Underground rock caverns for strategic crude oil storage in India – nature of studies, design and construction

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Storage of crude oil and other petroleum products in unlined caverns is a well-proven technique, with successful implementation in many parts of the world. The Government of India started the construction of underground crude oil caverns in 2008 to store 5.33 million metric tonnes (MMT) of imported crude oil in three crude reserves, based on a 15-day crude oil requirement in all the Indian refineries. 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 construction of an underground storage requires a large excavation within a short period. Typical construction schedule for 1.0 MMT storage is around 30 months for excavation and support and another 6 months for laying underground concrete and processing. This tight construction schedule requires careful planning, deployment of necessary equipment and qualified manpower and strict adherence to all quality and safety procedures. In this article, an attempt has been made to highlight the need for underground crude oil storage, principle of storage, types of investigations required to test for feasibility, detailed project report and construction stages, the requirement of geological, geohydrological and geotechnical models for engineering and design, construction methodology and geotechnical and geohydrological monitoring required during the construction and post-construction phase of the project based on the author's association with three projects.

Keywords: Fibre-reinforced shotcrete, hydraulic confinement, rock bolt, underground cavern, water curtain tunnel.

INDIA is home to 17% of the world population, but contain less than 1% of the known oil and gas reserves. It imports about 70% of its oil and gas requirement and this dependence may increase to 90% by 2020 as indicated by the trend in energy usage. Oil and gas are supplied to a great extent by the Organization of the Petroleum Exporting countries (OPEC) and the supply from these countries is expected to increase, especially from Saudi Arabia and Iraq, which shall be able to increase production from their new fuel reserves by 2035. The supply of liquid and gas fossil fuels to India is dependent on various geopolitical forces. If the supply is disrupted due to theft by pirates, geopolitical blocks/alignment, shipping accidents, cartel formation by companies, price shocks, wars, political unrest, threat by terrorist attacks, etc. the whole economy is forced to a grinding halt with losses to the tune of billions of rupees and the worst part is that it will take more than six months for the economy to normalize. So, strategic storage of fuels was envisaged by the Government of India to tide over sudden disruption in fuel supply. Strategic storage will also help in price stabilization as fuel can be strategic stocked during low demand and used during high demand. Storage of fuels only in underground unlined rock caverns is currently being implemented in India and locations with the most flexible means of oil and gas transport network have been selected. Storage of fuels in unlined rock caverns is a mature and well-proven technique that was originally developed in Sweden in order to achieve an advanced protection level against various munition attacks[1]. The storage principle has been implemented in several countries including Sweden, Finland, Norway, Japan and South Korea.

Underground storage of hydrocarbons in large quantities is technologically proven, more secure, safe and economical, generates less evaporation losses and more environment friendly than above-ground storage. Unlined rock caverns require low maintenance and safety is in-built as product storage occurs at an underground depth, which is fully isolated. Hazards on account of sabotage by terrorist activity, war, bombing (nuclear

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bombs), storms, earthquakes, floods, typhoons, tsunamis, external fires, etc. are minimized. Surface land requirement is low. The life of the underground storage is longer than above-ground storage. Generally, underground storage installations are below sea level, hence faster unloading of tankers/ships takes place. The control system and fire fighting system are much simpler and cheaper to construct and operate. The hydrogeological containment principle ensures that there is no leakage or contamination of underground water bodies. The construction cost of underground rock cavern storage is cheaper than that of surface tanks. As the size of the caverns increases, the cost of the cavern decreases, i.e. the cost decreases with storage volume. The most significant savings in operating costs are: (i) reduced land rent/cost, (ii) reduced amortization of construction costs, (iii) considerable savings in insurance costs (reduction of 60–70% when compared to above-ground facilities), (iv) reduced maintenance cost and (v) reduced safety requirement and cost. The huge rock mass that is excavated can be used as building material and aggregate for concrete reclamation work. In India, there is a shortage of steel, hence underground storage assumes great importance as steel requirement is lesser than that of surface storage[2].

