Some Lessons on the Hydrodynamic Containment Design and Construction of Oil Storage Cavern

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Abstract

Hydrodynamic containment principle for the storage of oil products in underground cavern is one of the key principles for the success of whole project. The key idea of hydrodynamic containment is straightforward i.e. to maintain gradient of total hydraulic head toward storage cavern high thus flow of ground water overpass the leakage of oil or gas. Where hydraulic gradient would not be naturally maintained, artificial hydraulic gradient and containment should be provided by so called water curtain system. In such a case, design of water curtain system should incorporate the onsite hydrogeological condition and structures, however in most cases it is based on the assumptions, which are homogeneous and isotropic condition probably due to limited information during the planning and basic design stages. Therefore success of system is heavily relying on steady monitoring and verification of system with comparison of model predictions and measurements. Inevitably, there will be discrepancy of actual measurement and model prediction, which could cause the amendment of design to cope with actual hydrogeological condition and probable performance degradation of system. We have observed that there are actual measurements and monitoring results inconsistent with the prediction based on homogeneous and isotropic hydrogeological model. In this paper, we have attempted to draw some lessons that would be food for thought to similar oil storage caverns from the experiences of detail design, investigations, construction and monitoring of hydrodynamic containment with focus on heterogeneous hydrogeological condition of natural ground.

Keywords: Oil Storage, Underground Cavern, Hydrogeology, Hydrodynamic Containment.

1. Introduction

It would not be an over exaggeration that success of unlined oil product storage cavern construction project is entirely relying on the hydrodynamic containment capability of natural ground condition or artificial system that emplaced in the cavern storage. To turn underground cavern into oil storage container, hydrodynamic containment principle is devised, whichrelies on the immiscibility and buoyance due to density differences of water and oil. Basic idea of the principle is as simple as by inducing water flows along joints against the oil or petro gas leakage, so that oil or gas remains inside cavern. For this, containment principle requires two things, full saturation and hydraulic head gradient to overcome the leakage. In locations, where condition is not naturally given, it should be provided by so called water curtain system to ensure full saturation and necessary hydraulic gradient.

Consequence of failure of hydrodynamic containment is significant in many ways such as economic loss due to loss of products, environmental damages to surrounding natural environment or even risk of fires and explosion due to leakage of gas. Therefore, it should be ensured thathydrodynamic containment principle is valid throughout the stages of construction and operation of caverns. To determine the validity of principle, first thing that we should know is saturation of groundwater in rock mass around cavern. Desaturation is critical indication of high leakage potential. Second thing that we should know is dynamic behavior of groundwater pressure around cavern in response to the inner pressure, subsequently hydraulic gradient between product and groundwater all along the tunnel perimeter surface.

For this, first thing is the establishment of the hydrogeological models with compiled information from various stages of investigation and design of cavern and water curtain system. Then next thing is simulation of the hydrogeological behavior using the hydrogeological models for major various stages. From the result, we could predict the degree of saturation, pressure distribution and hydraulic gradient of construction and operation stages.

As the initial models are built from the initial geological and hydrogeological information before commencement of construction, actual measurements of flowrate and monitored pressure can be deviated from the initial prediction. Thus, geological and hydrogeological model have to be updated with up to date information gathered during the construction, then new prediction from new round of simulation should be compared with the measurements and monitored values. Any discrepancy between prediction and measurements should be properly handled, for example if localized pressure drop observed from the monitoring information, which is not indicated in the model prediction, then investigation of local hydrogeological structure could be carried out. If major hydrogeological structures were found, then additional round of simulation and comparison will be carried out and so on.

2. Background and Precondition

To realize the hydrodynamic containment principle, gas containment or air tightness criteria should be defined in reliable androbust manner and subsequently be applied for the design andconstruction of underground oil caverns. First well known gas containmentcriteria, which is proposed byAberg (1977), is vertical hydraulic gradient criterion, i.e. vertical gradient shouldbe higher than 1(Io > 1).

