations are finalized considering the product storage and operational requirements as well as the geological and geotechnical conditions at site. The layout and cross-section is selected so as to achieve a favorable stress situation in the rock and also to take into account any major geological structures. The excavation sequence and methodology are also considered.

The depth of the cavern is selected to satisfy gas tightness criteria (Tilak & Nanda, 2006). A minimum of 20 m hydraulic margin is to be maintained over the maximum gas pressure in the cavern throughout the entire life period of the caverns. In addition to that a minimum hydraulic gradient of 1.0 is required at the roof of the caverns to preserve hydraulic confinement of the caverns. The hydraulic margin mainly depends on the cavern geometry, the natural hydro-geological context, the presence of water curtain system and operating conditions of the storage cavern units. Predicting flow patterns around the storage caverns is essential for a safe calculation of the hydraulic margin and the consequent cavern depth.

Based on the rock mass conditions detailed finite element studies are carried out in order to study stresses and deformations around the caverns. Rock-support interaction studies are also carried out to study their effect on resultant deformations and yielding. In addition wedge stability is also checked. The rock support is finalized based on both empirical methods and the results of these analyses. Finite element analysis is carried out for the estimation of seepage into the cavern and to analyse the flow pattern for design of the water curtain system.

4 ANALYSIS

4.1 *Parametric study-Stress-deformation analysis*

In order to analyse the large scale stability of the proposed caverns due to progressive excavation and rock support installation, several two-dimensional finite element numerical analyses have been performed using the code Phase^2 (RocScience, 2007). In the present study two units of caverns each 60 m apart and consisting of two caverns each which are 30 apart are considered as shown in Fig. 1.

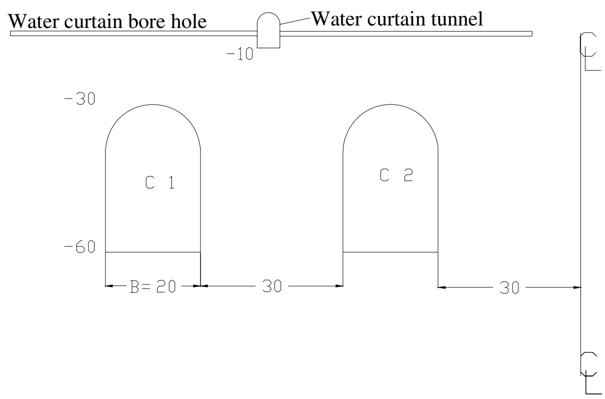

Figure 1.Cross-section of caverns

The floor level of the caverns can be either constant or can vary along the length of the cavern. In the present analysis the maximum cavern height has been considered, Due to symmetry of the geometry only left half of the model is considered. The caverns are U-shaped in plan with an approximate 'D' shaped cross-section. The roof of the caverns is at an elevation of -30 msl. The caverns are 20 m wide and 30 m high and are aligned at an angle of 50 with respect to the maximum principal horizontal insitu stress. Consequently the insitu boundary horizontal stress acting perpendicular to the cavern alignment will be 7.1 MPa.

The values of rock parameters have been estimated based on the results from the field investigation for two quality of rock masses (Hoek & Brown, 1997) i.e. good Rock (10<Q<40) and fair rock (4<Q<10). The parameters used in the analysis are shown in Table 1.

Table 1. Properties of rock mass

Parameter	Fair	Good
E (MPa)	7838	22137
μ	0.180	0.180
Tensile strength (MPa)	0.088	0.262
UCS (MPa)	70	90
mb (H-B Criterion)	4.695	7.336
s (H-B Criterion)	0.0059	0.0214
a (H-B Criterion)	0.5028	0.5014
Density (MN/m3)	0.028	0.028

The primary stress condition is governed by the overburden weight and horizontal initial stresses. The weight of the rock cover is used to simulate vertical insitu stresses. As the stress measurements were carried out at lower elevations (+25 msl) and the horizontal stress recorded was quite high, it was understood that large values of stress ratio were evident. In order to cater variation of horizontal insitu stresses along the caverns two values of K_o =2 & 4 were considered in the analysis. The modeling is carried out using three-noded triangular elements having an element size of 20 m at the model external boundaries and is reduced to 2 m close to the excavation having a gradation factor of 0.1. The distance between the cavern and the left side model boundary is taken as five times the width of excavation i.e. 100 m to eliminate the effect of boundaries on the cavern behaviour and the remaining boundaries were considered as per the model shown in Fig.1

The rock mass are analyzed using the Generalized Hoek-Brown (H-B) criterion obeying elasto-plastic conditions. The analyses were carried out for two depths of rock surface, i.e. +25 msl and +125 msl levels representing total depths of 55m and 155 m respectively to study the effect of overburden on the stresses and deformation of caverns for two different qualities of rock masses. The excavation of the caverns is simulated in three excavation steps with initializing of insitu stresses in first stage, material softening of the material to be excavated within the tunnel in the second step and subsequent excavation along with the application of rock support in the third stage. Material softening stage allows the design of realistic support by permitting the required tunnel displacement to occur in the model before the support is installed. The rock support installations were modeled using 25 mm diameter rock bolts having a tensile capacity of 180 kN and a modulus of 200 GPa. Fully bonded rock bolts of five meter in length with a centre to centre spacing of 1.75 m in fair rock and 2 m in good rock were used in the analysis. The final support also includes fibre reinforced shotcrete however it was not modeled in the analysis keeping in view the short term stability of the caverns.

