Crude Oil Storage in Large Underground Rock Caverns

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Abstract

The paper discusses the planning, design and construction of storage of crude oil in large unlined rock caverns. Underground storage of hydrocarbons is not only more secure, safe and economical than above ground storage, but also has several environmental and operational advantages. The paper also shares the experiences gained to date and discusses the future prospects for underground storage.

Introduction

General

In the present geo-political scenario of the world, energy security of a nation has gained paramount importance. In order to ensure energy security, hydrocarbon stocks are stored in huge underground storage caverns. Several methods may be employed for strategic storage of hydrocarbons such as storage in rock caverns, salt caverns, depleted aquifers or unused mines. Strategic locations are selected with an option of providing the most flexible means of oil and gas transport network. Storage in Underground Unlined Rock Caverns is currently under implementation in India. The present paper outlines the planning, design and construction aspects of unlined underground mined rock caverns.

Types of Storage

Several methods may be employed for strategic storage of hydrocarbons such as storage in rock caverns, salt caverns, depleted aquifers or unused mines. Salt caverns are carved out of underground salt domes by a process called "Solution Mining". Essentially, the process involves drilling a well into a salt formation, then injecting massive amounts of fresh water. The dissolved salts are removed as brine and disposed. Depleted oil and gas reservoirs are the most commonly used underground storage sites for natural gas because of their wide availability and are least expensive. Since the depleted reservoir formerly contained gas or oil, hence it satisfies the permeability and porosity conditions required for storage. Underground concrete tanks have also been adopted in a limited number of cases. Storage of hydrocarbons in an unlined rock caverns has been found to be one of the most economical solution for storage of large volumes. This form of storage relies on hydraulic containment.

Underground storage of hydrocarbons in large quantities is more secure, safe and economical than above ground storage. Further, land use is minimized, which can be a major advantage in many cases. Also operational costs are lower than conventional storage. Generally salt caverns have the lowest costs, but require thick salt deposits. Underground concrete tanks are also economical; however these are not as secure or safe as underground salt or rock caverns.

Unlined rock caverns are large underground excavations. Typical size of caverns is 20m in width, 30m in height and length between 600m to 1000m. Several such caverns are excavated with access tunnels, water curtain tunnels and shafts.

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Strategic Storage Program

Phase 1 of the strategic storage program consists of the storage of 5.33 MMT of imported crude oil at three locations: Vishakapatnam (1.33 MMT), Mangalore (1.5 MMT) and Padur (2.5 MMT) in unlined rock caverns, which are currently under implementation and are to be completed between 2012 & 2013.

In Phase 2 of the strategic storage program about 15 MMT of crude oil is to be stored with the objective of having at least 90 days reserve of imports of crude oil considering both operational and strategic storage. Storage options include unlined rock caverns, underground concrete tanks and solution mined salt caverns.

Unlined rock caverns

Principal of Storage

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. In order to check and secure the water flow from the rock mass towards the cavern 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 all the joints of rock mass. A saturated rock mass and ground water flowing into caverns, ensures proper sealing of the stored product from leakage. Particular attention is given to ensure that the rock mass remains saturated with water even while excavation works are in progress.

Layout

The components of the underground storage include caverns, access tunnels, water curtain tunnels with water curtain boreholes, shafts and pump pits. The cavern and shafts are closed with concrete plugs to ensure gas tightness.

Underground Process Facilities

The underground process facilities include crude oil and seepage pumps in the shafts, instrumentation cables and hot oil circulation pipe on the cavern floor.

