Hydrogeological and Geochemical Evaluations in Support of Mine Water Management for the Jurong Rock Cavern Project, Singapore

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Abstract The Jurong Rock Cavern Project is a hydrocarbon cavern storage project in Singapore. Upon completion, the combined storage volume will exceed 1.5 Mm^3, sited as deep as 160 m beneath the overlying seabed, within a saturated groundwater environment. The project relies on the well-established principles of hydrodynamic containment. Ongoing hydrogeological and geochemical testing programs at the site are used to validate and inform groundwater and geochemical models. Results are relied upon for the final design and management of treated water injection curtains, grouting approaches, and groundwater monitoring and sampling systems associated with the project.

Keywords Jurong, hydrodynamic containment, hydrogeology, geochemistry, mine water

Introduction

The Jurong Rock Cavern (JRC) hydrocarbon storage facility is being excavated via drill and blast techniques underneath Banyan Basin, a bay located within a constructed island in an industrial zone off the coast of western Singapore. The underground facility reaches as deep as 185 m below sea level and consists of five separate storage caverns that are over 300 m long each. The entire cavern ensemble volume is sufficient to store over 1.5 Mm^3 of hydrocarbons. Two access shafts on either side of the rectangular bay and thousands of meters of auxiliary tunnels at two distinct levels facilitate the overall benching construction and the supporting infrastructure for cavern management, which includes an array of subsurface monitor systems, product and injection water pumps, and piping and headspace control. The overall project is divided into two levels. Level 1, which is approximately 90 m below sea level Admiralty Chart Datum (ACD), hosts the maintenance infrastructure and the network of water curtain galleries. Level 0, approximately -120 m ACD, hosts the construction tunnels used to excavate each storage cavern and haul rock. Caverns extend below Level 0. Once the cavern complex is fully constructed and tested, Level 0 will be sealed from each cavern and flooded.

The cavern complex will notably use the hydrodynamic containment principle to isolate the low vapor pressure products. The hydrodynamic containment principle involves isolating each cavern by taking advantage of natural water gradients that are augmented by artificial gradients provided by water curtain galleries, which are long specialty tunnels that are parallel to each cavern. Each gallery hosts approximately 50 individual boreholes, at various lengths (up to 60 m) and inclinations depending on hydrologic conditions, that inject treated water at pressure into the rock formations hosting the storage caverns. The successful design and operation of these galleries depends on a host of factors, and not the least of which includes a sound understanding of the hydrogeology and the geochemistry of the surrounding host rock formations.

Hydrogeological Setting and Investigation

The guiding principal of hydrodynamic containment is that a positive hydraulic gradient of water directed towards each cavern will prevent the stored hydrocarbon products from migrating away (Goodall *et al.* 1988; King 1999). Numerous storage cavern complexes throughout the world have operated over many decades using this approach. That guiding principal is reinforced by a suite of best industry practices that include groundwater and geochemical modeling and testing to optimize any system for long-term effectiveness and safety. Groundwater modeling aids in the synthesis of the available information to improve the design, estimate seepage rates, estimate water injection demands, interpret hydraulic tests, determine the best locations for monitor features (such as manometers), and facilitate knowledge transfer to the numerous technical and administrative team members. Geochemical modeling serves similar purposes but with a focus on the prevention of clogging of injection boreholes, which may be possible either through microbial action as well as through geochemical reactions between the injection water and the host rock.

A necessary condition for hydrodynamic containment is that the rock that overlies and surrounds each storage cavern must remain saturated with water throughout the excavation and operations periods. However, for construction purposes, caverns and tunnels must be kept relatively dry during excavation. Therefore developing best estimates of groundwater flow into those caverns and tunnels under excavation conditions is important to determine the size of the dewatering pumps and to design a rock grouting system and a water curtain injection system. Best estimates of the prevailing hydrogeological conditions during the operation phase must also be developed to evaluate the effectiveness of the proposed design for hydrodynamic containment. Hydrodynamic containment is designed for two objectives: (1) for preventing product migration from a cavern to operations tunnels (an essential component of worker safety) and (2) for preventing the mixing of products between storage caverns.

