Chapter 8

Innovative Method of LNG Storage in Underground Lined Rock Caverns

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Additional information is available at the end of the chapter

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1. Introduction

Today, the demand for LNG (Liquefied Natural Gas) in Korea is growing rapidly. However, it is difficult to solve problems regarding the adjustment of the demand and supply of LNG due to factors such as seasonal variations of the domestic demand for LNG, discordance among import patterns, limits of storage facilities, and so on. The supply of LNG can become unstable due to accidents at LNG producing areas. Furthermore, it is very important to secure large LNG storage facilities and to stabilize LNG supply management on a long-term basis (Chung et al, 2006).

Since natural gas is imported in the liquid phase by ships, the refrigerated storage of LNG is more economical than the conventional storage in the form of gas. Furthermore, all the storage of natural gas in Korea needs to cater for the storage of LNG in the condition of LNG from ships. Therefore, a different storage concept is required for the country's imported gas, in order to store it in the same condition as that of LNG from ships (Cha et al, 2006). At LNG terminals, conventional aboveground tank or in-ground tank type has been successfully used worldwide to store LNG. Nevertheless, these types of the storage tanks are less attractive as they require large land area for storage. Large reclamation of seaside and industrial area has already progressed and free remaining area is very small and expensive.

Based on experience of underground storage for crude oil and various types of hydrocarbons, underground storage system was thought to be more economical way to store LNG regardless of the above-mentioned conditions. Many attempts have therefore been made in the past to store LNG underground in unlined containment, though without success (Anderson, 1989; Dahlström and Evans, 2002). One of the most significant problems related to the underground storage of cryogenic material is the need to prevent leakage of liquid and gas from the containment system to the rock mass caused by tensile failures due to shrinkage of the rock mass around the caverns (Monsen and Barton, 2001). The failures of underground storage caverns were due to thermal stresses generating cracks in the host rock mass. The thermal cracks induced by extremely low temperatures in the rock mass contributed to the deterioration of the operational efficiency. Gas leakage and increased heat flux between the ground and storage occurred (Dahlström, 1992; Glamheden and Lindblom, 2002).

The way to prevent a hard rock mass from cracking at LNG boiling temperatures (–162°C) is to locate the unlined storage cavern deep enough below ground level so that the geostatic stresses counterbalance the tensile stresses caused by the cooling. The necessary depth varies with rock type from 500 to 1000m, which renders this unlined cavern storage concept very expensive (Amantini and Chanfreau, 2004; Amantini et al., 2005).

New concept of storing LNG in a lined rock cavern (LRC) with containment system which can overcome these problems has been developed by Geostock, SKEC and SN Technigaz with the help of KIGAM (Korea Institute of Geoscience and Mineral Resources). To demonstrate the technical feasibility of this concept, a pilot plant was constructed at the KIGAM in Daejeon Science Complex in 2003, which was operated for storing liquid nitrogen (LN2, Boiling temperature: -196°C) from January 2004 to the end of 2004, and now been decommissioned.

2. Concept of a lined rock cavern for LNG storage

The basic concept for the development of LNG storage in membrane lined rock cavern is a combination of well-proven technologies and a new concept named as "formation of ice ring (Fig. 1):

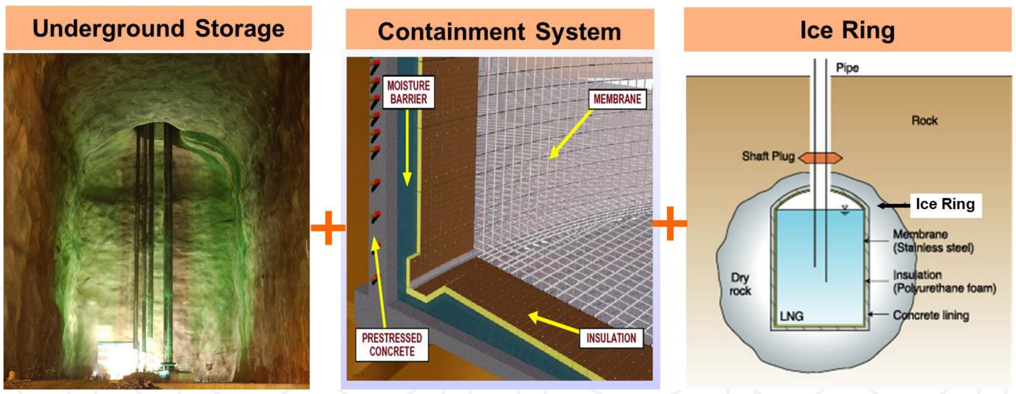

Figure 1. Three basic concept of the lined rock cavern system for storing LNG

2.1. Underground storage cavern

The underground storage technology, which proved reliable, experienced a strong development related to its intrinsic qualities but also on the innovations and technical progress from which it regularly profited. Currently, large capacity of storage cavern units with more than several hundreds of thousands of cubic meter, for a broad range type of hydrocarbon products and crude oil, are constructed and operated successfully especially in Korea.

2.2. Membrane containment system

The membrane containment system, which was introduced in 1962 on a prototype ship, has since been successfully used in several LNG carriers and storage tanks. This membrane system provides the proper thermal protection to the surrounding rock mass, preventing excessive stresses and crack formation and reducing boil-off to level comparable with conventional LNG storage tanks.

2.3. Ice ring and drainage system

Formation of ice ring as an impervious second barrier against the leakage of contained LNG can be explained by the each stage of construction of lined rock cavern (Fig. 2).

Groundwater is temporarily removed from the rock surrounding the cavern during the first phase of construction. This preliminary de-saturation of the host rock mass aims at preventing unacceptable hydrostatic pore pressure and ice formation behind the cavern lining. After excavation of cavern and installation of containment system are completed, LNG will be stored in the cavern and then the cold front starts propagation from the cavern at the same time. When the cold front has advanced far enough from the cavern wall, drainage can be stopped to allow groundwater progressively to rise up and quickly form a thick ring of ice around the cavern. After ice ring is completely formed, operation of the drainage system is stopped. The drainage period during LNG storage will last several months or years depending on the thermal properties of rock masses and hydro-geological characteristics on the site.

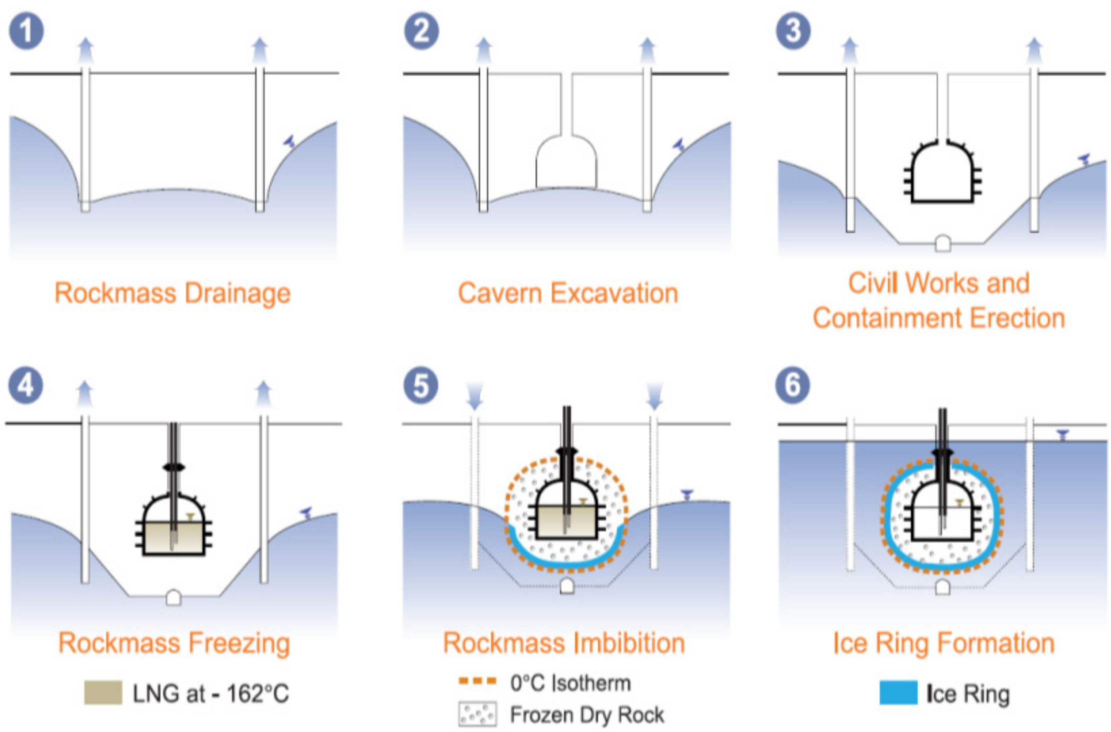

Figure 2. Schematic diagram of formation of ice ring

3. LNG pilot plant

The objectives of this pilot project are as follows:

- To demonstrate the feasibility of the lined rock cavern concept,
- To check adequacy between the results of previous computations and laboratory tests regarding in-situ measurements,
- To test the overall performance of the storage and
- To gain sufficient experience to improve design and construction of industrial scale projects

3.1. Underground pilot cavern

The LNG pilot plant is located in Daejeon, about 200 km south of Seoul, in an existing 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. The base rock consists of Jurassic biotitic granite intruding Pre-Cambrian gneiss, which has an RQD of 80-86 and the most frequent Q-value of 12.5. The Q-value requires 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.