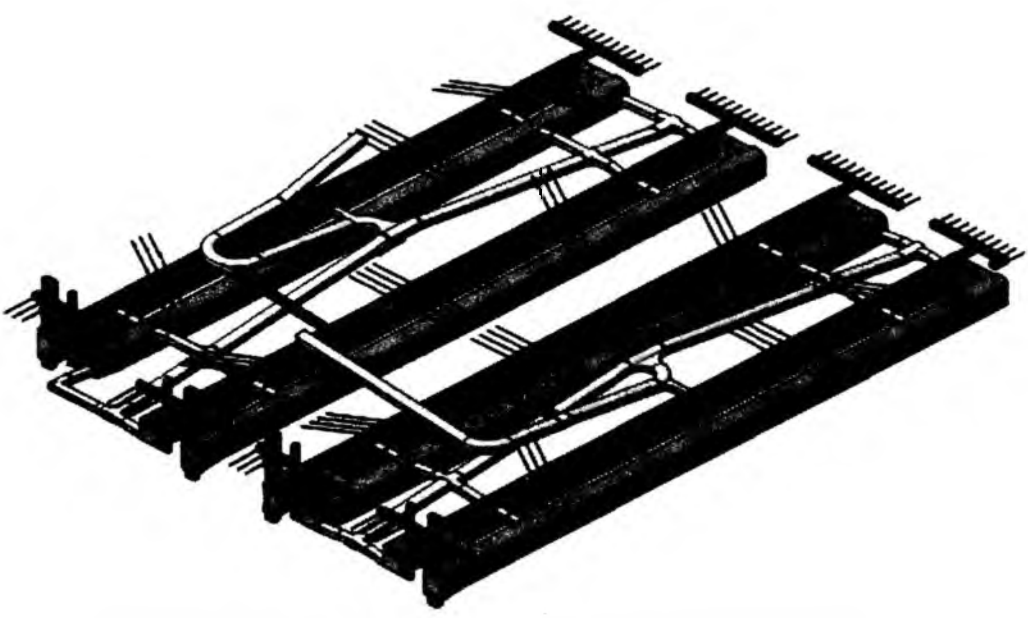

Fig. 1: A typical cavern layout along with superimposed water curtain system.

Investigations

Extensive and planned investigations are necessary to minimize geological surprise during construction. Geological, geo-technical, geo-physical and hydro-geological investigations are carried out to establish the rock mass characteristics, engineering geological map, virgin stresses and hydro-geological conditions of the proposed area.

Geotechnical investigation includes vertical and inclined coring holes located suitably to detect geological profile. The depth of investigation is planned at least up to 10m below the invert of the cavern. Core Recovery, RQD, discontinuities spacing, joint condition, orientation, dip of strata, cavities, fissures, the occurrence of shear seams, gouge material, etc. are duly recorded. The engineering geological map is prepared with the interpretation of the geotechnical findings. This information later provides help to establish the layout of the rock caverns. The other parameter for orientation of the cavern is the virgin stress. For this, hydro-fracture stress test is carried out to measure the maximum and minimum horizontal *in situ* stress. The investigation scheme also involves seismic refraction test, electrical resistivity test and sonic well logging along with extensive laboratory testing to augment findings of other investigation.

To establish the permeability profile and seepage water quantity assessment in the caverns, water pressure tests and pumping interference test are carried out. Water pressure tests are conducted in selected sections of the borehole using either inflatable or mechanical packers. Packer test, covering all the previously tested sections are also performed. The kind of water pressure test depends on the ground water and rock mass conditions.

The water level and flow variation is monitored both for pre and post monsoon periods for which piezometers are installed. Meteorological statistics such as average rainfall in the area is very important to assess the ground water recharge conditions.