Goodall et al. (1988)pointed out thatthe Aberg'scriterion neglects gravity forces, frictionaldrag and capillary force, and generalized criterion as gas leakage canbe prevented as long as water pressure increases for some intervalalong all possible gas leakage paths away from thecaverns. Liang and Lindblom (1994) advocated the Goodall's criterion and carried out extensive numerical simulation to presentcritical pressure, at which hydrocarbon gas may leak out of cavern,for various condition of natural hydraulic head, water curtain pressureand various depth of cavern.

Geostock (1984) carried out a series of tests withvarious shaped cavities. The results of these tests revealed thatthe pressure difference between the required groundwater depth abovethe cavities and the maximum tolerable pressure depends on the shapeof the cavities and their environments. The relation is defined asfollows

$$H > P_{max} + P + S \quad (1)$$

where$H$ is height from the ceilings of a cavern to groundwater level(m), $P_{max}$is maximum tolerable gas pressure expressed as a head in thecavern (m), P is shape factor (m) and S: safety factor(m).Geostock's criterion is handy, flexible and robust in terms of safety by incorporating margins that is safety factor and shape factor to ensure air tightness.

Where hydraulic containment condition is not naturally given, it should be provided by so called water curtain system to ensure full saturation and necessary hydraulic gradient. Moreover in the case where natural condition is favorable such that high groundwater level with infinite recharge,although water level kept high, hydraulic gradient could be lowered down below the necessary. In that case, water curtain system will be effective to maintain required hydraulic gradient. Water curtain system consists of water curtain galleries, boreholes and water supply units. Design factors for water curtain system are distance of water curtain boreholes from cavern crown, spacing, length, inclination of boreholes and hydraulic head at water curtain gallery. All these factors should be properly chosen in accordance with ground hydrogeological condition and cross-checked in initial hydrogeological model.

Initial hydrogeological model before commencement of construction contains only limited geological and hydrogeological information, additional information gathered during construction should be updated as per the progress. Additional information can be construction progress of caverns, geological/hydrogeological structures, implementation of water curtain system, amount of water supply through water curtain system, seepage flowrate into caverns, aboveground piezometer monitoring etc. From the hydrogeological model, we are able to simulate the hydraulic head drawdownamount of seepage into cavern and amount of water curtain water supply. To be equipped with valid hydrogeological model, the model has to be constantly updated.

As noted in previous section, it is widely known that saturation is one of the important factors for the success of oil storage cavern. The issue, which is related with relative permeability of joints, with saturation is that once rock mass is desaturated during the construction without recharging the water, then complete resaturation is much more difficult as the permeability of dry surface is very low compared to wet surface. Thus, the water flows preferably through wet surface, while dry surface remains as dry and unsaturated, which are so-called channeling effect. To make things worse, once dry surface is invaded with oil or petro gas, and then relative permeability of water will never be recovered as the surface is covered with hydrophobic compound. This is more probable to happen as the unsaturated joints are the most probable oil leaking points.

In the following section, we would discuss the experiences or learnings on containment principles, water curtain borehole construction, and desaturation and propose some suggestions.

3. Practical Problems and Lessons Learnt

3.1 Hydrodynamic Containment Criteria

In this section, we would like to revisit the hydrodynamic containment principle and water curtain design inregards to heterogeneous nature of rock mass. Heterogeneous nature also affects hydrogeological modelling,monitoring and validation processes. First of all, we need to think about the relation between head differencecriterion such as GEOSTOCK (1984) and hydraulic head gradient criterion such as Aberg (1977) or Goodallet al. (1988). The former is more suitable for design purpose, however actual gas tightness is determined bylatter for the individual joint level. This could be arguable but we could understand that head difference criterionis handy conversion of hydraulic gradient criterion for typical configurations of cavern and water curtain gallery,ultimately supposed to satisfy hydraulic gradient criterion.

Jung et al. (2003) considered heterogeneity of rock mass hydraulic conductivity by introducing stochasticapproach in calculation of hydraulic gradient using continuum based numerical simulation, which result invariation of hydraulic head and gradient along the perimeter of cavern, and probability of risks of gas leakage.As a result, he proposed to adopt the stochastic safety margin to compensate the uncertainty due to heterogeneityas in equation (2):

$$H > P_{max} + P + S + S_S \qquad (2)$$

where S_S is a stochastic hydraulic safety factor (m) under a given probability.

