Geotechnical Monitoring for Safe Excavation of Large Rock Cavern: A Case Study

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Abstract -

The present study highlight the methods used to monitor the geotechnical behaviour and performance of the cavern during excavation in order to verify and, if necessary, adjust the rock support to ensure safe construction at every stage. The present geotechnical monitoring practice for underground structures involve convergence monitoring with the help of optical targets and rock mass displacement with help of bore hole extensometers. More importantly it involve detailed planning to finalize the position of each monitoring instruments based on location and orientation of geological features. Further it is equally important to ensure proper recording of monitoring data in order to analyze and take immediate action in case of any adverse situation. This requires a dedicated high end automated software, which can record, analyse and produce significant results out of large quantity of recorded data which otherwise turns out to be only ravage. Initially geotechnical monitoring was carried out in recently excavated zone of cavern on daily basis. Further based on continuous monitoring data for at least one week, frequency of monitoring is further decided. In most of the cases the deformation of rock mass was quite less compare to the alarming values which were evaluated based on detailed design for different rock classes.

Keywords -

Underground excavation, Cavern, Tunnel, Geotechnical Monitoring

1 Introduction

This paper discusses in detail geotechnical monitoring activity carried out during construction of an underground unlined rock cavern complex for storage of crude oil at western part of India. The total storage capacity was 2.5MMT of crude oil. As four numbers of rock cavern units were to be built, for the ease of construction, the caverns were divided into two parts. Each part consists of two U shaped storage units with two legs. Each leg was extended almost 700 m, thus total length of cavern was around six kilometres. This project involve the excavation of vertical shaft for crude intake and out let, access tunnel to facilitate excavation at required depth, water curtain tunnel for continuous ground water recharge and the large cavern for storage space. However, present study only concentrates on the geotechnical monitoring activity implemented inside the cavern as it was most critical due to its large size and extent. Each U shaped cavern unit (in plan) is designed with 30.0 m high and 20.0 m wide (in cross section) to create the required storage space. On and average cavern crown was 60.0 m below the ground surface with a trend of $60^0/240^0$.

As this construction involves lot of excavation activity at different depth and direction, it was very essential to ensure global stability of this zone along with the stability of each structure. Any underground excavation involves certain amount of geological uncertainties. The more the extent of such excavation more the uncertainties have to deal with. So, the available option to handle such situation was continuous geotechnical monitoring, Geological assessment and suitable design provision to incorporate different geological conditions during excavation.

The support philosophy of all underground openings within the project is based on staged excavation, incremental installation of rock support measures and verification by monitoring. In addition robust design approached was followed to accommodate modification of rock supports based on actual characteristic of rock mass, thus leading to cost effective and practical rock support.

2 Geological Assessment of Site

Geological and geotechnical investigation was carried out in three phases during the period 2005 to 2010. In total 20 nos of bore holes were drilled in vertical and some of them in inclined orientation in each phases. Initially six numbers of boreholes were drilled in the year 2005 at some specific locations based on the information available from geophysical survey as well as out crops observed during site visit. The data obtained from first phase survey was used to develop tentative Geological map of this site projecting the extension and orientation of different features. Based on this map, second phase of investigation was planned which includes another six bore holes to ensure the possibility of projected geological features. Finally detailed geological map was developed after completion of third phase investigation which includes additional drilling of eight numbers of bore holes. This geological map kept on updating as excavation progress incorporating the geological information obtained from excavated zone. Further this map was used to plan the location of optical targets and bore hole extensometer along cavern section for continuous monitoring of critical area.

2.1 Geology

This area was located within 'Peninsular Gneisses' (M.S. Krishnan, (1953). The Peninsular Gneisses are characterized by heterogeneous mixture of different types of granite intrusive into the schistose rocks after the latter were folded and crumpled. Within the project area, Peninsular Gneiss is by far the most represented rock type. However, types of granite are also found in some places. The details of the structural discontinuities within the rock mass as determined from the mapping reveal 3 significant joint sets, 1 minor joint set and the foliation as show in Table 1.

Generally it was expected that very poor to poor quality rock will be encountered up to a depth of approximately 3 to 5 m below ground level, whilst fair and good rock is anticipated greater than 20 to 30 m below ground level. The local geological conditions of the project site are characterized by three geotechnical relevant rock mass layers of varying thickness.

