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An example of a comprehensive technical and administrative mine closure process on the Urcuit mining site (France)

A Lecomte *French National Institute for Industrial Environment and Risks (Ineris), France*

A Charmoille *French National Institute for Industrial Environment and Risks (Ineris), France*

F Laoufa *French National Institute for Industrial Environment and Risks (Ineris), France*

S Rupasinghe *French National Institute for Industrial Environment and Risks (Ineris), France*

P Gombert *French National Institute for Industrial Environment and Risks (Ineris), France*

Abstract

The salt mine of Urcuit is located on the Southwest of France near Bayonne between the Pyrenean piedmont plain and the Adour valley. First mine shafts were sunk at the end of the 19th century. Then, exploitation, which lasted more than a century, consisted to mine out a Triassic salt deposit located between 20 m deep to 200 m. Several solution mining technics have been used creating cavities. Some of which are still opened in underground. Locally in the past, depending on the method of exploitation used and the geological and hydrogeological contexts, subsidence or collapses have been observed at surface. In 2013, the mining operator, according to Mining Code, has initiated studies for mine shutdown and has entrusted Ineris for the realization of all the technical documents of the official report (named DADT).

Ineris provided technical and administrative support to the site operator throughout the abandonment process. Thanks to 2-year field investigations, Ineris was able to understand the geological, geotechnical, and hydrogeological contexts of the mining site to assess, on the long term, the stability of the known cavities. Investigations carried out on surface and underground waters showed that dissolution processes are always running on Urcuit site, but their extent and magnitude were greatly reduced, following the end of operations and thanks to the surface works performed. The feedback analysis of the measurements of ground movements and the knowledge of the current state of the cavities (volume, shape, depth) were used to evaluate residual ground movement on the surface. Geomechanical study of cavities stability using numerical modelling and taking account the viscoplastic behaviour of salt has also complemented this evaluation. Thus, the risk assessment for ground movements and the definition of their surface area show that the repercussions almost exclusively concern the perimeter of the operator's property. Considering this land use, Ineris has proposed innovative and adapted solutions to monitor and secure this complex site. Validated by the mining authorities in mid-2017, these recommendations (cavity pressure monitoring, water quality monitoring, closure of boreholes, etc.) are currently the subject of a second phase of monitoring and work on the site.

This paper will describe the results of technical studies conducted on the Urcuit mine to identify risks and, for each one, the mitigation works defined that are currently implemented.

Keywords: *post-mining management, salt deposit, dissolution exploitation, ground movements, land safety*

1 Introduction

Mining operations at the Urcuit site, located in the French Atlantic Pyrenees, took place over a period of nearly 120 years and consisted in extracting Triassic salt (halite) deposits by solution mining.

Various solution mining techniques were employed. These systematically created cavities. Locally in the past, mining was carried out intensively, which destabilised the cavities, leading to subsidence or surface collapses Nevertheless, a large number of cavities, among the most recent, are still present in the subsoil, open and not collapsed.

In 2010, the mining operator decided to cease exploitation and in accordance with the French mining code, initiated the Definitive Declaration of Cessation of Mining Operations and Use of Mining Facilities (*Dossier de Déclaration d'Arrêt Définitif des Travaux miniers et d'utilisation d'installations minières – DADT*)

In the context of establishing this type of declaration, the operator was asked to write up a precise assessment of the current state of the mining site, as well as to evaluate the residual hazards and risks. This makes it possible, if necessary, to define compensatory measures aimed at mitigating or even eliminating these risks.

Even though this mining site covers a relatively small area (less than one square kilometre), it brings together a number of different and very contrasting geological, mining and hydrogeological configurations that give it remarkable complexity. Its hydrogeological context, in particular the shallow depth of the salt layer and the permeable overburden due to hydraulic interconnections created by the mining operation (collapses or subsidence), results in the occurrence of solution phenomena, underground brine circulation, and persistent saltwater resurgences. In addition, many cavities are still open and some of these are likely to collapse in the short or medium term. These developments are all the more probable given that a natural underground solution and drainage system persists in the vicinity of the cavities.

This specific context required answers to be given in the context of establishing the cessation declaration, in order for it to be accepted by the Administration.

This article presents the works carried out during the first phase of the cessation of operations declaration, which took place from 2011 to 2016. This initial phase involved defining the residual risks associated with the former Urcuit salt mining operation, as well as identifying the compensatory measures and safety work based on the available knowledge Even if some of these methods are novel because they were adapted to the specific context of the site, they were validated by the Administration in 2017, thereby allowing the operator to initiate the second phase dedicated to site safety and monitoring work. This second phase, which was initiated in 2018 and is still underway in 2023, should lead, in a few years, to restitution of the site to the State, as provided for in French administrative procedure.

2 Presentation of the former operation

2.1 Elements of the geological and hydraulic context

2.1.1 Geological context

The Urcuit salt deposit is located within Triassic formations present in the form of a thin shell of terrain, rooted towards the north under Tertiary formations. The top of the salt deposit is situated at a depth of between 20 and 40 m on average in the southern part of the site and reaches a depth of over 150 m and 230 m in the eastern and the northern parts of the site respectively. Where the deposit is at its shallowest (in the south), its thickness is also least (20 to 50 m), whereas in the western and eastern parts of the site, it exceeds 150 m.

In the central and southern part of the site, the deposit is only covered by marly Triassic terrain. Towards the north, the marly and sandstone flysches of the Cretaceous give way to the marl-limestones of the Tertiary covering the Triassic terrains.

The deposit is bounded to the south and west of the site by Triassic land outcrops and to the east by a fault oriented N20°. In the north, the limit is unknown since the deposit is lodged at depths that have not been probed by drilling (Solvay, 1963).

2.1.2 Hydrogeological context

The former mining zone is characterised by two types of surface water: flowing and stagnant water within bodies of water (Figure 1). Some of these bodies of water are the consequence of ground movements caused by the operation, whereas others are natural or artificial ponds. The main body of water located in the middle of the site, was created during mining operations in order to hold any brine discharges in the event of collapses of cavities located in the northern part of the site.

