Coupled geological and hydrogeological models in fractured systems: understanding interactions between underground storages and their rockmass

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Abstract Underground unlined mined storage caverns are a technique used worldwide for storing LPG and liquid hydrocarbons products. The knowledge of the structural conditions and the hydrogeological behaviour of the rockmass are essential for the elaboration of an optimized and safe design of the underground storage project. For each underground mined storage, and at each project stage, a visual geological and hydrogeological model integrating all observations from the investigation and construction phases is developed. It gives the best representation of the geological and hydrogeological characteristics of the host rockmass with the available data. At the design stage the model is used to optimize the position of the underground works and especially the orientation of the boreholes of the water curtain system. During the construction and operation phases, it is used to interpret the measurements recorded by the monitoring network and to understand water flow paths through the fracture network.

Key words geology; hydrogeology; model; visualization; underground storage; fissured rockmass

1 INTRODUCTION

For more than half a century, underground unlined mined storage caverns for storing liquid petroleum gas (LPG) and liquid hydrocarbon products, proved a reliable technology, and experienced a strong development related to its intrinsic qualities, but also to the innovations and technical progress from which it regularly benefited. Currently, large capacity storage cavern units (with more than several hundred of thousands of cubic metres) for a broad range of hydrocarbon products are successfully operated.

The selection of the site and the location and orientation of the storage caverns are crucial preliminary steps before designing the underground facilities. Most storage caverns are implemented in fissured hard rockmasses likely to exhibit a large range of permeability values. Product containment is ensured by maintaining at all times conditions of water flow from the host rockmass into the cavern (Amantini *et al.*, 2005). In certain cases the hydrogeological conditions are naturally sufficient to maintain acceptable hydrodynamic containment conditions. Nevertheless, in most cases and especially in a discontinuous medium, adding specific artificial water supply systems is required. However, if the groundwater flow gradient towards the cavern is essential for the containment of the stored product, for environmental and economic reasons the resulting water seepage must remain limited. Consequently the knowledge of the structural conditions (mainly the 3-D geometry of layers, folds, faults and joints) and the hydrogeological characteristics of the rockmass are essential for the elaboration of an optimized and safe design of the underground storage project based on representative hydrogeological models.

Unlined mined storage caverns are often located in fissured hard rockmasses that by definition cannot be considered as continuum media and are likely to exhibit significant anisotropic hydraulic behaviour. In many cases it is impossible to define an equivalent porous continuum media around the underground works, owing to the fact that a hypothetical representative elementary volume (REV) is either too large, compared to the storage cavern size, or even non-existent. This scale effect problem is commonly observed for underground works in fissured rockmass engineering, and especially when designing the hydraulic containment conditions for a storage cavern. Therefore, it is necessary:

- to focus on the sensitive areas of the underground works, such as the crown of the storage

galleries, the inverts of the connection galleries, the pillars and the water curtain boreholes system,
- to identify the characteristics of the intersections of these sensitive areas with permeable discontinuities of the rockmass,
- to highlight possible critical flow patterns as far as the hydraulic conditions necessary for the product containment in the cavern are concerned.

Joints and faults are the preferential pathway for water and the distribution of hydraulic conductivities is generally complex but needs to be characterized as precisely as possible to:

- locate the storage where it is the most appropriate,
- optimize the design of the storage to ensure its tightness during operation,
- interpret the monitoring data collected during the construction phase and adjust the design to the actual hydrogeological conditions encountered,
- carry out an analysis of the monitoring data collected during the whole life of the storage and interpret observed tendencies,
- be able to propose efficient remedial actions if a degradation of the initial hydraulic containment conditions of the storage appears in the course of operation.

Although information needs to be collected on a large scale (about a few hundreds of thousands of square metres) to have a good knowledge of the site, borehole drilling and testing is costly and consequently data are only available locally. Geological and hydrogeological visualization models are a tool able to represent the correlations between data gathered on several boreholes and enable the representation of several pieces of information at the same time.