Type of storage

Several methods may be employed for strategic storage of hydrocarbons such as salt-leached caverns, aquifers or depleted fields, disused mines, unlined rock caverns, barge storage, in-ground concrete tanks, above-ground steel tanks. Depleted oil and gas reserves are the most commonly used underground storage sites for natural gas because of their wide availability and are less expensive. As the depleted reservoir formerly contained gas or oil, it satisfies the permeability and porosity conditions required for storage. 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 and dissolved salts are removed as brine and disposed. Salt formations in India are situated over a 50 sq. km area in Bikaner District of Rajasthan. Unlined rock caverns are large underground excavations in rock formations. Typically, a cavern is 20 m wide, 30 m height and its length varies depending upon the storage capacity from 300 to 1000 m. Caverns are not lined with concrete as are hydro/road/metro/rail tunnels. Unlined rock caverns, after salt caverns, are the second cheapest caverns used to storage hydrocarbons. Generally, the inverts of the storage units are inclined from the intake to the pump pit to minimize the interface between product and water and to facilitate circulation of crude oil. Several such caverns are being excavated in India with access tunnels, water curtain tunnels with water curtain boreholes, shafts and pump pits. Cavern and shafts are closed with concrete plugs to ensure gas tightness. The underground process facilities of unlined rock cavern include crude oil and seepage pumps in the shafts, instrumentation cables and hot oil circulating pipe on the cavern floor.

Strategic storage programme

Phase-I of the Indian strategic crude oil reserve programme involves construction of the storage units of 5.33 million metric tonnes (MMT) of imported crude oil at Visakhapatnam (1.33 MMT), Mangalore (1.50 MMT) and Padur (2.50 MMT) in unlined rock cavern, which is currently in progress and will be completed in 2013. The storage unit at Visakhapatnam comprises five parallel caverns; three of them are 840 m long and two are 320 m long. The cavern width is 20 m with a maximum height of 30 m. Padur site comprises 8 parallel caverns, six of them 700 m long and two are 656 m long. The cavern width is 20 m with a maximum height of 31.40 m. Mangalore site comprises four parallel caverns, two of them 913 m long and two are 873 m long. The cavern width is 20 m with a maximum height of 31 m. The government plans to maintain static stocks at these locations purely for the purpose of strategic storage. These measures will help to create energy security which shall go a long way in creating economic stability in the country. It was envisioned that, these reserves would ensure supplies of petroleum products across the country for about 15 days. In USA, Japan, South Korea, Germany, Hungary and France, strategic stocks are static stocks kept as an insurance against supply disruptions and are not used for price management. USA, South Korea and Hungary store crude and petroleum products equivalent to 90 days of consumption whereas Japan, Germany and France store for 92, 105 and 95 days of consumption respectively. In phase-II of India’s strategic storage programme, about 15 MMT of crude oil will be stored to serve as a reserve for at least 90 days considering both operational and strategic storage. Strategic storage equivalent to 90 days of annual consumption is the current international norm, i.e. three months are available to arrange fuel supplies. Storage options include unlined rock caverns, underground concrete tanks and solution mined salt caverns.

Principle of storage

The basic principle of storage in unlined rock cavern is hydraulic confinement, as there is no concrete lining to create a barrier between the stored product and the water outside. Due to the huge size of the caverns, lining them with concrete will be expensive; hence hydraulic confinement is used to contain oil inside the cavern. Rock caverns are planned at a depth such that there is sufficient hydrostatic pressure to counter the vapour pressure of the stored hydrocarbon. Storage in unlined caverns is based on the fundamental principle that the stored cavern is located well below the surrounding groundwater level and the stored oil is lighter than water and is not soluble in water. When the cavern is excavated below the surrounding groundwater level, due to natural fissures in the rock, water continuously percolates towards the cavern, thus preventing oil from leaking out. Crown elevations for the caverns in the Visakhapatnam, Padur and Mangalore projects are –30, –40 and –35 m respectively. In order to check and secure 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. Saturated rock mass and groundwater flowing into caverns ensure proper sealing of the stored product. Water leaking in through the rock mass joints into the cavern is drained to a pump pit and pumped out at regular intervals. Particular attention is given to ensure that the rock mass remains saturated with water even while excavation is being carried out[3].

