Hydrogeological Aspects during Closure of an Underground LPG Storage

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Abstract This article presents the successive steps of the GEOVEXIN LPG underground cavern storage closure from the decision to stop the activity in April 2006 for economic reasons until the present situation. It describes the operation termination phase (product removal and water flooding of the cavern), the partial backfilling of the cavern and access tunnel, the modeling and specific hydrogeological studies (considering the vicinity of drinking water fields), the monitoring network adaptation and the water quality and level of groundwater supervisions. Each step has been successfully carried out by the company GEOSTOCK according to the Environmental French Administration requirements.

Keywords Underground cavern storage, closure, hydrogeology, monitoring

Introduction

Many hydrocarbon storage caverns are currently operated around the world. Few of them have been already closed and abandoned. The GEOVEXIN cavern provides a successful and recent example of such a closure, in spite of technical and hydrogeological constrains.

LPG storage of GEOVEXIN presentation

GEOVEXIN underground storage was located near a refinery site alongside the Seine River, 40 km west of Paris. The facility was initially planned for storing 3 products: propane, gasoline and heavy fuel oil. Priority was subsequently given to heavy fuel oil and the design proceeded on this basis. The planned caverns were arranged like a comb with the oil pumped in from small galleries at a higher level, circulating in the "forks" of the comb and then along the main connecting gallery and a central branch where it could be pumped to the surface (fig. 1). Due to the oil crisis of the mid 70's, the initial planned oil storage project was converted into a smaller propane storage project. The cavern eventually built in 1975 consisted of 2620 m (8590 ft) of egg-shaped gallery of 47 m^2 cross section, with a storage volume of 130 000 m^3. Gallery depths ranged from

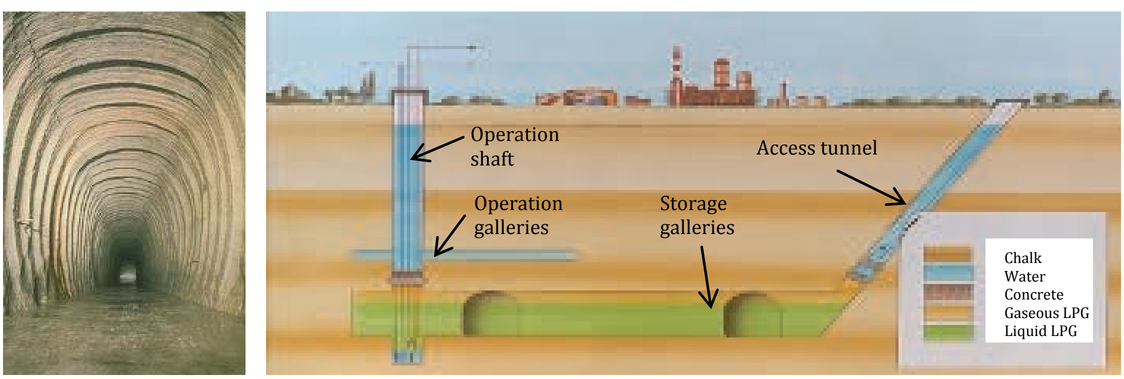

Fig. 1 *View of main gallery (left) and schematic cross section of underground storage (right).*

120 m (393 ft) to 145 m (475 ft). Access to the storage galleries was made through shafts and an access tunnel of 1045 m (3428 ft) long (Maury 1977).

Only chalk was suitable for such an underground storage in this area of the Paris basin. The Turonian chalk was selected. The geological section of the site starts at the top with about 100 m (328 ft) of Lower Senonian, a white chalk containing silex, with solution pockets at the higher levels. A more pervious detritic level is found near the top of the Turonian. The next layer is the Turonian chalk itself where the cavern is located, followed by the Cenomanian, a bed of sandy chalk about 50 m (164 ft) thick.

The hydraulic conductivity of the surface Quaternary zone and top of weathered chalk is several tens of Darcy (30 to 40 10^{-5} m/s). The hydraulic conductivity in the Turonian chalk is approximately 4 mD (4 10^{-8} m/s). The detritic level is sometimes much more permeable but is often not continuous. Lastly, a few irregular and discontinuous silex beds, a few centimeters thick, probably produce some anisotropy.

The hydrodynamic containment principle was used to obtain gas- tightness. A permanent flow of water from the surrounding rock is designed and maintained in such a way as it is always directed inwards, into the storage galleries, in order to oppose any outward migration of the propane. The storage facility must therefore be located at sufficient depth below the groundwater table and in the vicinity of a permanent source of groundwater recharge so that the natural hydrostatic head cannot be depleted by drainage into the cavern. Thus, the depth of the cavern is to be designed accordingly to the product pressure, approximately 8 bar gauge (116 psig) in the case of propane.

