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Evaluation of drainage system around a lined pilot cavern for underground cryogenic LNG storage

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Abstract

A lined pilot cavern for underground cryogenic LNG (liquefied natural gas) storage was constructed in granite in Daejeon, Korea in 2003 and commissioned in 2004. As the hydrostatic pressure of groundwater and thermal stress due to the formation of ice lenses may damage the containment system, rock drainage around the pilot cavern is needed to maintain the stability of the containment system. Once the drainage works were completed, the level of groundwater around the pilot cavern was controlled using drainage holes to form an ice ring as a second barrier to prevent the leakage of LNG from the cavern. In order to establish the drainage system for the pilot cavern, 15 boreholes were drilled into the rock. Fractures in the rock mass around the pilot cavern were characterized to determine the most appropriate orientation for the drainage holes. The major joints acting as conduits for inflow water were designed for efficient drainage. After the 15 drainage holes were drilled and their efficiency tested during the dry season in April 2003, it was found that there was a problem with the inflow of water through the main joint along the right-hand wall of the cavern, indicating the system was less efficient on the right-hand side. Hence, three more boreholes were drilled in the correct direction on the right-hand wall of the cavern. A second drainage test was conducted during the rainy season in August. This showed some seepage into the bottom of the pilot cavern. In order to reduce this seepage, two more additional drainage holes were drilled and grouted below the concrete invert. Although the drainage system was very efficient, weak points in the system were found by testing and changes were made to the system to improve its efficiency.

Keywords: Underground cryogenic LNG storage; Rock drainage system; Drainage testing

1. Introduction

There are two main forms of natural gas storage, namely using either high pressure or low temperature to reduce the storage volume. Studies in countries where natural gas is supplied via a pipeline have focused on high-pressure storage. Underground storage of natural gas under high pressure has developed into three main types of storage: depleted gas reservoirs, aquifers and salt caverns (EIA, 2004). A new concept known as hard rock storage has been developed which uses either lined or unlined caverns. Pilot tests in lined rock caverns were carried out in Sweden (Lindbo et al., 1989). Recently, the first lined rock cavern where natural gas was stored under high pressure was introduced in Sweden (Glamheden and Curtis, 2006).

In-ground and aboveground storage in insulated steel tanks near the coast is a conventional method for storing LNG worldwide as LNG is transported by sea and is handled in gas terminals. Underground storage of LNG in mined rock caverns has been attempted numerous times but few attempts were ever reported (Bresson, 1962; Khan et al., 1967). An experiment was conducted in Belgium testing a pilot cavity for low-temperature storage of LNG in clay (Laguerie, 1989). Tests of an unlined refrigerated

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pilot cavern were performed in Sweden (Dahlström, 1992; Glamheden, 2001).

A lined pilot cavern for underground cryogenic LNG storage was constructed in Daejeon, Korea in 2003 and commissioned in 2004 (Fig. 1). In common with the water curtain used in the underground storage of gas using hydrostatic pressure (Kim et al., 2000; Lee and Song, 2003), the drainage system in lined caverns is important for maintaining appropriate hydrogeological conditions for the stable cryogenic storage of LNG (Cha et al., 2006). In order to protect the LNG containment system from the hydrostatic pressure of groundwater and thermal stress from ice lenses, a drainage system was constructed around the pilot cavern. The drainage system consisted of drainage holes and a ditch under the cavern invert. The upward boreholes drained the rock mass by gravity while the downward boreholes drained the rock by pumping.

The drainage system was operated for the early months of the storage operation. When a sufficient thickness of rock mass around the pilot cavern was refrigerated, the drainage pumps in the downward boreholes were stopped and the valves for the upward boreholes were closed to allow refill into the refrigerated rock. The controlled recharge of groundwater into the refrigerated rock forms an impervious ring of ice. The ice ring can absorb the hydrostatic pressure of groundwater and forms a natural barrier to the leakage of LNG in the case of an accident.

The drainage efficiency of fractured rock is highly influenced by the orientation and distribution of the fractures. In order to determine the most appropriate orientation for the drainage holes, the fractures were characterized by window mapping survey, core inspection and acoustic borehole televiewer. The orientation of the drainage holes was designed to align with the major water-carrying joints.

The initial drainage system was made of 15 drainage holes numbered from D1 to D16 (there was no D13), based on a theoretical and numerical study and on the results of hydraulic tests and fracture characterization. The drainage tests were performed before and after construction of the concrete lining. The first drainage test was carried out in April 2003 and the second test was carried out in August. Although heavy rainfall occurred in the middle of the second test, thus preventing the results from being compared with the results of the first test, it provided the chance to test the efficiency of the system under heavy rainfall conditions.

The purpose of this study was to evaluate the efficiency of the drainage system before concrete casting, and then to confirm whether the system of 18 boreholes was sufficient to reduce water entry into the cavern after a change in the hydrogeological conditions brought about by construction of a concrete lining and after contact grouting.

2. Site conditions

A pilot lined cavern for cryogenic LNG storage was constructed in Daejeon, about 200 km south from Seoul, Korea. The cavern for LNG storage was made by enlarging and modifying a facility originally constructed at the site in 1995 for research into underground storage of food under low temperatures (Park et al., 1999; Synn et al., 1999; Choi et al., 2000). The working net storage volume of the LNG-storage cavern was 110 m^3. The volume of the ultimate cavern was planned to be about 1,500,000 m^3. A program of hydraulic tests at the site was started in 2002. The pilot cavern and the containment system were constructed in 2003 and the pilot plant was commissioned in January 2004. Liquid nitrogen was used as a substitute for LNG in this pilot test for safety reasons. The injection of liquid nitrogen at −196 °C, which resulted in the cooling of the rock around the pilot cavern, was carried out for 6 months.

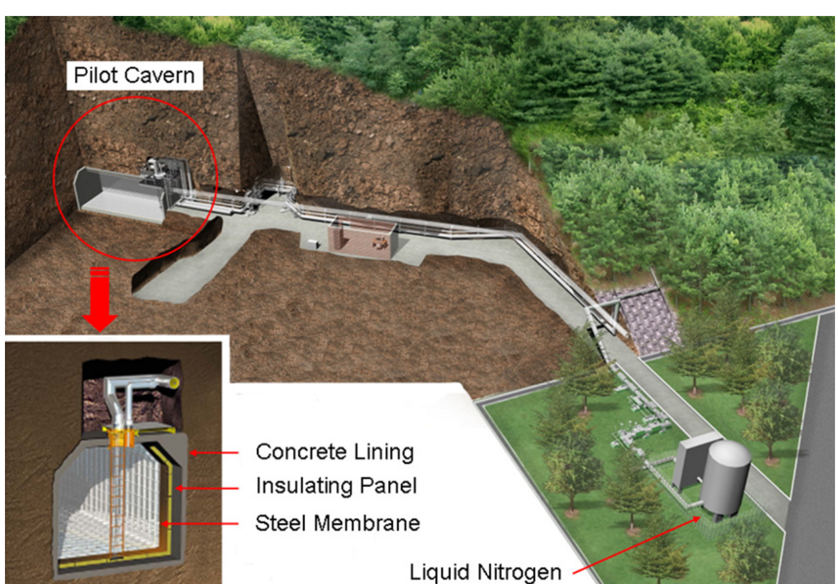

Fig. 1. Diagram of the cryogenic pilot plant.