Given the challenging environment and objectives, there would likely never be too much information to work with. However, only near-surface, tidal, borehole and geophysical information was initially available for the preliminary designs that were developed. As additional information became available from excavations and additional surface and subsurface studies during the construction phase, the hydrodynamic containment parameters were continually re-evaluated.

The geological strata encountered in downward sequence in borehole drilling at the Banyan Basin locale include newly reclaimed sand, marine sediments, and sedimentary bedrocks of the Jurong Formation, such as siltstone; sandstone; conglomerate; limestone; and some intrusive rock dykes, sills, and veins. In addition, several joints and strike-slip faults were mapped. Within the layered sedimentary units, a shallow aquifer system includes the reclaimed sand aquifer, the marine sediments, and the weathered rock unit. The deeper fresh rock aquifer at the Level 0 and cavern horizons includes the low confined zone and the sedimentary rock zone. The structural features that include an acid dyke set, zones of perturbed rock associated with the dyke, and vertical and horizontal (thrusting) faults and fracture sets are found within these two zones.

Over the early period of construction in 2009 and 2010, we conducted preliminary hydrogeological and geochemical model activities based on this geologic model. Based on earlier interpretations, the three-dimensional steady state hydrogeological simulations using MODFLOW (Harbaugh *et al.* 2000) assumed that the vertical dike and fracture features were the most important water-bearing features at the cavern horizons. Our initial groundwater and geochemical models employed this early information to produce estimates for grouting targets, mine dewatering, and water treatment strategies and injection rates.

As excavation and testing progressed, it became clear that these vertical features are not important water-bearing zones over the scales of interest. Rather, sub-horizontal water-bearing features in or adjacent to the Level 1 horizon have been shown to significantly dominate the hydraulic flow regime. Although the lack of high-flow, water-bearing features in the cavern horizons is a benefit to the timely excavation of the caverns (so far), these water-bearing features posed significant obstacles, at times, to the excavation of tunnels in Level 1. As a result, some modifications to the cavern system were developed. Accordingly, revisions were made to the hydrogeological model to aid in developing alternative designs and new seepage and water curtain injection estimates (RESPEC 2013).

The previous models did not extend under land, but the new model does for a significant distance to allow, in part, the consideration of shoreline piezometer hydrographs (changes in measured depth to water over time). Those records were used to calibrate a recharge boundary condition (based on rainfall) applied over portions of the model that underlie the land. This allowed us to develop more realistic scenarios and to include a significant majority of the construction features in an integrated approach. In this capacity, the new boundary conditions and setup led to a hydrogeological model that closely matched the overall behavior of the system. Table 1 provides a sample comparison of the hydrogeological model results to historical mine seepage data. As the system is still under construction, we do not claim that our model's fidelity to the observed system is ideal, but so far the information does appear to show that our simulations are fair estimators of hydrodynamic performance.

The hydrogeological model has also been useful for considering various scenarios. One scenario concerned a hypothetical "marine clay" layer in the shallow seabed sediments. Such a layer might block natural recharge from the ocean. If that were the case, then additional overlying horizontal water curtains might be required. Through conservative model evaluations and an analysis of tidal perturbations on shoreline piezometers, we have been able to posit that such a marine clay layer, were it to exist over the cavern complex, would not adversely impact performance. Another scenario considered a high permeability arch that was postulated to connect cavern crowns to an overlying operations tunnel. Through the modeling exercise, a signature hydraulic pressure pattern was developed, which might indicate such a feature. If such a signature were to be observed as construction is advanced, then

Seepage inflow location	Measured seepage (m^3/hr)	Construction simulation of seepage (m^3/hr)
Level 1 and Level 0	234 and 20	241 and 14
Caverns CS 1/1, 1/2, and 1/3	13, 28, and 4	14, 26, and 26
WG 1/1 through 1/4 tunnels seepage	19, 15, 25, and 15	12, 10, 10, and 11
WG 1/1 through 1/4 curtain injection	-20, -20,-16, -22	-21, -19, -17, and -22
Entire excavation inflow	435	418

Table 1 *Selected preliminary comparisons of recent hydrogeological model results to in situ measurements over the mid-2012 time frame (RESPEC 2013).*

added grouting and water curtain borehole modifications could be employed to remediate any deficiencies in the containment system in advance. The possibility of seismic impacts to hydrodynamic containment was not directly addressed. Seismic disruption is considered to be a fairly unlikely scenario, due to the relatively low rate and degree of tectonic events in the locale (Balendra and Zi 2008).

