Construction of Namikata underground LPG storage cavern in Japan


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ABSTRACT

Japan Oil, Gas and Metals National Corporation (JOGMEC) has constructed the world’s largest level underground LPG storage cavern in Namikata (450,000 tons) and Kurashiki (400,000 tons). In order to ensure the air-tightness performance of storage caverns, the authors developed a new observational design/construction system for the construction of the underground LPG storage cavern and the hydraulic containment system. The developed observational design/construction system integrates the geological/hydro-geological data to evaluate the hydraulic behaviors and mechanical stability during excavation. In this study, the authors applied the developed observational design/construction system to evaluate the hydraulic behaviors during the site-scale hydraulic test in Namikata underground LPG storage site. The pore pressure distribution and seepage of tunnel walls were compared with simulation results for evaluation. As the result, it has been confirmed that the hydraulic potential has been recovered in the inner area of water curtain and the amount of seepage inflow has been kept under the criterion.

Keywords: Underground cavern, LPG storage cavern, hydro-geological model, Construction process, groundwater simulation

1. INTRODUCTION

Japan Oil, Gas and Metals National Corporation (JOGMEC) has constructed the three aboveground LPG storage sites in Nanao (Ishikawa prefecture, 250,000 tons), Fukushima (Nagasaki prefecture, 200,000 tons), Kamisu (Ibaraki prefecture, 200,000 tons) and two of the world’s largest level underground LPG storage caverns in Namikata (Ehime prefecture, 450,000 tons) and Kurashiki (Okayama prefecture, 400,000 tons) to provide total 1,500,000 tons national LPG stockpile capacity (Figure 1). Even many construction experiences of underground LPG storage caverns in worldwide and also underground crude oil storage caverns in Japan, this is a very first attempt to construct the local underground storage caverns for high pressure LPG preservation. Both constructions of the both sites were started from 2002. In 2012, both the site were completed the construction and passed the air-tightness test. After certification, the two storage caverns have received LPG and launched their operation to contribute more than half of the 1,500,000 tons national stockpile target.

The underground LPG storage caverns apply natural groundwater with artificial hydraulic containment system to preserve the LPG at high gas pressure and normal temperature (e.g. Propane, boiling point; 20°C at 0.80MPa) instead of the concrete or steel linings. The authors have designed the water-curtain galleries and water-curtain boreholes to maintain the surrounding pore pressure higher than the storage pressure and to ensure the groundwater flow toward the storage caverns constantly (Figure 2). Therefore, despite the mechanical stability demanded in the conventional tunnels and caverns constructions, the groundwater table should be kept above a critical level to avoid the occurrence of unsaturated zone during excavation.
For the purpose, the authors have developed an observational design/construction system to evaluate the hydraulic behaviours for the underground LPG storage caverns. The developed system does not only integrate the geological/hydro-geological investigation data to evaluate the hydraulic behaviours/mechanical stability during excavation, but also aids the designers and constructors to select the proper countermeasures for the unfavourable seepage and pressure dropping during excavation.

2. BACKGROUND OF THE NAMIKATA SITE

2.1 Layout of underground structures and groundwater monitoring system

Namikata underground LPG storage site is composed of a 430m long butane/propane dual purposes storage cavern (capacity: 150,000 tons), and two 485m long propane-storage caverns (capacity: 300,000 tons). Each of the storage caverns was designed as egg-shape in dimension of 30m(H)×26m(W) and located in EL.-150m depth. Furthermore, the authors have designed water curtain galleries and horizontal/vertical boreholes 25m above the cavern crown (EL.-125m) to enclose the storage caverns (Figure 3). From the cavern excavation throughout the operation phase, the water curtain galleries and water curtain boreholes are designed to provide stable high water pressure to avoid the development of unsaturated zone and to ensure the air-tightness of the storage cavern.

2.2 Geology

The Namikata site is located at a cape of Takanawa peninsula of Ehime prefecture, Japan. As illustrated in Figure 4, the pink area gives the typical lithology as Namikata granite in south of Namikata site (Ochi, 1982). Contrarily, the orange north part at the shore side is intruded by cretaceous granodiorite dikes, named as Takanawa granite.