2.1. Layout and geometry

The width of the pilot cavern, including both storage volume and containment system, was 4.52 m, its height was 4.02 m and its length was 10.64 m. The roof of the pilot cavern lay at a depth of more than 20 m below the surface. The cavern had a 'horseshoe' shape. The roof of the pilot cavern was enlarged around entrance points for pipes. The galleries and mechanical rooms were used as drilling chambers. The access tunnel was excavated from the foot of hill that contained the pilot cavern, running parallel with the ground. A steel membrane, an insulating panel, and concrete lining constituted the containment system of this pilot storage cavern (see Fig. 1). The basic concept of the cryogenic pilot cavern is to store LNG at −162 °C in a cavern mined from hard rock and equipped with a liner for containing the LNG instead of storing pressurized natural gas directly in an underground cavern.

2.2. Geology

The base rock at the site consisted of Jurassic biotite granite. The main mineral components of the rock as determined from a photomicrograph were quartz, K-feldspar, plagioclase and biotite. The granite had a light gray color and a fine or medium grain size. Some quartz veins and pegmatite appeared in the drilling cores. The average depth of hard rock was approximately 9 m below the surface. The average rock quality designation (RQD) of the hard rock was approximately 90 with an average Q value of 8.

The geological investigation was performed by window mapping survey of the pilot cavern, core logging, and using an acoustic borehole televiewer. The survey was grouped into four cells, being the left and right walls, the roof and the rear wall of the pilot cavern. The orientation, frequency and apparent persistence of whole joints in the rock were measured. Analysis using the acoustic borehole televiewer was carried out in two vertical surface boreholes and a downward underground borehole. The results were compared with core logging data. The orientations (dip/dip direction) of the three major joint sets observed during the site investigation (Fig. 2) were 60/209, 40/171, and 29/331. Although open joints were seemingly scattered around the pilot cavern, there was a slight concentration of open joints around the major joint sets. The joint (30/154) passing diagonally through the roof of the pilot cavern and carrying a large inflow of water was unique among the joint sets at the site. Even though this joint was not part of any major joint sets and joints of this type seemed not to occur frequently at this site, its presence showed hydrogeologically important behavior in the pilot cavern.

2.3. Hydrogeology

Sixty-five percent of the annual precipitation occurred from June to September in the study area. The amount of rainfall in August 2003, in which the second drainage test was performed, was 254.9 mm. The water table varied from 51 m above mean sea level (about 1 m below the bottom of the pilot cavern) in the dry season to 63 m (about 8 m above the cavern roof) in the rainy season. The geometric mean of the hydraulic conductivity in the drainage holes measured using the Lugeon test was 4.9×10^{-7} m/s. Seepage into the pilot cavern was examined during the site investigation stage. The flow rates of water at various flow points numbered from L1 to L4 were measured using a waterspout. The waterspout and basket were set up on all flow points. The flow meters were equipped with a basket and the small quantities of water flowing through the flow points were measured with a beaker. Although the

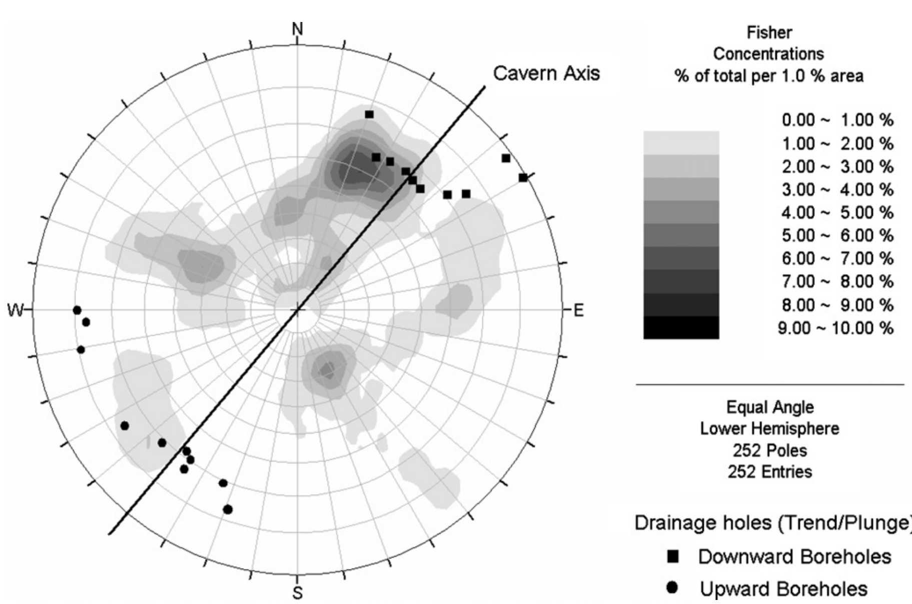

Fig. 2. Stereographic plot of joints and drainage borehole orientation showing trend/plunge.

large water-carrying joint (30/154) was not evaluated in the fracture analysis, the joint was distinctly shown to be present across the roof of the pilot cavern. This joint shows that the joint that meets the cavern can greatly influence seepage flow.

3. Drainage system

3.1. Design

It was planned for the rock mass around the cavern to be drained during the first few months of the cooling period in order to dry the cavern. When the cold front had advanced far enough, the drainage was stopped to allow water to reenter the rock progressively. The refill water formed a thick ring of ice of approximately one to two meters thickness around the cavern. This ice ring was able to withstand the pressure of the water outside the cavern.

Åberg (1977) presents an equation for pressure distribution that shows the relationship between well spacing and the distance of the wells from the cavern walls. The relationship is estimated as $a = y/0.6$, where a is the maximum borehole spacing and y is the distance between the cavern wall and the drainage hole. Taking into consideration the position of the water-freezing front in the rock mass determined by thermal calculation, the drainage holes were planned to be located more than 5 m from the cavern walls. The calculated borehole spacing was about 8.3 m.

This simple calculation was simulated by UDEC (Universal Distinct Element Code). Numerical modeling was performed with 15 boreholes that had box type drainage. The initial position of the water table used in the simulation was the maximum value measured during the site investigation. The result showed that the set of 15 boreholes was sufficient to drain the rock mass around the pilot cavern.