Access to the pilot cavern was provided through an existing horizontal tunnel, and the experimental cavern roof lies at a depth of about 20 m below the ground surface. In order to have the containment system completed, a concrete wall closes the entrance of the cavern. The south concrete wall of the cavern is exposed to the entrance tunnel, which is not a typical case for full-scale facilities. Additionally, a platform above the entrance of the cavern is made to install instruments, manhole and piping. The internal dimensions of the completed pilot plant have a sectional dimension of 3.5 m x 3.5 m, a length of 10 m, amounting to a working volume of 110 m^3 (Fig. 3).

Figure 3. A bird's-eye-view and cross section of the pilot cavern

3.2. Containment system

The containment system, which is used for underground lined rock caverns, is similar to the one used and improved by SN Technigaz since 1962 for the membrane type LNG storage tanks and LNG carriers. The modular structure of the containment system makes it very flexible, improving construction and adaptation to cavern geometry. The thickness of the insulating panels can be chosen as per the requirement of the thermal efficiency and the nearly unstressed membrane permits its usage in very large scale future projects.

The containment system is composed of several layers, from rock to LNG as follows (Fig. 4).

For the Daejeon LNG pilot cavern, insulating panels made of foam are sandwiched between plywood sheets and are bonded on the concrete using load-bearing mastic. The insulation panel thickness is 300 mm to ensure that the rock temperature will not fall below -50°C after 30 years and the boil-off rate will stay at an acceptable limit. Finally, a 1.2 mm thick stainless steel corrugated membrane attached to the insulation panel provides gas tightness at a low temperature. All the surfaces (e.g. bottom, walls, chambers and vault) are covered with concrete lining, insulating panels and the stainless steel membrane sheets.

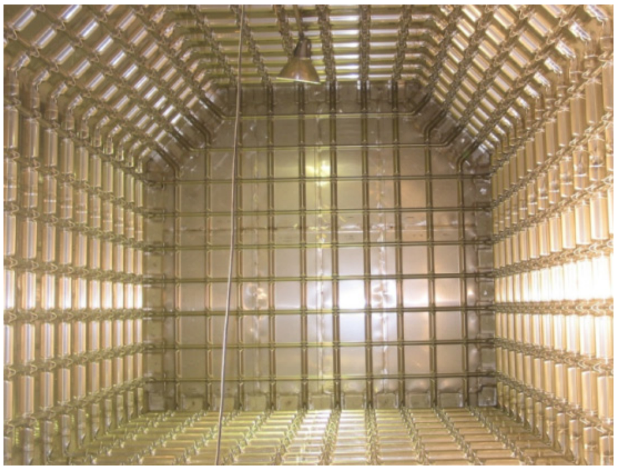

Figure 4. Containment system used for the pilot test

3.3. Drainage system

The purpose of the drainage system is to reduce water entry in the cavern during concrete casting, to reduce humidity percolating through the concrete during the installation of the containment system, to drain the rock mass and maintain a low water saturation degree in the surrounding rock mass during the cooling phase, and to control the re-saturation of the host rock mass once the frozen area around the cavern reaches a suitable thickness.

Before the cavern was excavated, 21 boreholes from the tunnel drifts were drilled for drainage near the cavern walls (Fig. 5), and the water table was lowered to 8 m below the cavern floor. Also, an acceptance test for the cavern was performed by an interference test after full installation of the concrete structure. The drainage system must be operated during the construction and operation of the LNG storage cavern.

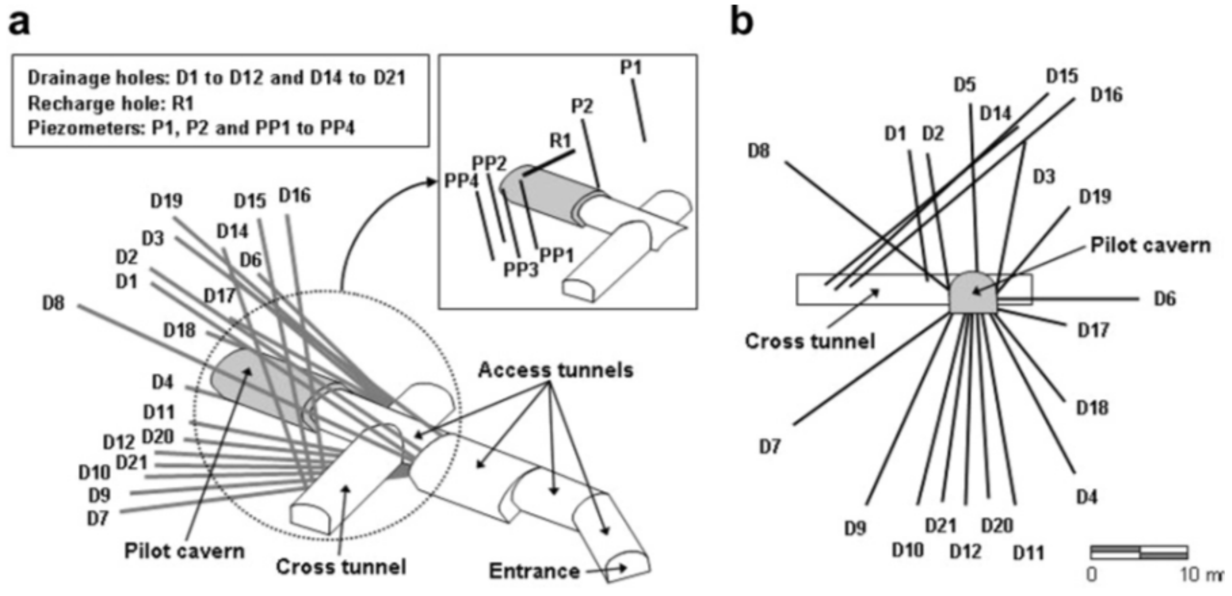

Figure 5. Schematic diagram of the pilot cavern, (a) Oblique view of drainage holes (D series), recharge hole (R1), and piezometers (P and PP series) & (b) front view of drainage holes (Cha et al., 2007)

3.4. Construction works

The transition structure between the rock and the containment system consists of reinforced concrete cast in place between a formwork and the rock, with injection holes for contact grouting. The interface cavern/access tunnel is constructed of reinforced concrete cast in place between two formworks including a closing wall and a platform used for access, piping and instrumentation. Thickness of the polyurethane insulation panel was 10 cm, and reinforced concrete barriers of 20 cm thickness were formed between the rock and the containment system.

4. Pilot test

4.1. Operation of the pilot plant

For safety and practical reasons, LN2 is used instead of LNG. The cryogenic pilot is operated from a laboratory room located in the access tunnel. It houses the Data Control System (DCS) for the process of the cryogenic pilot and for the rock monitoring. An LN2 plant is installed outside on a fenced site, containing one LN2 storage tank, a vaporizer and associated control systems in order to inert, cool down the cryogenic pilot, fill it completely with LN2 and make up to compensate for the gaseous N2 boil-off.

These operations use two insulated pipes from this dedicated site to the cryogenic pilot through the access tunnel and the special local enlargement in the cavern roof to go over the plug and penetrate inside the cavern. The additional line is necessary to release overpressures if they happen. Some instruments installed in the containment system and cavern permit to follow the main parameters (inner pressure and temperature, LN2 level, containment deformation) and to operate the pilot (Fig. 6).