The salt mining site is crossed from west to east by the Hourgatxa stream. This stream is fed by three equally perennial flows. Two come from the west of the mining site; their confluence is not far from the boundary of the mining claim. The third, the Larriat, flows in from the north. Before 2006, this flow rejoined the Hourgatxa stream after crossing the largest of the collapse craters in the north zone. Today the Larriat has been diverted and bypasses this crater.

The Hourgatxa crosses a number of bodies of water. This stream is a tributary of the Ardanavy, a watercourse located in the east, outside the mining zone (Figure 1).

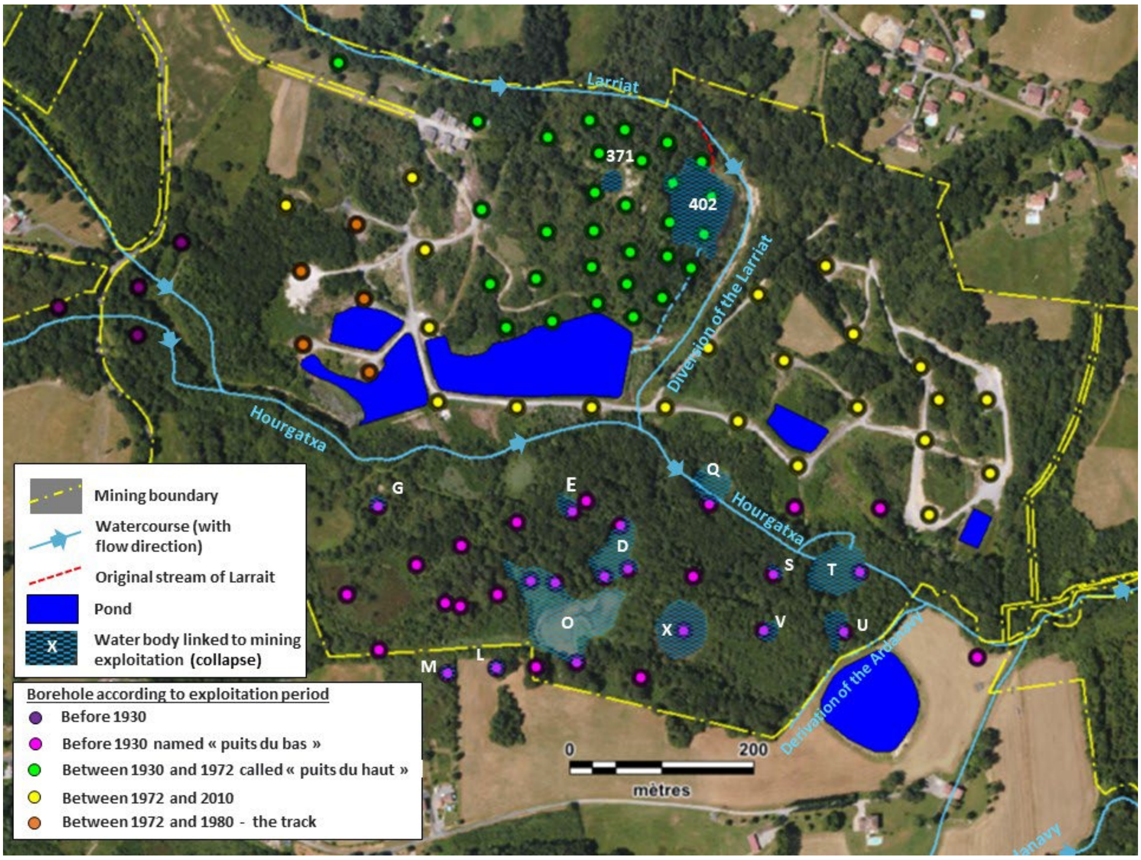

Figure 1: Surface water at the Urcuit salt mine and exploitation sectors delimited according to exploitation periods

2.2 History and mining methods

Salt mining on the Urcuit concession took place from 1890 to 2010. Four different mining periods have been identified according to the location of the boreholes and, more specifically, to the mining method implemented (Solvay, 2001, Sanglerat, 1987 and Inkmann, 1986).

At the start of mining, work was confined mainly to the south of the Hourgatxa stream, where the salt was closest to the surface. Up to 1908, 13 boreholes were drilled in the east and west of the site. Most stop at the top of the salt deposit (at a depth of about 30 to 40 m) or penetrate it slightly (shown in pink in Figure 1). These boreholes were mainly drilled to define the extent of the deposit with a view to extending the concession.

Between 1926 and 1930, 22 additional boreholes were drilled, constituting the zone known as 'puits du bas' (shown in pink in Figure 1). Mining, via isolated boreholes, is carried out by injecting fresh water into the mass of salt (case a., Figure 2), either by injecting fresh water into the top of the salt deposit (case b., Figure 2), or into the top by pulsed injection (case c., Figure 2).