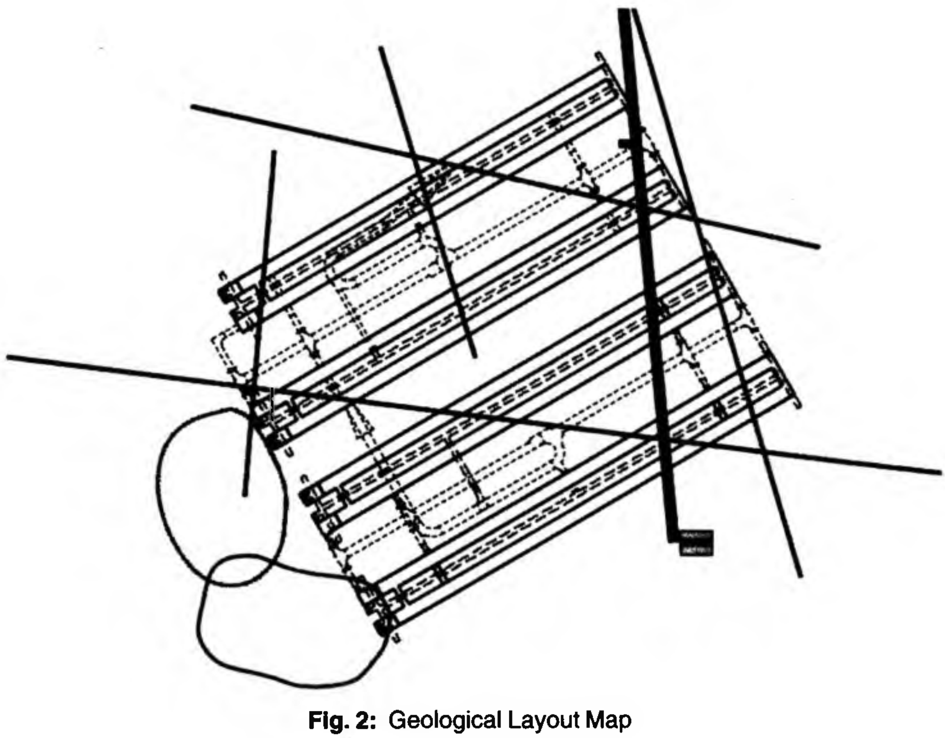

Fig. 2: Geological Layout Map

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 favourable stress situation in the rock and also take into account any major geological structures. The excavation sequence and methodology is also considered in the layout and sizing of the tunnels.

Geological Model

The Geological model needs to cover the regional geological settings so as to further focus on the project geological setting. The later encompass the following key aspects: Topography, Geomorphology, Rock Type, Tectonics and Major Discontinuities (Fig. 2).

Geological Model also describes the thickness of soil cover and extent of weathered rock. The intrusive features like dyke and hydrothermal zone are delineated from the bed rock. The anticipated region of weakness zones intersecting the layout are marked on model as geological hot spots.

Hydro-geological Model

Owing to the containment principle of storage, the hydro-geological regime of the project forms an important aspect, which encompasses the following aspects: Topography, Annual rainfall, recharge, Geological setting and Hydro-geological properties. Hydro-geological model studies are carried out to check the flow pattern around the caverns so as to confirm hydraulic containment and estimate seepage rates based on the data collected during the investigations. The following design parameters are considered: Provision of water curtain above the cavern with boreholes charged to a head equivalent to required pressure, maximum operating gas pressure at the cavern crown and the vertical distance between water curtain gallery and cavern to satisfy the requirement of hydraulic gradient greater than 1.0 at cavern roof level (Aberg, 1977). Finite element studies are carried out to estimate hydraulic gradient, seepage in the caverns during construction and water requirement during construction (3), The analysis are carried out for several conditions of operation, i.e. completely empty at atmospheric pressure, maximum normal vapour pressure, cavern units under different pressures, etc,. (Fig. 3).

Geotechnical Model

Support system design and the excavation method are evaluated by the following methods: Rock mass Classification, Stress Analysis and Wedge analysis. Rock mass classification has the following general aim in an engineering application:

To divide a particular rock mass into groups of similar behaviour,

To provide a basis for understanding the characteristics of each group,

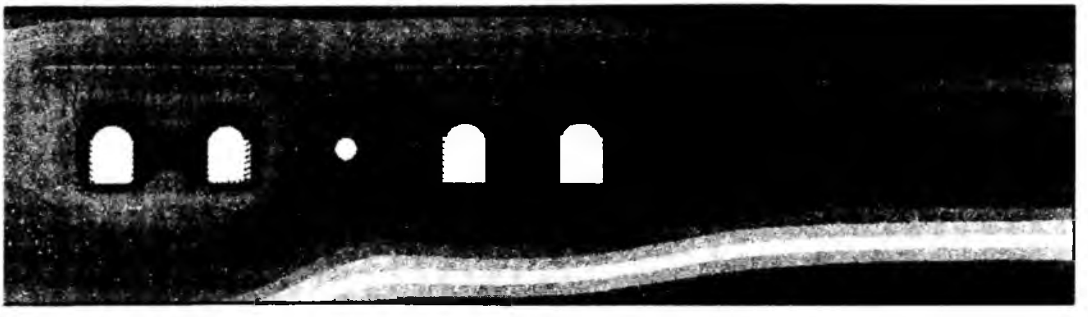

Fig. 3: Flow vectors from water curtain system towards cavern

To yield quantitative data for engineering design and

To provide a common basis for communication.