Table 1: Observed Geological features

Features	Dip Direction	Dip.
Joint set 1	070	85
Joint set 2	100	85
Joint set 3	200	85
Minor Joint set	045	45
Foliation	020	85

The top layer is varying in thickness and consists of residual soil and lateritic. Immediate second layer is characterized by weather, jointed and fractured rock with boulders with varying thickness and bottom layer is hard fresh and massive rock. Most of the project component is located in the bottom layer (bed rock) except initial portion of access tunnel and shaft. No major tectonic event has occurred in this zone subsequent to formation of these rocks.

2.2 Geotechnical Assessment

The main geotechnical failure modes expected in the caverns of this storage complex are sliding of blocks/wedges along discontinuities, toppling and rotational failures and the development of overbreak in and around zones of fractured and weather rock. Weathering and ground water are deemed to have had little influence on the regional rock mass condition. The main influencing factor is the quantity and quality of discontinuities. A number of small fault like features were recorded during the investigation. However, it was expected to have little impact of these faults on rock mass behaviour in most cases. No major pre existing inactive and active mass movements were detected. However, this area is classified as Zone-III with seismic coefficient of about 0.04g as per Seismic Zone map of India (IS 1893).

Relatively high horizontal stress (S_H) in the range of app. 6 to 9 MPa was envisaged along the cavern roof. For the typical vertical stress at the site of about 4 MPa, corresponding approximately 50 to 80m of overburden, the typical values of the in-situ stress ratios was in a range of 2.2 MPa.

3 Geotechnical Monitoring Plan

In this project two differ types of instrumentations were used to measure the deformation i.e.

convergence monitoring by optical targets and rock mass deformation by extensometer. Convergence monitoring was carried out along the cavern section. However, deformation measurement by extensometer was only limited to geological hot spot as observed during investigation and subsequently substantiated during the excavation of other components (access tunnel and water curtain tunnel) of this project, specifically from the excavation of water curtain tunnel which was located just 20.0 m above the cavern crown.

3.1 Optical Targets

The deformation monitoring of excavation surfaces of cavern using 3D measurement of optical targets (in x-y and z direction) was the main geotechnical monitoring method in order to assess the rock mass behaviour during excavation.

Optical targets were fixed to reference points through bolting to the rock surface. The bolt was installed through a drill hole of diameter 25 mm upto a depth of 220 mm from rock surface. Then bi reflex target was fitted to the installed bolt with the help of the screw. Monitoring section within the caverns are typically arranged at every 25.0 m of interval with five targets within the top heading (one in crown and two at each side) and 4 targets along each side wall as shown in Fig. 1. However, additional section of optical targets was installed based on observed geological features in updated geological map.

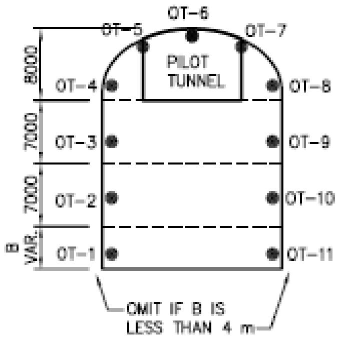

Fig. 1: Cavern cross section with optical targets and excavation stage.

The dotted line in the cross section of cavern shows the excavation stage of each bench. Initially pilot tunnel was excavated which was further extended by side slashing to complete the heading excavation. Similarly each bench excavation is also associated with side slashing to complete each bench thus total three bench excavations were carried out. All three optical targets at the crown location were installed immediately after the completion of necessary support activity in pilot tunnel and other two targets at heading were installed after completion of first bench excavation. The targets at the wall were installed after completion of subsequent bench excavation. Initially at few locations, the damage of optical targets was reported during first bench excavation. Therefore, necessary precaution was taken to protect the targets by removing it from the bolt during blasting activity and placed thereafter.

3.2 Extensometer

Extensometer was installed in drilled boreholes from the invert of water curtain tunnel at some geologically critical locations as identified from updated geological map. This water curtain tunnel is located just 20.0 m above the crown of the cavern which will be filled with water during operation to ensure continuous flow of water around caverns to maintain require hydrostatic pressure around the cavern for confinement of crude oil. This tunnel is extended along the cavern length.

At each location two different extensometers were installed toward the cavern on either side of the water curtain tunnel as shown in Fig. 2. Extensometer was installed in drilled boreholes with three point instrument at 5.0 m interval thus maximum length of 20.0 m and furthest point is approximately 5.0 m away from cavern roof. This will monitor the rock mass movement at crown of the cavern which was envisaged as most critical part from stability point of view.

Each extensometer rod was grouted where the rod end is located in rock to develop strong bonding between the rod and surrounding rock mass. Thus minimize the chances of slippage between extensometer rod and surrounding rock. The head of the instrument was housed within a steel protection cap to avoid disturbance and damage from different construction activity. The sole purpose of these extensometers was to monitor the rock mass behaviour during construction.