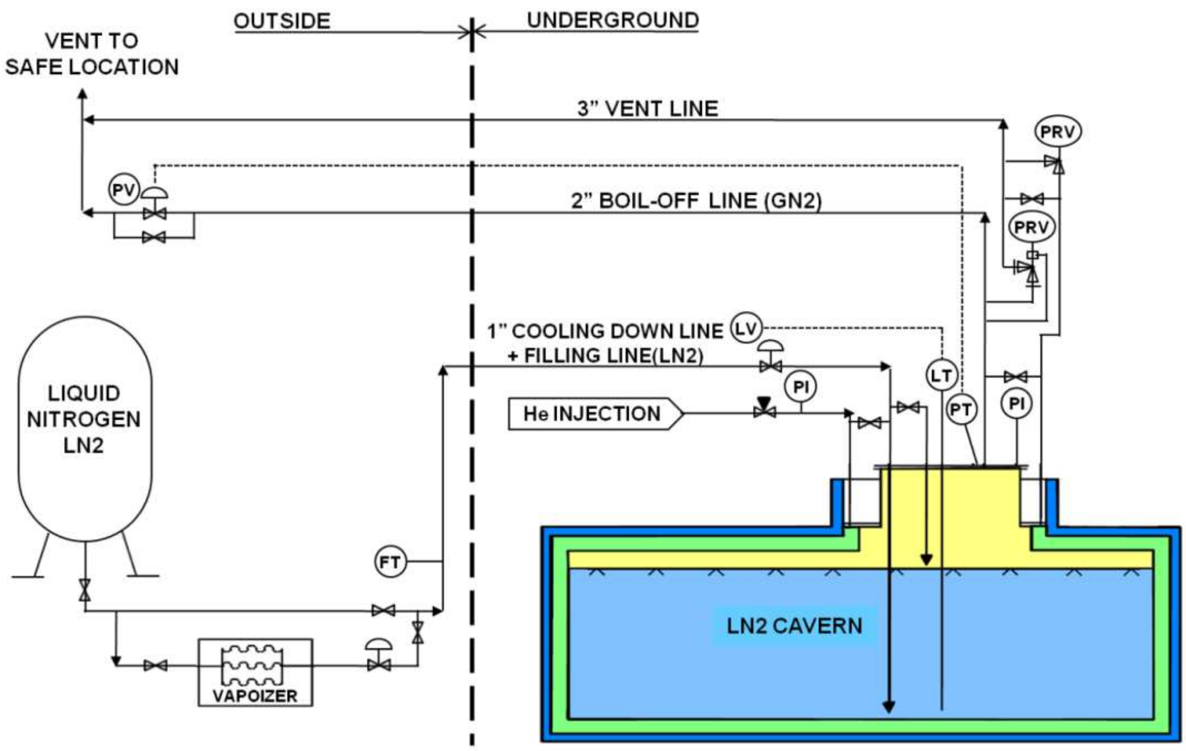

Figure 6. Schematic process flow diagram of the pilot plant

After several commissioning tests, the operation started from 10 January 2004 with a 2.6 m 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 has been completely empty since 12th of August, 2004.

4.2. Geotechnical monitoring system

A comprehensive monitoring system was provided for measuring temperature, thermo-mechanical and groundwater responses of the rock and concrete during pilot test. The pilot cavern and its surrounding rock mass are equipped with a comprehensive set of geotechnical instruments, which allows monitoring of temperature profiles and temperature induced displacements in rock around the cavern, the opening of rock joints on the cavern surface, the load on the installed rock bolts, settlement of ground surface, pore pressure distribution in the rock mass and the variation of ground water level. All instruments are equipped with thermal sensors to measure the temperature at the installed depth. Fig. 7 presents the general arrangement of the instruments in a cross section and a plan view (Chung et al., 2007a).

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 rocks and the containment system was recorded during three successive phases of operation: a) first six months duration during which a full level is maintained by filling with LN2 in order to compensate for loss of boil-off, b) second six months during which no more filling is performed allowing the cavern to empty naturally, and c) third six months during which the empty cavern is heated up till the ambient temperature is reached and the pilot cavern is decommissioned (Chung et al., 2004).

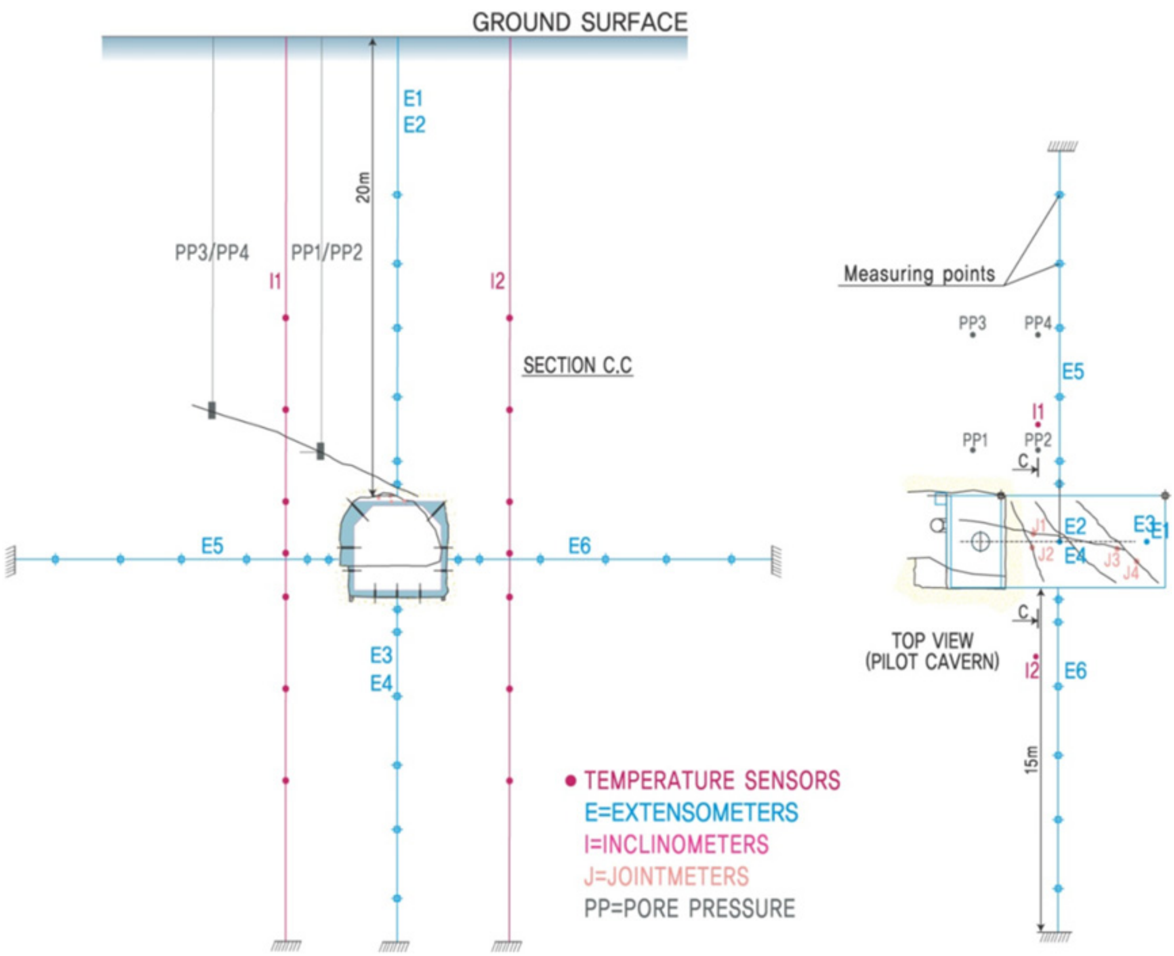

Figure 7. Arrangement of geotechnical instruments around the pilot cavern

4.3. Major results of the pilot test

The behavior of surrounding rock mass and the containment system measured during the operation of the pilot plant are analyzed and the following conclusions are made:

- The 21 boreholes drainage system has proved its efficiency during the successive construction and operation periods and allowed maintaining the rock mass de-saturated during the cooling down period. Efficiency tests performed at this stage showed that almost 99% of the natural water flows towards the pilot cavern could be drained back by the drainage system. The re-saturation of the rock mass was performed by stopping progressively the drainage. Finally, the drainage system allowed draining again the host rockmass during the thawing progress of the rockmass (Fig. 8).
- Thermal responses of the rock mass under a very low temperature of about -30°C around the rock cavern, with an absence of water, could be well predicted by numerical models such as FLAC2D code (Fig. 9).

