Rock Mechanics for the Stability of Underground Oil and Gas Storage Caverns – Mechanical and hydrological aspect

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Abstract

For about thirty years from early 1970s, Korea has constructed many large-scale underground energy storage caverns in response to the rapid industrial development. In this period, rock mechanics engineers in Korea gained valuable experiences in the area of underground space technologies. Rock mechanics and rock engineering played an important role in design and construction of underground oil and gas storage projects. In this paper, we briefly review the underground oil and gas storage projects completed in South Korea and some related research works published by authors for ten years from 1990 at Rock Mechanics and Rock Engineering Laboratory, Seoul National University. These research works include the mechanical and hydrological, stability analyses of the storage caverns by using a finite element method, back analysis, rock block analysis, and fracture network analysis.

Keywords: Underground, Oil and gas storage, Rock Engineering Lab., Mechanical and hydrological.

1. Introduction

Korea is ranked 109th in the world in terms of area and about 70 percent of the territory is mountainous regions. It is, however, ranked 25th in population and 13th in gross domestic product (GDP) as of 2014. With regard to energy consumption, Korea is the 6th largest crude oil importing country and the 9th for oil consumption. It is also ranked 10th for electricity consumption in the world.

Korea built many large-scale underground energy storage caverns in a relatively short period of time. Construction of such underground facilities for crude oil and liquefied petroleum gas (LPG) was stimulated by the rapid industrialization of Korea and two oil crises in the 1970s. The engineers of rock mechanics have played key roles in the construction projects: for site investigation, designing, and construction stages, for example.

The first underground oil storage project in Korea was K-1 initiated in 1975. Several underground facilities for oil or gas storage have been successfully constructed since then. Some of those caverns – K-1, L-1, U-1, and U-2, for example, were extended for securing further storage. Above ground tanks for oil storage in Ulsan are now under way of dismantling to change into underground storage.

Not only for stable energy supplying and overcoming the adverse topography but also for environmental and safety concerns, Korea is expected to further its effort in constructing underground storage facilities, which means that rock mechanics engineers continue to develop technologies for designing and constructing advanced underground structures.

Various rock engineering topics related to the underground energy storage have been studied in Korea. In this paper, some of the topics dealt by rock mechanics and rock engineering laboratory at Seoul National University are introduced. They are based on FEM and deterministic/stochastic rock block models for mechanical stability analysis and on fracture network and elasto-plastic porous media models for hydrological stabilities analysis.

2. Oil and gas projects

After experiencing the first and the second oil crises, most of oil importing countries started to stockpile crude oil so much in proportion to their annual oil consumption. According to Korea's stockpiling program, the construction of oil storage facilities began in the late 1970s, and the first large underground cavern for crude oil was built in 1985. Three additional facilities for underground LPG storage were constructed to satisfy the goal of stockpiling crude oil for the 60-day's consumption in 1988. The rapid increase in oil consumption, however, required more construction of storage facilities in order to maintain the stock corresponding to the 60-day consumption.

Fig. 1 shows the locations of the oil and gas storage caverns. Table 1 lists the storage caverns in operation in Korea.

Table 1. Oil and LPG storage caverns in Korea

Project name	Contained material	Owner	Dimension of Caverns (m)			Storage capacity (kl)	Rock type	Cavern roof elevation (m)	Construction period
			Section (WxH)	Max. length of a single cavern	Total Length				
U-2	Crude oil	KNOC**	18x30	875	8,814	4,293,000	Ggrano-diorite	-30	1981~1985
L-1	LPG	KNOC	18x22.5	135	879	300,000	Andesite	C_3:-115 C_4:-60	1986~1989
K-1	Gasoline Kerosene	KNOC	15x20.5	235	1,262	231,000	Granite	-12.7	1975~1982
Yosu	LPG	Yosu Energy	C_3:15x19.5 C_4:16x21.0	400	968	290,000	Andesite tuff	C_3:-114 C_4:-60	1981~1983
Ulsan	LPG	SK Gas	19x21	310	1,482	500,000	Siltstone Sandstone	C_3:-119 C_4:-60	1985~1988
K-1*	Gasoline	KNOC	18x22.5	394	440	159,000	Granite	-10	1990~1994
U-1	Crude oil	KNOC	18x30	1,030	8,685	4,452,000	Andesite tuff	-30	1990~1998
$U\text{-}2_1$*	Crude oil	KNOC	18x30	678	3,794	1,908,000	Grano-diorite	-30	1990~1997
L-1*	LPG	KNOC	18x22.5	210	830	315,000	Gneiss	C_3:-115 C_4:-60	1990~1996
Pyong-taek	LPG	SK Gas	17.5x22	278	740	277,000	Gneiss	C_3:-115	1996~1999
Y-2	LPG	LG-Caltex Gas	16x26	275	1,133	465,000	Gneiss	C_3:-134 C_4:-114	1997~2000
$U\text{-}2_2$*	Crude oil	KNOC	18x30	450	1,505	800,000	Grano-diorite	-30	2002~2006
Daejeon LNG pilot cavern	LNG (Nitrogen)	SKEC et al.	3.5x3.5	10	10	110	Gneiss	-20	2003
U-1*	Crude oil	KNOC	18x30	547	5,315	2,770,000	Andesite tuff	-100	1997~2009
Ulsan*	Crude oil	KNOC	18x30	667	2,032	1,600,000	Granite	-70	2005~2010