Once it was decided to use the facility for storing propane, the main service shaft was deepened 22 m (72 ft) and a concrete plug was built between the storage level and the operation galleries, which were subsequently filled with water. All the other shaft and adits were also sealed off. A double concrete plug with water seal at controlled pressure was built at the bottom of the access tunnel.

Operation termination (2006–2010)

Considered no longer economically viable for the LPG market, its shareholders decided to stop the GEOVEXIN activity on the 13 April 2006. At the time of the decision to stop the activity, the storage contained 123 000 m³ of product which represented approximately 2 000 tons at the cavern storage pressure of 7.4 bar gauge and the geothermal temperature of 16 °C.

The first action was to drain away the cavern of the liquid LPG by the usual means (pumping by means of the submerged pumps towards rail tanks) until reaching the low level and pump shut down.

Then the cavern was gradually flooded by the seepage water. At the same time, the residual gaseous propane was progressively evacuated and recovered by the recompression system available on the site and sent towards the rail tanks loading station. This operation was carried out with permanent control of the pressure in cavern and of the water level to guarantee the integrity of the storage. During the evacuation phase of the gaseous propane, the pressure of the cavern was monitored by successive stops and starts of the compression system. The pressure varied between the minimal value of 5.0 bar gauge (stop of the compressor) and 7.4 bar gauge (start of the compressor).

The seepage water filling was made up to a level very close to the roof of the cavern.

The next stage consisted of a flare operation which was introduced in November 2008, and ended in January 2009, which allowed extracting a remaining 148 tons of propane.

During this time, the company GEOSTOCK prepared a closure file for the DRIEE (French Environmental Administration). The technical definitive operation termination declaration defined the necessary works for placing the storage in safety mode, removing the LPG and supervising the storage installations. This closure declaration file was analysed by DRIEE in 2008 which resulted in the publication in September of the Prefect's first order which gave GEOVEXIN notice of the definitive operation termination declaration and listed the works to be carried out. This order which imposed that the seepage water pumping was maintained until an opposite decision is taken by an additional Prefect's order was then used as a basis for the definition of the closure works program.

After the flare operation was completed and during the closure file analysis by the Administration, the inerting gas phase was carried out. The goal was to reach a hydrocarbon content in the extracted mixture below 1 % molar. Three inerting cycles were necessary. Every inerting cycle consisted of a step of nitrogen injection to dilute the vapour phase, of a step of homogenization of the LPG/Nitrogen mixture and of a step of decompression and elimination of a fraction of the gaseous phase in the roof. The first inerting cycle lasted from April 2009 till October 2009 and allowed to lower the content in propane in the gas phase from 75 % to 11.5 % molar. The second inerting cycle took place from November 2009 till June 2010 and allowed to lower the content in propane from 11.5 % to 1.8 % molar. Finally the third and last cycle took place from July till August 2010 and allowed reaching a propane content lower than the target value of 1 % molar.

The inerting cycles took place under the permanent control of the pressure and the level of liquid in cavern to guarantee the integrity of the storage. The cavern pressure was monitored by successive stops and starts of the seepage water pumping system. The pressure varied between the minimal value of 5.5 bar gauge (stop of the pump) and 7.1 bar gauge (start of the pump) and the level of liquid was monitored between the high level of 8.1 m (start of the pump) and the low level of 5.1 m (stop of pump).

In December 2010, an additional Prefect's order was published in order to define the main condition of the seepage water pump stop authorization. The hydrocarbon content in extracted water must be lower than 5 mg/L and the parameter must be checked on three successive weekly analyses.

In preparation of this order, seepage water analyses were regularly made. The last three analyses carried out in October and November 2010 resulted in a propane content lower than the imposed value of 5 mg/L.

The definitive stop of the seepage water pumps took place on the 23 November 2010 and the seepage water gradually flooded the cavern up to its roof.

Partial backfilling of the cavern and access tunnel (2011)

The partial backfilling of the caverns and access tunnel was carried out through small diameter cased holes (5" diameter) fitted with a blow out preventer for the cavern.

This technique derived from conventional grouting works has allowed backfilling without having to gain access to the underground submerged parts. This is an advantage for various reasons, mostly worker's safety and environmental reasons: *e.g.* possible instabilities when rapidly discharging the cavern wall to atmospheric pressure, management of very large water volumes for working in dry conditions involving water table modifications, huge water treatment costs.

A very specific aspect of the project is the concept of partial backfilling. The cavern is globally stable and only sensitive areas have been treated. The sensitivity has been judged based on depth, shape and geological conditions.