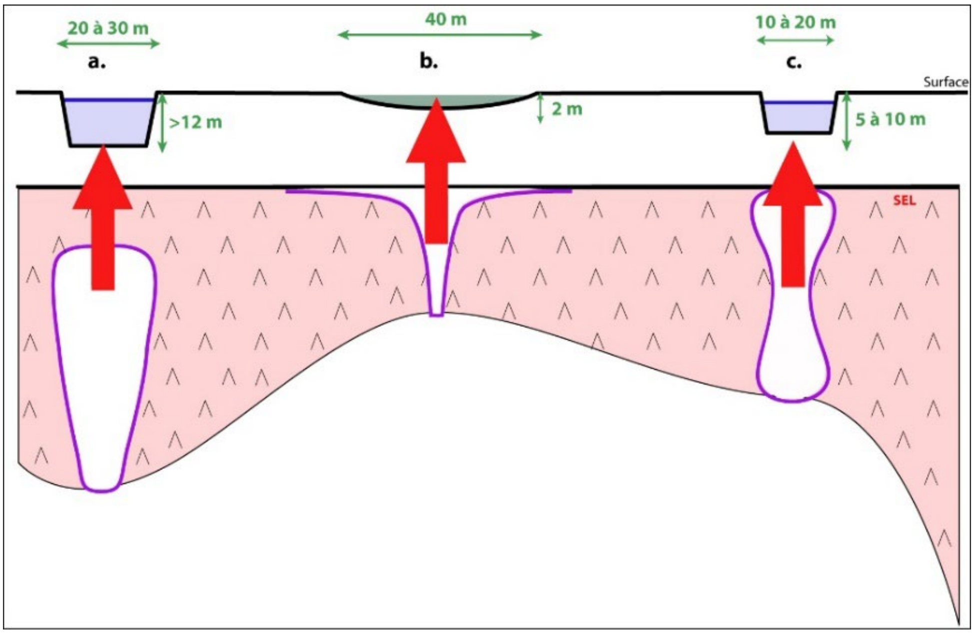

Figure 2: Configuration of the disorders observed in the sector of the 'puits du bas' according to the different mining methods a) into the mass of salt, b) into the top of the salt c) into the top by pulsed injection (source: Ineris)

At the surface, depressions of varying sizes, most of which are now ponds, correspond to the surface effects of cavity collapse. It can be shown that the characteristics of these depressions depend mainly on the mining method implemented.

In the 1930s, mining operations moved to the north of the Hourgatxa stream. Between 1934 and 1963, 29 boreholes were drilled (known as the '*puits du haut'*– in green in Figure 1) spaced about 40 metres apart. Mining is carried out throughout the entire thickness of the salt with extraction via isolated cavities. These boreholes are located in a zone where the salt layer is deeper and generally thicker (on average: 170 m deep and 100 m thick). In this sector, known as the 'puits du haut', the closely spaced boreholes used to extract the salt have become interconnected. The absence of a salt pillar supporting the top of the cavities led to the occurrence of two large collapses.

From 1972 to 2001, 26 boreholes were drilled north of the Hourgatxa stream, with a first cluster in the northeast of the site, a second to the west of the boreholes known as the 'puits du haut' and finally a third running along the path bordering the large basins (shown in yellow in Figure 1). These boreholes, located to the east and to the west of the site, have revealed that the characteristics of the deposit vary a great deal with the depth of the salt top varying between 25 and 160 m. Mining conditions have remained unchanged, but some changes have been made in order to avoid further collapses. A salt pillar of approximately 30 to 40 m is left to support the top of the cavity and prevent it from collapsing and a distance of 80 m is established between the boreholes in order to leave at least 30 m of intact salt between two neighbouring cavities.

From 2001, a series of easily connected isolated boreholes was converted into a track (Antea, 1998): boreholes 723, 801, 802, 805 and 807 located to the northwest of the site (shown in orange in Figure 1). A track corresponds to systematic mining of the deposit along a line of boreholes whose bases connected at the base by dissolution. Mining is carried out by dissolution, by injecting fresh water into one end and pumping brine out of the other end. Dissolution thus progresses both along the track axis and vertically until it mines away the entire thickness of the salt. A specific feature of this method is that it leads to the deliberate and controlled collapse of the surface terrain.

Mining was stopped in 2010 following closure of the site for economic reasons. During the stoppage, the brine was mainly extracted via the track. This operation, which continued for about ten years, was not completed. The expected collapses did not occur because the size reached by the cavities at this stage was not sufficient. There thus remains, in this northwest sector, a set of connected cavities with a residual salt thickness at their summit of 20 to 70 m.

2.3 State and development of the cavities

92 boreholes were drilled on the former Urcuit salt mining site (79 extraction boreholes and 13 reconnaissance boreholes). Only 41 boreholes have been physically identified on the surface, by dint of their heads protruding about thirty centimetres from the ground, during investigations carried out upon the cessation of mining.

During mining, and more recently in 2013, the accessible cavities were inspected using SONAR in order to more precisely establish their geometry and depth and to characterise any changes that have occurred since previous investigations, when the site was still being mined. The diameter of the known cavities is between 20 and 60 m on average and reaches 110 m in the track sector (Figure 3). Comparison of different SONAR runs has revealed the absence of changes in almost all of the cavities.

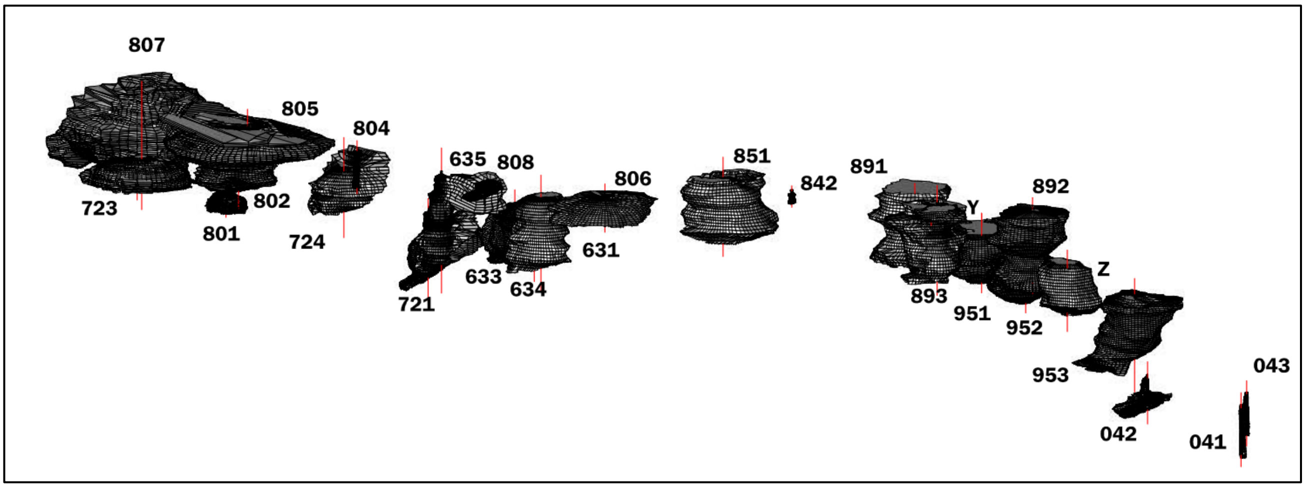

Figure 3: 3D view, from the south with a 10° overhang, of the cavities inspected by SONAR (Source: Flodim)

In order to evaluate the rates of closure of the cavities by creep, and their long-term surface effects, numerical modelling was carried out. The mechanical stability of the top of the cavities was also assessed These computations were performed for all cavities with known geometry (about 30).

