

Challenges for 3D hydrogeological modelling of an LNG mined underground storage during construction

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Abstract Hydrogeological modelling of a membrane-lined LNG underground storage has different aims at different stages of a project: design, construction or operation. 2D modelling focusing on local scale for cavern design is well adapted for optimising cavern depth, as well as for determining the spacing and location of the boreholes of the drainage system. Evaluation of desaturation timing and efficiency as well as impact on hydrogeological environment requires models of larger extent performed in 2D or 3D. A 3D model created by finite element software FEFLOW[®] has been used to simulate the progress of excavation and its impact on the hydrogeological environment. Challenges for 3D modelling cover the representation of the storage geometry, the modelling of unsaturated zones and the determining of the most significant parameters influencing the results.

Key words underground storage, mined cavern, membrane lining, design, construction, desaturation, salt intrusion, hydrogeology, modelling, LNG.

1. OPERATION PRINCIPLES OF MEMBRANE-LINED ROCK CAVERNS FOR UNDERGROUND STORAGE OF LIQUEFIED NATURAL GAS (LNG)

Mined caverns for underground storage of LNG are lined caverns where the product is stored at a temperature of -162°C . To ensure the LNG containment and to protect the rockmass against the extremely low LNG temperature, the storage cavern is lined by the combination of a corrugated stainless steel membrane and polyurethane foam insulation panels. The concept of membrane-lined rock cavern for underground storage of LNG is developed in Claude and Londe (1994) and Amantini and Chanfreau (2004).

During the construction and operation periods of a LNG rock cavern, the insulation membrane shall not be in contact with water. In order to comply with this requirement the rockmass needs to be desaturated during storage construction. A drainage system is therefore implemented in order to desaturate the rockmass. This drainage system is composed of a drainage gallery from which drainage boreholes are drilled. This system is located below and at the periphery of the storage galleries. In case of significant recharge by rainfall or important seasonal contrasts, an additional drainage system may be implemented above the storage galleries to avoid rainfall infiltrating down to the storage.

The cooling down process of the rockmass begins with the storage cavern operation start-up. During the first years of the storage cavern operation, the drainage system is maintained active in order to control the ice formation in the rockmass. This corresponds to the time necessary to freeze the rock faces on a thickness of a few meters. Once the frozen thickness is sufficient, drainage is stopped and the water table builds up to its hydrostatic level.

2. DIFFERENT AIMS, DIFFERENT ISSUES: WHEN TO PERFORM A 3D MODEL?

2.1 Designing the storage

The geological formations that are preferred for implementing such caverns are low permeable hard rock type, such as granite, gneiss, volcanic rocks and limestone. Weak materials like marls or clays or porous materials like chalk or sandstone are second choice since they would require design adaptations.

In order to ensure that the rockmass will be desaturated at the end of construction, the main parameters to be determined during the design stage are:

i) Depth, size and layout of the storage cavern galleries: they are mainly determined by the geological and hydrogeological characteristics of the site and shall be optimized to avoid:

- unacceptable thermo-mechanical and hydrogeological environmental impact,
- excessive construction cost,
- excessive water seepage and drainage quantities during construction and cooling down periods,

ii) Characteristics of the drainage system(s), i.e. distance between the drainage system and the caverns, as well as spacing of the drainage boreholes: a sufficient number of boreholes shall be implemented to allow the desaturation in due time but drilling boreholes that are not necessary to achieve desaturation will lead to additional construction costs and time for completion.

iii) Need for an upper drainage system. Depending on the hydrogeological conditions, a box-type upper drainage system might be required:

- to speed up the drainage of the water table and allow complete desaturation of the rockmass before the installation of the containment system,
- to control the possible rockmass imbibition effect due to the infiltration of heavy rainfalls.

iv) Specific monitoring and efficiency test procedures and guidelines (Amantini et al., 2005) are required for identifying unavoidable drainage system design adaptation to effective geological and hydrogeological conditions which are observed during the excavation works progress

iv) Seepage and drainage flow rates: this figure is necessary to determine the characteristics of the water pumps.

v) Grouting works procedures and guidelines for storage galleries: such works could be necessary for improving the desaturation of cavern walls by the drainage system in areas exhibiting high permeability.