For drainage in fractured rock, the geometry between boreholes and fractures is important for maximizing drainage efficiency. If the linear frequency of boreholes along a line normal to a set of parallel planar discontinuities is λ, then the observed frequency, λ_s, along a sampling line that makes an acute angle δ with the normal set is given by $\lambda_s = \lambda \cos\delta$ (Priest, 1993). Therefore, the discontinuity frequency in the boreholes is related to δ. The direction of drainage holes was determined from the orientation of the major joint sets. In order to increase the discontinuity frequency of the drainage holes, drilling the boreholes so they intersected the joint sets perpendicularly was attempted. It was difficult to drill the drainage holes so they intersected the every joint set perpendicularly because of limitations in the layout and geometry in the pilot cavern and the galleries. Although perpendicular penetration of drainage holes with joint sets maximizes the joint frequency in drainage holes, inclined crossing of borehole with joints also improves drainage. The stereographic plot in Fig. 2 demonstrates the trend/plunge of drainage holes with joint distribution. Although the major water-carrying joint (30/

Table 1
Characteristics of drainage boreholes around the pilot caver

Borehole	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D14	D15	D16	D17	D18	D19	D20	D21
Length (m)	38.0	35.0	38.0	38.0	38.7	30.4	38.5	38.3	38.3	38.0	38.3	38.8	30.2	30.1	30.0	30.6	30.1	31.1	38.0	38.0
Trend	38	38	45	52	40	60	20	20	28	33	45	40	81	87	91	55	55	55	43	25
Plunge	−20	−18	−18	20	−22	0	13	−15	24	24	24	24	−20	−24	−21	3	15	−15	24	−19
Manometer height (m)	0.4	0.4	0.4	0.15	0.4	0.4	0.15	0.4	0.1	0.17	0.17	0.17	0.4	0.4	0.4	1.55	1.34	0.4	0.2	0.4
Hydraulic conductivity ($\times 10^{-7}$ m/s)	6.4	14.7	11.1	0.6	0.3	6.4	6.1	5.7	5.8	6.6	6.8	6.1	7.1	7.7	6.4	–	–	–	–	–
Stage	I	I	I	I	II	II	II	II	II	II	II	II	II	II	II	III	III	III	IV	IV

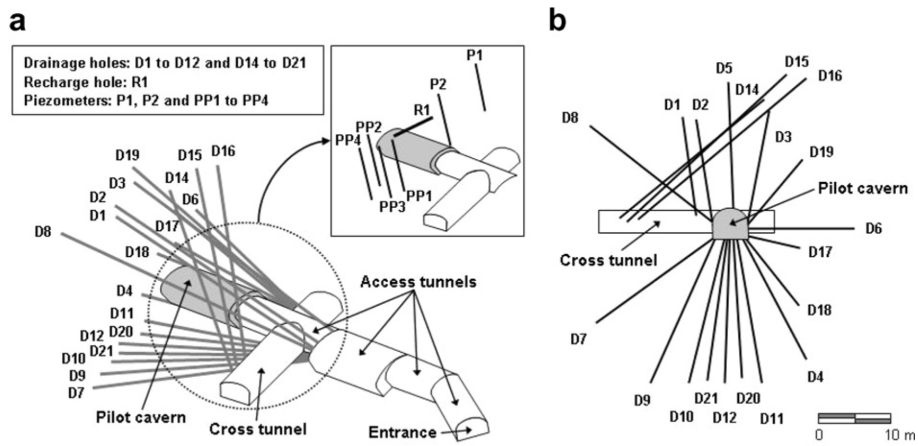

Fig. 3. Schematic diagram of the pilot cavern. (a) Oblique view of drainage holes (D series), recharge hole (R1), and piezometers (P and PP series), (b) front view of drainage holes.

154) in the cavern cannot be penetrated perpendicularly by the drainage holes, downward borehole D7 and upward borehole D8 can connect with joint (30/154) at an angle of approximately 45°.

The major group of drainage holes that is sub-parallel to the cavern axis was drilled at the entrance to the cavern. The drainage holes directly cover joint set 1 (60/209). Other drainage holes that were drilled at an angle to the cavern axis were drilled to penetrate joint set 5 (62/265) in the chamber perpendicularly. Other joint sets were intersected at an angle by neighboring boreholes.

3.2. Drilling

Table 1 summarizes the characteristics of the drainage holes. The drainage system was originally designed to consist of 15 boreholes. Six boreholes (D4, D7 and D9–D12) were inclined downwards, eight boreholes (D1–D3, D5, D8 and D14–D16) were inclined upwards, and one borehole (D6) was horizontal. Four boreholes (D1–D4) were drilled for the hydraulic test that was conducted in the preliminary site investigation (stage I). Eleven new boreholes (D5–D12 and D14–D16) were designed and drilled during the first drainage test (stage II). After the first drainage test (stage III), three boreholes were drilled in upward (D19) and downward (D17 and D18) direction, while two more downward boreholes (D20 and D21) were drilled after the second test (stage IV). The diameter of drainage boreholes was 76 mm. A schematic diagram of drainage holes (D1–D12 and D14–D21), recharge hole (R1), and piezometers (P1, P2 and PP1–PP4) is shown in Fig. 3.

4. Drainage tests

4.1. Test procedure

The test procedure consisted of four phases, summarized in Table 2. In phase 1 of the procedure, the hydraulic head of the groundwater was calculated from the pressure measured in each borehole and this information was used to determine the variation in the water table. Half drainage (phase 2) and full drainage (phase 3) of the system of boreholes were carried out to check the effectiveness of the drainage from the boreholes. Artificial recharge with full drainage (phase 4) was carried out in phase 4 in order to simulate heavy rainfall. Phase 4 allowed the maximum capacity of the drainage system to be evaluated.

The test schedule is summarized in Table 3. All boreholes were equipped with an individual manometer and flow meter. Pressure gauges for automatic recording of the water level were installed in the six piezometers named P1, P2, PP1, PP2, PP3, and PP4 (Fig. 3). Wellhead pressures were measured in all closed boreholes and flow rates were measured in open drainage holes. Seepage rates into the pilot cavern and the galleries were examined every 6 h. Total water balance was recorded in order to evaluate net water seepage rates into the pilot cavern.