Field and laboratory studies

For an overall geological and geotechnical framework of unlined rock caverns for crude oil storage projects, detailed site characterization in terms of geology, hydrogeology, geochemistry, geophysical, geomechanics and geotechnical studies is required. During feasibility and detailed site studies, geological mapping of outcrops, seismic refraction and resistivity surveys, core drilling and subsequent water pressure testing, sonic well logging, laboratory tests, *in situ* stress measurements, groundwater level monitoring and groundwater quality analysis were carried out for all the crude oil cavern projects. At the feasibility stage, geotechnical data were acquired for assessing the feasibility of the proposed location and to decide on a tentative location and orientation of the facilities. Using the data generated at the detail project report (DPR) stage, investigations from geological and structural mapping, subsurface explorations, *in situ* and lab testing, location, alignment and dimensions of the caverns were finalized. The purpose of geological and geotechnical studies is to provide basic data for economic and fail-safe design and construction of the cavern.

Geophysical surveys

Geophysical surveys (seismic refraction and resistivity surveys) are used to define the attitude and overall distribution of major geological structures such as faults, shear zones, intrusions, hydrogeological condition including geothermal occurrences, etc. These types of oriented data are essentially required for the development of a three-dimensional model of the subsurface. At an advanced stage of investigations for cavern crown optimization studies, down-hole techniques and cross-hole tomography are applied for establishing a variation in rock mass and fracture properties. Geophysical survey was conducted intensively and extensively to obtain fast and reliable subsurface information and also to rationally plan the exploratory drilling programme. Sonic well-logging was performed to measure the velocity of the strata immediately adjacent to the drill-hole wall. This *in situ* measured velocity can provide data of a particular lithology.

Drilling

Based on geological and geophysical data, the exploratory drilling was planned. Exploratory drill-holes (vertical and inclined) were planned at project sites with the objective of determining the quality of the rock mass likely to be encountered, depth of overburden, depth of weathering/destressing, existence of shear zone/weak zone, rock cover above the proposed cavern. The pattern and depth depend upon the nature and size of the cavern. The depth of study was at least 10 m below the invert level of the cavern. Borehole studies provide a continuous record or geology of the bed rock or physical properties of the bed rock. Geotechnical maps were prepared by interpretation of all the geotechnical findings.

Water pressure test

To establish the permeability profile and assess the quantity of seepage water in the caverns, water pressure test and pumping interference test were carried out. Water pressure tests followed by Packer test were conducted in selected sections of the borehole using either inflatable or mechanical packers. The type of water pressure test depends on the ground water and rock mass conditions. Water level and flow variation were monitored both for pre- and post-monsoon periods by using piezometers. Meteorological statics such as average rainfall in the area is very important to assess the ground water recharge conditions.

Laboratory tests

Studies on laboratory rock mechanics were carried out on bore-drilled samples required for designing and modelling of caverns. This includes determination of uniaxial compressive strength, Young's modulus and Poisson's ratio of dry and water-saturated samples, tensile strength and triaxial compression test (cohesion and friction angle). All the tests were conducted according to methods suggested by the International Society for Rock Mechanics

(ISRM). Triaxial compression test was conducted using the multiple failure method.

A major problem that could be encountered during underground excavation is the unexpected behaviour of rock mass. During this stage, detailed site investigations were supplemented with site investigations and rock mass characterizations, i.e. geological and/or geotechnical investigations and geotechnical instrumentation and monitoring of rock, rock mass and ground water assessments. Monitoring records from underground locations should be studied vis-à-vis the results of numerical analysis. Appropriate corrective/preventive steps should be initiated, wherever necessary[4].