There are no geomechanical measurements on the site to characterise the materials present (overburden and ore). Mechanical properties were adopted by analogy with other sites where they are known (salt parameters from Cerville (France) and Asse (Germany)). This transposition was done with a conservative approach to stability. Other hypotheses were also considered with the same conservative approach (intercalation of marly horizons within the top salt layer, heavy materials for the overburden).

The results obtained show a low creep amplitude, given the relatively low depth of the cavities (the deeper ones are at a depth of 200 to 250 m). The highest computed rates of deformation are in the order of 0.3% of the cavity volume over a period of 500 years and this is for empty cavities (this approach is the most unfavorable because the cavities will continue to hold brine in the future). These creep rates will not generate perceptible ground movements at the surface on a human scale. The stability computations show that, in the current situation (cavities filled with brine under pressure), the indications of instability are not very significant for the set of configurations studied. Indeed, in the most critical case, where the extension of the cavity is the greatest with a limited thickness of salt at the roof of the cavity, the results show that plasticity develops only on the extremities of the lower salt bank (Figure 4).

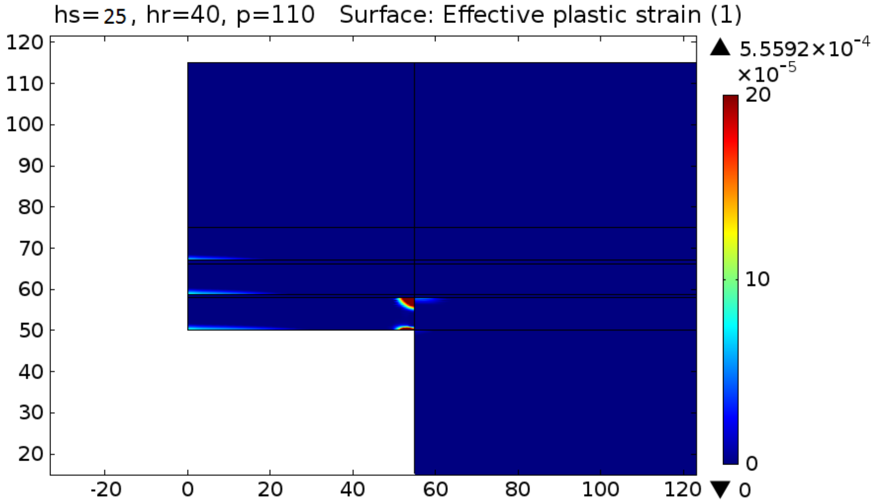

Figure 4: Spatial distribution of the effective plasticity developing for the cavity whose width is the most critical and in the case where the cavity is filled with brine (hr = overburden thickness; hs = thickness of the salt layer at the roof of the cavity)

2.4 Hydrogeological behaviour

The specific context of the Urcuit deposit and its mining has inevitably led to interconnections between surface waters and the salt present at depth. These interconnections could have come about either naturally via the overburden, which is very thin locally (less than 20 m in the southern sector), or through collapses. The system is therefore hydraulically open. The salt deposit can thus be the site of active dissolution if there is a flow dynamic between the surface fresh water and the deposit.

A saline load drained by the hydrographic network crossing the site has been identified in previous studies. In 1997, the flow was evaluated, during low water periods, at 34 g.s^{-1} of chlorides, which is approximately 56 g.s^{-1} of salt (Combes and Ledoux, 1997). This salt flow, calculated with a theoretical average flow of the Hourgatxa of 60 l.s^{-1}, indicated the existence of active dissolution of salt at depth.

The additional investigations that were carried out, following the cessation of operations on underground water (piezometers) and surface water (streams and lakes) made it possible to assess hydrogeological function.

Before 2006, the salt flow draining from the site outlet into the Hourgatxa stream came from dissolution taking place on the top of the salt deposit, starting with flows established between:

- the collapse zone of the northern part of the site and the part located to the south. The freshwater load imposed on the collapse lakes and neighbouring terrain was sufficient to generate a flow of fresh water towards the salt deposit. This inflow of fresh water resulted in dissolution of the salt at the top of the deposit. The brine produced was then drained to its outlet following the top of the salt. The outlet was located at the lowest point of the site. This is a characteristic function of a saline water table developing in the top of a salt deposit. Dissolution progresses towards the upstream dip of the deposit (the up-dip effect);

- the local high points of the southern part of the site and the collapse lakes of this zone. A saline water table was established in this sector according to the same behaviour pattern as described previously.

These two elements probably led to the development of a single continuous saline water table in the salt top across the entire Urcuit site.

After 2006, the Larriat stream, which had hitherto flowed into one of the two craters in the northern zone of the site, was diverted (Figure 1). This resulted in altered hydrogeological function with two more localised dissolution entities. The first, in the north, resulted from the isolated function of the two collapse craters (lakes and damaged zones around them): the higher one had become an entry point for freshwater, the lower had become a salt outlet. This was due to the reduced inflow of fresh water into the lower crater following the diversion of the Larriat. The second was linked to local function in the southern sector. Due to the low permeability of the geological formations and minimal load differentials, the activity of this aquifer is very limited. Overall, the dissolution activity of the top of the salt deposit reduced considerably between these two periods. The output salt flow had fallen by a factor of five, i.e. 12.5 $g.s^{-1}$ of salt in 2013.

2.5 Analysis of ground movements linked to the former mining operation

The levelling network established by the operator has made it possible to characterise the presence of low-amplitude subsidence, attributed in part to salt dissolution and in part to slope movements in the vicinity of craters due to the collapse of cavities (slope movements).