4.2. First drainage test

The first drainage test was conducted during the dry season, after the drilling of 15 drainage holes. The pilot cavern was not lined at this stage allowing seepage into the cavern to be measured directly. The test began at 12:00 noon April 15 and elapsed time was measured during the test procedure. During phase 1, when the initial hydrological status of the site was determined, pressures measured on the upward boreholes (D1–D3, D5, D8, and D14–D16) ranged from 0.32 to 0.69 bar (Fig. 4). A temporary increase in pressure in the drainage holes D14–D16, was observed at 18:00 April 16 (30 h after the start of the test), which was related to water leakage from a joint located on the right-hand cavern wall due to refilling of horizontal borehole D6 (Fig. 4). Because the groundwater of this area was used as drinking water, the dye tests to confirm the hypothetical routes were not permitted by the owner of

Table 2
Test procedures for testing the efficiency of the drainage system around the pilot cavern

Phase 1:	Initial hydrogeological determination All boreholes were filled with water and then closed Seepage flow into the pilot cavern and the galleries was allowed to stabilize Pressure was measured in each borehole
Phase 2:	Half drainage Half the boreholes were opened for drainage and the other half remained closed The upward boreholes were opened to allow gravity drainage, while the downward boreholes were pumped using electrical pumps
Phase 3:	Full drainage All boreholes were opened for drainage The upward boreholes were opened to allow gravity drainage, while the downward boreholes were pumped using electrical pumps
Phase 4:	Artificial recharge and full drainage The surface recharge hole R1, located above the pilot cavern, was injected with water All boreholes were opened for drainage The upward boreholes were opened to allow gravity drainage, while the downward boreholes were pumped using electrical pumps

Table 3
Schedule of drainage tests on the drainage system around the pilot cavern

Stage	First test			Second test		
	Start time	End time	Elapsed time	Start time	End time	Elapsed time
Phase 1	12:00 15 April	12:00 18 April	72	12:00 12 August	12:00 16 August	96
Phase 2	12:00 18 April	12:00 20 April	120	12:00 16 August	12:00 19 August	168
Phase 3	12:00 20 April	12:00 22 April	168	12:00 19 August	12:00 22 August	240
Phase 4	12:00 22 April	11:00 25 April	239	12:00 22 August	10:00 24 August	286

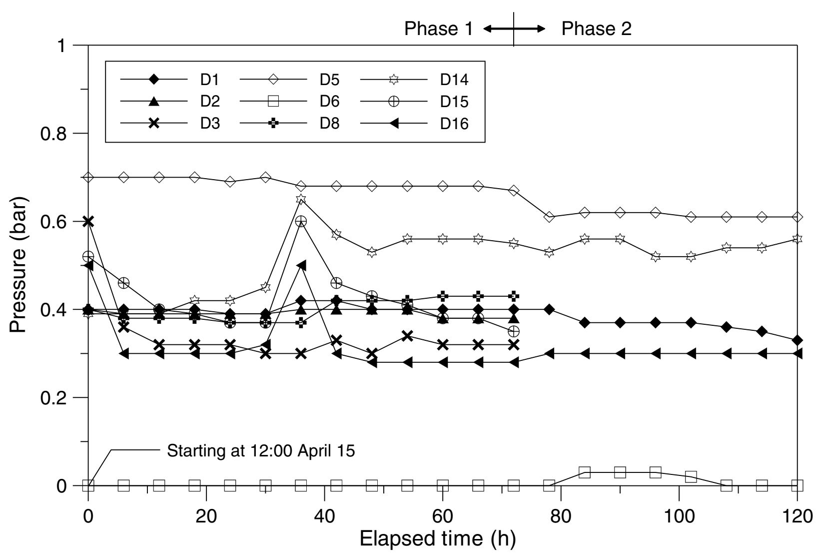

Fig. 4. Pressure responses in drainage holes in the initial hydrogeological determination (phase 1) and half drainage (phase 2) of the first drainage test.

the site. Borehole D6, which showed no pressure response during the test, is directly connected to the cavern and to boreholes D14–D16 by this joint. The temporary increase in seepage into the cavern, which can be seen in Fig. 5a, is also related to this injection of water into borehole D6. A small increase in pressure in the gallery (Fig. 5a) at 12:00 August 16 (24 h after the start of the test), occurred due to water that accumulated in the left-hand chamber instead of draining into the ditch. The average seepage rate into the pilot cavern, except for the temporary increase described above, was 70 l/h in phase 1 (Fig. 5a). Only one major localized intrusion of water occurred through the bottom of the left-hand cavern wall as well as two small leakages from the main joint in the cavern roof.

In the half drainage phase of the test procedure (phase 2), upward boreholes D2, D3, D8, and D15 were drained by gravity drainage and downward boreholes D4, D9, and D12 were flushed using the air-lift pumping system.

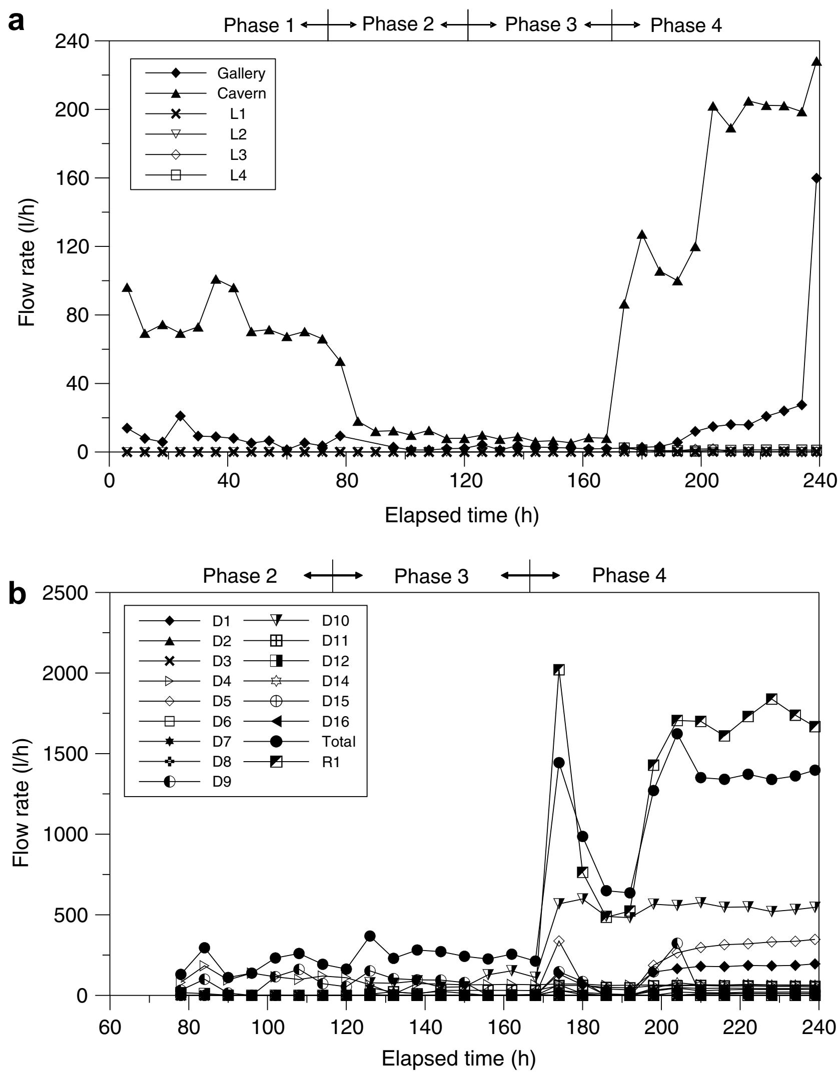

Fig. 5. Flow rates of (a) gallery and cavern, and (b) drainage boreholes, during the first drainage test.