At the stage of running sensitivity studies, 2D hydrogeological modelling was carried out as it is easier and faster. However, in 2D models it is not always possible to take into account the exact direction of the boreholes for the drainage system. These boreholes are directed such as to intersect the main permeable and water bearing joints, in order to constitute an interconnected network of joints and boreholes allowing an optimized drainage process. Consequently they are not always located in the plane of the 2D section used for the different sensitivity studies of the storage.

Moreover, 2D models are not adapted for reliable evaluation of the hydrogeological impact of the underground works, which necessitates integrating complex hydrological boundary conditions and lateral variations of the hydrogeological context.

2.2 Confirming the design

However, once the definitive geometry of the storage has been determined, the use of 3D modelling is particularly appropriate for:

i) Modelling hydraulic interactions between the different parts of the underground works

The main advantage of 3D modelling consists in the ability of 3D models to represent exactly the shape of the underground storage. This enables to consider tunnels and galleries and their various intersections, bends and down slopes, and to take into account their mutual hydraulic effects.

ii) Confirming the drainage system design obtained from 2D modelling

3D models allow to represent exactly the drainage system with all its boreholes. Transient simulation at the end of construction provides the shape of the water table and indicates whether the rockmass is maintained under stable desaturated conditions before the installation of the membrane lining containment system. If this is not the case, the efficiency of the drainage system is to be improved and the design is to be adapted.

Although 3D models do not appear as the most appropriate tool for performing sensitivity study, the mesh of the model can include boreholes that do not appear in the design but may be activated if the design proves not to be adapted and therefore allows to perform a sensitivity study. For example, if the design spacing is 20 m in between successive drainage boreholes, the mesh can include boreholes every 10 m so that if 20 m spacing is not appropriate, the efficiency of a higher density of drainage boreholes can be tested. This type of alternative solution has to be decided prior to creating the mesh.

3. PARTICULAR BOUNDARY CONDITIONS

As the membrane has to be installed in a dry environment, the main aim of modelling is to determine whether the design of the drainage system is adapted to reach in due time a desaturated rockmass in the vicinity of the storage. The consequences of the drainage on the nearby environment are also to be assessed. This implies to create a transient unsaturated model that simulates the storage construction progress.

The mesh of the model shall include all the different parts of the storage, i.e. access tunnel, upper and lower drainage systems, storage galleries and maintenance chambers. The simulation is based on a weekly or monthly schedule covering the construction period for the excavation of the different tunnels and galleries but also the commissioning of both the upper and the lower drainage systems. With the progress of excavation works, atmospheric pressure boundary condition is applied to the excavated parts of the storage. With the installation of the containment system, a no flow condition is progressively applied along completed walls of the storage galleries.

4. CASE STUDY: EXAMPLE OF MODEL FOR A LNG STORAGE

4.1 Hypotheses and challenges

For a theoretical case of membrane-lined cavern for underground storage of LNG, the consecutive construction steps of the storage have been modelled using FEFLOW[®] (DHI-WASY GmbH, Germany). So far only the construction phase, from the excavation to the set-up of the concrete lining, has been modelled. The construction duration was reckoned to be 4 years and a monthly schedule was established as the basis of changing boundary conditions. A specific module was developed by DHI-WASY GmbH to ease the change of boundary conditions (Schätzl et al., 2008).

The storage has a complex geometry including an access tunnel, three parallel storage units with their operation shaft and maintenance chambers, operation tunnels located above the storage galleries and from which boreholes are drilled for the upper drainage system, and the lower drainage gallery with associated drainage boreholes located below the storage galleries for drainage purposes (Figure 1a). The mesh was created to take into account all the different elements of the storage (Figure 2).

One of the challenges for representing exactly the storage was to represent an inclined structure (down sloping access tunnel) in a model with horizontal layers. Horizontal layering had been

chosen for developing this 3D model because the surface topography is pronounced and horizontal layers were considered most appropriate for this purpose. The inclined access tunnel was implemented by adapting the horizontal layers elevation along the tunnel. The tunnel has been implemented with a shape as close as possible to the designed geometry and with only a few recesses due to the horizontal layering (Figure 1b).