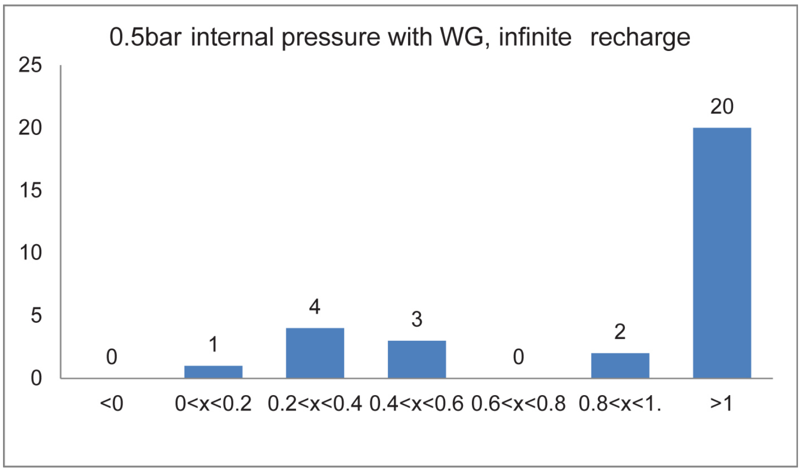

Fig. 1.Histogram of hydraulic gradient of the case of internal pressure 0.5 with water curtain system

Recently, Song (2014) carried out discontinuum based numerical simulation using distinctiveelement methodto investigate the influence of discontinuity on hydrodynamic containment. In his research, ground water flowsonly through joints and flows from water curtain boreholes to cavern. As results of series of simulations, distributionof hydraulic gradients in joints is obtained. Similar to Jung et al. (2003), even with water curtain system emplaced on infinite recharge from the surface, it is observed that there are joints with low hydraulic gradientinsufficient for water tight conditionFig.1.

As both continuum and discontinuum analysis with heterogeneity show the uncertainty and inconsistencybetween criteria in water tight condition, consideration of hydraulic safety factor would be highly suggested.

3.2 Water Curtain System

First thing to discuss is the benefit of water curtain system in hydraulic gradient. Although this is well known,we would reiterate it as this is one of the clue for the next discussion. Fig. 2. conceptually shows thehydraulic pressure above the cavern for the cases (a) no pressure inside cavern, (b) product pressure insidecavern without water curtain system and (c) product pressure inside cavern with water curtain system. Fig.2. shows hydrostatic pressure and actual pressure, which is curvature branched from hydrostatic pressuredue to zero pressure inside cavern. In Fig.2, hydraulic head gradient is indicated as relative gradient withrespect to the hydrostatic pressure line because total hydraulic head is summation of elevation and pressurehead. As shown in Fig. 2b, hydraulic gradient decreases as the internal pressure (Pi) increases, eventuallyno hydraulic gradient as internal pressure reaches hydrostatic pressure. It is worthy to note decrease of hydraulicgradient due to pressure head loss above the cavern. Whereas as shown in Fig. 2c, hydraulic gradient is kept high as water curtain system installed above cavern maintain the pressure head.

Second thing to discuss is the condition that water curtain system is required. There is no doubt that we needwater curtain system when depth of cavern below natural water level is not sufficient or not maintained, thenwe need the system. The common question is when the condition is favourable in such as way that depth ofcavern below natural ground water level is high with infinite recharge source. There are two clues to decide thenecessity of water curtain in this favourable condition: uncertainty of heterogeneous nature of ground discussedin section (3.1) and loss of pressure head discussed in this section. Without water curtain system, there will beno control over the hydrodynamic behaviour of hydrogeology in response to the variation of product pressureduring filling and emptying of product. Therefore, we could say water curtain system is always preferable.