*Extension of pre-existing facilities, **Korea National Oil Corporation, C_3: Propane caverns, C_4 : Butane caverns

As shown in Table 1 and Fig. 1, the first underground storage facility (K-1), which can store 231,000 *kl* of refined oil, was built in a granitic rock mass near Seoul. The cross sectional dimension is 15 $m \times 20$ m with the total length of 1,262 *m*. The construction began in 1975 and was completed in 1982. A French company led the design and supervision of the construction while Korean companies did the actual building.

The first crude oil storage facility was the U-2 caverns, located in the southern coastal area of the Korean Peninsula, where the dominant rock type is granodiorite. This facility is located –30m below sea level and consists of twelve caverns. The sectional area of each cavern is 18 $m \times 30$ m and the longest cavern is 875 *m* long. The total length of twelve caverns is 8,814 *m*. The caverns can store 4,293,000 *kl* of crude oil and is world-famous for its single-storage facility. The project started in 1981 and finished in 1985. During this period, Korea lacked the experience and technology to carry out such projects. Korean companies, however, were able to acquire technologies of design for oil storage caverns in cooperation with Swedish companies.

In the projects of the three LPG storage facilities (L-1, Yosu, and Ulsan) only basic designs were conducted by French company. Other facilities such as U-1, U-2 (ext.), L-1 (ext.) and K-1 (ext.), however, were designed mostly by Korean companies' technology, which is a significant achievement in the area of underground oil and LPG storage. The Y-2 caverns, completed in 2010, are located under the sea near Inchoen, Korea. The geology of Y-2 site is so adverse that underground caverns were constructed in an artificial island. The 127 *m* long construction shaft (diameter of 15.5 *m*) was excavated after installation of slurry wall, and a car lift system was introduced for rapid mucking out. The depth of caverns is about 145 *m* below the sea level, and the height and width of the cavern are 26m and 16 *m*, respectively.

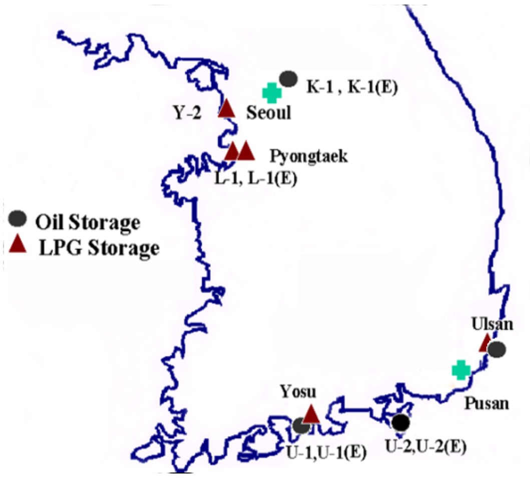


Fig. 1. Location of the underground oil and LPG storage caverns

Table 2. Design criteria of water curtain borehole

Facilities	K-1 (ext.)	L-1 (ext.)	U-1 Site 1	U-1 Site 2	U-2 (ext.)	Pyong -taek
Borehole Interval (m)	12	10	8,16	10.5, 21	7,14	10
Injection Pressure (bar)	2	10	2	2	2	9.5~ 10
W/C Depth (msl)	+5	-90	0	0	-10	-90
Borehole Length(m)	100~ 120	100~ 110	90~ 110	90~ 110	110	100~ 120
Distance from Cavern (m)	15	25	30	30	20	25

