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Numerical study on the estimation of the temperature profile and thermo-mechanical behaviour in rock around the Taejon LNG Pilot Cavern

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Abstract: For Taejon LNG Pilot Cavern being constructed to verify the technical aspects for storing LNG in lined rock cavern, various numerical studies were carried out to estimate the temperature profile and to understand thermo-mechanical behaviour in the rock around the cavern. With the help of Claesson's analytical solution and numerical models, the extent of zero degree isotherm and possible boil-off rate of gas to be stored were estimated. Even though the tensile stress by cooling down is very large compared to the tensile strength of the rock, it has been shown that possible rock yielding might bring about the dramatic reduction of the stress.

1. Introduction

To verify the technical all aspects of a new concept developed for storing LNG in a hard rock lined cavern, GEOSTOCK, S.N. TECHNIGAZ and SKEC are now constructing Taejon LNG Pilot Cavern in Daejeon area. The basic concept developed is based on the combination of: - a containment system to insure LNG containment and rock protection against thermal shock, - a drainage system used during the first months of the storage operation, before the surrounding rock is frozen, to drain water around the cavern and prevent hydrostatic pressure acting against containment system. A typical containment system is composed of 1.2mm thick stainless steel membrane and PU foam insulation panel with specified thickness to control the designed gas boil-off rate.

These thermal and thermo-mechanical analyses were performed with the aim to estimate the temperature profile in containment structure including rock mass, and to study both mechanical response of the rock mass under a thermal loading and the behaviour of a rock joint crossing the storage cavity. Thermal analysis was performed in three different steps: a) an analytical approach (Claesson, 2001), b) 2-dimensional numerical modelling with FLAC2D and UDEC, c) 3-dimensional modelling with FLAC3D. As the Pilot Cavern has a very unique 3-dimenional shape, 3D thermal analysis was preferred to understand particularly the profile of a local area composed of the concrete lining exposed to room air, being not constrained by rock.

Claesson's fully explicit thermo-elastic analytical solution for a spherical cavern is based on constant temperature boundary condition at the rock wall during a temperature decline step. The temperature of the cavern wall is decreased in several steps. After the final step, the cooling is stopped, which means that the heat flux through the cavern wall is zero from that time. All formulas have been implemented in a mathematical computer program.

As a supporting structure of the containment system, a 20 cm thick concrete layer has been allowed. Insulation panel is simulated with the constant 10 cm thick layer of PU foam.

2. Model preparation

Material properties of rock, concrete and PU foam

Rock type around the cavern is biotite granite. Thermal and mechanical properties of rock, concrete and PU foam are given in Table 1. Thermal expansion coefficient of rock was measured at zero degree for a core specimen, while thermal conductivity and specific heat were obtained by laboratory tests for a thin section. Strength parameters such as friction angle and cohesion were determined by the empirical estimation from RMR rock classification in accordance with the procedure proposed by Serafin and Pereira (1983). Concrete properties were taken from data on usual un-reinforced concrete in Korea. As the thermal stress induced by storing a cryogenic gas is tensile in rock it is very important to know the tensile strength dependency on the variation of temperatures. Relevant various tests were performed to show the variation of tensile strength with decline of temperature under both dry and wet condition. Even if saturated specimens show strong dependency with temperature, dry rock, which will be real case due to drainage of groundwater in rock around the cavern, shows a little increase with an average of 8 MPa. As shown in Table 2, the joint mechanical properties were also obtained from laboratory tests. Properties of the rock and concrete contact have been also chosen in order to allow possible sliding and/or opening.

Table 1. Thermal and mechanical properties of rock around the Taejon LNG Pilot Cavern.

	Thermal			Mechanical						
	Thermal expansion coefficient	Thermal conductivity	Specific heat	Density	Elastic modulus	Poisson ratio	Cohesion	Friction angle	Tensile strength	Dilatancy
	(10^{-6}/℃)	(W/m/℃)	(J/Kg/℃)	(kg/m^3)	(GPa)		(MPa)	(deg.)	(MPa)	(deg.)
Rock	6.64	2.63	710	2660	20.3	0.28	0.31	26	8.0	26
Concrete	6.64	2.63	710	2550	23.0	0.25	8.0	30	2.4	30
PU foam	-	0.02	1674	65	0.023	0.20	10000	70	10000	0

Table 2. Rock joint properties around the Taejon LNG Pilot Cavern.

