Experience of Operating an Underground LNG Storage Pilot Cavern

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ABSTRACT

One of the important problems related to underground storage of cryogenic material is to prevent leakage of liquid and gas from containment system to the rock mass caused by tensile failures due to shrinkage of the rock mass around the caverns (Monsen & Barton, 2001). So a new concept of storing liquefied natural gas (LNG) in a lined rock cavern with containment system has been developed. It consists of protecting the host rock against the extremely low temperature and providing a liquid and gas tight liner. Moreover, moderated and controlled frost development in the surrounded rock mass contributes to create an ice ring, which acts as a secondary barrier against any possible leakage. To demonstrate the feasibility of this concept and validate numerical modeling and calculations, a pilot plant was constructed in the Daejeon Science Complex in 2003. A pilot test using liquefied nitrogen was conducted from January through August 2004. In this paper, measured in-situ rock mass responses from the operation of Daejeon LNG storage pilot cavern are presented and analyzed on rock mechanical point of view. Overall monitored results from the pilot experiences confirmed that construction and operation of underground LNG storage in lined rock caverns are technically feasible from rock mechanical point of view. The Daejeon LNG storage pilot cavern represents a further important step in the validation of the technology of lined LNG underground storage. Even though the cavern was small, this project will permit to address the potential and critical points for construction, start up and operation of such new technology.

1. INTRODUCTION

Many attempts have been made to store LNG (Boiling Temperature: -162°C) in unlined rock caverns but were not successful. If the storage is unlined and frozen down to -162°C, the rock is cooled and the rock joints start to reopen, a part of the gas flows into the joints and continues cooling inside the rock wall. This opens the joints successively and heavily increases the cooled area and the extent of the cooling front. The failures were due to thermal stresses generating cracks in the host rock and the thermal cracks contributed to deteriorating the operational efficiency of the cavern because of induced gas leakage and increased heat flux between ground and storage (Dalström 1992, Glamheden & Lindblom 2002).

To provide a safe and cost-effective solution, a new concept of storing LNG in a lined hard rock cavern (LRC) has been developed by Geostock, SKEC and SN Technigaz with the help of KIGAM. It consists of protecting the host rock against the extremely low temperature by using a containment system with a gas-tight steel liner and insulation panels as illustrated in Figure 1. Groundwater in the rock mass around the cavern has to be fully drained during the early stage of the storage operation, before the surrounding rock is frozen, to avoid possible adverse effects of hydrostatic pressure acting against the containment system, and then the rock mass should be resaturated to form an impervious ring of ice, which acts as a secondary barrier against any possible leakage. In order to verify the
technical feasibility of such a storage concept, a pilot plant was constructed in 2003 and had been operated by storing liquid nitrogen (LN2) (Boiling Temperature: -196°C) from January to August, 2004. The cavern has, more recently, been decommissioned.

This paper presents rock mass responses under very low temperatures from the operation of the pilot cavern including heat transfer, deformation and thermo-mechanical stability of rock and rock joints. The observed behavior of the rock mass at different operational situations is discussed and compared with predictions made previously using numerical models.

Fig. 1. Concept for storing LNG in a lined rock cavern.

2. OVERVIEW OF THE PILOT CAVERN

2.1 Daejeon pilot cavern for LNG Storage

The pilot cavern is located in Daejeon, about 200 km south from Seoul, in an existing research cavern implemented within the KIGAM research facilities. The previous room for cold food storage was enlarged to test the overall performance of a lined rock cavern for LNG storage. Access to the pilot cavern was provided through an existing horizontal tunnel, and the cavern roof lies at a depth of about 20 m below the ground.

The rock type around the cavern mainly consists of fresh granite with RQD of 80-86. In order to characterize the quality of rock drill core, Q-values for each hole were evaluated. Table 1 shows the summary of each drilled holes for describing details of Q-evaluation.

Table 1. Summary of Q values for each holes.