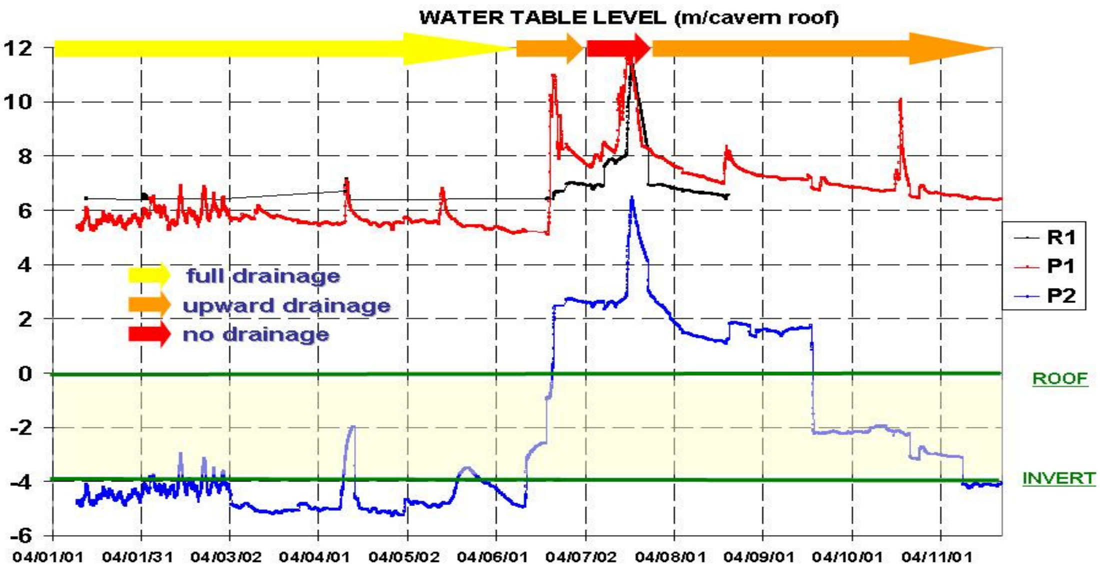

Figure 8. Piezometric variations by operation of the drainage system

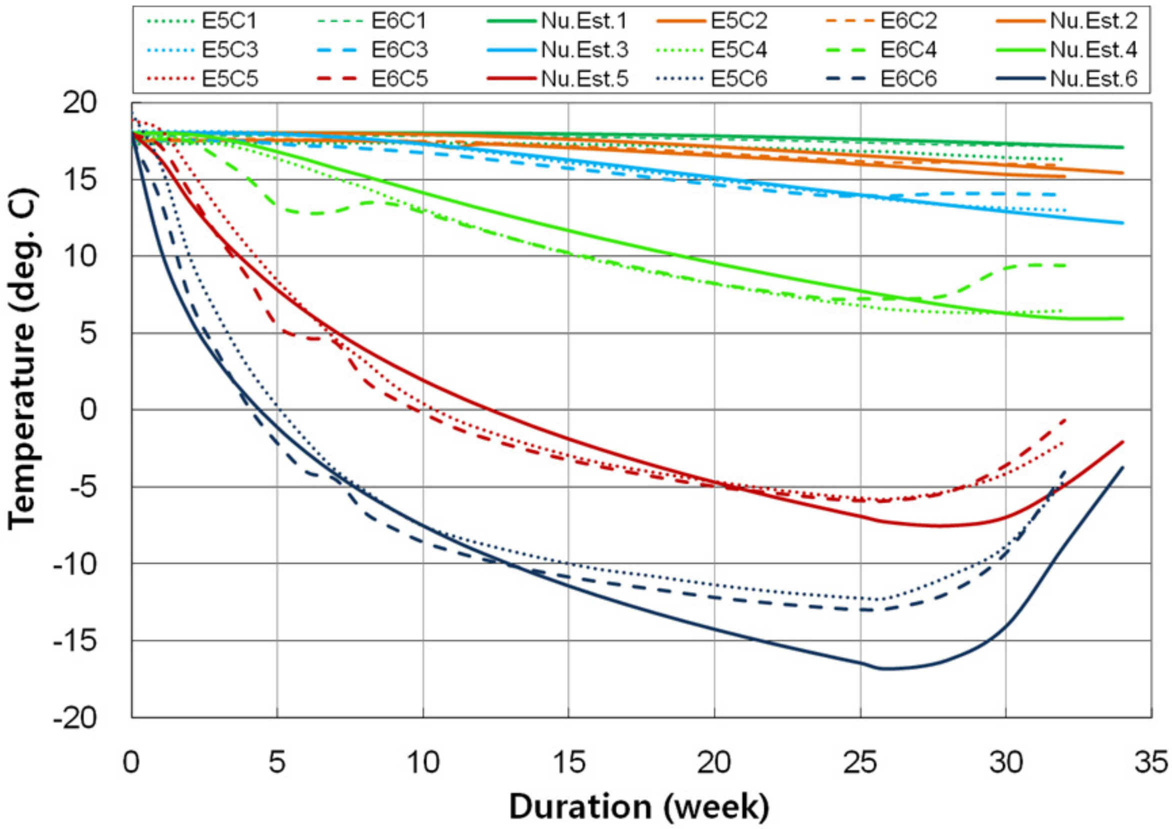

Figure 9. Comparison between measured and predicted temperatures of rock mass around the side wall of the cavern (dotted line: measured temperature, solid line: predicted temperature).

- Thermal stress-induced displacements occurred toward inner rock mass, which is favorable to stability aspects of the cavern. Displacements are of relatively low amplitude within 3~5 mm corresponding to about 0.2 % of cavern radius. Data recorded at the end of thawing period shows that small displacement (about 1 mm) is expected due to local rearrangement of the rockmass. And conventional rock reinforcements such as rock bolt and shotcrete remain effective at very low temperature during the pilot operation (Fig. 10).
- By comparing boil off gas ratio (BOR) occurred during operation of the pilot with estimated ones, BOR from underground LNG storage cavern can be estimated by numerical and theoretical methods (Fig. 11).

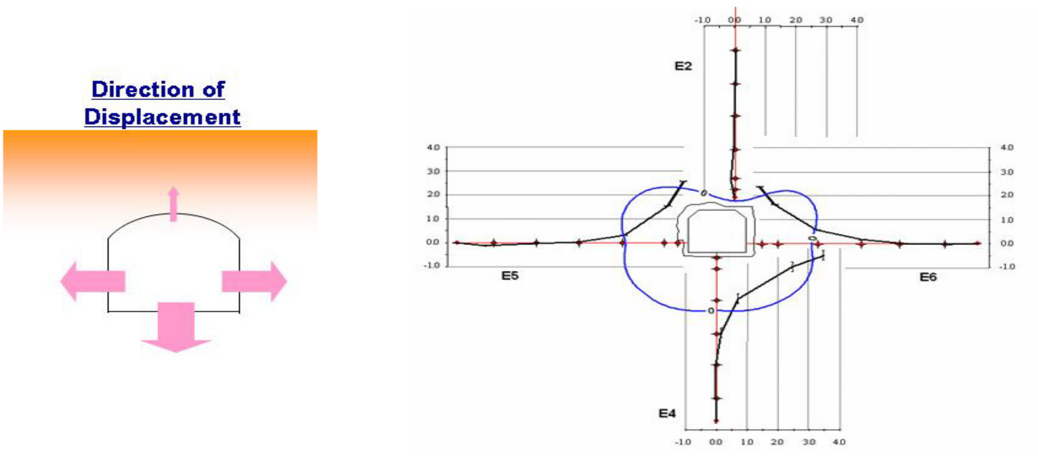

Figure 10. Displacement of rock mass around the pilot cavern

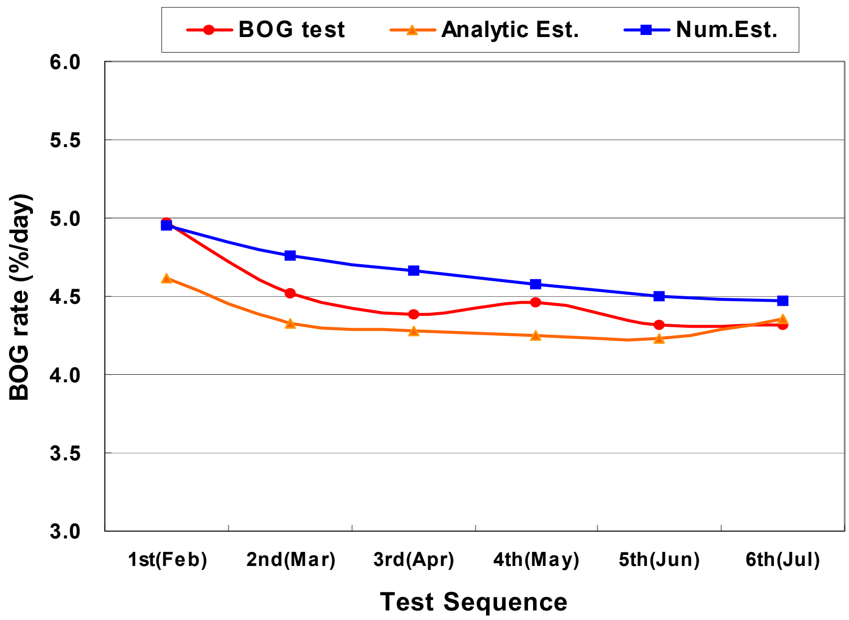

Figure 11. Boil-off gas ratio occurred during operation of the pilot plant

- 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. There was no thermal shock by abrupt cooling near the cavern wall due to insulation barriers (Fig. 12).
- Overall, the results from the pilot test confirm that both construction and operation of underground LNG storage in a lined rock cavern is technically feasible.

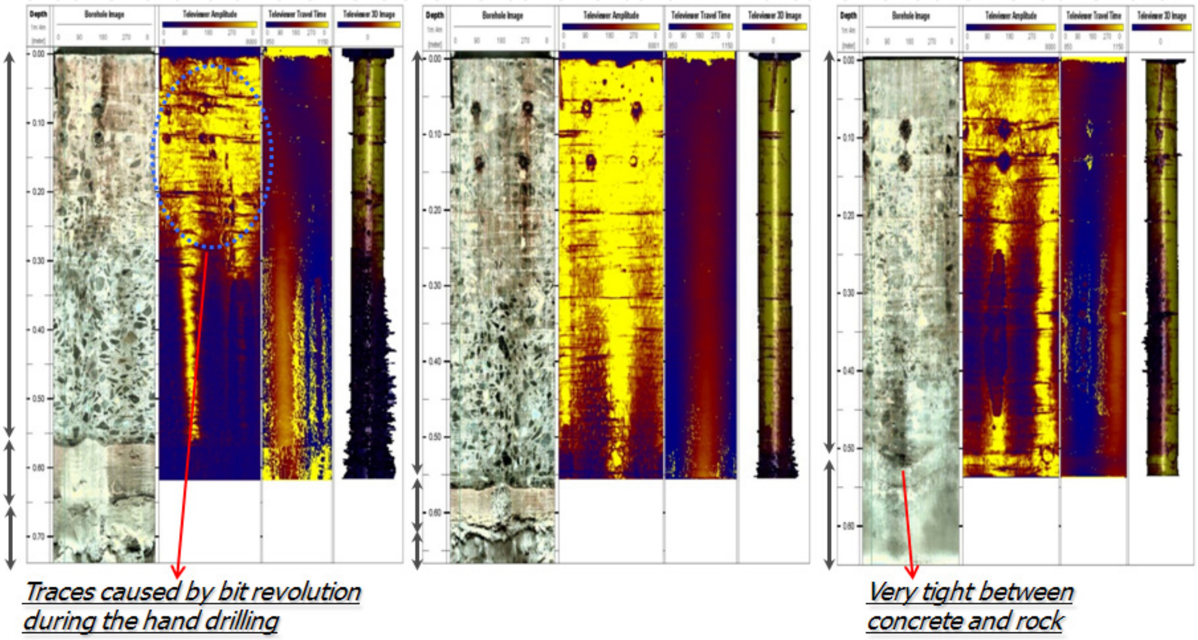

Figure 12. Results of crack inspection after decommissioning of the pilot plant

4.4. Hydro-thermal coupled analyses for formation of ice ring

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 zero degree isotherms 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.