2. DATA COLLECTION DURING SITE INVESTIGATION AND CONSTRUCTION

2.1 Site investigation

At the feasibility stage, one to three boreholes are core-drilled to determine if the geology of the site is appropriate for an underground storage. If the site is found to be suitable, additional boreholes are performed to enhance the knowledge of the rockmass. Depending on the complexity of the site geology, the number of storage units and the volume of the storage, a total of five to twenty boreholes are fully core-drilled to collect information on the rockmass. These boreholes are usually between 100 m and 200 m long to reach the estimated depth of the storage. In practice data are collected over several kilometres of cores, but only a few cubic metres of rock are brought to surface and analysed to understand the behaviour of a rockmass composed of the matrix plus discontinuities that will host a storage of a few hundreds of thousands of cubic metres.

The boreholes are not implemented all at the same time. Geological information is analysed continuously during the investigation and the results obtained in the first boreholes are used to locate and orientate the next boreholes. This methodology allows optimizing of the location of the cored holes to characterize the major geological structures that will affect the construction and operation of the storage, as well as confirming or invalidating and completing the first conclusions. Several analyses and tests are performed, but only those whose results are used in the geological and hydrogeological model are mentioned in the present paper.

A visual description of the cores is performed by an engineering geologist in a first step to describe the lithology and determine the different rock types encountered. All discontinuities are recorded in terms of geometry, i.e. depth and dip angle, and described in terms of thickness and filling. However the strike cannot be assessed on unoriented cores and acoustic borehole televiewer (BHTV) logging is often used to get an image of the borehole wall and to orientate the joints that have been identified during core inspection. Combining visual inspection of the cores and BHTV allows determining the different joint sets and their characteristics.

From the geological survey, the rock quality designation index (RQD; Deere, 1963) is calculated, giving a first quantification of the overall quality of the rockmass, where the underground storage is implemented.

A geophysical survey, especially refraction seismic, is performed over the investigated area to get large-scale data and to make correlations between boreholes. The three main results provided by the geophysical survey are first the thickness of the weathered zone and consequently the depth of the fresh rockmass, second the location of low velocity zones such as fractured and faulted zones, and third the bottom velocity of the fresh rockmass.

Hydraulic tests are performed in the boreholes to get a profile of hydraulic conductivity *versus* depth. In each borehole, intervals about 10-m long are individually tested and a hydraulic conductivity is evaluated for each interval.

Data collected during site investigation and that will be used for elaborating the visualisation model are summarized in Table 1.

Table 1 Summary of data collected during site investigation and construction and used as input data in the geological and hydrogeological model.

	Site investigation	Storage construction
Geology	surface topography of site thickness of weathered zone topography of fresh rock roof lithology oriented discontinuities RQD	oriented joints in galleries structural relationships between discontinuities
Hydrogeology	profile of hydraulic conductivity *versus* depth	hydraulic conductivity in water curtain and monitoring boreholes

2.2 Construction

The most complete knowledge of the rockmass is obtained at the end of the storage construction because the rockmass has been observed from the inside when excavating galleries with a section of several hundred square metres. For each excavated gallery or tunnel, geological mapping is performed by surveying precisely all the joints that have been crossed during excavation and characterizing them in terms of location, filling and water ingress. The scale of the mapping is generally about 1:200.

Discontinuities are locally measured in 3-D during the mapping with their strike and dip. In addition, the existence of tunnels or galleries, such as water curtain galleries, above or below the storage galleries, allows larger correlations of joints identified at different levels and provides an image of their persistence in space. Once all joints have been mapped they are organized into a hierarchy depending on their impact with regards to stability of the works and water ingress (Giafferi *et al*., 2003). Only the joints having significant impact will be input into the model.

Hydraulic testing is performed (Amantini *et al*., 2005):

- in the boreholes drilled from the water curtain gallery, which will be used to inject water and enhance the distribution of hydraulic potentials, and
- in the boreholes that will be used for underground monitoring and equipped with a pressure cell or a manometer.

This testing provides a map of the distribution of hydraulic conductivities into the rockmass. Data collected during construction that will be used for elaborating the visualisation model are summarized in Table 1.