In-depth study of the hydrogeological context and its behaviour has revealed the presence of low-intensity active dissolution in the top of the salt deposit. The loss of material induced by the dissolution of salt in the top of the deposit is continuously offset by the gradual settling of the overburden, resulting in surface collapses.

Since the 1990s, more levelling data has been available and for a denser network. During this period, the intensities measured varied but remained low: in the order of a centimetre per year at most. A net slowing in the subsidence rate was noted as of 2006, the year of diversion of the Larriat, thus validating the connection between the subsidence and the dissolution of the salt deposit top (Figure 5).

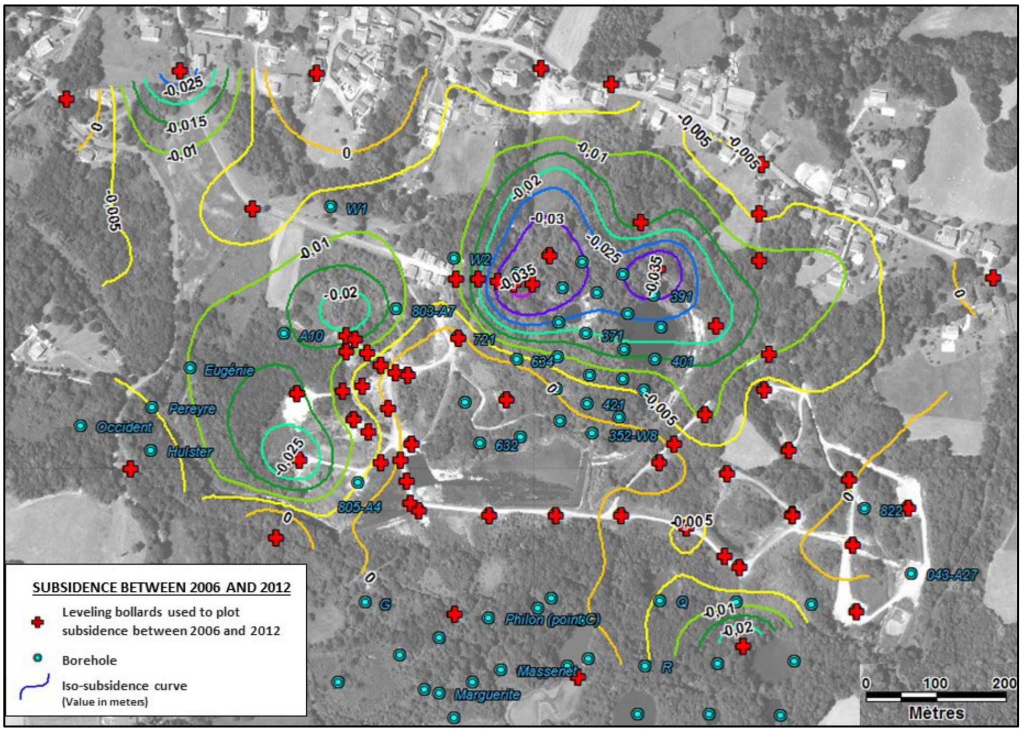

Figure 5: Vertical displacement of the ground between 2006 and 2012

3 Impacts in terms of ground movement

Long-term ground movement assessments have mainly been carried out according to the mining methods implemented (mining depth, salt thickness in the tops of cavities, existing interconnections, etc.) and knowledge of the cavity conditions acquired through SONAR investigations. The feedback analysis of known ground movements at the site (subsidence and collapse) as well as the geomechanical study of the stability of the cavities derived from the results of digital modelling made it possible to specify the hazard levels adopted, depending on the sectors. There are three types of ground movements at the Urcuit site: subsidence linked to dissolution process, general collapse of saline cavities, slope movement” linked to the collapse craters.

3.1 Subsidence-type ground movements linked to dissolution

The hydrogeological changes induced by salt mining may lead, permanently or for prolonged periods, to flows of low or unsaturated water at the surface of salt layers. When active dissolution is established at the salt-terrain interface overburden, if the underlying terrains are mechanically weak (clays, marls, alluvium, etc.), the loss of material caused by dissolution at this interface will be continuously offset by the gradual lowering of the overburden, thus creating surface subsidence as is the case at Urcuit.

The predisposition to the phenomenon of subsidence linked to dissolution of the salt in the top of the layer is assessed by taking into account the possibility of the arrival of fresh water in the top of the salt deposit, the dip in the top of the salt deposit and past or still-active ground movements. Based on the three criteria defined above, two dissolution zones can be distinguished: the first extending from the craters in ‘puits du haut’ zone up to the Triassic outcrop boundary south of the site and the second concentrated in the ‘puits du bas’ zone. The predisposition of the first is assessed to be highly likely where ground movements are currently active, and unlikely in the remaining zone (recent but currently limited or even non-existent ground movements). The predisposition of the dissolution zone originating from the ‘puits du bas’ is qualified as unlikely, considering the limited ground movements observed.

Subsidence intensity classes are defined by considering the ground sloping effect (Salmon, 2019). For both of the zones concerned, the slopes calculated using known levelling data ('puits du haut' zone) and salt flow ('puits du bas' zone) were between 0.06 and 0.1%, in other words, a very limited intensity.

By cross-referencing predisposition and intensity, the level of hazard of subsidence linked to dissolution of the salt in the top of the layer is qualified as moderate within the active dissolution zone south of the collapse craters in the 'puits du haut' sector, and as low in the 'puits du bas' zone.

3.2 Collapse-type ground movements linked to mining cavities

The generalised collapse characterises a movement of significant spatial extension. It manifests itself as the often dynamic rupture of the mining cavity, thereby affecting the stability of surface terrains over areas that can span several hectares. Here, the dreaded phenomenon results from the delayed rupture of the top of the cavity, whose size has finally exceeded a limit value that assures the stability of the structure.