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. Processes of ice ring formation with effective porosity of 3% are shown in Fig. 13 together with the temperature distribution of groundwater respectively. Ice ring in rock mass below the cavern is thicker than other regions. Dry zone inside of ice ring is obtained with thickness of maximum 2m. Until August 10th, ice ring is fully formed in surrounding rock. However, ice ring contacts partially the corner between wall and floor. It is found from comparison with the early interpretation of the geophysical campaign data that the real process of ice ring formation is very similar to the result from two dimensional simulations (Fig. 14).

10 June 20 June 30 June 10 July 20 July 30 July 10 August

Figure 13. Formation of ice ring and groundwater temperature around the pilot cavern (2-D simulation)

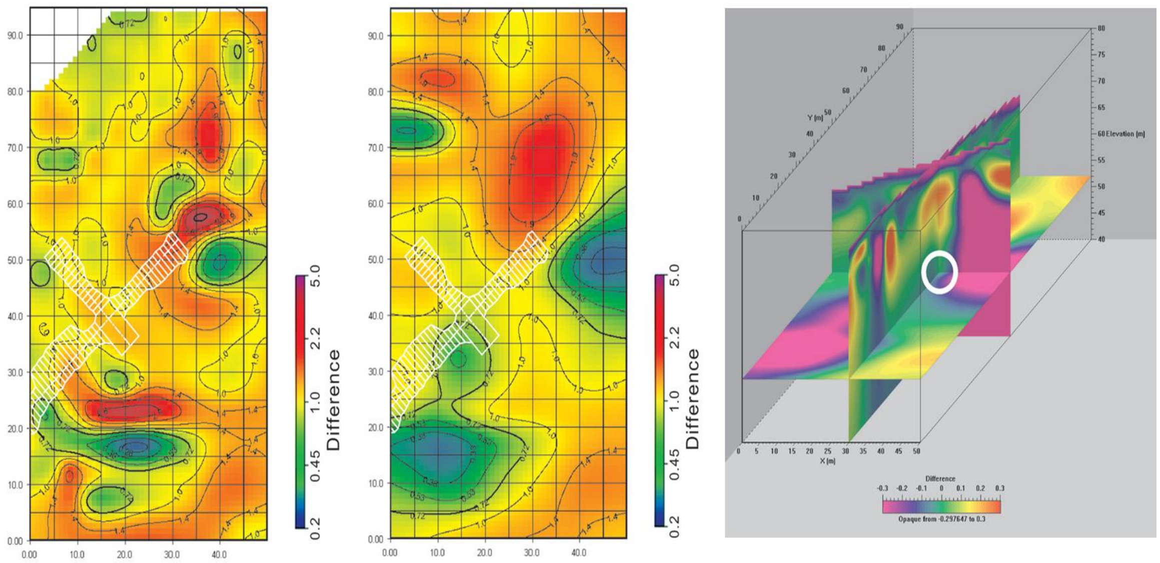

Figure 14. Change in resistivity distribution between Phase III and Phase II. Horizontal slice was made at the elevation (a) above and (b) at the level of the storage cavern. (c) 3-D fence diagram of resistivity change between two phases (Yi et al, 2005)

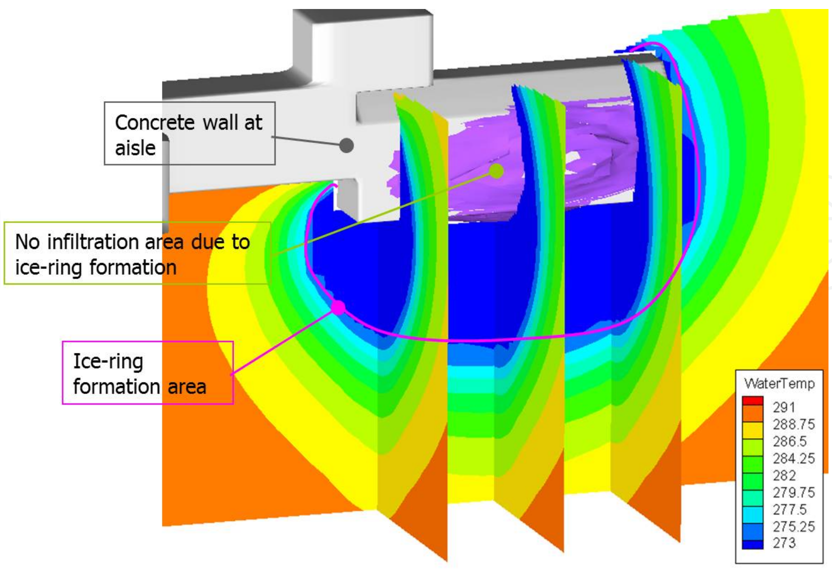

Figure 15. Shows the processes of ice ring formation by three dimensional simulations when the access tunnel is considered. Due to concrete wall exposed to the open air, ice ring was not formed and groundwater penetrated to a portion of the cavern.

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

- The convective heat transfer coefficient through the roof membrane containing gaseous sky was obtained as 3 $W/m^2.K$ in the containment system with 10 cm thick insulation panel. When the containment system with more thick non-reinforced PU foam such as 30 cm or 40cm is considered, the coefficient would be reduced down to about 0.1 or 0.01 $W/m^2.K$. Because consideration of this coefficient is very important in rock mass above the cavern, probable range of the coefficient in full-scale cavern model with standard insulation specification should be obtained by appropriate numerical scheme for design purpose.
- 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.
- Numerical simulation with thermal properties of dry rock obtained by laboratory could effectively estimate the real temperature profiles in rock mass around a cavern.
- 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.
- By controlling groundwater drainage system, the ice ring cab be formed easily based on the assumption that average distance of zero degree isotherm reaches 3 or 4 meter from the cavern wall in rock mass with the hydraulic conductivity of 10^{-7} to 10^{-6} m/s.
- In order to keep the continuous propagation of zero degree isotherms, groundwater close to cavern end faces should be effectively drained.

5. Typical underground storage system

This new concept of LNG storage in membrane lined rock cavern is valid for any type of export or receiving terminal, but also for peak-shaving or large capacity stockpile storage. Fig. 16 shows a full scale model for underground LNG storage system including above-ground facilities. Layout of the underground storage system and the number of storage caverns can be varied with storage capacity of LNG.

The drainage system of the lined underground LNG storage cavern is composed of drainage tunnel excavated beneath the cavern and drain holes drilled on rock surface of the drainage tunnel (Fig. 17). After the access tunnel for constructing caverns reaches to depth of cavern bottom, drainage access tunnel is excavated by depth of drainage tunnel bottom. And then drainage tunnels are excavated in parallel to the cavern with a little longer length than that. On the surface of the drainage tunnel, several drain holes should be drilled upward and arranged with same spacing. Drain holes outside the cavern boundary are inclined with a steep slope and those within the cavern boundary have a gentle slope.

The reason why drain holes are upward is that the drainage system is designed to let the groundwater be drained only by gravitational forces. That is, the groundwater within rock