3 INTEGRATING THE DATA IN THE VISUALIZATION MODEL

The aim of the 3-D visualization model is to present in 3-D the major geological features of the rockmass, essentially the structure and the tectonic defects, as well as the results of the hydrogeological tests. The method for creating the model is based on observations and manual correlations and the elaborated model is neither a numerical analysis model nor the result of automatic interpolation by a software system. It is a conceptual model established on a fully deterministic approach which requires classification of observations and/or measurements in order to clearly distinguish facts from interpretations.

3.1 Creating a database

Upstream, the software Drill&Log® of Pöyry Infra Corporation (Austria) is used. It is a georeferenced database used to store general (coordinates, length, inclination, deflection) geological (lithology, RQD, weathering grades, discontinuities), hydrogeological (permeability, static pressures, piezometric completion) and geotechnical data. The Drill&Log® database allows a representation of 2-D as well as 3-D geological drillings in order to facilitate visualisation and therefore geological correlations and interpretations. Drill&Log® also outputs graphics in the AutoCAD® 2-D/3-D format, which is very convenient for further data treatment and project integration.

3.2 Creating a visualization of the data

The procedure for building the structural 3-D model is centred on AutoCAD® software (Fig. 1), which is a universal and powerful software used world-wide, allowing easy integration of data or pre-existing maps. This software has advanced 3-D functions allowing the creation of very realistic 3-D models of the storages. It is possible to design structures and smooth the plans, providing a visual rendering of excellent quality. In addition, to get a better visual rendering of 3-D representations (caverns, faults, layers, etc.), 3ds Max®, which is also developed by Autodesk® and fully compatible with AutoCAD®, is used.

The output graphics from Drill&Log® are imported into AutoCAD®. The method for creating the model being manual, the correlations between the faults and the faults' movements are issued on the interpretation and hypothesis of the engineering geologist and represented by him in AutoCAD®.

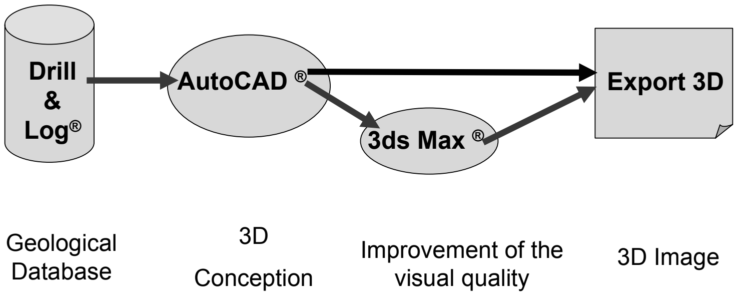

Fig. 1 Modelling procedure.

3.3 Visualizing the model

The geological 3-D model, when generated, is finally exported in VRML 97 format (Virtual Reality Modelling Language) for representing 3-D interactive vector graphics. The export VRML model has been chosen for several reasons:

- the 3-D image is relatively small (a few Mb). The image file can be sent easily over the Internet or carried on a USB key and can be opened on any type of computer as no sophisticated computer configuration is required;
- the VRML export file provides a 3-D static image which cannot be changed by a third party;
- VRML files do not have any loss of accuracy depending on the zooming. There is no pixelization when zooming in or out since the image is recalculated automatically to fit the screen;

- the VRML image supports structuring elements in groups and subgroups. This type of export gives the choice to display desired elements (for example, boreholes, faults, layers).
- VRML files can be opened by free software, and Drill&Log®, AutoCAD® or 3ds Max® is not needed to visualize the model.

4 USING THE MODEL TO UNDERSTAND THE HYDROGEOLOGICAL BEHAVIOUR OF THE ROCKMASS: TWO EXAMPLES

4.1 Use of the model

The first model for a site is built by taking into account all data from the site investigation. This model is a visualization of the geological and hydrogeological understanding of the site at the design stage. Once the shape of the underground works is determined to provide the volume required for a specific project and to ensure stability of the storage, the storage geometry can be input into the model, which is used to optimize the storage depth as well as its orientation with regards to geological structures. For example, it is in the interest of any project to avoid as much as possible locating tunnels or galleries in horizons showing high hydraulic conductivities or to follow sub-vertical discontinuities with high water ingress or instable rock conditions over the whole length of a gallery.