<table>
<thead>
<tr>
<th>Hole number</th>
<th>Q_average</th>
<th>Q_most frequent</th>
<th>Range of Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>3.7</td>
<td>3.3</td>
<td>0.4 to 8.8</td>
</tr>
<tr>
<td>D2</td>
<td>6.5</td>
<td>8.4</td>
<td>0.8 to 13.2</td>
</tr>
<tr>
<td>D3</td>
<td>6.9</td>
<td>6.3</td>
<td>0.1 to 26.4</td>
</tr>
<tr>
<td>D4</td>
<td>10.7</td>
<td>6.3</td>
<td>1.9 to 19.8</td>
</tr>
<tr>
<td>R1</td>
<td>1.6</td>
<td>N/A</td>
<td>0.02 to 2.6</td>
</tr>
<tr>
<td>P1</td>
<td>5.2</td>
<td>11.2</td>
<td>0.2 to 10.8</td>
</tr>
<tr>
<td>P2</td>
<td>12.2</td>
<td>13.2</td>
<td>0.02 to 26.4</td>
</tr>
</tbody>
</table>
Although the rock around the cavern shows broad range of “poor to fair quality”, most frequent occurrence is fair quality excluding R1 hole. The above Q-value will require no supports or minor unreinforced shotcrete (about 40mm) and bolt according to support categories of Q-system. Therefore, it is proper to adapt rock bolting to stabilize main cracks of existing cavern and ensure stability of possible crack position.

Figure 2(a) shows a bird’s-eye-view of the pilot cavern for LNG storage, and figure 2(b) shows a cutaway view of the pilot cavern, insulation system, piping and so on for storing LNG. Thickness of the polyurethane insulation panel was 10cm, and reinforced concrete barriers of 20cm thickness were formed between the rock and the containment system. South concrete wall was exposed to the entrance tunnel, which is not a typical case for full-scale facilities. A platform above the entrance of the cavern was also required to install instruments, manhole and piping. The internal dimensions of the completed pilot are a section of 3.5 by 3.5m, and a length of 10m with a working volume of 110m$^3$.

The objectives of this pilot project are the followings:
- to demonstrate the feasibility of the lined rock cavern concept;
- to examine the overall performance of the storage; and
- to have efficient returns of experience to improve construction and design of industrial scale projects.

Before the cavern was excavated, 20 boreholes from the tunnel drifts were drilled for drainage near the cavern walls, and the water table was lowered to 8 m below the cavern floor. For the safety and practical reasons, liquid nitrogen (LN2, $T=-196^\circ C$) is used instead of LNG. After several commissioning tests, operation started from 10 January 2004 with 2.6m level of LN2 and the drainage system was stopped gradually from 10 June 2004 to 8 July 2004. The filling pipeline was closed on July 10th, and the storage cavern has been completely empty since 12th of August, 2004.

2.2 Geotechnical monitoring system

A comprehensive monitoring system was provided for measuring temperature, thermo-mechanical and groundwater responses of the rock and concrete during the implementation of the LNG storage. Temperature variations were monitored at a total of 69 points from 6 borehole extensometers with 6 points each, 6 concrete strain gages, 5 jointmeters, 4 instrumented rockbolts and 2 inclinometers with 7 points from the cavern wall and the surface. Four pore pressure cells were also used to check water pressure around the cavern along with temperature. Figure 3 shows a schematic diagram of the locations of the installed instruments at a representative section.
Moreover, numerous parameters such as level, temperatures, pressure and boil off rate for the containment system were monitored during the operation. The behavior of surrounding rock and the containment system was recorded during three successive phases of operation: a) first six months during which a full level was maintained by filling with LN2 in order to compensate for loss of boil-off, b) second six months during which no more filling was performed allowing the cavern to empty naturally, and c) third six months during which the empty cavern was heated up till the ambient temperature was reached and the pilot cavern was decommissioned.