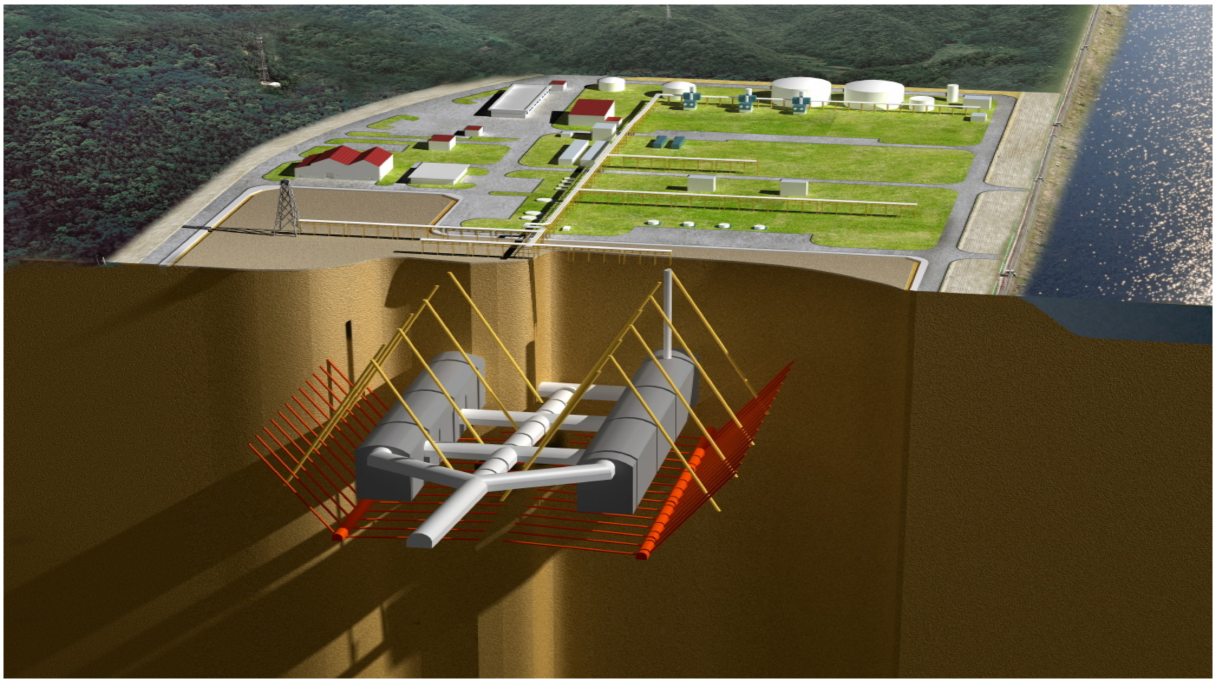

Figure 16. Bird's-eye view of a full scale model for underground LNG storage (Storage capacity of 140,000 m³)

mass flows into the drain holes along the joint-fracture channels connected those holes and is collected into the drainage tunnel only by gravitational force without pumping. In order to de-saturate sufficiently rock mass around the cavern, the position and horizontal spacing of drain holes should be designed efficiently.

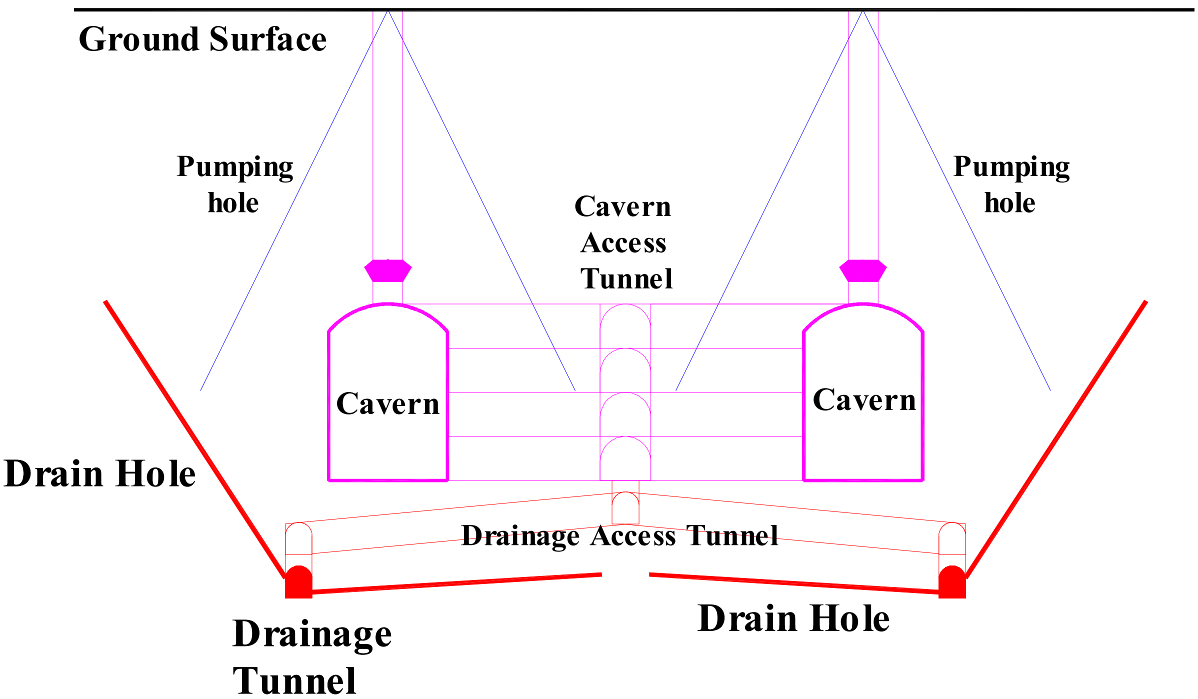

Figure 17. Typical cross section of the underground LNG storage system

5.1. Shape of storage cavern and tunnel

Geometry of the storage cavern should be adapted to local geological and hydro-geological conditions of the LNG terminal facilities. A wide variety of different geometries can be considered.

The general cross section of storage gallery is comparable to unlined underground storage technology, with horse shape galleries. Dimension of the gallery is typical 30 m height by 20 m width, which can be adapted to rock conditions. The length of cavern can be from 150 m up to 270 m, which depends upon the unit capacity per gallery. Fig. 18 shows typical sections of underground works and galleries arrangement that can be considered in good rock mass conditions.

5.2. Equipment, shaft and pipework arrangement

The equipment of storage cavern is similar to the ones of a conventional LNG terminal, allowing it to operate in exactly the same way as an aboveground tank (Fig. 19). Internal piping arrangement is also similar to the one of a membrane LNG storage tank. All pipes are embedded in a concrete structure near the bottom of the operation shaft. Inside the cavern the pipes are joined together by braces forming a pipe tower designed to permit differential pipe contraction.

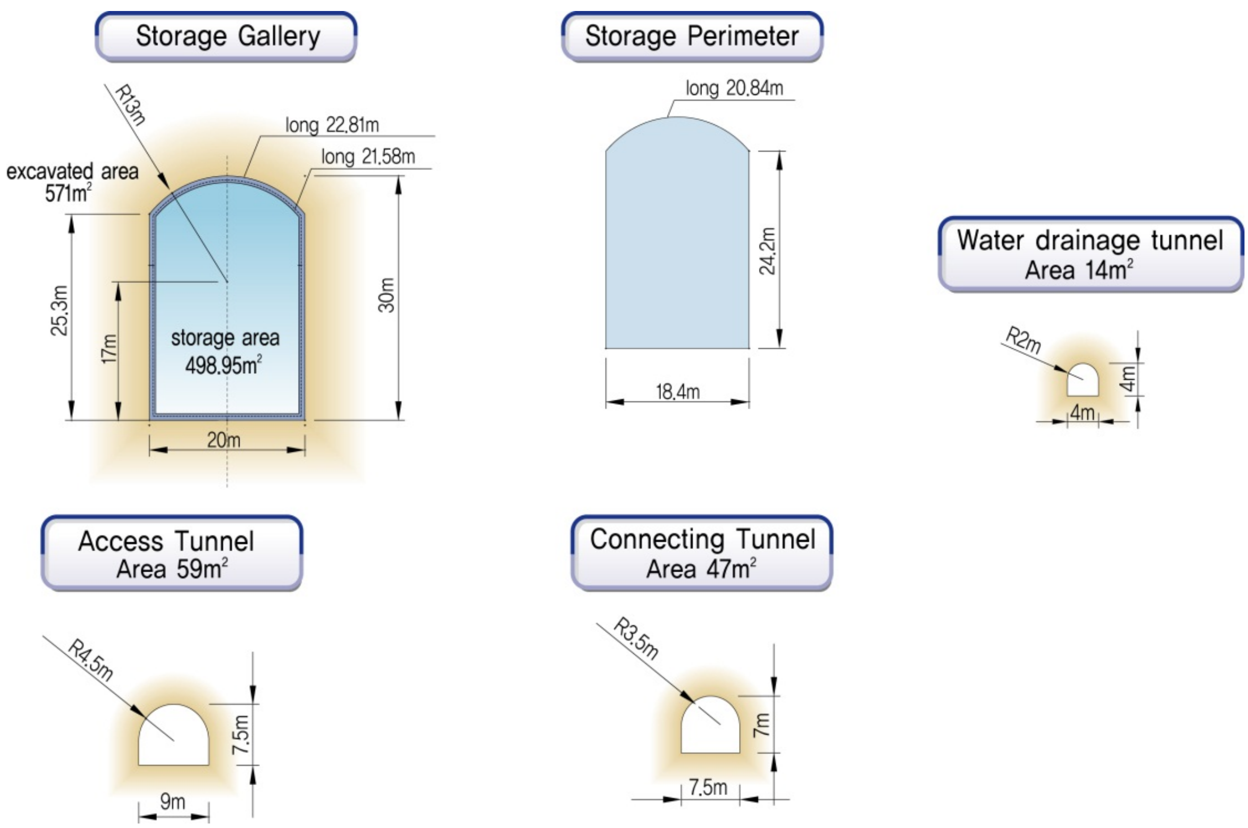

Figure 18. Typical cross section of underground galleries

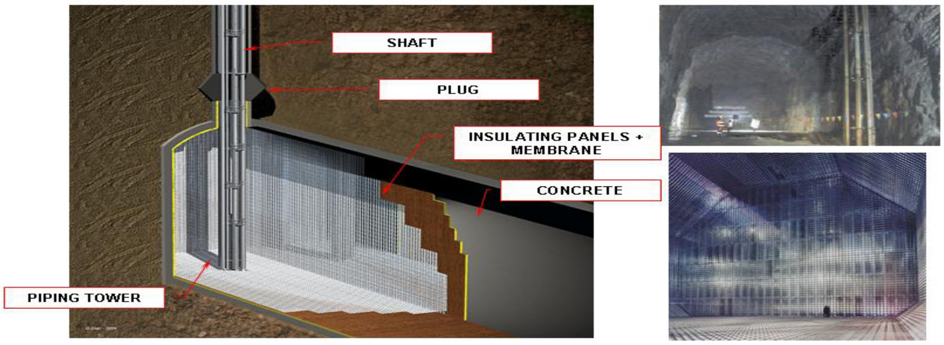

Figure 19. Typical cavern equipment arrangement (with pictures of LPG cavern storage and membrane tank of LNG carrier)