During construction, the model can be updated with the data collected during geological mapping and hydrogeological tests (see Section 2.2). It is therefore possible to confront the interpretation made at the design stage with the reality and to determine whether the design choices that have been made are adapted to the site. In some cases they may not be optimal and the design might require to be adapted during construction. Adaptation can include shortening or lengthening some galleries, modifying the orientation of water curtain boreholes, adding water curtain boreholes or modifying the provisional location of underground monitoring devices. The model is in this respect a useful tool to adapt the design to the geological and hydrogeological characteristics of the site.

In addition, the model is used to interpret the results of the monitoring performed during construction and operation phases. An extensive network of piezometers and underground pore pressure cells is installed to monitor how the hydraulic potential distribution in the rockmass is reacting, and to ensure that the water table is not significantly disturbed (van Hasselt *et a*l., 2003). In fissured hard rockmasses, interpreting hydraulic head measurements requires one to understand how fissures are hydraulically interconnected and what are the pathways water uses. The two examples developed in the next section illustrate how the model can be used to interpret hydrogeological observations. The first example illustrates how the model was used on a site to interpret a piezometric drop. The second example illustrates how the model was used on another site to confirm the design of the hydrogeological support from surface.

4.2 Example of interaction between piezometric levels and water curtain boreholes supply pressure

The studied underground storage is an LPG storage, excavated in gneiss, consisting of two parallel galleries with a roof elevation of –162 m a.m.s.l. and a horizontal water curtain. Figure 2 shows the storage galleries and the two shafts (in red and green) with the water curtain gallery (in blue) and horizontal water curtain boreholes located 15 m above the storage galleries. Water curtain boreholes in pink are the boreholes with the highest hydraulic conductivity (higher than 10^{-8} m/s) while boreholes in blue have a hydraulic conductivity lower than 10^{-8} m/s. Four piezometers belonging to the piezometric network and measuring the hydraulic head at the depth of the cavern are represented in Fig. 2, with their observation interval indicated in purple. Underground manometer holes are represented in red as the inclined boreholes drilled from the water curtain gallery. The line in purple above the storage represents the storage perimeter.

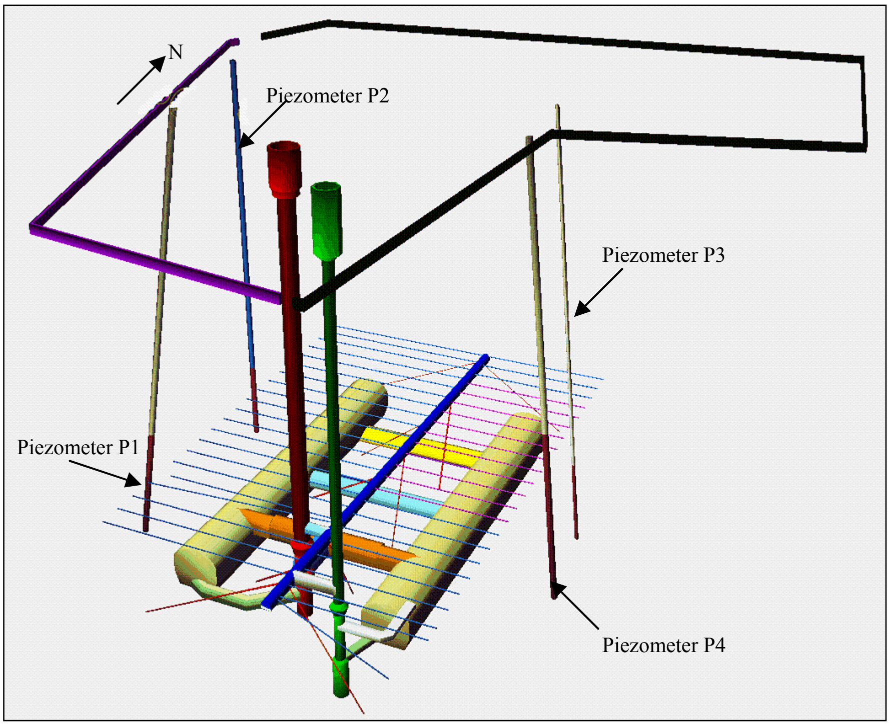

Fig. 2 Representation of the studied LPG storage showing some of the deep piezometers belonging to the monitoring network as well as the water curtain system implemented above the storage cavern.