In order to evaluate the time required to reach desaturation of the rockmass during storage construction and active drainage phase, two different values at both sides of the model have been taken for hydraulic conductivity of the rockmass (10^{-9} m/sec and 10^{-7} m/sec). Another important challenge was to perform unsaturated transient modelling to represent the rock desaturation process during the construction of the membrane-lined cavern. The main aim for the modelling was to determine whether the rockmass was sufficiently desaturated by the end of construction since this condition is required for the installation of the membrane (Amantini and Chanfreau, 2004). Figure 3 represents the water table before and after construction around the storage. A compromise had to be found between mesh size, simulation time and input parameters in order to optimize the runs of the model.

The projected LNG underground storage is located close to the seashore as it will be loaded by LNG tankers. The model was also run as a transport model in order to assess the impact of the storage construction on the salinity of the underground water and namely sea water intrusion resulting from the progressive drainage.

4.2 Results

Infiltrating seepage water has been computed in the different parts of the storage (Figure 3) to determine the exact role played by the drainage gallery and associated boreholes and therefore evaluate their efficiency. Logically the lower drainage system contributes the most to the drainage which confirms that this lower drainage system is a key point of the design. Both the access tunnel and the cavern itself play a significant role especially in the early time of excavation progress but the access tunnel continues to play an important role throughout the construction.

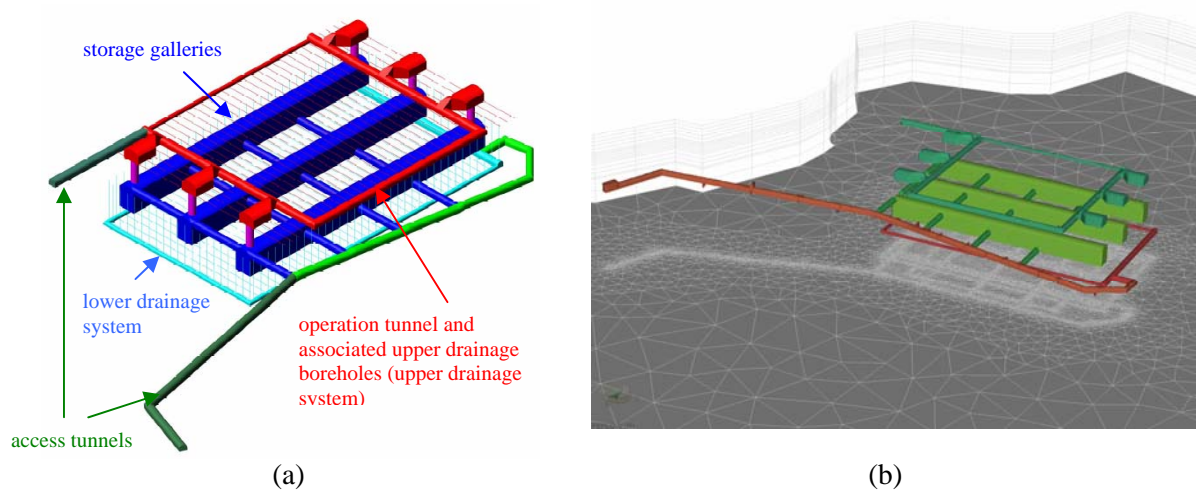


Fig. 1 Geometry of the considered LNG storage cavern. (a) Theoretical geometry represented with a computer-aided design software. (b) Geometry of the model as represented in the model (drainage boreholes have been implemented but are not shown).

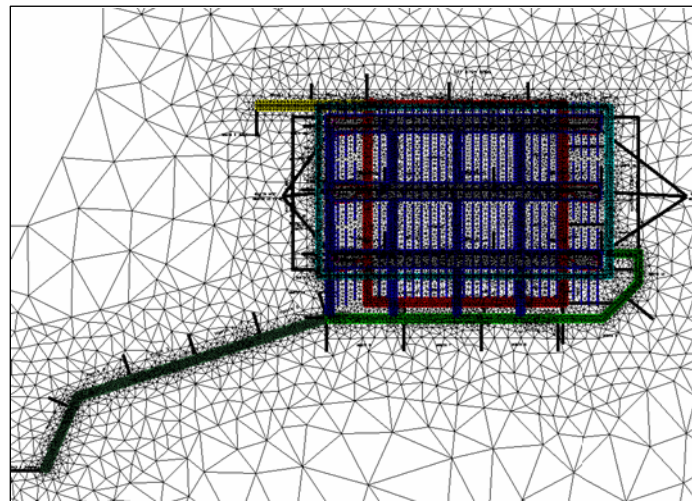


Fig. 2 View of the mesh showing the different parts of the storage as well as the boreholes of the lower drainage system (in blue).