Fig. 3. Location of geotechnical instruments around the pilot cavern.

3. LESSONS LEARNED FROM THE PILOT TEST

3.1 Thermo-mechanical behaviors of in-situ rock mass

The measured in-situ rock mass responses from the operation of the pilot cavern are analyzed on rock mechanical view. The following conclusions are made based on the investigation results.
(a) Thermal responses of the rock mass under very low temperature of about -30°C around the LNG storing lined rock cavern could be well predicted by numerical models due to absence of water.
(b) Thermal stress-induced displacements occurred toward inner rock mass, which is favorable to stability aspects of the cavern.
(c) In-situ thermal expansion was as 5-11 times large as laboratory obtained data, and showed typical nonlinear hysteresis during cooling and thawing stages.
(d) Joint separation was small compared to rock displacement, and a linear increase in deformation was observed except temperature near 0°C.
(e) There was no thermal shock by abrupt cooling near the cavern wall due to insulation barriers.
3.2 Hydro-thermal coupled analyses for ice ring formation

Combined hydro-thermal numerical models were adapted and used for investigating relevant mechanisms such as propagation of the cold front, and migration of water and ice formation in the host rock mass.

A new groundwater control system was introduced to create an ice ring (ice barrier) around the LRC cavern to protect it from groundwater intrusion into the containment system. However, it can be used to balance the migration of the 0-isotherme by applying water with a specific temperature for water infiltration. In addition, the ice ring is supposed to play an important part as a secondary barrier against leakage of stored material. In the case of groundwater intrusion into the containment system, the integrity of the containment system could be destroyed because of the volume expansion of the groundwater during the freezing process. Therefore, the location and thickness of the ice ring are important factors for the stable storage of LNG in a lined rock cavern.

From the hydro-thermal coupled analyses for simulating ice ring formation in the LNG pilot cavern, the following conclusions were drawn:

(a) The temperature dependency of the input properties must be considered for appropriate modeling of the cryogenic environment. Particularly when the temperature range of the simulation is wide, the variation of properties has to be taken into account.

(b) The capability of hydro-thermal modeling of ice ring formation has been verified by a comparison of numerical results with in-situ measurement data. Therefore, a similar approach could be extended to the simulation of ice ring formation in a full-scale LNG storage cavern.

(c) The location and range of the ice ring is an important design factor in this new concept of LNG storage and is dependent upon the 0°C isotherm spread as well as the time of the drainage stop, which can be quantitatively determined by the numerical method.

4. CONCLUSIONS

In this paper, the experiences from the design and operation of the Daejeon LNG pilot cavern have been presented.

(a) Thermal responses of the rock mass under very low temperature of about -30°C around the LNG storing lined rock cavern could be well predicted by numerical models due to absence of water. And thermal stress-induced displacements occurred toward the rock masses, which are favorable to the stability aspect of a cavern.

(b) From the hydro-thermal coupled analyses for simulating ice ring formation, the location and range of the ice ring is dependent upon the 0°C isotherm spread as well as the time of the drainage stop, which can be quantitatively determined by the numerical method.

(c) After completion of the scheduled operations, the cavern and containment system were dismantled in order to judge the validity and safety of the proposed concept. Successfully, no remarkable thermal cracks were detected in the rock mass and concrete lining.

(d) Overall, results obtained from the pilot test confirm that construction and operation of underground LNG storage in a lined rock cavern is technically feasible from a rock mechanical point of view. The Daejeon LNG storage pilot cavern represents a further important step in the validation of the technology of lined LNG underground storage. Even though the cavern was small, this project has provided information suitable for assessing the potential of this new technology, and for identifying critical points for its construction, start up and operation.

ACKNOWLEDGEMENTS

This study was funded by the Korea Institute of Construction and Transportation Technology Evaluation and Planning under the Ministry of Construction and Transportation in Korea (Grant No. 05-D10, Development of Water Control Technology in Undersea Structures).
REFERENCES