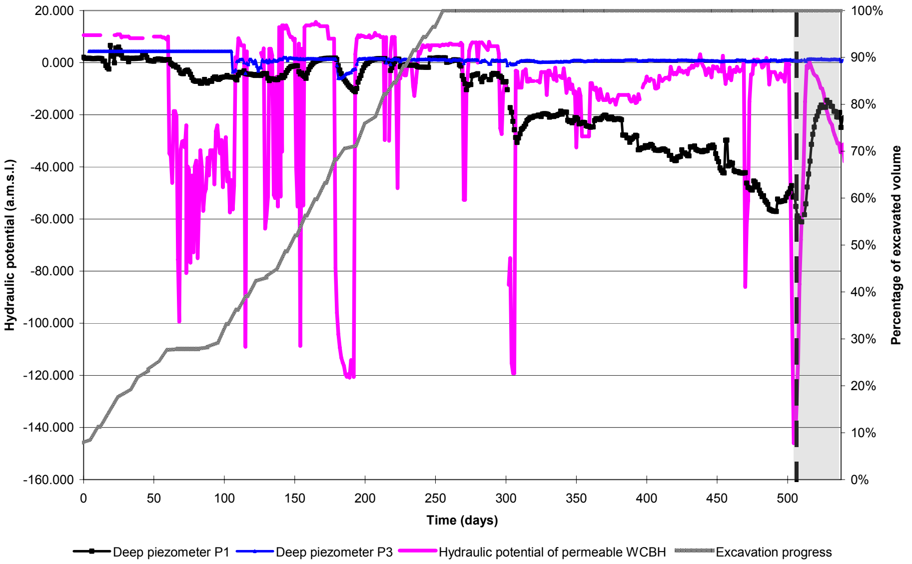

Fig. 3 Evolution of P1 and P3 piezometric level and of the mean hydraulic potential of permeable water curtain boreholes together with excavation progress. Day 0 corresponds to the start of P1 monitoring. Period in white corresponds to the period when the water curtain gallery is at atmospheric pressure and only water curtain boreholes are supplied while the period shaded in grey corresponds to the time span when the water curtain system has been water filled.

During construction the hydraulic potential of piezometers P1 and P2 showed an important decrease: sixteen months after the start of the monitoring the water level had dropped 64 m below its initial monitoring level. Figure 3 shows the hydraulic head measured only for piezometer P1. The hydraulic head for piezometer P2 is not represented since it is very similar to the hydraulic head evolution of piezometer P1. As the observation interval of piezometer P1 is located at the depth of the cavern, this decrease took place in the immediate zone of interest for the cavern. At the same time, the hydraulic head for piezometers P3 and P4 remained relatively stable. Similarly, Fig. 3 only shows the hydraulic head of piezometer P3 since the hydraulic head of piezometer P4 is similar to that of P3.

An analysis was performed to understand the reasons for the decrease of hydraulic head in piezometers P1 and P2 and to recommend remedial actions. Figure 3 shows in addition to the hydraulic head of piezometers P1 and P3, the average hydraulic head in the permeable water curtain boreholes (in pink on Fig. 2) and the progress of excavation shown as the percentage of excavated volume. Figure 3 shows that the hydraulic head of piezometer P1 was influenced by the hydraulic potential in the permeable water curtain boreholes: each time the hydraulic head in the water curtain boreholes dropped, the hydraulic head of piezometer P1 also dropped. Increasing the water supply pressure in the boreholes leads to a recovery of the piezometric level for P1 and P2, which stayed relatively stable until the storage was fully excavated.