	Kn (GPa/m)	Ks (GPa/m)	Cohesion (MPa)	Friction (deg.)	Tensile Str.(MPa)	Dilatancy (deg.)
Rock/rock	1.9	5.42	0.05	41.2	0	0
Rock/concrete	0.2	0.5	0	10.0	0	0

Initial and boundary condition

Initial temperature is assumed to be homogenous in the model and equal to +12℃, Assumptions for thermal boundary condition are as follows: the bottom, top and right vertical boundary are adiabatic, and for the case of the analytical approach the left vertical boundary is simulated as a symmetrical plane. For the case of thermo-mechanical analysis, in-situ stresses are assumed to be isotropic and correspond to the weight of the overburden. For the case of the analytical solution, the temperature of the cavern wall is decreased in steps and a temperature step is maintained under a prescribed time.

Thermal loading

For the thermal analysis, LN2 temperature to be stored at atmospheric pressure (T= -196℃) is set instantaneously to the intrados of the insulation layer. For the thermo-mechanical analysis, after stress initialisation and cavern excavation, numerical runs were performed to reach the mechanical equilibrium, the temperature being constant and uniform. After having set to zero the displacements form the preceding phase, the LN2 temperature is set fixed instantaneously to the intrados of the PU foam. Thermal cycles with mechanical ones have been applied in two different ways as follows: (a) thermal and mechanical cycles are repeated with different increments to a given date; one day cooling and the corresponding mechanical equilibrium. Numbers of these increments were determined after many runs in order to reach the most stable equilibrium, and avoid possible thermal shock. Calculations are performed for the following duration of cooling: 1 week, 12 weeks and 24 weeks. (b) thermal cycles are performed up to a given date, then the corresponding mechanical equilibrium is reached. Calculations are performed for the following duration of cooling: 1 week, 2, 4, 8, 12, 16, 20 and 24 weeks. For the analytical solution, temperatures prescribed at the sphere wall have been selected from numerically monitored values in a FLAC model.

UDEC joint model

From the rock joint investigation including face mapping, core logging and BIPS survey, three dominant joint sets were classified in dip/dip direction as follows: a) Set 1 of 53/199, b) Set 2 of 38/315, c) Set 3 of 45/098. However, major water conveying joint passing diagonally through the roof of the cavern is distinguished from three m major joint sets. It is guessed that this joint doesn't occur frequently in the site but is important hydro-geologically. The UDEC model includes such a main water convey joint with an inclination equal to 42 degree with respect to the horizontal line.

3. Thermal analysis results

Isothermal contour

The following table 3 summarized the extent of the 0℃ isothermal contour above the cavern roof for all runs performed including Claesson solution, FLAC 2D and UDEC2D for a typical cross-section, and FLAC3D. It should be noted that three sets of the thermal rock properties have been studied to consider the unknown properties of rock mass as follows: (a) basic set, k=2.63 W/m/℃, Cp=710 J/kg/℃, (b) low diffusivity set, k=2.08 W/m/℃, Cp=885 J/kg/℃, (c) high diffusivity set, k=2.71 W/m/℃, Cp=634 J/kg/℃.

Table 3. Isothermal 0℃ extent including concrete layer from the insulation panel (unit : metre).

	Basic set									Low diffusivity			High diffusivity		
	WIGS			WOGS											
	UDEC	FLAC2D	Claes.	UDEC	FLAC2D	Claes.	FL3A	FL3R	FL3E	UDEC	FLAC2D	Claes.	UDEC	FLAC2D	Claes.
1 yr	3.1	3.0	1.8	4.8	4.5	3.3	2.6	2.5	1.7	4.3	4.2	3.0	5.1	4.8	3.4
0.5 yr	1.4	1.5	1.3	2.8	2.6	2.4	2.0	1.9	1.3	2.5	2.5	2.0	3.3	3.0	2.4

Note: WIGS & WOGS = with & without gaseous sky. FL3A,3R & 3E : above, right & rear the cavern in FLAC3D.

Clearly, Claesson's analytical solution shows large deviation from the UDEC and FLAC2d calculation. The deviations are more relatively increased after 1 year cooling down, and also in the high diffusivity property set. On the while, ice front estimation with both UDEC and FLAD 2D are almost the same within error of maximum 0.3 m.

FLAC 3D analysis shows different temperature profile due to local shape deviation from typical cross-section as in Fig. 1. 0℃ isothermal contour is much lower than the result of 2D analyses with difference of maximum 1.5 m at 0.5 year cooling . At the initial stage of numerical cooling, the temperatures on some part of the containment exposed to room air are firstly lowered than others, and thus isothermal conduction is delayed in rear rock mass following the rear face of the containment. It is worthy to note that there is a difference (about 1m) of isothermal 0℃ extent between in rear rock mass and others. It is due to a different delay in thermal conduction induced by 3D configuration.