The complete study carried out during this work is described in tabular form in Table 2. The analyses as shown in Table 2 were carried out using K_o values of 2 and 4. The results are presented in Tables 2 and 3.

Table 2. Rock mass deformation

Case no.	K_o	Rock mass	GL (m)	Deformation (mm)	
				Crown	Wall
1	4	Fair	+25	5.95	19.6
2	4	Good	+25	2.4	6.6
3	2	Fair	+125	8	36
4	2	Good	+125	5.5	12
5	4	Fair	+125	16	84
6	4	Good	+125	6	27

It is observed from Table 2 that maximum deformation is estimated in fair rock conditions for +125 msl under gravity loading conditions with K_o=4. It is also seen from Table 3 that yielding of rock bolts is found to occur only in case 5, i.e. fair rock under an overburden of 125 m and a stress ratio of K_o=4 where the tensile capacity of rock bolt is exceeded. It is also assessed from the analysis that effect of stress ratio is significant on the resultant deformations of the caverns as depicted in Table 2. It is also observed from the study that reflection of insitu stresses during modeling is an important aspect and results in appreciable difference in deformations and stresses under same conditions of rock as the overburden increases. The extent of yielding is also found to be substantial and all around the periphery of the caverns in case of higher overburden under fair rock conditions with K_o=4 while it is limited for the case of K_o=2. Thus the assumption of initial stress condition can have significant impact on the results.

Table 3. Stresses in caverns

Case no.	Sigma 1 (MPa)		Sigma3 (MPa)		Max.Bolt force (MN)
	Crown	Wall	Crown	Wall	
1	7.6	0	0.75	0	0.064 (Wall)
2	7.6	0	0.75	0	0.022 (Wall)
3	18.7	4.25	2	0.4	0.145 (Roof)
4	19	4.75	2.4	0	0.0427(Wall)
5	36	2	3.6	0	0.217 (Wall)
6	40	2	4	0	0.108(Wall)

It was also assessed during the investigation that actual stress distribution in the ground is not fully known as the stress measurements have been carried out at location with low ground elevation. However use of K_o=4 for a ground elevation of +125 msl may be unrealistic leading to prediction of very large deformation and stresses. However by carrying a number of analysis an realistic assessment of the stresses and deformations can be made, which can then be confirmed by monitoring the deformation during construction to obtain an optimum design. Figure 2 illustrates one deformation pattern around the cavern for case 1.

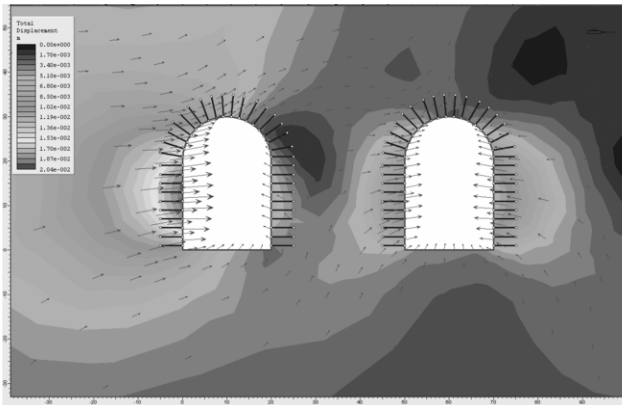

Figure 2. Deformation pattern for case 1

4.2 *Seepage studies*

As the hydraulic confinement is the main principle of this system of storage, the assessment of hydro-geological conditions, i.e. estimation of seepage entering into the cavern and hydraulic gradient available at roof is critical in design, The excavation of the water curtain tunnel and the pressurizing of water curtain boreholes is at least 50 m ahead of the excavation of the storage cavern to ensure that the rock mass around the tunnel is always saturated. Pressure in water curtain bore holes is kept as close as possible to the static water pressure before construction.