![Figure 3](image1.png)

Figure 3. Namikata site is compose of a 300,000m³ Butane/Propane dual purposes and a 600,000m³ Propane cavern, each cavern is located at EL.-150m and has independent operation shaft and water curtain system at EL.-125m.

![Figure 4](image2.png)

Figure 4. Geological map of Namikata site.
weathered granite is distributed from the ground surface to EL -40m~60m. The storage caverns are located in the fresh granite and the thickness of the overburden is 150-250m.

3. EXCAVATION BASED ON OBSERVATIONAL DESIGN/CONSTRUCTION METHOD

3.1 Methodology

Since the hydraulic containment type underground LPG storage caverns adopt the permanent groundwater flow toward storage caverns to ensure the tightness, from cavern excavation throughout the operation. The hydraulic behaviors are most critical aspect and should be evaluated. Therefore, the authors have established a 3-dimensional heterogeneous hydro-geological model based on the geostatistics method (Aoki et al., 2010; Maejima et al., 2007). Then, the established hydro-geological model is applied into 3-dimensional groundwater simulation model to estimate the hydraulic behaviors during excavation. The estimation results, such as seepage rate and pore pressure, are employed as the criterions to evaluate the necessity of the countermeasures. For the countermeasures, the grouting works were applied to reduce the seepage in caverns. On the other hand, the additional water-curtain boreholes are adopted to maintain the stable pore-pressure surrounding the excavated caverns (Figure 5).

3.2 Cavern excavation process

In order to maintain the stable groundwater level during cavern excavation, the water curtain boreholes were drilled and compressed to 0.65~0.7MPa prior to the cavern excavation. Additionally, the authors have installed 30 piezometers and 82 pore pressure cells to establish a monitoring network for hydraulic behaviors evaluation.

The cavern excavation was demarcated as an arch and 4 stages of bench excavation. After the arch excavation was completed, the excavations were proceeded downward to form a slope, meanwhile the bottom access tunnel was excavated for removing the excavated debris. After the bottom access tunnel was completed, the excavation was turned to the bench and removed the slope. For the cavern excavation, jumbo drill was applied in arch excavation, and crawler drills were added to enhance the efficiency of bench excavation (Figure 6).

After all the excavations of storage caverns were completed, the authors submerged the water curtain galleries and compressed the water curtain system to 1.2 MPa to recover the groundwater level which decreased in cavern excavation. Our observational design/construction system was also applied to evaluate the efficiency of water curtain and the grouting works.

Figure 6. Excavation procedure and excavation.
the pore pressure and the groundwater level, the seepage rate in the storage caverns and the injection pressure/injection rate of the water curtain boreholes are monitored and recorded periodically.

(ii) Evaluation by 3-dimensional groundwater simulation

Due to the heterogeneity and anisotropy of rock permeability are determined by the geological structures in fractured rock mass. The authors analyzed the primary orientation of discontinuity (e.g. geological structures, fracture zones, metamorphic zones etc.) to recognize the forming process of Naimikata granite and to delimit the site area into seven geological sub-units by the fracture orientations and densities (Figure 9). For each geological sub-unit, the derived rock permeability from the hydraulic test in water curtain boreholes, investigation boreholes and grouting boreholes are integrated by the geo-statistical sequential indicator simulation method (SIS) (Journel, A. G., 1994) to establish the 3-dimensional heterogeneous hydro-geological model. Additionally, the authors analyzed the relationship between rock permeability and the fracture orientation to clarify the anisotropy of rock permeability. The established heterogeneous 3-dimensional hydro-geological model is in dimension of 1260m(W)×1340m (L)×500m(H) as illustrated in Figure 10.