Daejeon LNG pilot cavern was constructed in 2003 based on partnership between a Korean company and two French ones. The pilot cavern is accessed through a pre-existing horizontal tunnel and the roof of an experiment opening is at a depth of about 20 *m* below the ground. A platform above the entrance of the cavern is required to install instruments, manholes and pipes. The internal room of the completed pilot has dimensions of 3.5 *m* × 3.5 *m* in section and 10 *m* in length, of which working volume is 110 *kl*. Operating and monitoring started in February 2004. The purpose of this pilot plant is to validate the new technology for underground storage of LNG at –160 °C in a lined rock cavern.

Various tests of rock mechanics were conducted to characterize the site. Among the important in-situ tests were hydraulic fracturing and overcoring tests for stress measurement, Goodman jack test for static modulus, seismic downhole test for dynamic modulus, injection fall off test for permeability, and geotechnical borehole logging.

When underground oil and gas storage caverns are constructed, one of the most important problems to consider is leakage of the oil or gas from the caverns. To seal up the caverns, water curtain systems having diameter of 76 *mm* were designed. Table 2 shows the design criteria of water curtain boreholes for several Korean storage facilities.

3. Mechanical and hydrological stability analysis of storage cavern

3.1 Visco-elastic finite element analysis

Two dimensional visco-elastic stress analyses considering the variation of elastic modulus of rock induced by excavation are conducted for two adjacent caverns by Lee, Kim and Sun (1986). These caverns have the same dimensions as the oil storage caverns (U1, U2, and U2 (ext.)) whose cross section is of a long-wall horseshoe shape having a height of 30 m and width of 18 m. The depth from the ground surface to cavern arch is assumed as 150 *m*.

Mohr-Griffith envelope was adopted as failure criteria of rock. A variable, R indicating the level of freshness of rock has been introduced as follows.

$$R = d / D \qquad (1)$$

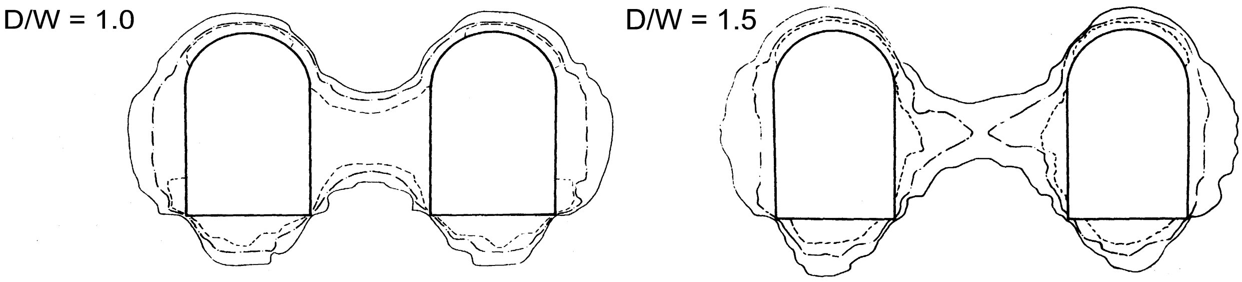
where D is a distance from the center of Mohr's circle to the envelope and d is a distance from the circumference to the envelope.

Lee, Kim, and Sun (1986) adopted the following equation proposed by Motojima et al. (1978) to evaluate the elastic modulus and Poisson's ratio of rock according to R.

$$E = E_o R^n + (1-R^n)\, E_f \quad (2)$$

$$\nu = \nu_o R^n + (1-R^n)\, \nu_f \quad (3)$$

where, E_o and ν_o are the elastic modulus and Poisson's ratio under the hydrostatic condition, and E_f and ν_f are values at failure, respectively. The index n is an intrinsic factor representing non-linearity and it mainly depends on rock types. In this analysis, n is assumed to be 1.8.



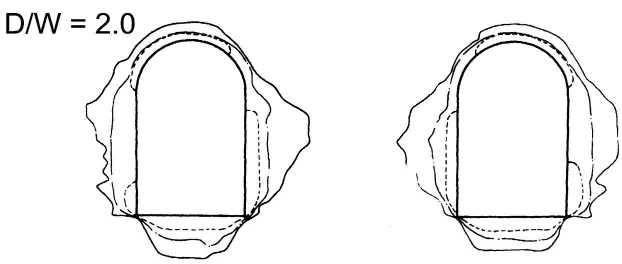


Fig. 2. Distributions of Poisson's ratios for various ratios of pillar width (D) to cavern width (W) at K = 1.2.