Engineering and design

The layout, cross-section and elevations of the caverns were finalized considering the geological and geotechnical conditions at site as well as product storage and operational requirements. The excavation sequence and methodology were also considered while finalizing the layout and size of the tunnels. An observational approach for permanent support was followed, i.e. original design assumptions were updated by means of the results from the monitoring during construction, to allow for an optimized design.

In situ stresses testing – design parameter

For designing caverns, *in situ* stress parameters are most essential. *In situ* stresses in rock mass are induced by geological loading which may be due to tectonic activity (active or remanent) and gravitational loading caused by mass of overburden. During the excavation of an underground opening, rock mass behaviour undergoes significant changes due to changes in stress condition and in pattern of readjustment of stresses around the opening. The ratio of *in situ* stress to the strength rock mass determines the scope and degree of deformation or failure that can occur. If the stress is much higher than the strength, local to large failure can occur, and in an extreme case, rock mass may behave in a plastic manner in a way similar to soil. *In situ* stresses are defined as horizontal and vertical stresses in x, y and z-axes which are perpendicular to each other. Horizontal stresses are of two types – major horizontal principal stress (σH) and minor horizontal principal stress (σh) and the vertical normal stress (σv) is equal to the weight of the overlying rock material which is 0.027 MPa/m on an average[5]. The magnitude of stresses σH, σh and σv is expressed in MPa and direction of σH is given in respect of north. For the measurement of virgin stress in the underground rock caverns, hydro-fracture stress test was carried out to measure the major and minor horizontal *in situ* stresses. The longer axis of the underground cavern is normally kept parallel to the major horizontal principal axis in order to ensure maximum stability of the structure.

Geological model

The geological model has to include the regional geological settings so as to further focus on the project geological setting. High resolution satellite imageries/cartosat data were used for identifying major lineaments/faults, shears, etc. in and around the project site. Large-scale geological mapping was done using high-precision Total Station. A geological map of the project area was prepared showing details of topography, geomorphology, rock type, tectonics, major/minor discontinuities, dykes, hydrothermal zones and shear zones. These features are required for geological modelling of the project site. Geological model also describes the thickness of soil cover and extent of weathered rock. The anticipated region of weakness zones intersecting the layout was marked on the model as geological hotspots. The models were modified regularly as we progressed to reflect the actual position.

Hydro-geological model

The principle of hydraulic confinement involves the maintenance of water level around the cavern for which we need to understand the topography, annual rainfall, recharge, geological settings and hydrogeological properties. We also need data on water seepage as water should seep into the caverns from outside, but we have to control the seepage at a manageable level and if required rock mass grouting has to be performed to block excessive seepage. The following design parameters are considered for all the caverns: provision of water curtain above the cavern with boreholes charged with water to a head equivalent to the 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 a hydraulic gradient greater than 1.0 at the cavern roof level[6]. Finite element studies were carried out to estimate hydraulic gradient, seepage in the caverns during construction and water requirement during construction[7]. The analyses were carried out for several conditions of operation, i.e. completely empty at atmospheric pressure, maximum normal vapour pressure, cavern units under different pressures, etc.

Geotechnical model

The rock mass stability is mainly related to joint configuration, block size, shear strength of discontinuities and the corresponding formation of wedges. Designing the support system of rock mass and the excavation methodology to be carried out was done through rock mass classification and stress and wedge analyses. Static load caused by overburden weight and horizontal initial stresses; dynamic load, i.e. earthquake loading and water pressure as per the requirements of water curtain system are considered as part of the analysis. Rock mass classification is being done with an aim to divide a particular rock mass into groups of similar behaviour, to provide a basis for understanding the characteristics of each group, to yield quantitative data for engineering design and to provide a common basis for communication. The Q-system of Barton *et al.*[8,9] is used for hard rock tunnelling, both as prognosis for detailed design and during excavation mapping. The Q-system of rock mass classification is based on six factors, viz. rock quality designation (RQD), joint set number (Jn), joint roughness number (Jr), joint alteration number (Ja), joint water reduction factors (Jw) and stress reduction factors (SRF).