Generally Q-system (Grimstad and Barton, 1993) is used for hard rock tunneling, both as prognosis for detailed design and during excavation mapping.

The total stress situation in the vicinity of an excavation depends on the in situ stress field, orientation of the excavation with respect to the *in situ* stress field, geometry of the excavation and excavation stages. The Stress analysis (Usmani, *et al.,* 2009) is carried out to analyze the following: Stress/Strain situation and distribution in the rock mass, extension of possible yielding zones, Pillar stresses and rock displacements, internal stresses and forces (Fig. 4).

After identification of main joint sets from core geological observation, the potential unstable wedges formed by the main gallery intersecting the identified joint sets are investigated using dedicated Block stability software. Results obtained from wedge analysis will give the factor of safety of the critical wedges formed, and size of the wedge. Based on these results length of the rock bolts is decided and the spacing of the rock bolts obtained from empirical methods is evaluated.

Other Aspects

The underground works include concrete floor, concrete plugs in access tunnels and shafts, pump pit, casings for crude and seepage pumps, instrument cables and concrete encased hot oil circulation pipe. Detailed design of these has to be carried out. The design of the concrete plugs is critical as these have to be designed for gas tightness. In addition to the above, detailed design of above-ground facilities has to be carried out

Construction

General

Construction of the underground storage works is carried out by the drill and blast method with fully grouted un-tensioned rock bolts and fibre reinforced shotcrete as the principal means of support. Steel sets and ground anchors may be adopted in exceptionally poor conditions. The typical construction cycle is survey, probing, drill and blast, scaling, mucking, geological mapping, rock support and grouting as required.

Water Curtain System

The water curtain system is the most critical part of the storage. The water curtain boreholes should be charged at least 40-50m ahead of the cavern excavation to ensure saturation of the joints. The water curtain tunnel, along with the boreholes, also serve

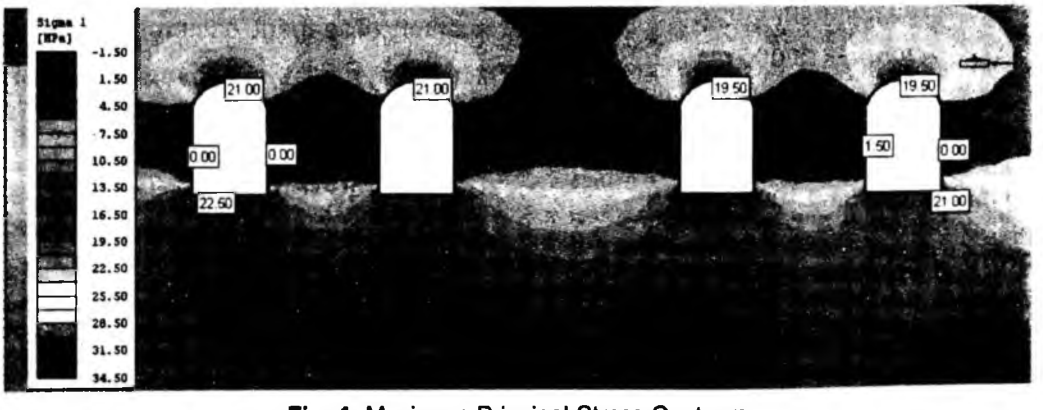

Fig. 4: Maximum Principal Stress Contours

to update the geology and hydrogeology and to decide on requirements of pre-grouting and any other specific requirements for excavation of the caverns.

Construction Equipments

The underground storage works require a large excavation within a short construction period. Typical construction schedule for 1.0 MMT storage is around 30 months for excavation and support and another 6 months for the underground concrete and process works. This tight construction schedule requires careful planning, deployment of necessary equipments and qualified manpower and strictly following all quality and safety procedures. The major construction equipments for 1.0 MMT storage are listed below.

a. 2 boom jumbos (5 numbers)

b. $20m^3/hr$ Shotcrete robots (4 numbers)

c. $6.5m^3$ Loaders (4 numbers)

d. 25 MT Dumpers (25 numbers)

e. Drilling rigs for water curtain bore holes (3 numbers coring/destructive)

f. Grouting equipments (2 numbers)

Production Statistics

To achieve the tight construction schedule high excavation rates are required without compromising quality and safety. The following excavation production rates have been achieved per month:

a. Access tunnels 30000 m^3

b. Water curtain tunnel 6000 m^3

c. Cavern heading 60000 m^3

d. Cavern benching 100000 m^3

Monitoring

Geotechnical Monitoring

The purpose of the Geotechnical monitoring is to understand the effect of the rock mass behaviour and tunnel supports in tunneling and secure the safety and economical efficiency during the construction process.