The distribution of principal stresses, displacements, and degree of relaxation of rock around the caverns were obtained for the ratios of initial horizontal stress to initial vertical stress (K), whose values were 0.5, 1.0 and 1.2, and for the ratios of the pillar width to the cavern width, whose values were 1.0, 1.5 and 2.0 in each model. The distribution of Poisson's ratios of the rock around the caverns for various ratios of pillar width to cavern width (D/W) at K=1.2 is shown in Fig. 2.

From the simulation analysis with various K values, the ratio of pillar width to cavern width, as a design parameter, should be at least 1.5 or more if K>1, and should be 2.0 if K < 1.

3.2 Visco-plastic finite element analysis

A two dimensional visco-plastic finite element model capable of simulating the multi-step excavation was adopted to investigate the effect of excavation-support sequences on the behavior of underground crude oil storages in the jointed rock mass (Lee, Lee, and Cho, 1995). Ubiquitous joint pattern was assumed, and fully-grouted passive rock bolts were considered in the numerical model.

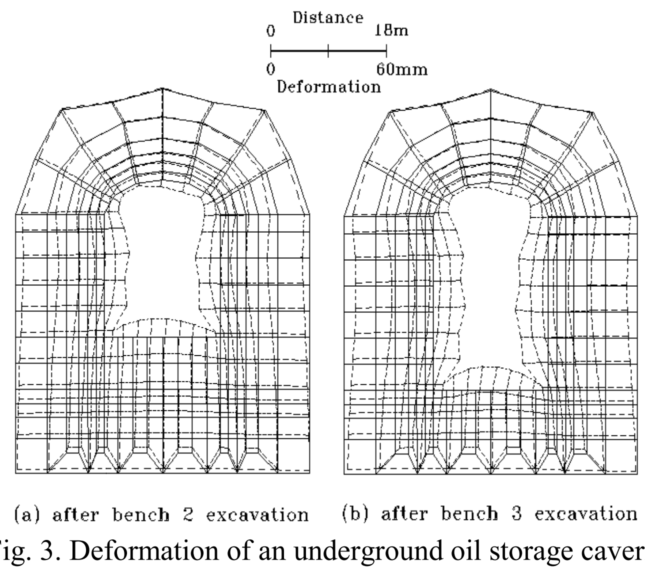


Fig. 3. Deformation of an underground oil storage cavern.

To check out the applicability of the model developed in this study to practical cases, a real underground oil storage cavern was adopted for stability analysis. The cavern, which is 18 *m* wide and 30 *m* high is located between -30 *m* to -60 *m* below the sea level. In practice, the whole section of the cavern is designed so that it is excavated by four successive steps; gallery, bench 1, bench 2, and bench 3. The height of each bench is 7.5 *m*. Four excavation steps were modeled in the simulation study. During the excavation, we observed two major joint sets (set 1: 88° of inclination and 0.9 *m* of spacing; set 2: 34° of inclination and 1.5 *m* of spacing).

Deformation of the storage cavern after excavation of bench 2 and bench 3 is shown in Fig. 3. As excavation continued, the displacement at side walls became larger than the displacements at the roof and bottom.

Tensile failure of joint set 1 was observed in the side walls of bench 1 and bench 2, and it extended as deep as 4 *m* from the wall surface. Shear failure of joint set 1 developed in the whole side wall regions. The maximum depth of shear failure was about 9 *m* in both walls: at bench 1 in the left wall and at bench 2 in the right wall. Shear failure zone of joint set 2 appeared mainly in the upper right and the lower left side walls.

Based on these results, the deformation behavior of storage cavern can be said to be significantly affected by the presence of joint set 1.

3.3 Deterministic analysis of rock blocks

Lee and Song (1998) proposed a block stability analysis method using a joint trace map. In this method, joint orientation, length, and location as well as cavern sectional dimension are used as input data. With these data, removable blocks around a cavern, which include key, potential key and stable blocks, are analyzed.