The role of the upper drainage system does not appear as significant; its main use would be in case of heavy rainfall but this case has not been modelled as the rainfall infiltration at this stage of the modelling was considered as constant in time. A sensitivity analysis performed on the 2D model preliminary to the 3D model showed that both the recharge rate and the characteristics of the upper weathered zone are sensitive parameters. As a consequence, for properly assessing the need of an upper drainage system, it will be necessary to collect very accurate information on the distribution of efficient rainfall but also to have a good knowledge of the rockmass characteristics.

The evolution of the water table (Figure 4) showed that the desaturation was feasible within the given time span for the part of the model where the storage is located in the rockmass with a 10^{-7} m/sec hydraulic conductivity. However in the part of the model where the storage is located in

the rockmass with a 10^{-9} m/sec hydraulic conductivity, rockmass desaturation was not achieved by the end of the construction. This indicates that the drainage system needs to be adapted to attain a higher efficiency in zones of lower hydraulic conductivity. Furthermore these results show it will be in the interest of the project, when possible, to start by excavating parts of the storage that are located in the least permeable zones.

The cone of desaturation does not extend very far beyond the caverns, which means that there will be no significant effects in terms of water table level far away from the storage caverns. In the natural state, salt water intrusion is not much developed due to the low conductivity of the rockmass and the recharge from fresh water due to rainfall. However during storage construction, salt intrusion occurs along the coast only at the locations close to the storage (Figure 6) but this intrusion remains limited. Results of the simulation also show a salt intrusion into the weathered zone. However it is believed that this intrusion results from the mesh refining techniques used to improve the numerical stability and are not representative of a physical phenomenon.

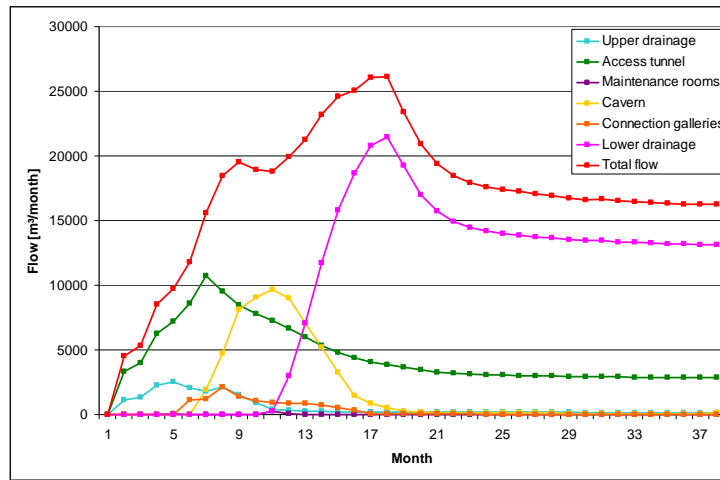


Fig. 3 Evolution of seepage water quantities for different parts of the lined storage cavern during excavation and construction works