At day 300 we observe a strong decrease in the mean hydraulic potential of the water curtain boreholes, which never recovered to its initial potential of about +7 a.m.s.l. At this stage the storage was fully excavated but not yet in operation, which implies that it was acting as a draining hydraulic boundary condition. From this point, the hydraulic potential of piezometer P1 decreased continuously. Increasing the mean hydraulic potential from day 400 to day 450 lead to a temporary stabilization of P1 hydraulic potential at about –34 a.m.s.l. but was not enough to have it stabilize.

From the observations, it appeared that the hydraulic potential of piezometers P1 and P2 was correlated to the injection pressure in the permeable boreholes of the water curtain, although P1 and P2 were located opposite the permeable water curtain boreholes. The model was then used to understand the phenomena involved in this unexpected lateral hydraulic interference. The combination of several joints observed during storage excavation and when drilling piezometers provided a communication between the permeable boreholes and piezometers P1 and P2 (see Fig. 4). It also appeared that P3 and P4 were not connected to the permeable water curtain boreholes: joint 1_7 is not intercepting the piezometers in their observation interval and joint H1 had not been observed on the cores, which is the reason why it does not intercept the piezometers.

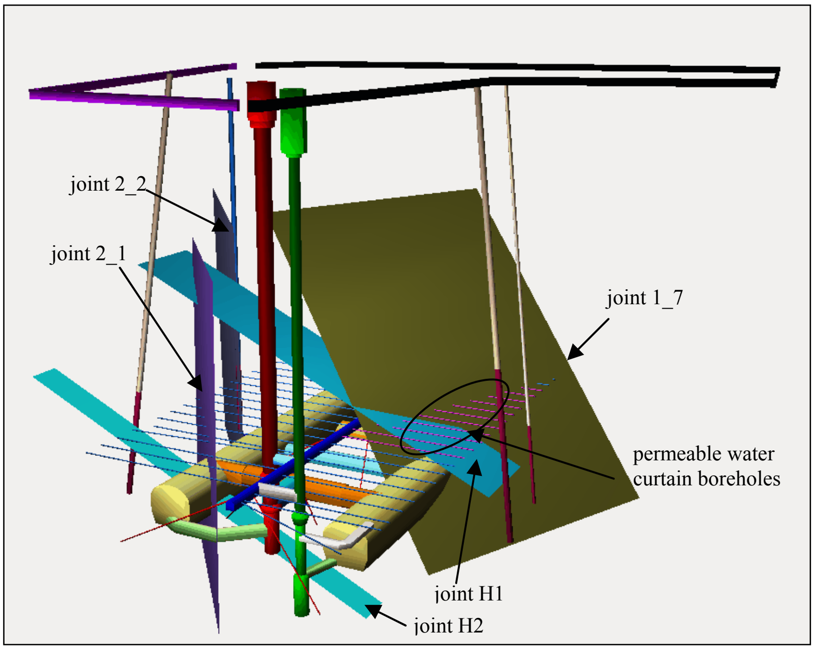

Fig. 4 Network of joints connecting piezometers P1 and P2 to the permeable water curtain boreholes (circled).

Geological structures as represented in the model, mainly joints and locally foliation, were consistent with hydrogeological observations and confirmed the hydraulic connection between piezometers P1 and P2 and the permeable part of the water curtain. The risk of having a hydraulic potential drop in the temporary supply lines used during construction being unavoidable, it was necessary to water fill the water curtain gallery and the shaft to ensure a stable potential that would allow the hydraulic potential of piezometers P1 and P2 to recover. Water filling was performed on day 506 (Fig. 4) and the hydraulic potential of piezometer P1 recovered to –14 a.m.s.l. for a hydraulic head of the water curtain of 0 a.m.s.l. As the water curtain was not supplied after its initial filling, we observe on Fig. 3 a decrease in water curtain potential which leads to an expected decrease in hydraulic heads of P1 and P2.

The visualisation model proved a very useful tool to analyse the hydrogeological monitoring measurements and to understand the hydrogeological connections between different parts of the rockmass surrounding the storage.