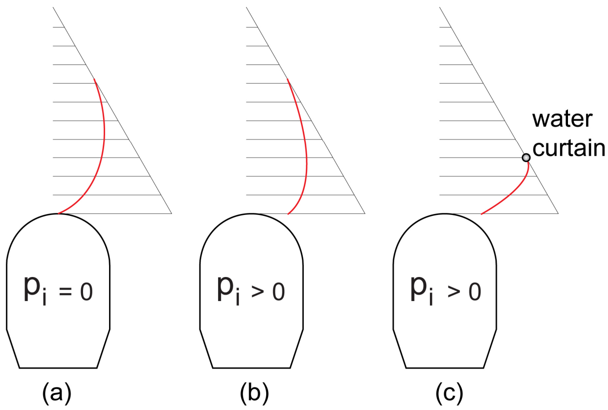

Fig. 2. Pressure heads above cavern with and without internal pressure and water curtain system

I would like to close this section with quotation taken from Kjørholt and Broch (1992).

> *To completely avoid leakage by groundwater control, the groundwater pressure in all potentialleakage paths, directed upward from the storage, must exceed the storage pressure over at least asmall (infinitesimal) distance. Complete gas tightness based on natural groundwater is, in general,not an economical alternative for high-pressure storages because of the requirement that the allowablestorage pressure must be low in relation to the thickness of the overburden. Therefore, a watercurtain should be used to increase the groundwater pressure artificially. This type of arrangementwill allow a higher ratio between storage pressure and depth, and will increase the operationalflexibility. Experience shows that water curtains have been used successfully to avoid gas leakageat storages with pressure up to twice the hydrostatic groundwater head.*

3.3 Desaturation

First question arising on desaturation is whether we are really able to prevent desaturation completely by watercurtain water supply during the construction of cavern. Let’s say underground rock mass is fully saturatedwith ground water. When tunnel in saturated rock mass is excavated, tunnel perimeter surface is exposed toatmospheric pressure, and then water in the pores and joints is discharged to tunnel. Some of the joints will besufficiently supplied from the reservoir though water bearing joints, however some other joints are suppliedinsufficiently. Then, portion of joints with insufficient supply will be dried up and dry portion will be extendeduntil the water supply and water flow become equilibrium and steady. This phenomenon is due to the well-knownchanneling effect, i.e. the water flows through the preferential path that is wet surface of the jointsrather than dry one.

For example if we imagine tunnel construction below the sea bed, then regardless of amount of seepage intotunnel, sea level remains the same. Then rock mass should be remained saturated as there will be no depletionof water source. However, it is observed that only 10 to 20 % of tunnel section shows seepage and the rest ofthe tunnel alignment remain dried.

To mitigate this phenomenon, it is recommended to implement water curtain water supply system beforethe commencement of cavern. Immediate second question is what if there are dry joints during construction.As mentioned in the previous section, if there is remaining dry joint when cavern is in operation, the oil or gasbubble will be leaked into dry joint and floated up to dead-end or ground surface. Once the oil is leaked fromthe cavern, leakage will be continued as the surface becomes hydrophobic. Therefore, complete resaturationof the dry joints is essential. One very positive observation is air tightness was recovered when water curtainoperation was resumed after several months of suspension due to the breakdown, during which air leakagereached back to the level without water curtain(Kjørholt and Broch 1992).

As a matter of fact, there are important steps in the construction of cavern, which are water curtain galleryfilling and cavern acceptance test. It includes the steps of water curtain gallery filling test, air tightness test, waterfilling test and subsequent replacing water with inert gas before first product filling. Current practices are mostlyrelying air tightness test after water curtain gallery water filling. Once test results are complying requirements,then cavern water filling would be carried out. Although, the purpose of cavern water filling is to measure thecavern storage volume as per the level of water filling in cavern. A good side effect of cavern water filling isafter filling water pressure eventually becomes hydrostatic pressure, which pushes up or dissolves air bubbleinside unsaturated or partially saturated joints, if any.

In this respect, desaturation during construction might not be a major concern and placement of water curtainsystem before the commencement of cavern construction seems to be conservative approach. Thus, it would besuggested that if placement of water curtain system before cavern construction is not a favorable option interms of time and cost, then elongation of cavern water filling before air tightness test could be considered. Inaddition, increment of water curtain pressure in consideration of hydraulic safety factor as per the heterogeneityof ground would be an option to ensure air tightness of cavern.

3.4 Some Difficulties in Construction of Water Curtain System

There are several types of boreholes either for monitoring or for investigation, which have to be installed in oilstorage cavern, such as water curtain holes for water supply, manometer (or pressuremeter) hole for hydraulicpressure monitoring, probe hole for permeability tests.