Dams – isolating backfilled and non-backfilled underground areas – have been constructed by a specific grouting technique based on mixing at cavern level a rich cement mix with an accelerator. Grouting was made in separate tubes and mixing was obtained at dam level to avoid clogging in the long grouting tubes (120 meters). This relatively conventional technique has never been used before at such depths and distances and many tests and trials have been conducted with the Contractor (SOLETANCHE – BACHY) before starting the main works.

Once dams were constructed and their tightness checked by radar, backfilling was implemented using conventional grout mixes with low mechanical properties.

Works lasted five months working in two shifts. Two underground dams were constructed and some 15000 m³ of backfilling have been placed.

One must also note that the access tunnel constructed in the seventies is now covered with housings of the nearby suburban town. Drilling and grouting activities have consequently been realized in a dense urban environment.

Concerning the backfilling of the operation shaft, it was cleaned of all extractible equipment and backfilled with clean gravel using a tremie tube placed under water

The surface installations were dismantled. Operation shaft casings which are sealed in the bottom plug were cut at water table level and backfilled with cement grout as they cannot be reasonably extracted

At the end of the works the surface used by the facility can be returned to any other usage such as housings or road construction. Only a small area around the operation shaft has been declared “non- constructible”

Regional and local hydrogeological context

At a regional scale, the geological encountered formations are as follows i) Quaternary alluvial deposits from the Seine river, ii) Senonian white chalk with silex beds, more or less weathered on the upper part and iii) Turonian light grey chalk, fresh. On a local scale, the various investigation holes rapidly indicate after the top soil and decalcification clays a strongly weathered chalk (most productive part) then a fresher chalk (fig. 2).

The hydrogeological context is summarised as follows:

- The existence of the Seine river roughly flowing towards West South-West,
- One aquifer composed by the alluvial deposits and the upper weathered chalk part. Due to the lack of impermeable layer, these complex formations are interconnected and constitute the Chalk aquifer and are sensitive as regards to pollutions.
- The existence of an important drinking water field area on the left side of the Seine River (South-east part of the underground storage area).

Relations between the surface water and groundwater are directed in general from the aquifer towards the river but are sometimes inversed especially during floods or overproduction of water from the drinking fields.

The cavern seepage was around 60 m³/h at the beginning of operation and was close to

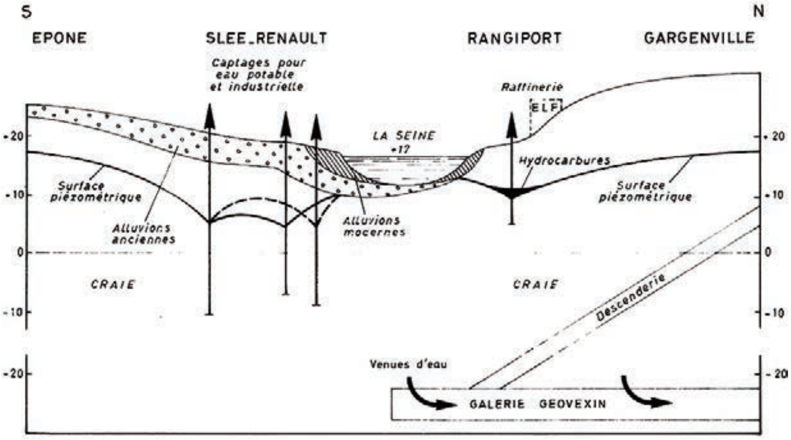

Fig. 2 *Schematic north-south hydrogeological cross section of the considered area (Mégnien 1979).*

20 m³/h just before the closure works. The withdrawal was low (200 times less than the water quantity taken from the drinking fields). The storage impact can be considered as negligible.

Monitoring network

Due to the hydrogeological context (vulnerability), the history of the area (existence of an oil refinery), the underground storage under operation and the vicinity of drinking water fields, an important monitoring network was located all around the underground facility in order to control the hydrogeological behaviour (fig. 3).

This network was composed of around forty monitoring points as shown in the following Fig. (piezometers, pumping wells and Seine river level).

For the post closure monitoring phase, several monitoring boreholes have been completed or abandoned.

Modeling and specific studies

During operation of underground storage, the hydraulic potential in the rockmass was higher than the cavern hydraulic potential and at that time the hydraulic gradients were directed towards the cavern. After the removing operations, the underground cavern was full of water and there was a modification of flow patterns around the cavern which do not seep into the cavern but go through the cavern and therefore lead to transportation of dissolved product.

Analytical and numerical modelling studies allowed to determine the distribution of the hydraulic potentials during these operations and to estimate the possible concentration of dissolved product at pumping well locations.

FEFLOW software was used (transient flow and mass transport considering free surface conditions). Modelling consisted of several steps and more specifically:

- a matching of the hydrodynamic parameters for the different considered layers in order to obtain an accurate distribution of the hydraulic potentials and
- a correct estimation of the seepage water compared to the operation measurements.