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. Stress analysis was carried out to analyse the stress/strain situation and distribution in the rock mass, extension of possible yielding zones, pillar stresses and rock displacements, internal stresses and forces[7].

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

The rock support system comprises fibre-reinforced shotcrete, untensioned, fully cement-grouted rock bolts, rock anchors and strengthening ribs of steel/concrete. After detailed study and analysis; length and spacing of rock bolts, and extent and thickness of fibre-reinforced shotcrete required to support the rock mass was determined. The rock support measures shall essentially limit and control rock mass deformation to achieve safe and stable excavation conditions in the roofs, side walls and floors in cavern, tunnels and shafts. All excavated openings are supported by systematic rock support measures designated to accommodate the design loadings. Unfavourable geomechanical or geometrical conditions require particular consideration and localized special rock support solutions may be necessary in some areas. Underground portion of the cavern includes 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 structures was carried out. The design of the concrete plugs is critical as they have to be designed for gas tightness. In addition, detailed design of above-ground facilities was also carried out.

Construction practices

During construction of underground storage caverns, drill and blast method with fully grouted un-tensioned rock bolts and fibre-reinforced shotcrete as the principal means of support are used. Steel sets and ground anchors may be adopted in exceptionally poor conditions. A typical construction cycle involves surveying, probing, drill and blast cycle, scaling, mucking, geological mapping, rock supporting (rock bolting and fibrecreting) and grouting as and when required. The drill and blast cycle includes six stages, i.e. drilling and surveying, charging with explosives, blasting and ventilation, loading and hauling, scaling and cleaning, and rock bolting. A jumbo pneumatic drilling machine is used to drill holes in the rock face (pneumatic means that the drill bits hammer as well as rotate). The drill holes are 2.4 to 4.5 m long and broken fragments of rocks are flushed out by water. Surveying is done with laser-based equipment to maintain correct direction and coordinates. Drilled holes are next filled with explosives. Individual fuses are connected to the main fuse in such a way that the holes are blasted in a proper sequence, from the centre outward, one after the other. After the blast, dust and gases are sucked out through the main tunnel while fresh air is delivered through a ventilation duct on the tunnel ceiling. The process of loading and hauling of muck is called ‘mucking out’ which is generally done by electric shovel loads and hauler dump or scoop tram and load-haul-dump. A hydraulic breaker or rotating cutting head is used for scaling, i.e. removing all the loose rock from the roofs and walls of the caverns. In a bad ground, where rocks are highly fractured, the concrete must be sprayed with a high-pressure air hose to prevent loose rock from continually sloughing off. To provide greater strength, high tensile strength steel fibre is added to concrete to form fibrecrete. The final method for stabilizing the rock face is rock bolting. A jumbo drilling machine is used here to first drill holes into the rock. The holes vary from being 2.4 to 6.0 m long. Next, a steel rod is inserted in the hole. The outside end of the rod is secured with a steel plate and large nut. Under the poorest ground conditions, it may be necessary to install steel arches to hold up the walls and roof of a tunnel. In other situations, a steel mesh may be secured to the walls and roof to prevent loose materials from falling on the workers below.

The water curtain system is the most critical part of the storage. The water curtain boreholes should be charged at least 40–50 m ahead of the cavern excavation to ensure saturation of joints. The water curtain tunnel along with the boreholes also serves to update the geology and hydrogeology and decide on requirements of pre-grouting and any other specific requirements for excavation of the caverns.