Before we talk about the various holes, it is better to clarify the differences between water curtain watersupply boreholes and manometer holes in regards to pressure gauge reading. As the name implies, manometerholes always present pressure inside boreholes. On the other hand, water curtain boreholes are little more complicatedas water curtain boreholes have additional data such as injection pressure, borehole pressure, and supplyflowrate. Moreover, water curtain borehole pressure is dependent on the injection pressure and flowrate. Injectionpressure here is nominal pressure at the entrance of water curtain gallery, therefore the injection pressureat the mouth of each water curtain supply boreholes is dependent on the head loss and elevation differencebetween entrance of water curtain gallery and water curtain borehole.

Ideally we expect to obtain the pressure distribution as expected in the model prediction. However, what wereally obtain from the permeability test and pressure monitoring water curtain borehole are quite diverse. Forexample, certainly there are water curtain water supply bore holes showing consistent pressure with predictioneven when water supply valve closed. We could simply interpret these types of holes have good connectionwith reservoir. One the other hand, there are types holes showing no pressure when water is not supplied butshow consistent pressure when water is supplied. There are holes showing low pressure with or without watersupply. There are holes show consistent pressures when adjacent holes are supplied. Most of these cases may notbe predicted from initial modelling and by right we should incorporate this behaviour of test and monitoringresults in the hydrogeological model.

In here, we have not only hydrogeological issues but also technical issues. For example, if some manometerholes show no or low pressure compared to prediction while most of other holes are showing consistent pressurewith prediction, then it is better to cross-check the permeability of those holes showing no pressure. If thepermeability is too low, then low pressure reading holes are located massive fresh rock mass. If the permeabilityis too high, then leakage of water from holes is suspected. The source of leakage can be either loose packer orjoints connecting tunnels or caverns. If packer is suspicious, then we canreinstall or replace the packer. Ifthis does not solve the problem, then we could change the packing location as rough surface at packer positioncan cause leakage.

After we screen out these technical issues, then hydrogeological issues left, for examplewater tight freshrock dyke or water bearing faults. In the end, some of boreholes are found not suitable as water curtain supplyborehole, such as fresh water tight holes or high leakage holes. Typically water tight holes have no contributionon the hydrodynamic containment or air tightness of cavern. Those holes are better to be demolished andreplaced by new holes. All these site issues are time consuming process to complete single borehole. Therefore,for the sake of flexibility and efficiency in construction, we would better adopt more on-site adaptation ofwater curtain system than pre-fixed design. In that case, design of water curtain system can be considered as aconceptual design and basic guideline for determining the borehole configuration as per the actual site condition.

For clarification, characteristics of holes are varying as per the progress of caverns. During the constructionof top heading and benches of cavern, if there are joints, which were dead end, connecting water curtain boreholeand cavern, then tight holes become leaking holes.

4. Conclusion

In this paper, we attempted to draw some lessons that would be food for thought to similar oil storage cavernsfrom the experiences with focus on heterogeneous hydrogeological condition of natural ground. Following aresome conclusions drawn in sections.

1. As both continuum and discontinuum analysis with heterogeneity consistently show the uncertainty andinconsistency between criterion in water tight condition, consideration of hydraulic safety factor(SS)would be highly suggested.
2. Water curtain system is always preferable, as there is uncertainty of heterogeneous nature of ground, loweringof hydraulic gradient due to loss of pressure head and no control over the hydrodynamic behaviorof hydrogeology in response to the variation of product pressure during filling and emptying of productwithout water curtain system.
3. Desaturation during construction might not be a major concern and placement of water curtain system beforethe commencement of cavern construction seems to be conservative approach. It would be suggestedto consider elongation of cavern water filling process before air tightness test increment of water curtainpressure in consideration of hydraulic safety factor as per the outcome of heterogeneous analysis.
4. For the sake of flexibility and efficiency in construction, it would be better to adopt more on-site adaptationof water curtain system than pre-fixed design. Design of water curtain system could be considered as apractical guideline for determining the hole configuration as the the actual site condition.

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