In order to assess the predisposition for the occurrence of mass collapse phenomena in former saline cavities formed by dissolution, one should particularly take into account the presence of saline cavities of large horizontal dimensions located at shallow depths, possible interconnections between the cavities, sometimes reduced separation between the cavities, the type of mining, uncertainties regarding the quality of the salt deposit in cavity tops, the thickness of the salt in cavity tops and uncertainties regarding the dimensions of some cavities. In this way, based on the items just detailed, the predisposition for mass collapse phenomena linked to underground cavities is defined as:

- Highly likely for boreholes used for mining within the salt mass where the salt thickness in the cavity top is low (<20 m) and where interconnections are known or suspected.
- Likely for isolated boreholes used for mining within the salt mass where the salt thickness in the cavity top is low (<20 m) or when the distance between boreholes is small (<10 m), but with a salt thickness in the cavity top exceeding 20 m.
- Zero for reconnaissance boreholes and isolated boreholes drilled in the salt mass where the salt thickness in the cavity top is relatively significant (>40 m);

Generalised collapse characterises a movement of significant spatial extension, the occurrence of which, regardless of the magnitude of surface subsidence (directly linked to the start of operations), can jeopardise the safety of people and assets located within the area of instability. Anticipated events, of significant magnitude (significantly exceeding 20 m, as evidenced by previous collapses), make it possible to define a high to very high intensity level (Salmon, 2019).

Therefore, by cross-referencing intensity with predisposition, the level of hazard of generalised collapse linked to dissolution cavities is qualified as high for boreholes with a highly likely predisposition and moderate for boreholes with a likely predisposition. No risk level is adopted for reconnaissance boreholes and isolated boreholes drilled in the salt mass where the salt thickness in the cavity top is relatively significant.

3.3 "Slope movement" hazard linked to the collapse craters

Deep slope movements, specifically of the sliding type, are anticipated at the Urcuit site. They correspond to the mass movements that can occur on the land located uphill of the slopes of the collapse craters (ridge retreat effect). Deep slope movements are exclusively anticipated for collapse craters in the 'puits du haut' zone as well as crater E located in the 'puits du bas' zone. In fact, as these craters are not located at the same altitude as the neighbouring terrain (unlike other craters on the site), slope failures can occur.

Typically, the height difference between the water level and the crater rim is approximately 5 to 15 m, resulting in a moderate gradient of around 30% depending on the area considered. The zone around the edge of the craters can be considered to have been strongly fragmented following the collapse, thus allowing surface water to infiltrate more easily into the massif. These zones are thus more liable to experience sliding-type movements. Based on the detailed information provided above and considering the levelling data (movements ranging from 0.02 to 0.5 cm/year since 2001), a likely predisposition of deep landslide is therefore adopted. The cumulative movements recorded by the levelling benchmarks (affecting a volume in the order of 500 m^3 since 2001) make it possible to define a moderate intensity level (Salmon, 2019). By cross-referencing the predisposition with intensity, the level of hazard defined for slope movement phenomena is moderate.

3.4 Risk assessment

The risk assessment for ground movements and the definition of their surface area show that the repercussions almost exclusively concern the perimeter of the operator's property. The issues were defined taking into account the current state of the site; in other words, a site closed to the public, to which only personnel involved in site operations are permitted access. Thus, considering the issues, the risks are assessed as low to medium for the entire site (Table 1).

Table 1 Assessment of risks linked to ground movements

Hazard		Target	Risk
Subsidence due to dissolution	low	Site personnel + traffic lanes	low
Subsidence due to dissolution	medium	Site personnel + traffic lanes	
Collapse of cavity	high	Site personnel + traffic lanes	medium
Collapse of cavity	medium	Site personnel + traffic lanes	low
Collapse of cavity	negligible	Site personnel + traffic lanes	negligible

4 Measures to mitigate ground movements

4.1 Subsidence-type ground movements linked to dissolution

The subsidence phenomenon is directly linked to the various inflows of fresh water into the system. There is no reasonably feasible technical solution that will significantly reduce or halt the phenomenon. Completely sealing all of the craters to minimise the freshwater flow into the salt deposit seems excessive compared to the effects of dissolution in the salt top and its associated risks. Nonetheless, the measure to close the boreholes located north of the collapse craters in the northern zone has been retained in order to limit inflows of fresh water into the system upstream of this zone.

4.2 Ground movements linked to cavity collapse

Few technical solutions can be applied to avoid the occurrence of such collapses. Elimination of the risk at source is a possible solution but it would require the implementation of considerable technical resources without any guarantee of success. This might involve collapsing the cavities or even completely filling them in. In the first case, the resources to implement this either no longer exist at the site (for resuming dissolution) or could not reasonably be considered (explosives, for example). In the second case, limited knowledge of the cavities (in the case of the 'puits du haut') and the difficulties of access make it improbable to foresee a positive result. In this context, it was only decided to put up fences around the most critical (high hazard) zones to prevent access to them, with the obligation to check them regularly.

4.3 Slope motion linked to crater rims

A hazard of deep slope movements has been defined for the steepest collapse craters. In order to block access to these sectors and thereby minimise the risk to personnel, it was only decided to implement fencing with the obligation to check them regularly.

4.4 Securing structures leading to the surface

There are no longer any specific reasons to keep open boreholes that are not at hazard of collapse (i.e. cavities assessed as stable). The “conventional” principle of sealing boreholes is aimed at maintaining their long-term hermeticity in order to avoid any contamination of the aquifers and enhance the stability of the cavities. At the Urcuit site, there are no exploitable aquifers in the overburden. The few flows of fresh water are limited in number, unevenly distributed throughout the site and at shallow depths.

Based on the calculations performed, the expected creep will be low over a significant period. The expected brine leaks through casings that would be left completely open are evaluated at less than 5 m^3/year (upper bound estimate). This amount of brine will not have any impact on the environment. It amounts to no more than a few litres per hour. The leaks will be distributed across the site and will mix with interstitial groundwater already highly concentrated in salt in a very low permeability environment. The small quantity of this water reaching the surface will be quickly diluted by surface waters.