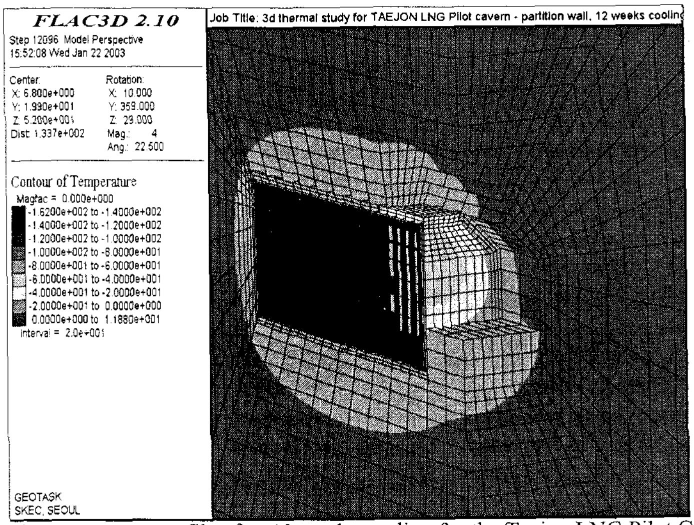


Fig. 1. A temperature profile after 12 weeks cooling for the Taejon LNG Pilot Cavern.

Boil-off rate

The boil-off rate as a function of time has been calculated roughly for all thermal analyses. After 24 weeks operation, the boil-off rate is estimated to be 2.3 %/day for 10 cm insulation. It represents for 24 weeks about four times the volumetric storage capacity of the cavern.

Maximum temperature adjacent to the containment

For all the cases, the maximum temperature at rock surface (concrete and rock contact) is equal to −27℃. It is likely to have the same tendency as in all analyses. It should be noted that the maximum temperature at PU foam/concrete contact is dramatically lowered to about −59℃after 24 weeks of cooling in front face of the containment of which concrete is also in outer surface exposed to room air. This part seems to have week points in thermal loading and response in concrete. To protect any possible cracking due to too low temperature decline, it is necessary to utilize the ventilation system for providing room space with climate air.

4. Thermo-mechanical analysis results

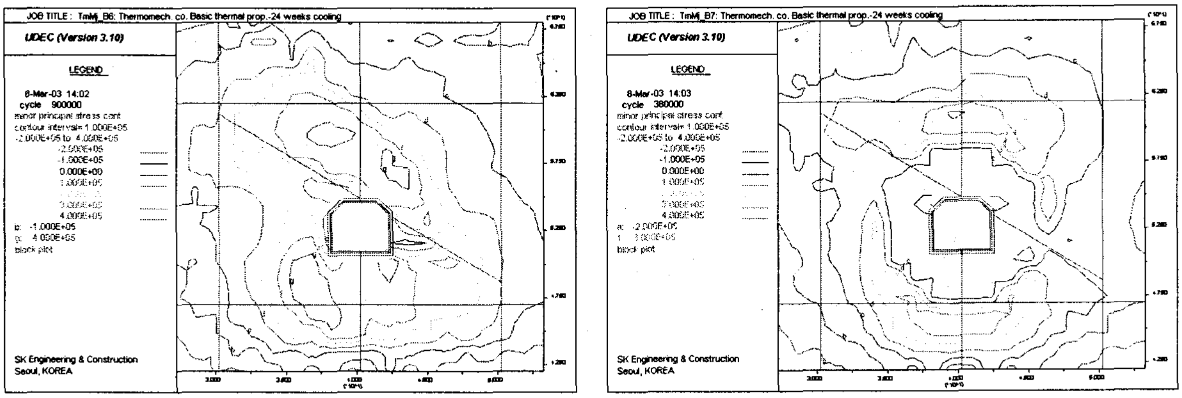
Thermo-elastic analytical solution

Roughly, the maximum displacement is about 0.44 mm at a distance of 4 m from the sphere wall after 1 year cooling down. Displacement is continuously increased at a distance from the wall and then slowly decreased. As this solution is thermo-elastic, the result shows the very slight dependency of thermal rock properties on the displacement profile. Anyway, it should be noted that the elastic displacement induced by thermal loading would be very small as expected. Interestingly, it can be found that the distance showing the maximum displacement advances far from the sphere wall as time step proceeds.