Once the cavern was fully excavated and its stability was further ascertained through the stabilized extensometer monitoring data, the instrument was abandoned and all void within the instrument was grouted with cement grout to avoid any potential passageway of water towards the cavern crown.

It is usually works based on the assumption that the deepest anchor is in stable ground and any change in anchor spacing is interpreted as rock mass movement. Here, the topmost anchor point (close to water curtain tunnel) was considered as in stable ground and will indicate any relative movement of rock in cavern crown during cavern excavation which will be recorded in it's head assembly.

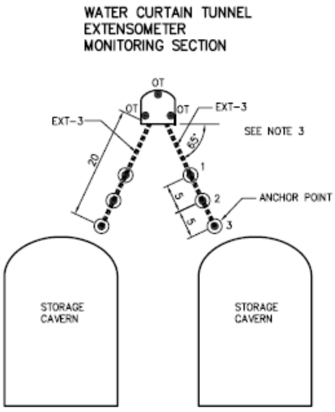

Fig. 2: Location and extent of Extensometer from Water Curtain Tunnel

4 Geotechnical Monitoring Procedure

Monitoring team comprises Project manager, Shift Manager, Site Engineer and Surveyor worked till the end of construction which completed in the year 2013 involving the underground excavation of 34.9 Lakh cum rock without any accident related to stability of rock.

4.1 Convergence Reading

Reading from optical targets was taken with the help of total station survey. The control points were fixed with reference to the original project co-ordinates at every section where the targets were fixed. First set of readings shall be zero readings of the targets. Data of all the readings were stored in the memory module of total station automatically and then down loaded it to the computer for further processing.

4.2 Extensometer Reading

Grouted anchored type borehole extensometer composed of head assembly, vibrating wire displacement sensors, connecting rod assembly and anchor or reinforcement bar were installed. Extension rods were installed in to the bore hole up to the required depths. Then the extensometer sensors were fixed after four days of grouting and initial reading were taken from read out unit. Data were stored and plotted to find the trend of rock mass behaviour.

4.3 Monitoring Frequency

The data manually obtained from optical targets and extensometers were entered and saved electronically in spreadsheet and plotted with time (frequency).

Table 2: Monitoring frequencies for convergence monitoring by Optical targets.

Instrument	Frequency	Condition-1	Condition-2
Optical Targets	Once per day	Within 30.0m from the excavation face	The differential deformation between the current and the previous reading is more than 5.0 mm.
	every other day	within 30.0m from the excavation face	The differential deformation between the current and the previous reading is more than 2.0 mm.
	Once every week	between 30.0m and 60.0m from the excavation face	The differential deformation between the current and the previous reading is larger than monitoring accuracy
	once per month	excavation face is more than 60.0 m away	The differential deformation between the current and the previous reading is within monitoring accuracy

These frequencies were mentioned in Table 2 & 3 with different condition. However, this frequency was further modified based on actual behaviour of rock mass observed after plotting and interpreting the recorded data. Observed data as per given frequency was plotted and uploaded to the centralize server and all concern person could have the access to the server whenever required. This was followed by the interpretation of all monitoring data by design engineer to assess the overall stability at certain stage to decide and verify further excavation strategy.

Table 3: Monitoring frequencies for Extensometers.

Instrument	Frequency	Condition-1	Condition-2
Extensometer	Once per day	Excavation face in cavern gallery is within 40.0 m of the instrument	The differential deformation between the current and the previous reading is still more than 5.0 mm
	Once every week	Excavation face in cavern gallery is more than 40.0 m away from the instrument.	The differential deformation between the current and the previous reading is larger than monitoring accuracy.
	Once per month	Excavation face in cavern gallery is more than 40 m away from the instrument.	The differential deformation between the current and the previous reading is within monitoring accuracy.

5 Monitoring Results and Discussion

In such large projects, compilation and recording of monitoring data is an important aspect and cannot be left to simple practice of sheets and tables. Presently with the advent of technology, this filed of data management has also witnessed lot of upgradation and automation. Therefore in this project also, all monitoring data were managed through a dedicated geo monitoring software, which works as a tunnel information system for continuous monitoring by concerned person at site as well as design office. Deformation value as observed in optical targets was plotted in all three direction (two horizontal and vertical) with respect to time of observation. Similarly, extensometer reading of three anchor points was also plotted with respect to time of observation. All these results were compared regularly in reference with different limit value.