While considering the “classic” method of borehole abandonment and the various contextual factors at the Urcuit site, an adapted method of treatment has been proposed. This method involves placing a cement plug into and onto the head of the casing at a height sufficient to counteract the pressurisation of the cavity that will develop as a result of salt creep. All cavities that have been sealed are cavities deemed to be stable in their current state over the long term. The additional pressure induced by their sealing will therefore provide an extra margin of stability. This plug minimises the leakage of brine into the environment caused by defects in the casings and potentially in the cement work around the casings underneath the plug. We reiterate that increased leakage resulting from significant deterioration of these components would have no impact on the environment and is considered negligible, even for open casings. The free casing below the cap is filled with brine to ensure maximum halmostatic pressure before any additional pressurisation due to creep.

Compared to conventional methods of abandonment that are technically much more complex to implement (in particular those consisting in placing a plug directly in contact with the salt), the proposed adaptation preserves the minimum objectives of no environmental impact and cavity stability.

5 Impact on ground and surface water

The investigations carried out have shown that dissolution processes are still active at the site. Their magnitude, however, has been greatly reduced and is now limited, following the developments carried out and probably also since the cessation of mining activity.

As regards surface waters, it has been shown that the residual salt flow draining from the site outlet is not perceptible in the Ardanavy river (into which the Hourgatxa flows). This is true in periods of both low and high water.

Salt concentrations in the groundwater of the superficial aquifer at the outlet of the site were very low in 2011–2012. After 2013, a resurgence in salinity that reached several grams of salt per litre was observed and must be monitored, even if this salinity remains low.

In the event of collapse of saline cavities, the possibility cannot be excluded, depending on the sectors considered, of an outpouring of brine occurring outside the craters, thus temporarily contaminating the surrounding environment.

Given the abrupt nature of the opening of a collapse crater at the surface and therefore of the associated resulting overflows, and given the estimated volumes of brine, the impact on fauna and flora can be considered major if no compensatory measures are implemented. Several hundred or even thousand cubic metres of saturated brine could be drained though the hydrographic network (Hourgatxa, Ardanavy), causing probable destruction of fauna and flora as the dilution effect of the waterways will be insufficient.

6 Measures to reduce impacts on ground and surface water

In order to minimise major discharges of brine into the environment, several technical solutions have been defined. For the track and 'puits du haut' sectors, dilution basins as well as a dam, located further down from the boreholes, had already been set up during mining operations in order to manage possible brine discharges following the collapse of cavities.

To evaluate the expected volumes of brine in the event of cavity collapse, calculations were performed that consider cavity volume, depth and insights from the collapse of a salt cavity at another site in Lorraine (Daupley, 2013). Thus, for the track and 'puits du haut' sector, the expected total discharge volume was in the order of 12,000 m^3. Taking the average depth to be 1 m, the two dilution basins situated north of the site can hold about 4,000 m^3 and 12,000 m^3 respectively. Connecting these reservoirs would enable them to contain the predicted brine discharges in the event of collapse.

These volumes were calculated for the empty basins. It is therefore necessary to keep the basins empty, clean, and maintained, with their interconnection permanently open. The brine would then be directed towards the Hourgatxa with its flow controlled by a valve installed at the confluence of the basins and the stream. The objective is to dilute the brine using the freshwater flow from the Hourgatxa, before it exits the site. The flow of brine will therefore depend on the flow of the Hourgatxa and will be controlled based on mineralisation measurements taken at the control point at the site outlet.

No treatment is planned for the 'puits du bas' zone; a catch basin solution like the one in place for the north sector is not technically feasible for this the sector. Nevertheless, the presence of the various craters at the site outlet and the successive dilutions contributed by the Ardanavy and its branches help to reduce the concentration of brine in the water in the event of a collapse in this sector.

7 General monitoring and prevention measures

7.1 Ground movement monitoring

The surface monitoring network, mainly installed alongside the mining zones, has been monitored since 1964. Since mining ceased, the network has been properly spatially redistributed and benchmarks have been added to cover the whole sector.

To ensure that the sectors at risk from salt dissolution do not change significantly over time, level monitoring continues at the site boundary (annually), confirming the absence of ground movements at the property boundary and at the benchmarks located outside the high-hazard zone (every two years).

In order to identify ground movements associated with any possible instability of the cavities and to guarantee the safety of personnel needing to access the site, two other monitoring activities are carried out:

1. The first involves ground level monitoring of the terrain located near the stretch of road impacted by the high-level risk of collapse (Figure 6). Due to the prohibition on access to this sector, levelling measurement is done remotely and carried out once a year at three control points, located directly above three boreholes on the track in a high-hazard zone.
2. The second involves monitoring of the hydraulically connected zones (track and 'puits du haut' sector) by means of two boreholes equipped with pressure sensors (Figure 6) that make it possible

to monitor the development of the cavities: creeps, collapse of a salt bed, etc. The data is monitored remotely and in real-time using a web monitoring service (the ecenaris platform). A warning system enabling site evacuation was set up in order to be able to react in the event of significant developments in the cavities. The warning activates in the event of sudden and repeated changes in pressure. It is broadcast across the site as an audible signal to warn any personnel present. A semi-automatic e-mail is also launched in these cases.

7.2 Water monitoring

In order to confirm that the former mining site will not contaminate surface aquifers at the site outlet, long-term automatic monitoring of the surface aquifers was set up using a multi-parametric sensor (temperature, conductivity, pressure) in the piezometer located at the site outlet (Figure 6).

In addition, the salt flow into the Hourgatxa is monitored at the retention basin outlet and at the site outlet. Water conductivity is continuously measured, as is the flow of the Hourgatxa, in order to detect any change in salt intake and any possible environmental contamination. This monitoring also makes it possible to check for potential accidental discharges of brine into the environment in the event of cavity collapse. The system installed at the basin outlet is connected to a warning device set for a salt concentration exceeding 10 g/l (a value that cannot be produced naturally and which reflects a massive release into the environment). Exceeding this value results in closure of the basin valves to control the discharge into the Hourgatxa.