Geochemical Setting and Investigation

Throughout the evolution of the project, different water sources for injection have been considered, including municipal fresh water, natural groundwater, and seawater. Currently, seawater is the injection liquid, and according to the hydrogeological model estimates, approximately 180 m^3/h of this water will be needed for injection on a continuous basis for containment needs. Early geochemical assessments identified the potential for clogging by chemical interactions between seawater injected into injection boreholes of the water curtain and the aquifer groundwater (Johnson 2011, RESPEC 2010).

The two potential causes of clogging that were identified by the geochemical assessments are (1) the precipitation of calcite caused primarily by pH changes and (2) the precipitation of iron hydroxide ($Fe(OH)_3$) in response to oxygen in the injection water. The precipitation of calcite depends on calcium concentration, pH, and temperature. Precipitation is favored under increasing pH conditions as well as increasing temperature. Under oxidizing conditions with Eh greater than approximately 200 mV (at pH conditions characteristic of the aquifer), iron hydroxide could precipitate and potentially reduce porosity and permeability.

To reach conclusive positions on the best long-term water-quality injection management strategy, a geochemical test was conducted. Three adjacent vertical boreholes spaced 10 m apart in a water curtain gallery were selected. All boreholes passed through an underlying subparallel, water-bearing feature approximately 10 m below the gallery invert. One borehole was used for injection, one for recovery, and the remaining borehole for added monitoring. All wells were monitored daily for pressure and water-quality parameters, including temperature, pH, ORP (later converted to Eh through standard practices), and electrical conductivity (EC). Samples of water from the injection and recovery boreholes were collected three times during the test and analyzed for a comprehensive list of parameters. Also, at three separate times, each well was subjected to a hydraulic test. Through this progression of hydraulic testing over the length of the test, it was believed that a pattern of decreasing hydraulic conductivity might be expressed if clogging was actually occurring.

The test was conducted in 2012 over a seven month period. Untreated seepage water recovered from the tunnels was injected over two months through the middle period of the test. Otherwise, treated and filtered seawater was injected. Some calibration and equipment issues prevented the full use of the data from the entire test period. However, the geochemical and hydraulic testing results, partly illustrated in Fig. 1, were sufficient in conjunction with some follow-up modeling calculations to determine that clogging by calcite precipitation was possible, and that this could likely be prevented through pH control of the injection fluid. Clogging by iron hydroxide precipitation, however, is no longer considered likely because of the significant presence of sulfite in the groundwater, which will consume any oxygen present in the injection water and, thereby, lower the Eh.

Summary and Conclusion

The Jurong Rock Cavern Project is a new underground hydrocarbon storage cavern facility being constructed under Banyan Basin in Singapore. It uses the principles of hydrodynamic containment for the effective storage of all hydrocarbons. These principals have guided the field investigations, ongoing data collection, and design and modeling studies for an integrated, hydrogeological and geochemical

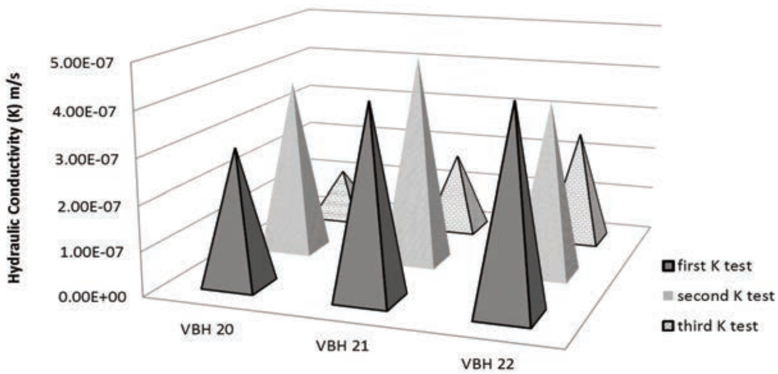

Fig. 1 *Results of hydraulic testing at boreholes (VHB 20 through VBH 22) used in geochemical test (RESPEC 2012).*

knowledge base that supports the project now and into the pending operations phase.

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