5.1 Deformation Limit

Monitoring values were used to evaluate the rock mass condition by comparing measurement results against expected soil/rock deformation. Different monitoring limit values were introduced to categorise measurements in terms of their severity. This limit was developed from the expected deformation in detailed design calculation and functioning and maintenance of the structure. In the detailed design calculation, rock mass as observed in this area was classified broadly in three classes as per their Q values i.e. Class 1. Good and Very Good Rock, 2. Fair Rock and 3.Poor Rock and expected deformation were defined for each of them. For all these three classes two limits were fixed namely “trigger level” and “allowable level”. Trigger level is defined as the permitted maximum displacements of a particular structure or area, which is critical to the safety, functioning of the structure. It was considered as 80% of design value.

Table 4: Monitoring limit values for different rock Class

Rock Class (Q-value)	Top Heading		Benching	
	Trigger (mm)	Allowable (mm)	Trigger (mm)	Allow able (mm)
Very Good and Good	5.0	10.0	5.0	8.0
Fair	5.0	10.0	5.0	7.0
Poor	24.0	42.0	13.0	22.0

Whereas allowable level, is the maximum limit which should not exceed in any case and this was set at 140% of the design value. Absolute values as considered in this project for different rock class at various stages of excavation are reported in Table 4.

5.2 Interpretation

In most of the case, the observed deformation in geotechnical monitoring data observed from optical targets was well within the trigger limit. There was not a single incident reported where the deformation exceed the allowable limit. However, at few locations sudden increase in deformation was observed due to the major excavation activity in that vicinity. When the deformation value exceed the trigger value at some section of the cavern, that location was visually inspected by engineer to check the possible distress in terms of increased seepage or any crack in the installed shotcrete to allow further excavation.

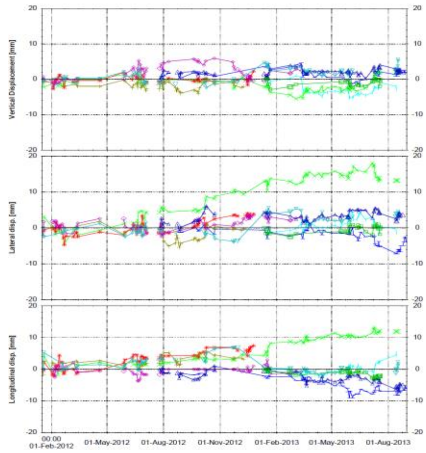

Fig. 3: Deformation plot for vertical and horizontal direction upto completion of project

Typical deformation of cavern section plotted in Fig. 3 for poor rock condition where relatively higher deformation was observed.

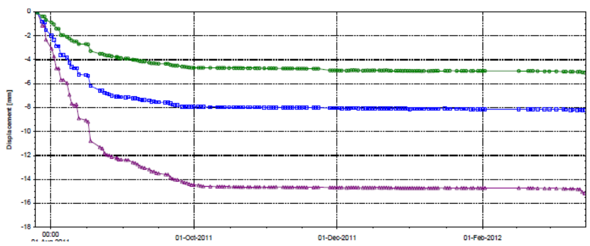

Fig. 4: Extensometer reading at poor rock condition

Similar trend of deformation was also observed in Extensometer reading as presented in Fig. 4. In this case increase in the deformation was observed during the pilot tunnel and side drift at heading excavation. Afterward there was no significant increase in deformation due to subsequent bench excavation. In both the measurement, the deformation values in poor rock condition were remarkably low compare to the trigger value at different stage of excavation. This may be due to the conservative design approach as followed in this project for poor rock class. However, the incident of poor rock class encountered was less than 5% as compare to total excavation length.

6 Observation and Comments

This paper was specifically developed to highlight the systematic approach followed for large cavern excavation to minimize the risk of rock fall due to sudden change in geology. Initially, three stage geological investigations were quite efficient to understand the rock mass character more accurately. Particularly it helped to minimize the occasion of geological surprises involved in underground excavation. Moreover, continuous design updation activity employing high end dedicated software's based on latest geological information along with geotechnical monitoring helps to use rock support system more efficiently and economically. However, geotechnical monitoring method using optical targets need to be improved for such large excavation. It was observed in many occasion during the excavation that the total station survey to take the reading suffer from accuracy due to disturbance from construction activity. The initial deformation which may have occurred immediately after excavation can't be recorded in optical targets measurement. This need to be addressed in future study by cost effective automatic instrumentation. Thus monitoring data will be more accurate and will definitely minimize the scope of human error involved in recording and uploading such huge data. Also the application of mobile technology can help to keep alert all concerned round the clock.

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