The analytical procedure is as follows. First, take the input data of joints such as dip/dip direction and coordinates of end points from the joint trace map. Then, considering the cavern shape and its dimension, convert the 2D coordinates of each joint trace into 3D ones. After constructing the 3D joint net, convex polygons are separated, and their possibility to make finite blocks is tested. Finally, analyze the stability of removable blocks distinguished from the finite blocks and report the calculation result. This algorithm was applied to the stability analysis of rock blocks around the Pyungtaek LPG storage cavern.

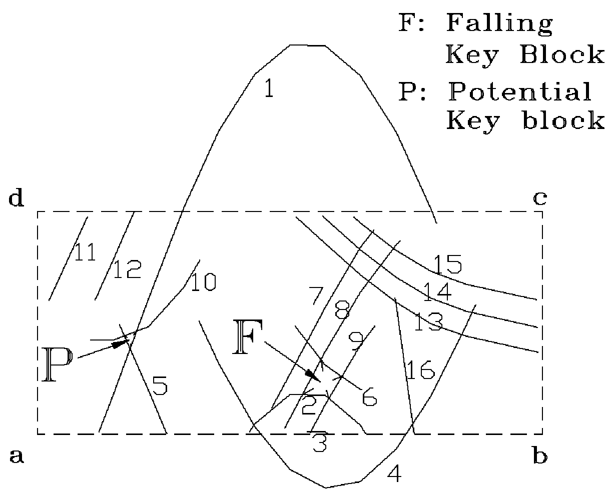


Fig. 4. Unrolled joint trace map of the 5th section

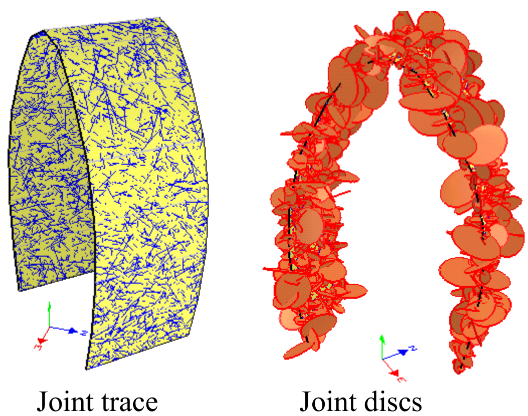


Fig. 5. Simulated joint traces and discs.

One of four storage caverns which was 222 *m* in length was divided into 11 sections for the block stability analysis. Fig. 4 shows the joint trace map of the 5th section, which is 20 *m* in the cavern axis direction. From this map, one falling key block in the roof and one potential key block on the side wall, were analyzed.

In all 11 sections, 388 blocks were found. Among the blocks, infinite blocks take up 70%, key blocks 14% and tapered 12%. Many of the key blocks turned out to be in the 6^{th} section, and most potential keys to be in the 7^{th} and 8^{th} sections.

This block stability analysis method can provide the exact block dimension and its exact location. This method is especially useful in reinforcement design of potential key blocks than key blocks falling down right after the excavation.

3.4 Stochastic analysis of rock blocks

Song, Lee, and Seto (2001) proposed a simulation method for block stability analysis using a statistical joint modeling. They applied this method to the Y-2 LPG storage cavern and observed good agreement in results with that from site experience.

In the joint modeling process of this study, the location and shape of joints are assumed to follow the Poisson disc model and their orientation is modeled as Fisher distribution. One of the least reliable procedures in the joint modeling is the estimation of the joint diameter distribution. Song and Lee (2001) suggested a distribution-independent technique of estimating the joint diameter distribution for the randomly located joint disc model using the window sampling method which has been adopted in this study.

Fig. 5 shows an example of joint traces on the cavern wall and their joint discs. As a result, it can be said that small blocks are likely to appear frequently on the walls and gallery of the cavern, and therefore shotcrete is more effective than rock bolts for reinforcement in this site. This result was consistent with real situations and shotcrete was applied to the area as a main supporting tool.