4.3 Example of correlations between the geological structures and the hydrogeological support network

The studied underground storage is a propane storage, excavated in gabbro, consisting of three parallel galleries with a roof elevation at –105 m a.m.s.l. and a horizontal and inclined water curtain. Figure 5 shows the storage galleries, the access tunnel with the above water curtain gallery located at –85 m a.m.s.l. and horizontal and inclined water curtain boreholes.

During construction, the existence of a major fault was observed in one of the three galleries on the western side of the investigated area. In gallery C and in the upper transverse connection gallery between galleries B and C, important water ingresses were detected (Fig. 5). Due to the existence of this unfavourable major faulted zone, it was essential to adapt the initial designed horizontal water curtain boreholes system to the geological conditions encountered. New water curtain boreholes were drilled during construction of the water curtain gallery, on both sides of the western part of gallery C, where the major fault is acting as an impervious barrier.

This first set of sub-vertical additional boreholes was necessary to improve the hydraulic conditions at the level of the storage cavern, but was inappropriate to enhance the hydraulic efficiency of the horizontal water curtain boreholes, above the southern part of gallery C. Consequently, complementary water curtain boreholes were performed by drilling additional boreholes from the surface as this was easier and allowed better orientation of the boreholes for intersecting the features involved.

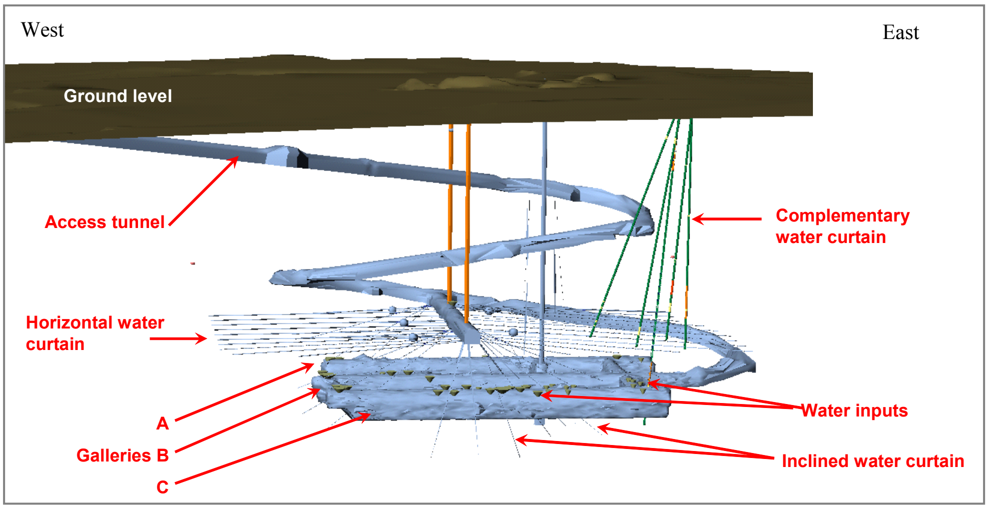

Fig. 5 Representation of studied propane storage.

A coupled geological and hydrogeological 3-D model was recently established to confirm the initial general interpretation of the structural characteristics of the site and to outline geological and hydrogeological conditions of the most sensitive area of the storage cavern. The 3-D model and its interface with the geometric characteristics of the underground works (storage cavern, water curtain systems and monitoring equipment network) provide a valuable support to the interpretation of the hydrogeological monitoring of the storage cavern.

From a geological point of view, the 3-D model has highlighted two perpendicular sets of subvertical major faults on the site. These different sets of faults create the presence of a fractured band bounded by the east–west major faults (close to gallery C and the upper connection between galleries B and C), that had not be identified during construction (Fig. 6).