Monitoring

Instrumentation of an underground structure is usually undertaken in order to gather information about the existing stress field in the surrounding rock mass, redistribution of stresses during excavation and any change in the geotechnical conditions, verification of effectiveness of remedial measures and long-term monitoring of structure and the rock mass. The safety of the structure, workers and machinery can be continuously monitored with a well-planned instrumentation programme. In the underground caverns, critical areas can be identified by instrumentation, where rock mass behaviour shows variations such as dilation, convergence, etc. and provision for additional support system/rock mass strengthening can be made. Geotechnical and hydro-geological monitoring are imperative during construction, for the underground crude oil project. These are required not only to validate the design assumptions and optimize the design, but also to check the quality of work and ensure hydraulic containment.

The purpose of geotechnical monitoring is to understand the effect of the rock mass behaviour and tunnel supports in tunnelling and ensure safety and economical efficiency during the construction process. Displacement of the rock mass is monitored with a borehole extensometer and convergence measurement equipment, i.e. optical targets at the surface or perimeter and within the rock mass of shafts, tunnels and storage caverns during excavation are used in order to verify, and if needed, fine-tune the excavation methods and supports. Displacement at the surface of the shafts, tunnels and storage caverns is measured using conventional optical surveying methods consisting of a theodolite or total station and optical targets fixed to reference points bolted to the rock and/or shotcrete surfaces. For each target point, the three components (x, y and z) of the deformation vector are measured with total station at regular intervals and relative convergence is calculated. Deformation at various depths within the rock mass above storage caverns is measured using multiple point borehole extensometers, installed in water curtain tunnels, so as to locate the potential failure zones, if any and to separate deep-seated movements from surface spalling. The three-point borehole extensometers, essentially consisting of anchors and a reference, are installed in drilled boreholes in water curtain tunnels above the storage cavern. The distance between the various anchors with respect to the reference is accurately measured on a daily basis using vibrating wire transducer and their relative displacements are estimated.

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 operation. Hydro-geological conditions necessary for the hydraulic confinement of the stored product shall be maintained at all times and no interruption in maintaining hydro-geological record is permitted in-between construction and operation phases. Hydro-geological monitoring of the rock caverns during construction shall include the 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 level, etc. analysis of water samples.

Concluding remarks

Phase-I involves stocking of strategic reserves by government, and in future, phase-II will involve joint participation, in the form of public private participation (PPP) model. Presently, caverns are being constructed for crude oil; in future, underground storage of products, compressed natural gas and liquefied natural gas will also be carried out. Salt caverns, in ground concrete tanks and other storage structures shall also be developed. The design lifetimes of underground storage is more than 50 years, developmental works such as optimizing the design, planning and construction management to suit Indian geology and requirements shall be carried out to improve life and reduce the costs and increase safety in construction and operation. For the design, project management and construction management, India is mainly dependent on foreign expertise; so, there is a need to develop in-house expertise in these fields. Presently Engineers India Limited has been entrusted the task of construction management, technology absorption and development. Indian Strategic Petroleum Reserves Limited (ISPRL), a wholly owned subsidiary of Oil Industry Development Board (OIDB) under the Ministry of Petroleum and Natural Gas is developing the human resources for operation, maintenance and oil trading, etc. Experience gained from the operation of phase-I crude oil projects can be incorporated in the planning, design and construction of the next generation of underground storages.

India imports about 70% of its oil and gas requirements. Solid fuels are also partly imported owing to the poor quality of the solid fuels available here. The dependence on fossil fuels is increasing and by 2020, hydrocarbon requirement will increase by 90%. Hence, India is developing strategic storage facilities to meet short-term supply disruptions. In future there will be need to link these strategic storages to the existing refineries so that if a port gets blocked, supplies can be restored by the nearest storage. There is also need to develop the hydro, nuclear and solar energy industries for long-term solutions.

The installed capacity of nuclear power in India is about 5000 MW only, which can be increased. Hydro power, known as green power, currently contributes 21%, i.e. 38,706 MW of the total power generated in the country, however estimated potential is 145,320 MW for conventional hydro and 94,000 MW for pumped storage. There is also a need to develop alternatives to hydrocarbons in the transportation sector, which is 90% dependent on liquid hydrocarbons at present. Thus, there is a long way to go, in achieving energy security.

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