In the present investigation two case studies employing a 2D model having natural ground water tables at +10 and +60 MSL were carried out. The analyses were carried out with and without water curtain boreholes and under two conditions of operation, i.e. completely empty at atmospheric pressure and another at uniform maximum normal vapour pressure of 0.13 MPa (case 1-4 & 6-9). The analysis was carried out using the finite element code Phase^2 (RocScience). The two -dimensional model consist of two units of caverns each 60 m apart and consisting of two caverns each which are 30 m apart as shown in Fig. 1. Due to axisymmetry of the geometry only left half of the model is considered. The distance between the cavern and the left side model boundary is taken as ten times the width of excavation i.e. 200 m to eliminate the effect of flow conditions on the cavern behaviour and the remaining boundaries were considered as per the model shown in Fig.1 having no flow conditions. The water curtain was located at -10 MSL where as the top of the caverns is located at -30MSL. The natural water table varied between levels of +10 to +60 msl. The water curtain tunnel was charged with a head equivalent to representing +10 MSL. In the present study the effect of hydrostatic fluid pressure variation of the crude oil in the cavern was also taken into account for water levels of +10 and +60 with a water curtain as shown in case no. 5 and 10. A permeability of 10^{-7} has been used in the analysis.

Table 4. Seepage analysis

No.	Water Table	Pressure in side Cavern (MPa)	Water Curtain head (m)	Discharge,Q (m^3/s/m) 10^{-6}		Hydraulic Gradient, i	
				C 1	C 2	C 1	C 2
1	+10	P_{atm}	-	9.15	6.57	1.2	1.1
2	+10	P_{atm}	70	12.7	10.7	2.4	2.4
3	+10	0.13	-	6.78	4.74	0.63	0.54
4	+10	0.13	70	9.35	7.66	1.52	1.52
5	+10	H	70	7.53	6.44	1.84	1.84
6	+60	P_{atm}	-	10.8	7.17	1.5	1.2
7	+60	P_{atm}	70	13.6	10.9	2.55	2.4
8	+60	0.13	-	9.39	6.19	1.21	0.88
9	+60	0.13	70	10.3	8.05	1.6	1.5
10	+60	H	70	8.97	6.92	1.96	1.79

A tabular representation of the analysis carried out as part of the seepage studies is shown in Table 4. It can be observed from the results that presence of water curtain significantly increases the potential and hence increases the hydraulic tightness of the cavern. The condition of minimum hydraulic gradient of 1.0 at the roof is not achieved under operational pressure of 0.13 MPa without the water curtain. The study also substantiates the necessity of water curtain tunnel in order to achieve sufficient vapour tightness of the caverns. Figure 3 illustrates the flow pattern around the caverns.

It may be noted that the flow conditions at the water curtain is truly three dimensional hence the head is expected to vary between the water curtain boreholes. To understand the three dimensional distribution, an efficiency study of the water curtain hole was also carried as part of the detailed investigation. The hole was modeled by a circular tunnel of 0.1 m under variable head conditions at the far off boundaries to ascertain the fall in heads during operation of the water curtain tunnel. Based on the above study an efficiency factor varying between 0.9 to 1.0.was estimated.

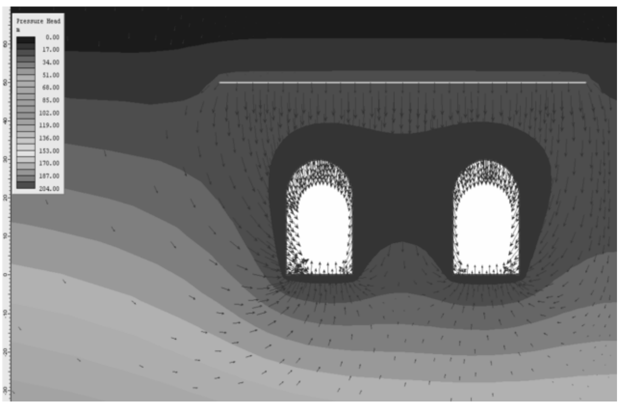

Figure 3. Flow around cavern for case 4

A few analyses were carried out to study the influence of efficiency of the water curtain system. The water curtain efficiency test results as shown in Table 5 indicate that a minimum efficiency of greater then 90% is essential to preserve vapour tightness criteria of the caverns.

Table 5. Water curtain efficiency

No.	Water Table	P (MPa)	Water curtain efficiency	Discharge Q (m^3/s/m)		Hydraulic Gradient, i	
				C1	C 2	C 1	C2
1	+10	0.13	100%	12.7	10.7	2.4	2.4
2	+10	0.13	95%	9.1	7.05	1.3	1.3
3	+10	0.13	90%	7.9	6.2	1.08	1.0

5 CONCLUSIONS

This paper discusses the design aspects of unlined rock caverns for crude oil storage including the investigations and analysis necessary to arrive at cavern elevation, layout and cross-section. Results of investigations and numerical analysis for stress and seepage studies were presented in this paper. The paper highlights important concerns on consideration of insitu stress conditions in the field. The study also presented simplified approach for the analysis of the seepage in underground caverns including the influence of water curtain on the hydraulic confinement.

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