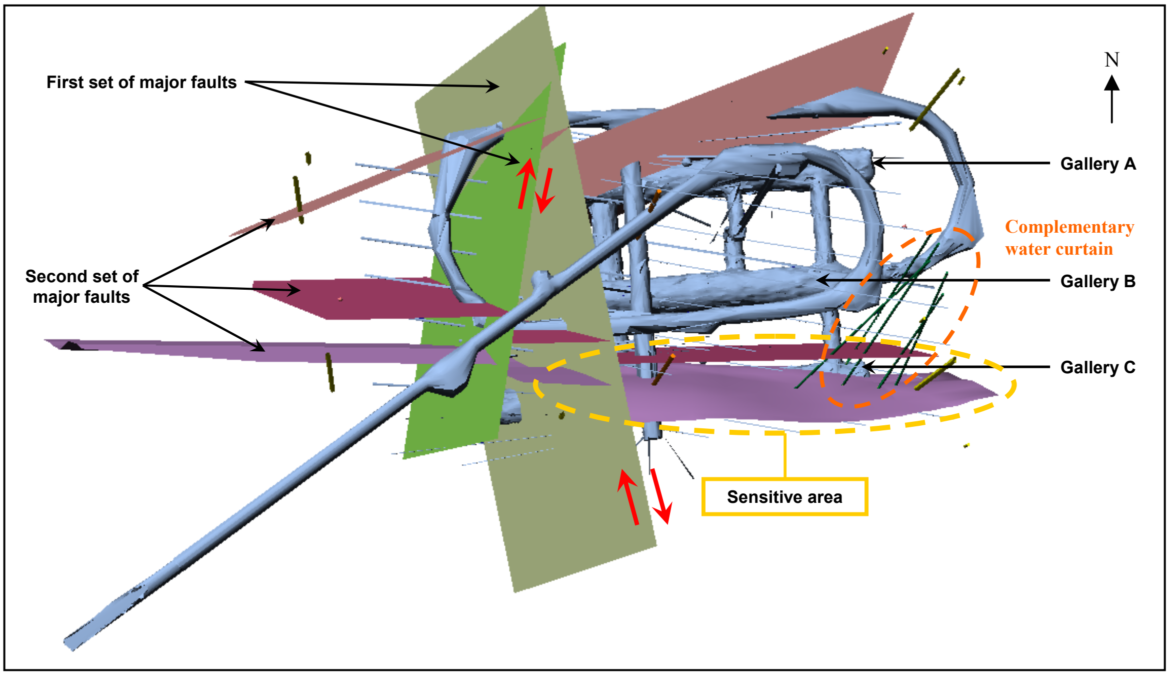

Fig. 6 3-D geological model showing the geological structure and their interaction with the galleries.

The combined geological and hydrogeological 3-D model allows exact visualization of the location of the major faults, but also of some minor faults that have had important consequences during construction. It also allows understanding of the interaction between the geological structures and the hydrogeological monitoring network in place, composed of piezometers and pressure cells. For example, the model highlights the parallelism between the water curtain and fractured band and indeed the rare horizontal water curtain cross the sensitive area (Fig. 6). Therefore the model has confirmed the necessity of the complementary water curtain boreholes drilled from the surface to locally improve the water recharge, and it can therefore be used to design additional water curtains if they appear to be necessary.

5 CONCLUSIONS

Geological and hydrogeological visualization models are developed using a series of software that enable a good picture quality as well as easy access to the model. Due to the export format the models can be easily used as a work tool. The two examples developed showed how the models can be used to understand the hydrogeological behaviour of the rockmass, interpret the data collected during monitoring and take the most adapted remedial actions when necessary.

Models are continuously evolving and representing observations more and more accurately. For the more recent models, joints and faults are represented with their measured thickness and with their observed shape, while in earlier projects they were only represented as planes. Our aim is to be able to compile complete sets of geological, hydrogeological and geomechanical data.

The models allow production of an image of the understanding of the hydrogeological behaviour of the site and this image can be used easily by all people involved in a project independently of their abilities in computer science, geology or hydrogeology. It therefore appears to be an essential tool to carry out the cross-analysis and the synthesis of numerous data of various sources, and draw up a clear representation of the main characteristics of the investigated site. It is also a decision tool that can be used on site for critical issues such as decision to grout, implementation of monitoring network and layout adaptation during construction.

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