3.5 Hydrological analysis using a fracture network

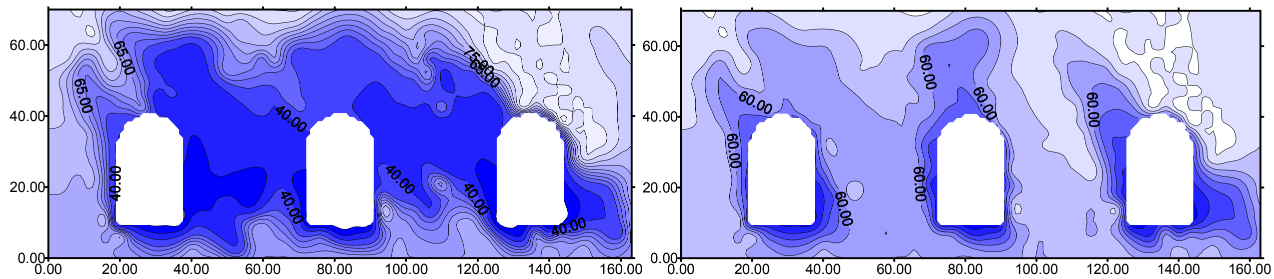
A case of groundwater flow analysis based on 2D fracture network concept is presented (Jang, Chang, and Lee, 1996). The fracture network model was also employed to analyze the requirements of hydraulic containment for the underground oil storage cavern.

The U-2 (ext.) oil storage facility consists of six main storage caverns, access tunnels, and water curtain. The horizontal distance between the storage caverns is 35 *m*. The water curtain tunnels are placed 30 *m* above the storage cavern.

Fig. 6 shows the groundwater head distributions around the caverns with or without the fracture network. The fracture zone was assumed to pass through the caverns and the internal pressure of the cavern was set to be 0.5 bars. The groundwater head along the discontinuities having large apertures changed greatly.

3.6 Hydrological analysis for an elasto-plastic porous media

Hydrological analysis was carried out on another case in the elasto-plastic porous medium model (Lee and Chang, 1995). In this study, the deformation of rock mass around the oil storage cavern, U-2 (ext.) was analyzed by using the elasto-plastic finite element method, and the permeability change was evaluated by using the relationships between strain and permeability. The influence of permeability change on groundwater flow was also analyzed.



(a) With fracture network (b) without fracture network

Fig. 6. Distribution of groundwater head around caverns

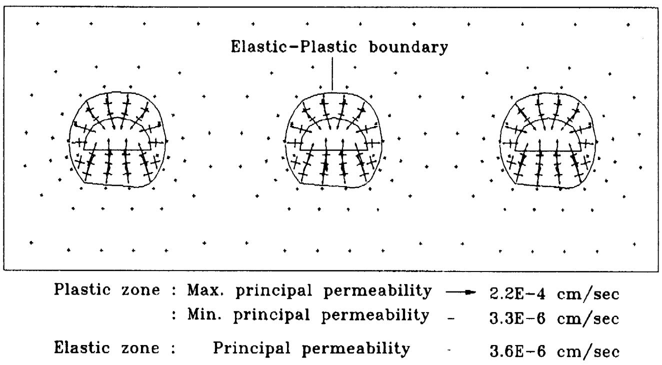


Fig. 7. Distribution of principal permeability

In Fig. 7, the permeability changes little in the elastic region. The maximum principal permeability is in radial direction at the upper regions of the caverns and is about sixty times greater than the principal permeability in the elastic zone. The minimum principal permeability in the plastic zone is slightly less than the one in the elastic zone. The analysis results of the elasto-plastic porous medium model showed that grouting of rocks was necessary to reduce groundwater inflow into the cavern and to maintain hydraulic equilibrium.

4. Conclusions

The construction of many large-scale underground storage caverns in Korea started in the 1970s to stockpile crude oil and liquefied petroleum gas. Now Korea has many huge underground structures comparable to other large structures around the world. Despite the steady expansion of such energy storage facilities, an increase of energy consumption due to industrial development and economic growth reduces the relative quantity of stored energy.

In the past 30 years, rock engineering technology has played an important role in site investigation, design, and construction of the large underground construction projects. Along with the technology accumulated to date, there is an increasing demand for the safe, economical, and environmentally friendly construction technologies. To develop these technologies, further research into the area of rock mechanics including stability analysis of discontinuous rock mass, precise in situ testing techniques, analysis of groundwater flow through discontinuities, and geophysical exploration techniques needs to be carried out. Some of these technologies are already being employed in practice in Korea.

Acknowledgements

This research was a part of the project titled "Development of Technology for CO_2 Marine Geological Storage" funded by the Ministry of Oceans and Fisheries of Korea. The authors also acknowledge the Korea National Oil Corporation for providing the design and construction data of underground oil and gas storage caverns.

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