Regarding the radial stress of rock outside the sphere, the maximum radial stress is equal to about (+) 2MPa at a distance of 2 m form the sphere wall after 1 year cooling down. Also it shows the negligible dependency of thermal rock properties on the stress profile. It is interesting to note that radial stress is tensile but relatively small compared to the tangential stress to be shown in the following. The tangential stress of rock is about (+) 6.54 MPa at the sphere wall after 1 year cooling down. It is very important to note that tensile tangential stress is very large compared to the tensile strength, 8 MPa of the rock. Fortunately, the extent of tensile stress over 4MPa, a half of the strength, is only about 1.5 m from the sphere surface. Anyway, large tensile stress may cause news cracks to occur and/or existent radial joints to open in the rock mass around the cavern.

Thermo-mechanical analysis

For the loading type of (a), the maximum tensile stress in the rock is equal to 0.61 MPa at the left corner between the floor and the wall (refer to (a) of Fig.2). For the loading type of (b), it is equal to 0.48 MPa around the isotherm of zero degree (refer to (b) of Fig.2). These values are dramatically reduced compared to 6.54 MPa as the Claesson thermo-elastic solution. The extent of the tensile zone for the minor principal stress is very large; 13 m above and 8 m below for the loading type of (a), and 7 m above and 8 m below for (b). The maximum opening of the major joint is about 1.75 mm and 0.28 mm for loading type of (a) and (b) respectively. The maximum shear displacement of the major joint is about 1.08 mm and below 0.02 mm for loading type of (a) and (b) respectively.



(a) (b)

Fig. 2. Minor principal stress map after 24 weeks cooling for the Taejon LNG Pilot Cavern.
(a) is for the thermal loading type of (a), and (b) is for the loading type of (b).

For loading types of (a) and (b) aforementioned, with the prescribed Mohr-Coulomb properties, the unreinforced layer of concrete is partially cracked in tension by the thermal loading. At the loading type (a), most of cracks are concentrated on contacts between the major joint and the cavern, while some occurs in the floor. At the loading type (b), most of cracks are concentrated at the corners between the floor and the wall.

For the loading type of (a), rock failures occur in shear around both ends of the major joint far away from the cavern. Due to small tensile stress, no tensile failure occurs in the rock. For the loading type of (b), many tension failures occur in the rock above the cavern within isotherm of zero degree. It also fails in shear in the rock around isotherm of zero degree below the cavern.

For the loading type of (a) and (b), the maximum displacement at the roof is about 2.26 mm and 2.89 mm respectively. The roof displacement is slightly asymmetric due to the presence of the major joint.

In order to find a reason of these low thermal tensile stresses, two additional runs have been performed separately with no joint and high strength properties for the rock. Two models are commonly applied with the same thermal loading type of (a). The distinct differences with previous runs are: in the case of no joint, maximum tensile stress in the rock is equal to 0.62 MPa like that of the above loading type of (a). It is due to rock failure in shear, which is identical to the above loading type of (a). In the case of no joint, all quantities are similar to the above loading type of (a). In the case of high rock strength properties, maximum tensile stress in the rock is equal to 7.2 MPa. It is due to no rock failure.

5. Conclusions

To estimate the temperature profile in the rock around the cavern and boil-off rate of stored gas, thermal analyses were performed with Claesson analytical solution, FLAC2D and UDEC, and FLAC3D.

The results of thermo-mechanical analyses are summarized in the following Table 4.

Table 4. Summary on the rock mass response through thermo-mechanical analyses.

	Constitutive model	Maximum displacement (mm)	Maximum tensile stress (MPa)	Maximum joint opening (mm)	Tensile zone from wall (m)
Claesson's Solution	Elastic	0.3	6.5	-	8
UDEC thermal loading (a)	Elasto-plastic (Mohr-Coulomb)	2.3	0.6	1.8	11
UDEC thermal loading (b)	Elasto-plastic (Mohr-Coulomb)	2.9	0.4	0.3	8
UDEC thermal loading (a)	Elastic	2.2	7.3	2.1	11

Regarding the stress state by thermal loading, it has been shown that possible yielding, although it is not large, of the rock around the cavern may bring about the dramatic reduction of tensile stress compared to no rock failure due to high rock strength parameters and elastic model. It is thought that no yielding of the rock during cooling down of the cavern would cause large tensile stresses but locally around the cavern. Fortunately, the damage induced by the thermal loading will be limited closed to the cavern. If the rock fails during the cooling down, it will release the thermal-induced mechanical energy, and lead small tensile stress and will occur at locations far away from the cavern.

It has also been shown that differences between thermal loading types in the thermo-mechanical coupling process will lead very different behaviours of the rock around the cavern. An important point to note is that while the system is far from yield, large temperature increases will be acceptable; near yield, only relatively small increases can be tolerated.

It is also true that the separation of the major joint roughly corresponds to the extent of the +5℃ isotherm. Also, the maximum displacement of the rock around the cavern is allowable compared to critical displacement of containment system.

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