The average static pressures on the upward boreholes that remained closed decreased slightly, except in borehole D14. The average seepage rate into the pilot cavern was 17 l/h (Fig. 5a). The total drainage rate from the seven open boreholes was 199 l/h and significant drainage rates were recorded on downward boreholes D4 and D9 (Table 4 and Fig. 5b). Except for these two boreholes, the opened upward boreholes showed a rapidly decreasing flow rate until drainage ceased completely. This can be attributed to the low water table.

During the full drainage phase (phase 3), all the upward boreholes were open to allow gravity drainage and all the downward boreholes were pumped using electrical pumps. The water drained by the upward boreholes and flushed by airlift pumps in the downward boreholes was removed to a ditch along with drainage water from the galleries. Therefore, the flow rates of the individual boreholes were subtracted from the total seepage rate of water from the gallery ditch. The average seepage rate into the pilot cavern was 8 l/h (Fig. 5a). The total drainage rate from the 15 boreholes was 260 l/h and significant drainage rates were recorded on downward boreholes D10, D9, D4, D11, and D7 (Table 4 and Fig. 5b).

In addition to full drainage, water was injected into the recharge hole R1 in phase 4. Within 3 h of injection, significant water flow was recorded through the two water leakage points found in the roof of the pilot cavern during phase 1. New leakage points were found in the roof and in both side walls of the cavern. The leaks came from the main joint and the joint crossing the cavern roof close to the entrance. After less than 2 days, a decrease in flow from the main leakage point in the cavern roof, named L3, which intersected the upper joint, was recorded while an increase in flow from the leakage point named L4 was observed (Fig. 5a). Moreover, a more significant water flow was observed on the right wall coming from the main joint. These observations are consistent with the geometry and location of the joints in side of the cavern and the two main joints dip towards the right-hand side, so the water coming from R1 arrives at upper part of joint on the left side then

Table 4
Average flow rates of the drainage holes observed during the drainage tests (l/h)

Borehole number		D2	D5	D19	D8	D10	D1	D18	D6	D17	D14	D3	D15	D12	D9	D4	D11	D7	Total	R1
First test	Phase 2	–	*	*	–	*	*	*	–	*	*	–	–	2	74	123	*	*	199	*
	Phase 3	–	–	*	–	94	–	*	–	*	–	–	–	2	66	61	27	10	260	*
	Phase 4	35	304	*	7	551	172	*	–	*	64	7	15	–	68	65	58	42	1388	1712
Second test	Phase 2	–	*	228	481	*	*	*	*	10	–	–	*	–	411	138	–	–	1268	*
	Phase 3	5	8	322	334	324	26	168	82	45	–	–	–	1	2	1	–	–	1318	*
	Phase 4	683	503	450	429	414	243	185	74	88	54	42	19	2	–	–	–	–	3186	1550

* Denotes closed borehole.

flows along the joint that dips toward the right-hand wall. As shown in Table 4 and Fig. 5b, flow was record from upward boreholes D1–D3, D5, D8, D14, and D15 where none had been observed previously. Flow rates increased in downward boreholes D10, D9, D4, D11, and D7 related to the drainage of the water injected through R1. Only boreholes D6, D12, and D16 showed no flow. As mentioned above in phase 1, borehole D6 was directly connected to the cavern by the joint in the right-hand cavern wall. Borehole D12 was located close to D10 which drained the greatest amount of water and D16 had the lowest elevation compared to upward boreholes D5, D14, and D15

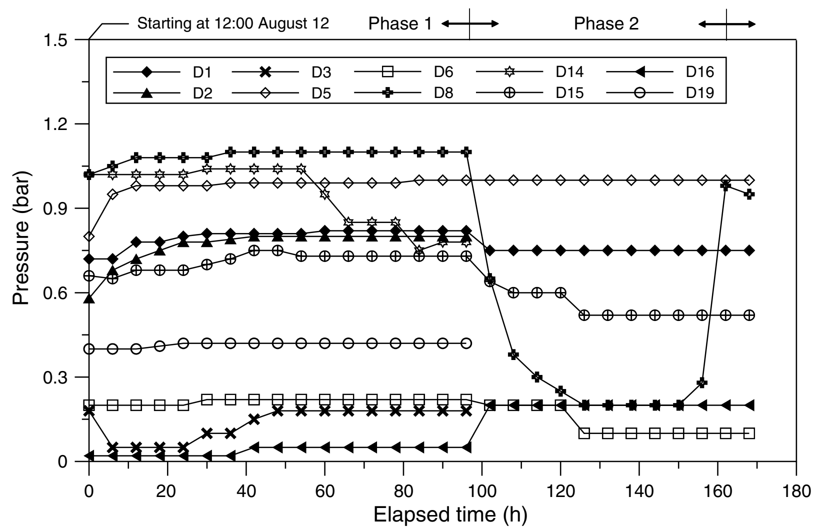

Fig. 6. Pressure responses in drainage holes in the initial hydrogeological determination (phase 1) and half drainage (phase 2) of the second drainage test.

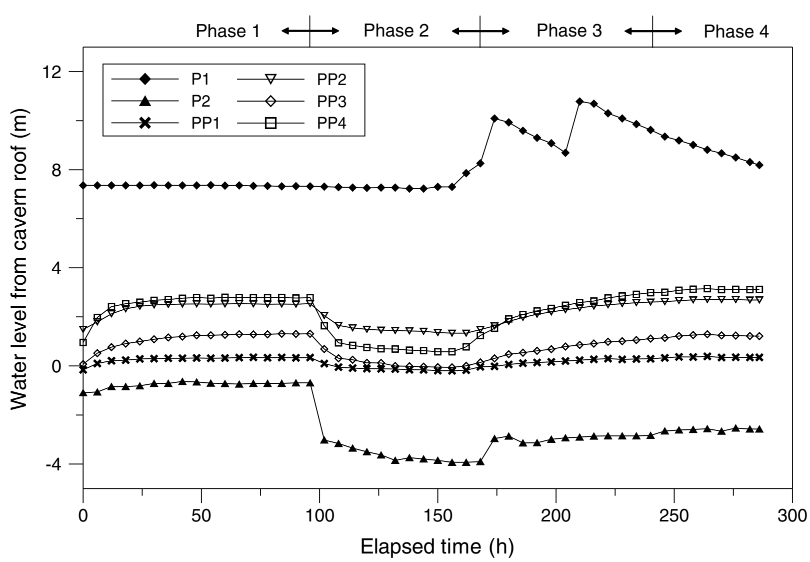

Fig. 7. Piezometer monitoring during the second drainage test.