Migration of product by inversion of the flow gradients from the cavern is not taken into account according to the favourable hydrogeological situation during operation (hydrodynamic containment, hydrogeological monitoring, water seepage changes and water quality of undergroundwaters). An estimation of the potential quantity of product and of the propagation distance into the rockmass from the cavern walls were performed in order to quantify the pollution risk once the natural gradient is restored.

The main conclusions show that a limited quantity of dissolved product, around one

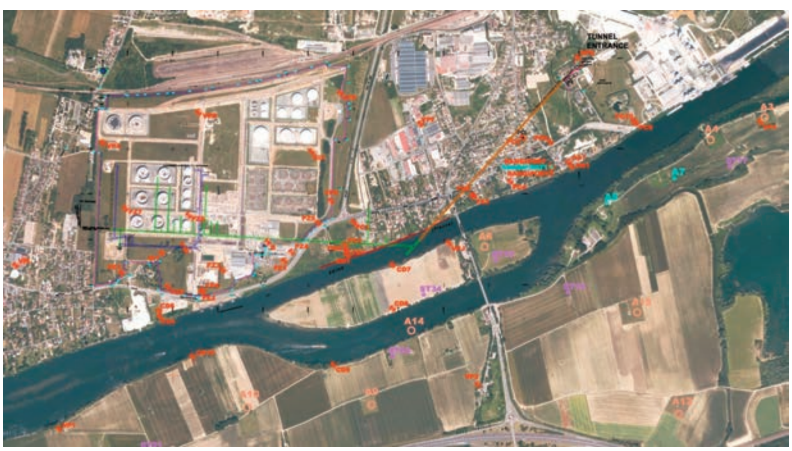

Fig. 3 Monitoring point location and underground cavern location (green line for cavern)

hundred kilogram, potentially moves into the aquifer and penetrates on several centimetres inside the rock mass. The impact on the drinking water wells will be negligible.

Post-closure and current situation

Once the closure works were ended, GEOSTOCK prepared an end of works file for the DRIEE. The technical file describes the various operations which were carried out. It was analysed by DRIEE in 2012 which resulted in the publication in December of a last Prefect's order which gave GEOVEXIN notice of definitive works termination and maintained the follow-up of a set of reference parameters already imposed in the previous Prefect's orders.

In particular, the supervision of the level of the groundwater and of the quality of surrounding waters of the storage was put into place (fig. 4).

The supervision of the work is effective since the end of 2011 but one should note that this takes place after technical follow-ups of the work which were carried out during the operation and then during the closure works. Indeed, a zero state of the gallery and piezometers water quality was already carried out at the end of the inerting operation. The program of supervision is thus an adaptation of the previous follow-ups of the cavern, and there has never been a break of the technical supervision of the work during all of the successive phases of its existence.

The supervision of the level of the groundwater is carried out by means of quarterly measures of the height of water in eight piezometers located around the storage and four wells in neighbouring potable drinking water fields. Two piezometers are also equipped with a daily recorder.

The supervision of the water quality consists of the analysis of the water taken from the eight surrounding piezometers, from the four wells of neighbouring potable drinking water fields and from the former storage gallery. These analyses are carried out every six months in periods of low waters and high waters and concern total hydrocarbons, methane, ethane, propane and butane. Mercaptans and BTEX (benzene, toluene and xylenes) are also analysed.

After two whole years of technical follow-up, the post-closure situation of the storage does not present any particular problem, whether it is from the hydrogeological or the chemical point of view.

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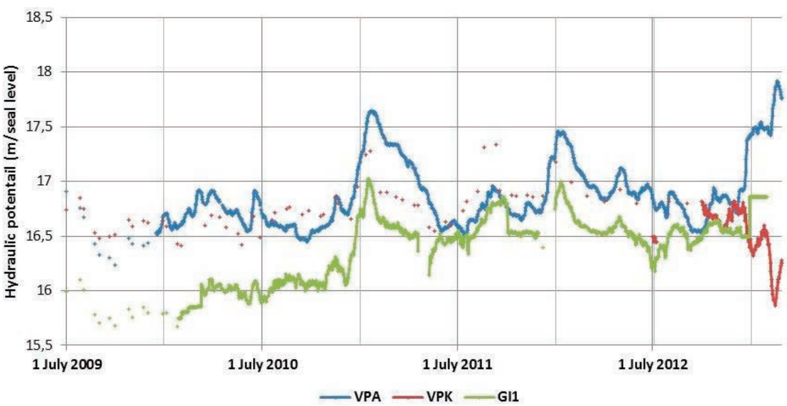

Fig. 4 *Variations of hydraulic potentials in some monitoring piezometers.*