Then the established hydro-geological model was involved into a 3-dimensional groundwater simulation code. In order to evaluate the performance of hydraulic containment system and grouting works, the element size surrounding the storage caverns is set less than 5m×5m×5m to model the construction structures in detail (Figure 11). For the boundary conditions, the top and lateral sides were set as static pressure, contrary to the bottom side was set as no-flow boundary.
4. SITE-SCALE HYDRAULIC TEST

4.1 Process

In Namikata, after all the excavations of storage caverns were completed, the authors conducted the site-scale hydraulic test to evaluate the performance of grouting works and hydraulic containment system. The hydraulic test submerged the hydraulic containment system and compressed it to 1.23 MPa in stepwise. Comparatively, the access tunnel and storage caverns are left at atmosphere pressure.

Figure 10. (a) Horizontal and (b) cross-sectional estimated distribution of rock permeability.

Figure 11. Groundwater simulation model. The element size is less than 5m×5m×5m to modelling the construction structures.

Figure 12. Submerged area for site scale hydraulic test, the access tunnel and storage caverns are left at atmosphere pressure.
Figure 13. Measured and simulated pore pressure evolution during site-scale hydraulic test.
(a) Pore pressure evolution at AB measurement section.
(b) and (c) Simulated pore pressure distribution before/after water compression test.
and the storage caverns were left as atmosphere pressure (Figure 12). The site-scale hydraulic test contributes to (1) recover the hydraulic potential which was decreased in cavern excavation and (2) examine the mechanical stability of storage caverns by the maximum pressure difference. Therefore, the authors also have applied the developed observational designed/construction system to evaluate the hydraulic behaviours and mechanical stability (Kurose et al., 2014; Nakamura et al., 2011).

4.2 Evaluation and results

Prior to the site-scale hydraulic test, the authors applied the developed observational design/construction system to estimate the hydraulic behaviours (e.g. pore pressure and the seepage) and to determine the criterion in water curtain compression. Then, we monitored the hydraulic behaviours in water curtain compression to evaluate the efficiency of water curtain system and grouting works. The evaluation results are described as follow:

(i) Pore pressure

Figure 13 gives an instance of pore pressure evolution at measurement section AB during the site-scale hydraulic test. The simulation results (pink lines) represent there are relative low pore pressure at pillar area between the butane and propane caverns (No. 19pp2) and between No.1 and No.2 propane caverns (P1AB-3). This phenomenon is considered to be reasonable because the storage caverns are in the condition of atmosphere pressure. Despite the No.30 pore pressure responded to the water curtain compression lately due to the high relationship with water tunnel submersion. Most of the pressure cells represent high hydraulic potential than expectation. Consequently, the hydraulic potential is recognized that it has been recovered more than our estimation in Figure 13.

(ii) Seepage

Seepage estimation is applied to evaluate the performance of grouting works on seepage reduction. For the seepage estimation, the permeability of grouted portions was set as the improvement criterion in the groundwater simulation model. An over-estimated seepage rate is recognized as an indication of high permeability at the cavern vicinity and low performance of grouting works. Figure 14 illustrates the simulated and measured seepage rate in propane storage cavern during the site-scale hydraulic test. Although the measured seepage rate increased with the compression of hydraulic containment system, the seepage rate is less than the simulation results. It is recognized that the grouting works achieve to reduce the seepage rate as estimation.

5. AIR TIGHTNESS TEST

After the construction of underground storage cavern was completed, the water curtain, water boreholes, water supply shaft and access tunnel were submerged and the hydraulic potential was decompressed to EL.-15m, contrarily the storage caverns were compressed to 985kPaG (EL.-48m) to examine the cavern tightness under severe condition. Since the butane cavern is independent system from propane caverns, the air-tightness test should be conducted for butane and propane storage caverns respectively. While butane cavern was in the air-tightness evaluation, the propane cavern pressure was controlled as atmosphere pressure and vice versa. Since the higher hydraulic potential than cavern pressure is most critical for air-tightness, during the cavern compression, the transient hydraulic behaviours were monitored and estimated forwardly. For the late transient hydraulic behaviours, the cavern pressurization rate should be adjusted to ensure the air-tightness.