which all showed significant drainage. A temporary decrease in seepage and drainage was observed at 0:00 April 23 (180 h after the start of the test), due to problems with the injection pump (Fig. 5a and b). The pump was repaired at 12:00 April 23 (192 h after the start). The seepage rate into the pilot cavern once seepage had stabilized was 203 l/h (Fig. 5a). The total drainage rate from the boreholes, once stabilized, was 1388 l/h while the stabilized flow rate of the injection into R1 was 1712 l/h (Table 4).

4.3. Second drainage test

The test began at 12:00 August 12 and elapsed time was recorded. The average pressure measured on the upward boreholes appeared to be higher than during the first drainage test, corresponding to a higher hydraulic head above the cavern. The pressure measured in the upward drainage holes ranged from 0.42 to 1.09 bar (Fig. 6). Measurements of the water level from the piezometers ranged from −0.8 to 7.4 m (Fig. 7). These water levels were higher than those observed during the first test, possibly due to the cumulative effect of both the construction of a concrete lining with contact grouting and the heavy rainfalls of 19 mm over 3 days that occurred before phase 1.

The average seepage rate into the pilot cavern was 259 l/h (Fig. 8a). The seepage was composed of three parts. A flow rate of 150 l/h was measured through the joints located in the roof of the excavated part of the cavern above the concrete structure and the manhole. Despite the contact grouting, seepage occurred at a rate of 20 l/h through the concrete floor of the cavern via the invert and/or the contact floor/wall. The remaining seepage

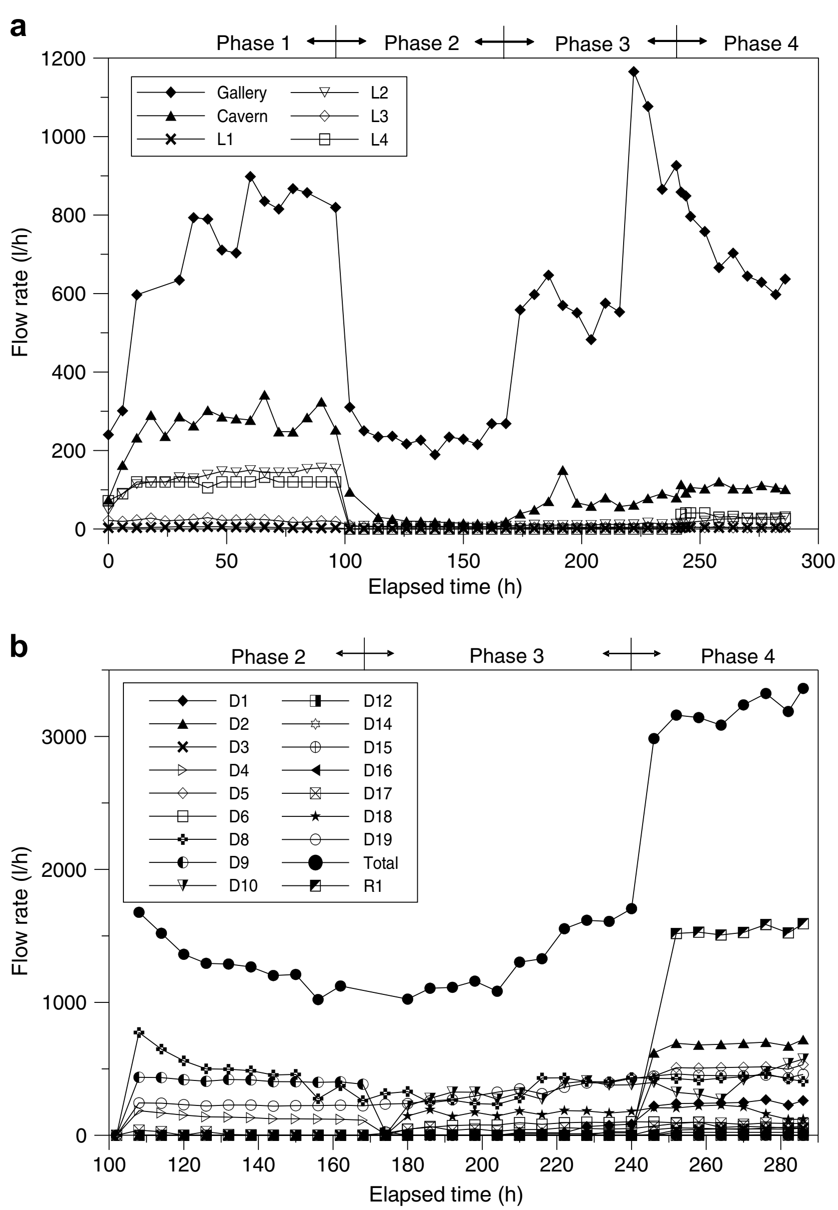

Fig. 8. Flow rates in (a) gallery and cavern, and (b) drainage boreholes, during the second drainage test.

(89 l/h) was drained via the water drainage system installed below the concrete invert.

Upward boreholes D2, D3, D8, D14, and D19 were opened to allow gravity drainage and downward holes D4, D9, D12, and D17 were pumped out during the half drainage phase (phase 2). The average seepage rate into the cavern during phase 2 was 26 l/h (Fig. 8a). The seepage rate into the pilot cavern was composed of seepage at 7 l/h from the roof and 4 l/h inside cavern with the remaining 15 l/h drainage occurring below the invert. As shown in Fig. 8b, the total drainage rate by the boreholes was 1268 l/h but this decreased to 1000 l/h at the very end of phase 2. Significant drainage rates were recorded in upward boreholes D8 and D19 and in downward boreholes D4 and D9. A decrease in flow rate was observed in D8, followed by a decrease in the total drainage rate in phase 2. A strong relationship existed between the drainage rate and water levels recorded from all piezometers except P1, which was located at a considerable distance from the cavern (Figs. 7 and 8b). Due to the transient effect of the heavy rainfalls recorded on August 18 (41 mm) and August 19 (49 mm) and then on August 21 (34.5 mm), a strong increase in seepage into the pilot cavern and especially the galleries was observed beginning at 18:00 August 19 (174 h after the start of the test). A maximum cavern seepage rate of 150 l/h was recorded on August 20 between 6:00 (186 h after the start) and 12:00 (192 h after the start). A strong interference of the rainfall can also be seen in the water levels measured by the piezometers beginning at the end of phase 2 (Fig. 7).