6. Advantages and economics of underground LNG storage

There are many advantages of underground storage in terms of safety, security and environmental acceptability compared with aboveground tanks and in-ground tanks:

- **Safety:** Underground storage is much safer in the case of fire on plant premises or decreased potential damages in the case of nearby industrial accidents, on account of its multi-component barrier with liner and ice ring, and lower vulnerability against earthquake and typhoon.
- **Security:** Enhances security, as underground storage can easily prevent sabotage or terrorism acts.
- **Environmental impact:** As there is no need of large reclaimed areas and less earthwork at ground level, underground storage is environmentally more friendly, and is readily accepted by people located nearby.
- **Use of land space:** Land of aboveground can be used better because of the minimization of total space required for the LNG terminal (Fig. 20). This is due to the fact that LNG storage is about 50 m underground, this can represent a huge cost saving especially in seashore areas where industries are already developed and free remaining areas are small and expensive. It is also the case in areas whose topography needs expensive reclaimed land.

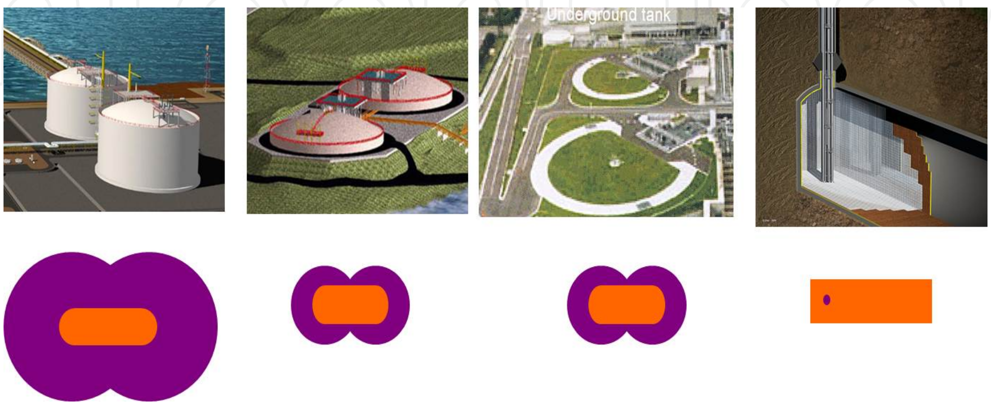

Figure 20. Required area at grade depending on storage type for 320,000 m³ (Orange colour means a storage space, purple colour means the required aboveground space)

Small galleries should be avoided wherever possible by reason of their poorer capacity/area ratio. Underground storage in the form of a gallery of around 20m width by 30m height cross section (Fig. 18) is the most favorable which has been studied geometry in cost terms versus rock behavior.

Moreover, mining technologies and membrane containment system have such flexibility that unit storage capacity has no limit. Crude oil caverns are up to 4,500,000 m^3 in Korea and LNG lined caverns can be increased till such value.

This comparative cost estimate between aboveground and cavern storage concerns only the storage itself and its equipment. It does not take into account the substantial cost saving which could be made, in the case of the cavern storage, for the safety equipment (impounding basin, peripheral retention wall, firefighting systems, etc.) and possibly for the piping length and terminal surface area reduction. Moreover, operation costs, including maintenance are very attractive.

In 2008, a national forum for cost comparison among conventional aboveground, in-ground LNG tank and underground storage was held in Korea where consisted of MKE(Ministry of Knowledge and Economics), KOGAS(Korea Gas Corp.), KNOC(Korea National Oil Corp.), KIGAM(Korea Institute of Geoscience and Mineral Resources), experts of engineering consultants and prestigious professors steered by Congress committee. Construction costs of varying stored volume from 200,000 kl to 1,000,000 kl with increment of 200,000 kl were evaluated and compared with reference price as of March 2006 in Korea (Fig. 21).

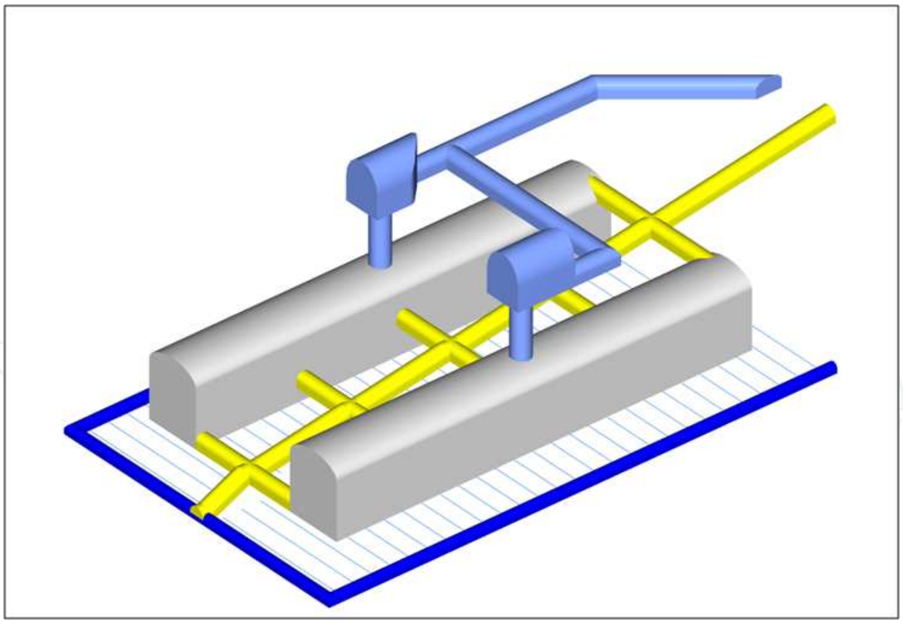

Figure 21. Typical layout of underground LNG storage system with capacity of 200,000 kl

In all cases, the underground LNG storage system is the most economic over the stored volume of 300,000 kl, and at 400,000 kl, the construction cost for underground LNG storage system can be economical by 8% and 34% compared to aboveground and in-ground tank respectively (Fig. 22).

Moreover, operation cost for underground storage units are highly competitive as compared to aboveground and in-ground tanks as systems like slab heating or fire water are not necessary or can be tremendously reduced. Based on Korean reference which has been implemented on crude oil storage by Korea National Oil Company, operation cost of underground storage is 63% less than that of aboveground one.

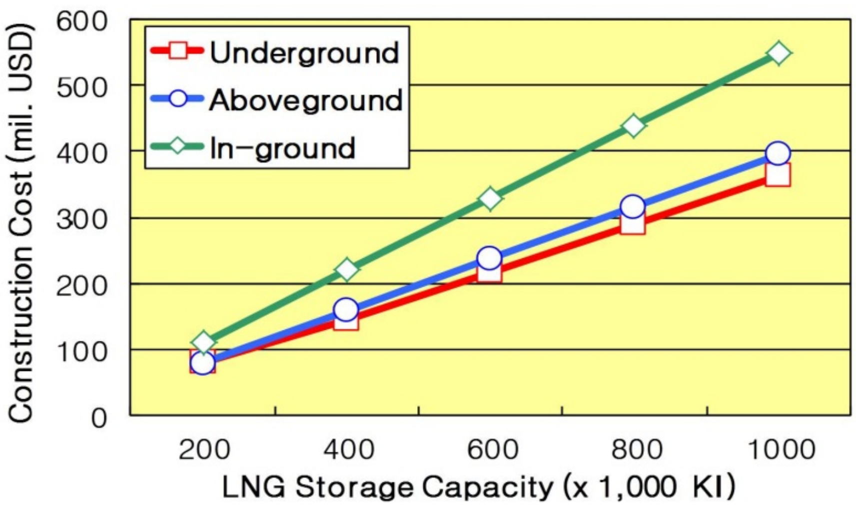

Figure 22. Capital expenditure (CAPEX) evaluation and comparison (South Korean context)

7. Conclusion

Based on experience of underground storage for crude oil and various types of hydrocarbons, underground storage system was thought to be more economical way to store LNG regardless of the above-mentioned conditions. An innovative method of LNG storage in lined rock caverns has been developed to provide a safe and cost-effective solution. It consists of protecting the host rock against the extremely low temperature and providing a liquid and gas tight liner.