5.1 Hydraulic behaviors during cavern compression

As stated in section 1 and illustrated in Figure 2, the cavern tightness is ensured by the permanent groundwater flow toward the storage caverns. However, during the cavern compression, the pore pressure at the locations where represent transient hydraulic behaviours in low permeability rock mass, may be exceeded by cavern pressure and induce leakage risk. Therefore, the pore pressure was continuously monitored during compression. Figure 15 illustrates the evolution of the pore pressure cells located at the roof of the caverns. The P2AB-1 pressure cell represented the minimum value among the pore pressure cells, it started from EL.-54m and increased 23m with slightly delayed pore pressure response to the cavern compression. However, the hydraulic potential difference between cavern pressure and pressure cell, named hydraulic margin, is above 17m throughout the cavern compression and represents the satisfactory hydraulic gradient (>0.5) for the cavern tightness on roof.

On the other hand, the minimum hydraulic margin of all pressure cells is located at P3D-1, where the hydraulic potential represented transient behaviour with long time-lag and no significant variation during the first four days in cavern compression duration. Considering the cavern pressure may exceed the delayed the P3D-1 pore pressure during compression and induce leakage risk, the 3-dimensional groundwater simulation model stated in section 3.3 has been applied on the transient hydraulic behaviour evaluation. We have adjusted the specific storage and attempted to fit measured the P3D-1 pore pressure curve during the initial 10 days of cavern compression, and then, predicted the transient hydraulic behaviour forwardly. The simulation result warns us the cavern pressure may exceed the P3D-1 pore pressure. Therefore, we postponed the compression 7 days at 700kPaG of the cavern pressure and reduced the compression rate while cavern pressure reached
to 940 kPaG. As the results, during cavern compression, the minimum hydraulic potential at P3D-1 has been kept as 11 m of hydraulic margin to ensure the air-tightness (Figure 16). The cross-sectional groundwater simulation result also represents the relative low but sufficient hydraulic potential at P3D-1.

For the seepage of storage cavern, Figure 17 illustrates the seepage evolution from cavern compression till the cavern air-tightness test. The seepage rate at the start of cavern compression was 43.6 m³/h and decreased to 18.4 m³/h when cavern pressure increased to the maximum value. As the measured seepage only slightly exceeded the estimation with similar trend, the seepage is also considered satisfactory.

5.2 Distribution of hydraulic potential in air-tightness test

After the cavern tightness has been confirmed by pressure evaluation in butane and propane caverns respectively, again, the pore pressure distribution during air-tightness test was reviewed to ensure the hydraulic condition for air-tightness. Figure 18 and 19 represent the simulated distribution of hydraulic margin. Generally, the low pore pressure locations are represented in the simulation results. For the butane cavern (Figure 18), the potential difference is concentrated at the pressure cell B2BC-1 as 10 m, equals to 0.67 of hydraulic gradient (=10 m/15 m) at the cavern wall. Meanwhile, the minimum potential difference 9 m appears at the pressure cell P1AB-3 in propane cavern, where potential difference contributes 0.6 (=9 m/15 m) hydraulic gradient, both the two minimum value are satisfactory with the designed criterion 0.5 for the hydraulic gradient of storage cavern (Figure 19). Consequently, the constructed water curtain boreholes provide sufficient hydraulic potential to ensure the air-tightness for the storage cavern.
6. CONCLUSION

In this study, the authors have developed a new observational design/construction system for the construction of underground LPG storage cavern with the hydraulic containment system. The authors applied the system to the excavation of Namikata underground LPG storage caverns and completed the excavation in June, 2006. Then, the authors conducted the site-scale hydraulic test and applied the observational design/construction system to evaluate the performance of the hydraulic containment system and the grouting works. The evaluation results indicate that the pore pressure has been recovered to the estimated level and the grouting works achieved to reduce the seepage as the estimation results. On the other hand, the measured displacement has verified the mechanical stability of the storage caverns.

For the air-tightness test, although several pressure cells represent slow response on the cavern compression. The authors also applied the groundwater simulation model to evaluate the transient hydraulic behaviors and adjusted to cavern compression to ensure the sufficient hydraulic potential in the cavern vicinity. As the results, the cavern have achieved on the air-tightness test by the high performance of constructed water curtain.

REFERENCE