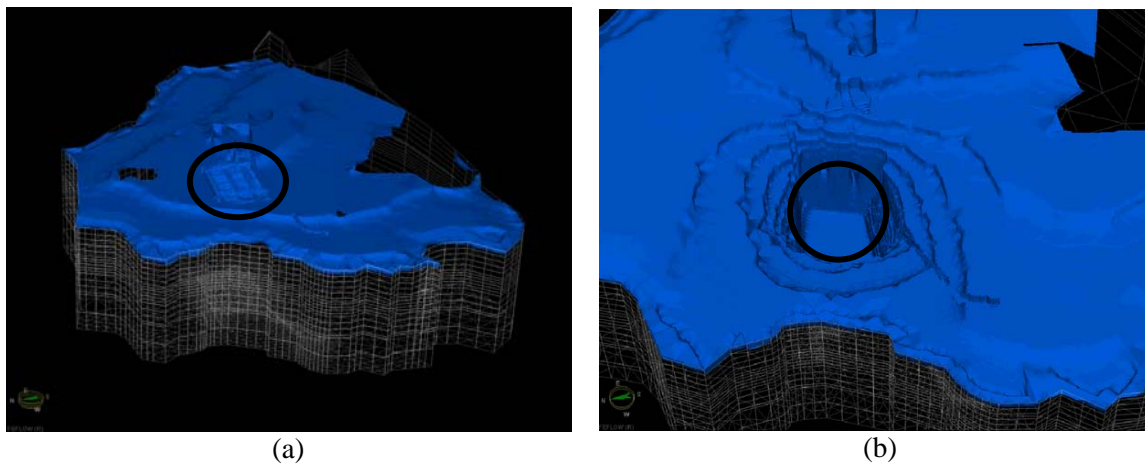


Fig. 4 Water table level (in blue) before LNG storage construction (a) and after storage construction before drainage is released (b). Storage location is circled.

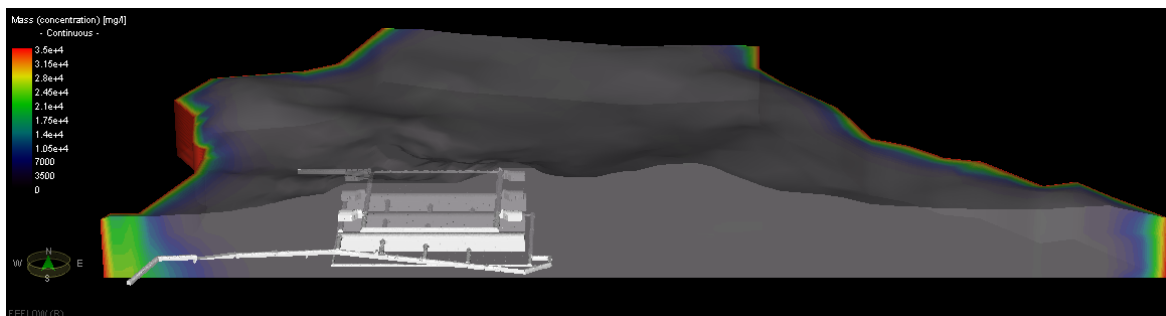


Fig. 5 Distribution of salt concentration at the end of the simulation.

4. CONCLUSION

Each stage of a project has specific needs for modelling which can be fulfilled by 2D or 3D finite element modelling. Two-dimension models are very convenient for most calculations in the design

stage and have the advantage of being easy to build and fast to run. Consequently they will be used when sensitivity analyses are required.

Three-dimension models are more difficult to set-up but are very important to confirm the design obtained in 2D as they allow to represent the storage in full including the total complex geometry as well as the spatial variations of hydraulic conductivity related to various types of rock formations and therefore to consider the hydraulic interactions between the different parts of the storage facility and ancillary galleries.

The 3D model developed for the LNG storage, presented numerous challenges regarding the representation of the inclined access tunnel, the simulation of the excavation progress with changes in boundary conditions and the calculation of the rockmass desaturation.

A next step for the model will be to simulate the formation of the cooled zone around the storage units and to determine how the water table will react during this cooling. In a subsequent step, after drainage has been released, the formation of the ice ring is to be simulated (spatial and time dependent expansion of a no flow boundary condition) in order to evaluate the impact on water table and environment.

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REFERENCES

- Amantini, E. and Chanfreau, E. (2004). "Development and construction of a pilot lined cavern for LNG underground storage." 14th International Conferences and Exhibition on Liquefied Natural Gas, Doha, Qatar, PO-33.
- Amantini E., Cabon F. and Moretto A., (2005) Groundwater management during the construction of underground hydrocarbon storage in rock caverns, *In: Loredó, J. & Pendás, F.: Mine Water 2005 – Mine Closure. – Oviedo (University of Oviedo), 311-315.*
- Claude, J and Londe, L, Gastech 1994. Kuala Lumpur, A New Concept for LNG Storage in Lined Rock Caverns.
- Schätzl, P., Clausnitzer V. and Diersch H.-J., (2008) Groundwater modelling for mining and underground construction – challenges and solutions. *In: Rapantova N. & Hrkal Z., Mine Water and the Environment, Proceedings of the 10th IMWA congress, VŠB – Technical University of Ostrava, 473-476.*