In the full drainage phase (phase 3), the average seepage rate into the pilot cavern was 74 l/h, which was composed of seepage at 15 l/h from the roof, 5 l/h inside the cavern 54 l/h that drained below the invert (see Fig. 8a). The average drainage rate by the 18 boreholes was 1318 l/h with an increase from 1100 l/h to 1600 l/h on August 21 between 0:00 (204 h after the start) and 18:00 (222 h after the start). This was mainly related to the increase in flow rates in D8, D10 and D19 (Fig. 8b). This increase seemed to be related to heavy rainfall recorded at night. A strong pressure increase in upward borehole D8 was observed from 18:00 August 18 (150 h after the start) to August 19, despite its high drainage rate (Fig. 6). After a decrease in its drainage rate, the pressure and flow rate increased again at 6:00 August 21 (222 h after the start). This behavior was possibly related to the effect of the rainfall, thus highlighting a reduced efficiency in this part of the drainage system. Significant drainage rates were recorded in downward boreholes D10 and D18 and upward boreholes D8 and D19 during phase 3 (Table 4).

In the full drainage and artificial recharge phase (phase 4), considering the effect of rainfall on cavern seepage and the likelihood of renewed heavy rainfall, it was decided to start injection before the rainfall began in order to see the influence of artificial recharge on the existing seepage. Less than 2 h after injection, important leakage was recorded from the existing leakage points, intersecting with the main joint in the roof of the pilot cavern. Significant water leakage was also observed from the pillar on the right-hand side of the chamber, from which leakage was observed in phase 1. This leakage occurred close to boreholes D17–D19. New flows were recorded in upward boreholes D1, D2, D5, and D14 and an increase in flow rates were recorded in boreholes D17–D19, because of the drainage of the water injected into R1. Downward boreholes except boreholes D10, D17 and D18 showed no flow. Borehole D16 had the lowest elevation compared to boreholes D5, D14 and D15. The average seepage rate into the pilot cavern was 107 l/h, which was composed of seepage of 35 l/h from the roof, 5 l/h inside the cavern and 67 l/h that drained below the invert. The total drainage rate by the 18 boreholes was 3186 l/h while the injected flow rate into R1 was 1550 l/h (Table 4).

5. Analysis of water balance

The initial hydrogeological status of the rock mass around the pilot cavern was determined over a period of 3 days during the dry season in the first test and over 4 days during the rainy season in the second test. Total rainfall was 136.4 mm during the second test. The hydraulic head acting on the rock mass due to seasonal variations can be determined by measuring the pressures in the boreholes and by direct measurement of water levels. The height of the manometers in the upward boreholes is 0.4 m from the bottom of the cavern and the cavern height is 3.1 m, so the hydraulic head can be calculated from the pressure in the upward boreholes. Fig. 9 shows the hydraulic heads in all the boreholes after stabilization during phase 1 of both first and second tests. The average hydraulic heads above the cavern roof were 1.6 m with values ranging from 0.5 to 4.2 m in the first test. In the second test, the average was 4.1 m and values ranged from 1.5 to 8.2 m. The hydraulic heads from drainage holes were consistent with measurements from the piezometers (Fig. 7). The water levels measured in downward boreholes around the invert ranged from −0.26 to −0.18 m in the first test but they overflowed in the second test. This overflow can be attributed to the cumulative effect of both the construction of the concrete lining and contact grouting and the heavy rainfall. These results will be taken into account in the design of drainage stop points and the water injection system for the cavern during the operation period.

The results of the water balance of the site and the efficiency of the drainage system obtained during each phase of the first and second tests are summarized in Table 5. In the first test, the seepage rate was initially 70 l/h. The rate decreased to 17 l/h during the half-drainage phase and to 8 l/h during the full-drainage phase. Allowing half drainage reduced the seepage into the pilot cavern to 76% of the initial inflow and full drainage resulted in an 89% reduction. The drainage holes drained 92% of water into the pilot cavern during half drainage and 97% during full drainage. Nevertheless, this result indicates that the drainage system showed a good level of efficiency in dry condi-

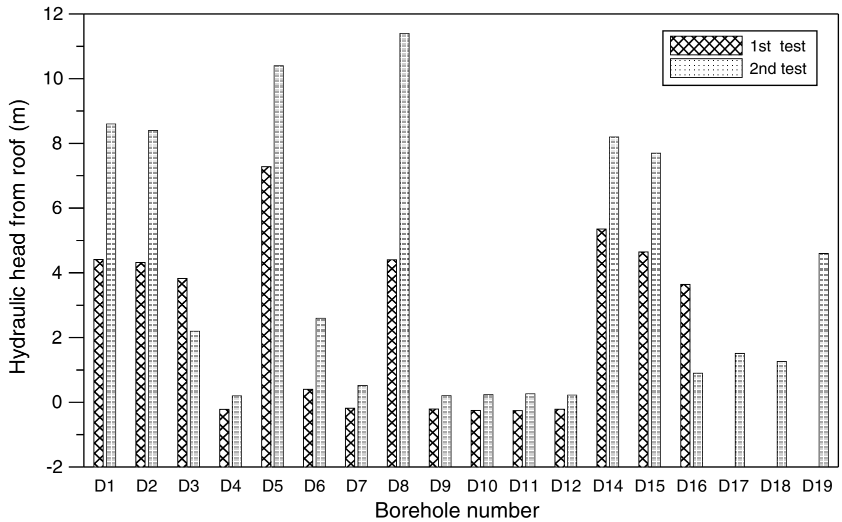

Fig. 9. Hydraulic head in all drainage holes during the initial hydrogeological determination of the first and second drainage tests.