Displacement of the rock mass is monitored with borehole extensometer and convergence measurement equipment. Optical targets installed at regular intervals for convergence measurement in all the underground facilities and borehole extensometers are installed in the invert of water curtain tunnel to monitor the displacement in the cavern during its excavation without any delay.

Hydro-geological Monitoring

The purpose of hydro geological monitoring is to ensure that there is no impact on the hydraulic safety of the caverns during construction phase and during operation. The hydrogeological conditions necessary for the hydraulic confinement of the stored product shall be maintained at all times and no interruption in maintaining hydrogeological record is permitted in between construction and operation phases.

Hydrogeological monitoring of the rock caverns during construction shall include the following:

Monitoring of water levels in piezometers,

Monitoring the flow rate of water injected and pressure in individual water curtain bore holes, Monitoring of seepage for individual sections of the underground works,

Inventory of seepage occurrences,

Monitoring rainfall, tide levels, etc. and

Analysis of water samples.

Concluding remarks

Some Observations

Based on our experience, to date, we have the following observations on the planning, design and construction of large underground storage projects.

a. Basic Engineering

The design and construction of large storage caverns is a complex work requiring the coordinated efforts of geologists, hydro-geologists, geotechnical, rock mechanics, structural, piping, instrumentation, rotating process and construction engineers.

b. Design-Construction Interface

The design philosophy for underground works should follow an observational approach, i.e. the original design assumptions are to be updated by means of the results from monitoring during construction, to allow for an optimized design. Further, the interface between design and construction processes should be given special attention with the objective to achieve consensus between the design and production teams in the organization. An active input of constructability aspects into the design process is considered as a crucial factor for a speedy construction. This process is facilitated by deployment an experienced Design Interface Manager.

c. Risk management

Risk management is one of the critical activities for successful implementation of large construction projects. Risk can be managed, shared, transferred or accepted using systematic risk management systems. A dedicated risk manager should be engaged for the design and construction period.

d. Geotechnical Reference Conditions

The main objective of the Geotechnical Reference Conditions is to give bidders one single, concise and workable description of the ground conditions upon which they shall base their tenders and give them a clear idea about the associated risks. These reference conditions also establishes a geotechnical baseline to be used in assessing the existence and scope of differing site conditions. The Geotechnical Reference Conditions shall provide a clear contractual arrangement for the allocation of the risks arising from differing site conditions and give the contractors the necessary understanding of the conditions and the rationales for selected solutions as the basis for their design and construction. They also serve to constitute the base for the contractors' estimate of cost and time and to serve as the basis for verification of site conditions during construction and the associated compensation of cost and time as well as possible claims.

e. Monitoring

Geotechnical and hydro-geological monitoring are vital during construction. These are required not only to validate the design assumptions and to optimize the design, but also to check the quality of works and ensure safety and hydraulic containment.

f. Safety

Safety is a key concern is all underground works and in particular for large storage works, where very large underground excavation works are carried out under tight schedules. Deployment of dedicated quality and HSE managers is vital for the successful implementation of these projects.

Future of underground storage

With the growing demand for hydrocarbons in virtually all sectors of the industry, we foresee a strong requirement for underground storage of hydrocarbons in the country, as by 2020 almost 90% of the crude oil will be imported. In addition to stock holding by the government for emergency situations, Indian public and private sector organizations in the hydrocarbon sector as well as foreign oil companies have expressed interest.

Further in addition to underground storage of crude and products, underground storage of both compressed natural gas as well as LNG are expected in the future. Further research and development is needed for gas, LNG and other hydrocarbon storage in lined rock caverns. Developmental work is also needed to optimize the design, construction and operation of established underground storage systems such as solution mined salt caverns, underground concrete tanks and mined rock caverns.

Underground storage systems have design lifetimes in excess of 50 years. As these storage systems are built and operated in the country, the experience gained from the operation of these systems needs to be incorporated in the planning, design and construction of the next generation of underground storages.

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