To demonstrate the technical feasibility of this method, a pilot plant was constructed at KIGAM area and had been operated from January 2004 to the end of 2004. From construction and operation of Daejeon pilot plant, technical feasibility of underground lined rock storage system can be well proved. And the real scale applicability of it has been evaluated by the results from a successful operation of the pilot plant.

As compared with the conventional aboveground and in-ground storage tanks, the use of lined rock cavern LNG storage system at the LNG terminals can be more economical way in the aspects of capital expenditures and operating expenditures. In addition, it has also the advantage of safety, security and environmental acceptability against the conventional tanks.

Underground LNG storage system in lined rock caverns can be realized in due course at some countries which have suffered from the shortage of storage capacity of LNG and seasonal extreme variation of domestic demand, and of which industries are already developed and free remaining areas are small and expensive.

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8. References

Anderson, U.H. (1989). Steel lined rock caverns. In: *Storage of Gases in Rock Caverns*, Nilsen, Olsen(Eds.), pp. 1-10, Balkema, Rotterdam.

Amantini, E. & Chanfreau, E. (2004). Development and construction of a pilot lined cavern for LNG underground storage. *14th International Conferences and Exhibition on Liquefied Natural Gas*, Doha, Quatar, PO-33.

Amantini, E.; Chanfreau, E. & Kim, H.Y. (2005). The LNG storage in lined rock cavern: pilot cavern project in Daejeon, South Korea. *Proceedings, GASTECH 2005: 21st International Conference and Exhibition for the LNG, LPG and Natural Gas Industries*, pp.1-16, Bilbao, Spain.

Cha, S.S.; Lee J.Y.; Lee, D.H.; Amatini, E. & Lee K.K. (2006). Engineering characterization of hydraulic properties in a pilot rock cavern for underground LNG storage, *Engineering Geology* 84, pp. 229-243.

Cha, S.S.; Bae, G.O.; Lee, K.K.; Lee, D.H. & Bodin, J.L. (2007). Evaluation of drainage system around a lined pilot cavern for underground cryogenic LNG storage, *Tunnelling and Underground Space Technology* 23, pp. 360-372.

Cha, S.S., Lee, K.K., Bae, G.O., Lee, D.H., Gatelier, 2007. Analysis of rock drainage and cooling experiments for underground cryogenic LNG storage. *Engineering Geology* 93, pp. 117–129.

Chanfreau, E.; Amantini, E. & Lee, D.H. (2006). Assesing the use of underground storage tanks at LNG terminals, *LNG Journal*, June 2006.

Chung, S.K. (2006). Thermo-mechanical behavior of rock masses around underground LNG storage cavern, *Keynote lectures in Rock Mechanics in Underground Construction – 4th Asian Rock Mechanics Symposium*, pp. 19-28, Singapore.

Chung, S.K; Park, E.S. & Han K.C. (2006). Feasibility study of underground LNG storage system in rock cavern, *Tunnel and Underground Space* 16 (4), pp. 296-306 (In Korean).

Chung, S.K.; Park, E.S.; Kim, H.Y.; Lee, H.S. & Lee, D.H. (2007a). Geotechnical monitoring of a pilot cavern for underground LNG storage, In: *11th International Congress on Rock Mechanics*, Sousa, Olalla & Grossman(Eds), pp.1245-1248, Taylor & Francis, Lisbon.

Chung, S.K.; Park, E.S. & Han, K.C. (2007b). Feasibility Study of Underground LNG Storage System in Rock Cavern, In: *11th ACUUS International Conference*, Kaliampakos, D. & Benardos, A.(Eds), pp.501-506, NTUA Press, Athene.

Dalström, L.O. (1992). Rock mechanical consequences of refrigeration – a study based on a pilot scale rock cavern. PhD thesis, Chalmers University of Technology, Gothenburg, Sweden.

Dalström, L.O. & Evans, J. (2002). Underground storage of petroleum and natural gas. In: *17th WPC*, pp. 128-129, London: Portland Press Ltd.

Glamheden, R. (2001). Thermo-mechanical Behavior of Refrigerated Caverns in Hard Rock. PhD thesis, Chalmers University of Technology, Goteborg, Sweden

Glamheden, R. & Lindblom, U. (2002). Thermal and mechanical behaviour of refrigerated caverns in hard rock. *Tunnelling and Underground Space Technology* 17 (4), pp.341-353.

Jeon, Y.S.; Park, E.S.; Chung, S.K.; Lee, D.H. & Kim, H.Y. (2006) Numerical simulation of fracture mechanisms for rock masses under low temperature conditions, *Tunnelling and Underground Space Technology* 21(3-4), pp.470-471.

Jeong, W.C.; Woo, S.W.; Lee, H.S.; Lee, D.H.; Lee, J.M.; Choi, Y.T.; Jung, Y.B.; Park, E.S. & Jeong, S.K. (2006). Coupled Heat Transfer and Water Flow Analysis on Ice Ring Formation around a Underground LNG Storage Cavern, In: *Proceedings of the GEOPROC 2006 International Symposium*, Weiya Xu (ed), pp. 602-625, Nanjing China.

Jung, Y.B.; Park, E.S.; Chung, S.K. & kim, H.Y. (2011). Coupled hydro-thermal modeling of ice ring formation around a pilot LNG cavern in rock, *Engineering Geology* 118, pp.122-133.

KIGAM. (2003). Development of Base Technology for Underground LNG Storage and the Analysis on the Operation Results of Pilot Plant. *Research report by KIGAM submitted for SKEC*, 147p (in Korean).

KIGAM. (2004). Development of Base Technology for Underground LNG Storage and the Analysis on the Operation Results of Pilot Plant—2004. *Research report by KIGAM submitted for SKEC*, 144p (in Korean).

KIGAM. (2005). Development of Base Technology for Underground LNG Storage and the Analysis on the Operation Results of Pilot Plant—2005. *Research report by KIGAM submitted for SKEC*, 123p (in Korean).

KIGAM. (2006). Development of Base Technology for Underground LNG Storage and the Analysis on the Operation Results of Pilot Plant—2006. *Research report by KIGAM submitted for SKEC*, 177p (in Korean).

Kim, J.H.; Park, S.G.; Yi, M.J.; Son J.S. & Cho, S.J. (2007), Borehole radar investigations for locating ice ring formed by cryogenic condition in an underground cavern, *Journal of Applied Geophysics* 62, pp. 204-214.

Lee, D.H. (2004). Thermo-geomechanical monitoring & results, In: *Proceedings of International Symposium on LNG Storage in Lined Rock Cavern*, Energies, Saint Quentin en Yvelines, France.

Lee, D.H.; Kim H.Y.; Gatelier, N. & Amantini, E. (2003). Numerical Study on the Estimation of the Temperature Profile and Thermo-mechanical Behaviour in Rock around the Taejon LNG Pilot Cavern, In: *International Symposium on the Fusion Tech. of Geosystem Eng., Rock Eng. And Geophys. Exploration*, pp. 233-237, Seoul, Korea.

Lee, D.H.; Lee, H.S.; Kim, H.Y & Gatelier, N. (2005). Measurements and Analysis of Rock Mass Responses around a Pilot Lined Rock Cavern for LNG Underground Storage, In: *Proceedings of EUROCK 2005*, Konecny, P.(Ed), pp.287-292, Balkema, Brno.

Monsen, K. & Barton, N. (2001). A numerical study of cryogenic storage in underground excavations with emphasis on the rock joint response, *International Journal of Rock mechanics and Mining Sciences* 38 (7), pp.1035-1045.

Park, E.S. (2006). Thermo-mechanical consideration for the cryogenic storage, In: *International workshop on the Underground Storage Facilities in conjunction with the 4th ARMS*, pp.81-98, Singapore.

Park, E.S.; Chung, S.K.; Lee, D.H. & Kim, H.Y. (2007a). Experience of operating an underground LNG storage pilot cavern, In: *11th ACUUS Conference*, pp. 157~162, Athens, Greece.

Park, E.S.; Chung, S.K.; Lee, H.S.; Lee, D.H & Kim, H.Y. (2007b). Design and Operation of a Pilot Plant for Underground LNG Storage, In: *Proceedings of 1st Canada-US Rock Mechanics Symposium*, Eberhardt, E., Stead, D. & Morrison, T. (Eds), pp.1221-1226, Taylor & Francis, Vancouver.

Park, E.S.; Chung, S.K.; Kim, H.Y. & Lee, D.H. (2011). The new way to store LNG in lined rock caverns, In: *The2011 World Congress on Advances in Structural Engineering and Mechanics(ASEM'11)*, pp.3951-3956, Seoul, Korea.

Park, E.S.; Jung, Y.B.; Song, W.K.; Lee, D.H. & Chung, S.K. (2010). Pilot study on the underground lined rock cavern for LNG storage, *Engineering Geology* 116(##), pp.44-52

SKEC; Geostock; SN Technigaz. (2004). Proceedings of International Symposium on LNG Storage in Lined Rock Caverns, Seoul, Korea.

Yi, M.J.; Kim, J.H.; Park, S.G. & Son, J.S. (2005). Investigation of ground condition change due to cryogenic conditions in an underground LNG pilot plant, *Exploration Geophysics* 36, pp. 67–72.