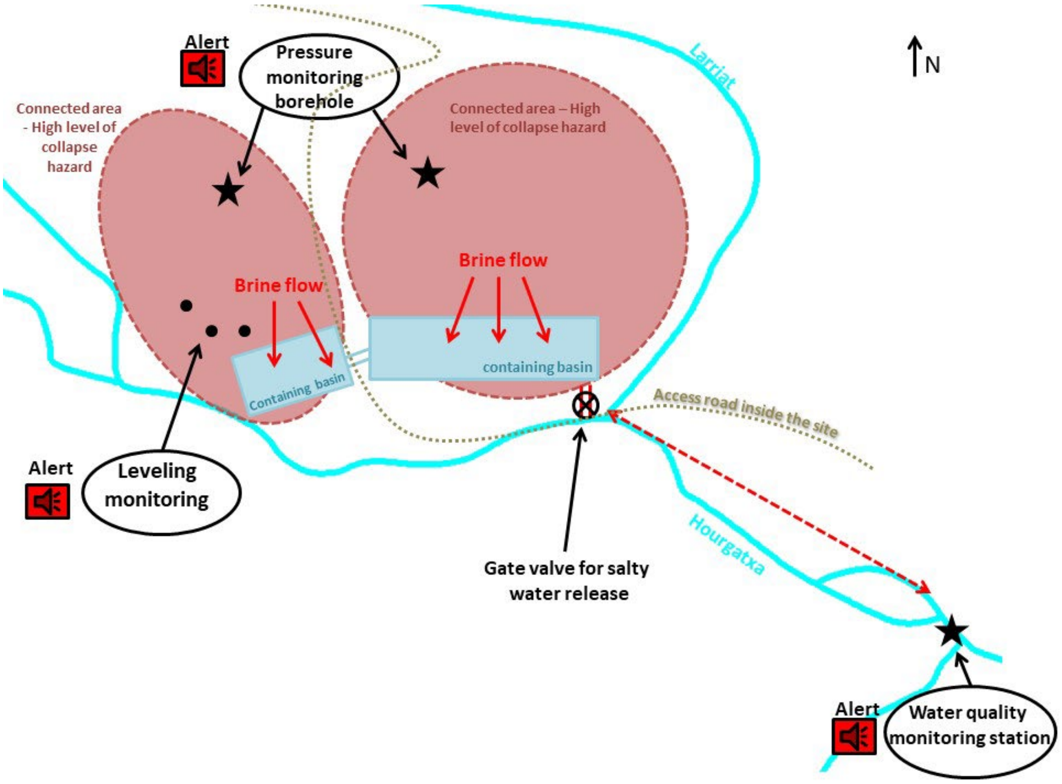

Figure 6: Synoptic diagram of the monitoring defined on the Urcuit site

8 Safety and monitoring works

The first phase of DADT has made it possible to define the residual risks as well as the related compensatory measures to implement at the Urcuit site, with the aim of returning the site to the State, as provided for by French administrative procedure. Since 2018, the operator has thus implemented the recommendations made and the recommended works.

8.1 Borehole pressure monitoring

In order to detect any possible instability in the cavities and to ensure the safety of personnel needing access to the site, monitoring of the hydraulically interconnected zones (borehole track zone and 'puits du haut' zone) was implemented in July 2018.

8.2 Closing the boreholes

In accordance with the stipulations, borehole closure works began in 2019 with preliminary reconnaissance work and the filling of the borehole columns with brine. This last phase made it possible to observe that the apparent compressibility of the cavities turns out to be higher (by an order of magnitude) than what was "normally" expected. Therefore, the volumes of brine necessary to replace the existing fluid in the borehole columns prior to treatment proved to be larger than originally planned. Hydraulic interconnections that were initially unknown have now been observed, requiring the closure protocol to be modified for some boreholes. Finally, the stabilisation times observed for the level of brine in the columns of the boreholes were longer than expected, meaning that they could not be sealed immediately after being filled with brine.

8.3 Water monitoring and implementation of the dilution basin

In 2023, only the conductivity sensors had been installed in the Hourgatxa and in the piezometer at the site outlet. This data is checked regularly to ensure that environmental contamination remains in line with forecasts and is intrinsically limited. Works to drain the basin have not yet been carried out. Additional investigations carried out during drainage and cleaning of the basin have shown that the dykes around the basin need to be reshaped in order to contain the brine in the event of cavity collapse. According to the schedule, the system should become operational in 2024.

9 Conclusion

Mining at the Urcuit site, at all times, consisted in injecting fresh water into the top or into the salt mass in order to dissolve the salt deposit and pump out the resulting brine. These mining methods have resulted in dissolution in the top of the salt or, in most cases, cavities within the salt mass.

In order to define the ground movement hazard resulting from this mining operation, studies were carried out of the hydrogeological function of the site, cavity configurations (via SONAR investigations) and ground movement monitoring using levelling techniques, and cavity creep and stability were modelled.

These various studies have mainly helped define the zones currently affected by the hazard of subsidence linked to the dissolution of the salt top, as well as other zones affected by the hazard of collapse linked to the instability of certain dissolution cavities. Since the extent of these risks is limited to the boundaries of the mining concessions, they currently do not affect any assets other than those owned by the operator. Therefore, the residual risks are generally limited.

For each of the identified risks, and where the level of risk justified it, compensatory solutions have been proposed to the extent that these are technically and economically feasible. These involve safety and/or monitoring work. Measures have been proposed to restrict access to specific zones (those at high hazard of collapse) and to seal off boreholes into stable, isolated cavities. The procedures for closing them have been defined. A relatively original principle for abandoning boreholes was implemented, suited to the specifics of the Urcuit site. This involved filling them with brine before sealing them only at the head. A large proportion of these boreholes were sealed in 2023. To maintain safe access to the whole site, a monitoring device combining continuous measurement of the pressure of certain unstable cavities with the levelling of their vertical alignment has been defined and implemented.

Finally, in the event of the collapse of one of the cavities, the presence of retention basins will permit gradual dilution of the brine into the environment. The conductivity sensor installed to temporarily monitor the development of the dissolution system will be maintained to issue an alert upon any accidental overflow of brine. This will allow measures to be taken to keep the brine contained within the basins. These works will be carried out in 2024.

At the end of all of these safety works and when the monitoring is all operational and specifically provisioned, the site may be returned to the State, as provided for by the French administrative procedure.

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