Table 5
Water balance of the pilot cavern during the drainage tests (for first and second test stages)

	Phase 1		Phase 2		Phase 3		Phase 4	
	First	Second	First	Second	First	Second	First	Second
Pilot cavern (l/h)	70	259	17	26	8	74	203	107
Galleries (l/h)	7	704	3	240	3	714	19	679
Drainage holes (l/h)	0	0	199	1268	260	1318	1388	3186
Water table flow (l/h)[a]	−77	−963	−219	−1534	−271	−2106	(102)	−2422
Artificial recharge (l/h)[b]	0	0	0	0	0	0	−1712	−1550
Drainage percentage (%)[c]	–	–	92	98	97	95[*]	87	97
Seepage reduction (%)[d]	–	–	−76	−90	−89	−71[*]	+190	−59
Remarks	Initial condition		Half drainage		Full drainage		Recharge/Full drainage	

[a] Seepage rate from natural water table.
[b] Injection rate through the surface recharge hole R1.
[c] Drained water as a percentage of inflow around the pilot cavern (drainage rate/inflow rate).
[d] Seepage reduction as a percentage of the seepage rate measured during the initial hydrogeological determination (Seepage rate difference/ Initial seepage rate).
[*] Denotes a disturbed value due to heavy rainfalls.

tions but some problems became apparent in the drainage system when accompanied by artificial recharge. In order to simulate the heavy rainfall conditions, water was injected artificially through the recharge hole R1 at a flow rate of 1712 l/h. After recharge, there was a strong increase in seepage to 203 l/h and there were significant inflows from the main joint along the right wall of the pilot cavern. This indicated a lower efficiency of the drainage system on the right-hand side of the pilot cavern. Under artificial recharge conditions, the drainage holes drained 87% of water into the pilot cavern. Even when 13% of the water injected into the recharge hole seeped into the cavern and the galleries, the increase in flow rate resulted in a seepage that occurred at no less than twice the initial flow rate. A 190% increase was observed in the cavern due to injection through recharge hole.

As the second test was performed during the rainy season, the initial seepage flow into the cavern was three times higher than in the first test. The seepage rate into the cavern was initially 259 l/h. Half drainage resulted in a 90% reduction in flow rate to 26 l/h. The drainage holes drained 98% of water into the pilot cavern during the half-drainage phase. Heavy rainfall brought a strong increase in seepage from the end of the half-drainage phase to the beginning of the full-drainage phase. Due to the heavy rain, the efficiency of full drainage measured during the second test cannot be compared directly with the first test. In spite of the heavy rainfall, the full drainage resulted in a 71% reduction of seepage into the cavern compared to the initial amount of seepage. Considering the results of the first test, this should theoretically represent more than a 90% reduction compared with the half-drainage phase. During the full-drainage phase, the drainage holes drained 95% of water into the pilot cavern. In the artificial recharge phase, the drainage holes drained 97% of water into the pilot cavern and reduced seepage into the cavern by 59% of the initial amount. Although the second drainage system with 18 boreholes was shown to be efficient at reducing the entry of water into the pilot cavern during the heavy rainfall and during the artificial recharge phase, non-negligible flows onto the floor of the cavern and below the concrete invert were observed. These flows will cause problems from ice formation during the cooling stage.

Seepage into the cavern increased from 70 l/h in the dry season to 259 l/h in the rainy season, and seepage into the galleries increased from 7 l/h to 740 l/h in the galleries. Thus, seepage during the rainy season was more than 12 times greater than that seen in the dry season. In addition, the concrete lining and the contact grouting lead to an increase in the hydraulic head above the cavern roof, causing an increase in the seepage rate. Artificial injection accompanied by heavy rainfall in the second test may have caused the amount of water contained in the rock mass around the pilot cavern to reach its maximum. Under those conditions, the drainage holes drained 97% of the injected water into the pilot cavern and improved the efficiency of drainage from a 164% increase to a 59% reduction, even though the drainage rate of water from the boreholes greatly increased from 1388 l/h in the first test to 3186 l/h in the second test.

Comparing the drainage system between the first and second tests, the reduction increased from 76% to 90% during the half-drainage phase. The third system, which had two more boreholes added below the invert of the cavern after the second drainage test may further improve the efficiency of the drainage system.

6. Discussion and conclusions

An efficient drainage system is important in a lined LNG-storage cavern. The drainage system in the pilot cavern studied here was designed taking into account the fracture and hydrogeological characteristics of the site. The orientation of drainage holes was limited by the geometry of the pilot cavern and the galleries. Even though perpendicular penetration of the drainage holes into joints increased the discontinuity frequency in the drainage holes, the drainage tests showed that inclined crossing also performed acceptably. The separation of half- and full-drainage phases in each drainage test was done to estimate the effectiveness of the spacing and number of drainage holes in the drainage system. Phase 2 of the first test showed drainage in downward holes D4 and D9 but in the second test, upward holes D8 and D19 also drained significant amounts of water (see Table 4). This can be attributed to variation in the height of the water table. Table 4 shows that the drainage holes most important for drainage changed depending on the hydrogeological conditions. The main drainage holes in the second test were different from those in the first test because of the heavy rainfall that occurred during the second test. Although the recharge test is useful for heavy rainfall simulation, an increase in the number of recharge holes needs to be considered.

Despite the system showing good efficiency, the first test indicated problems with the main joint along the right wall of the cavern, indicating a lower efficiency in the system on this side. The first drainage system had greater separation of boreholes in the right-hand side wall. Significant seepage occurred in the right-hand side of the cavern. Three additional drainage holes were drilled on the right side of the cavern to cross the main joints at several points in the pilot cavern and another main joint that was at a minimum distance of five meters from the left wall. These downward boreholes were drilled from the right-hand chamber. Table 4 shows that drainage from these holes was very efficient.

The overall efficiency of the second drainage system consisting of 18 boreholes after the concrete lining was installed was better than the first drainage system consisting of only 15 boreholes. Although the efficiency of the second drainage system was very high even during artificial recharge, a significant increase in seepage was observed during high rainfall. Moreover, water seepage into the cavern and below the invert drained to the ditch during half drainage were not negligible considering the potential for the detrimental formation of ice below both the membrane and the concrete floor during the cooling stage. According to the results of the second test, the drainage system below the concrete invert was grouted from the cavern ditch. Two additional downward drainage holes were drilled below the concrete invert to improve the efficiency of drainage.

The drainage system allowed efficient drainage of the rock around the cavern. The system was sufficient to reduce the entry of water into the pilot cavern. The drainage tests indicated problems in the system. The tests showed that drainage efficiency depends on the number, spacing and orientation of drainage holes. Some conclusions could be reached from the results of this study. These are shown below.

- The rock drainage system worked very efficiently for dewatering the rock mass around the lined pilot cavern used for underground LNG storage. The drainage system drained 97% of inflow around the pilot cavern, even under heavy rainfall conditions and artificial recharge.
- The efficiency of a drainage hole was highly influenced by the hydrogeological conditions. Therefore, an artificial recharge test was needed to simulate heavy rainfall.
- A drainage system is effective when it is tested rather than being directly designed and constructed because unexpected fracture networks can act as conduits and decrease the efficiency of the drainage system. The drainage tests indicated weak points in the drainage system after the system was directly designed based on data obtained from a site investigation.
- The comparison between half and full drainage shows that the spacing and the number of drainage holes influence the drainage efficiency. Even in the case of low transmissivity and storativity, sufficiently close spacing of the drainage holes is needed in fractured rock because minor joints can affect water flow. The spacing and number of drainage holes can be optimized by conducting a drainage test.

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