Crater Formation above Salt Caverns: Piston vs Hourglass

Salt Production

Keywords: Salt Caverns, Sinkhole

Abstract

Conditions leading to crater formation above salt caverns are discussed. Two bedded salt formations are considered: the Keuper formation in Lorraine (France), and the Permian Hutchinson formation in Kansas.

In these two cases, the cavern roof at the end of leaching had reached the top of the salt formation, allowing direct contact between brine and marl layers that compose the overburden of the salt formation. These layers are prone to weathering when in contact with saturated brine. Stoping takes place, and the cavern roof rises through the overburden. This process may take from several to dozens of years.

In Lorraine, stoping ends when the rising cavern top reaches a competent layer, the Beaumont Dolomite. Operators then lower cavern-brine pressure to trigger collapse. A rigid cylinder of rock (a "*piston*"), with a diameter often larger than 100 m, drops into the cavern, and a crater with initial vertical edges is created (Figure 1, top). The contour of the piston is circular, as a circle is the shape for which the ratio between perimeter and area is minimal.

In Kansas, no such competent layer exists. The cavern rises until the uppermost keystone in the bedrock at shallow depth is breached, permitting loose materials to flow into the cavern through a relatively narrow hole at the bottom of the sinkhole, as in an *hourglass* (Figure 1, bottom).

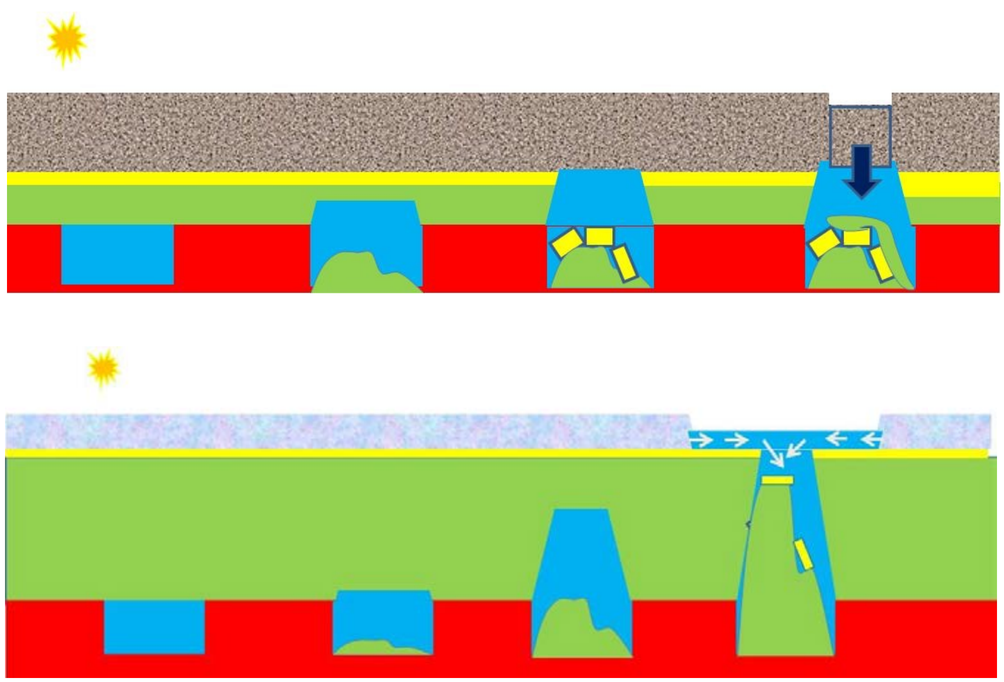

Figure 1. Piston (top) versus Hourglass (bottom)

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Lorraine craters

Three craters

Brine has been produced in Lorraine for more than a century. The stratigraphy is typically as follows: from 0 to 120 m, a succession of marls, limestones, sandstones (Rhetian aquifer) and marly anhydrite, whose strength is low. From 120 to 130 m, a competent Dolomite layer (Beaumont Dolomite); from 130 m to 183.5 m (top of the salt formation), poorly consolidated anhydritic marls; and below 183.5 m, the Keuper salt formation. In the 1990s, the Gellenoncourt and La Rape brine fields were operated by CSME and Novacarb, respectively, according to the "stable cavern" method. A 10-m thick salt layer was left below the top of the salt formation to prevent direct contact between cavern brine and overlying argillite layers. However, in some cases, the cavern roof reached the top of the salt. Two such cases were described by Buffet (1998) and Jeanneau (2005) (see Figures 2 and 3). Caverns were monitored. Stoping occurred. After several years, a large area was cleared below the competent Dolomite layer. It was decided to trigger cavern collapse at this point. Brine was pumped out, and air at atmospheric pressure entered the upper part of the two caverns. Several months later, collapse occurred. In both cases, the leveling system provided no warning — even 15 minutes before the final collapse

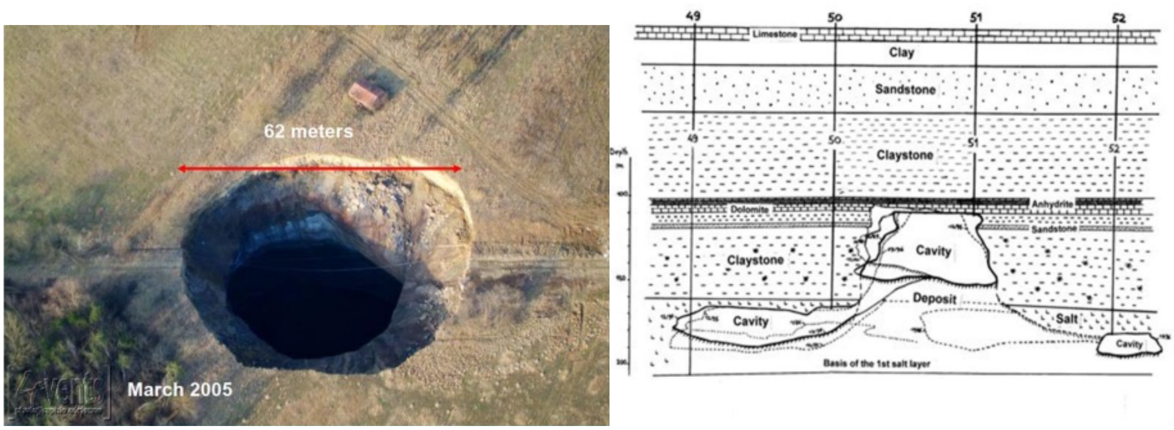

Figure 2. The LR51 crater in March 2005 (left) and cavern-shape evolution (right) [after Jeanneau, 2005].

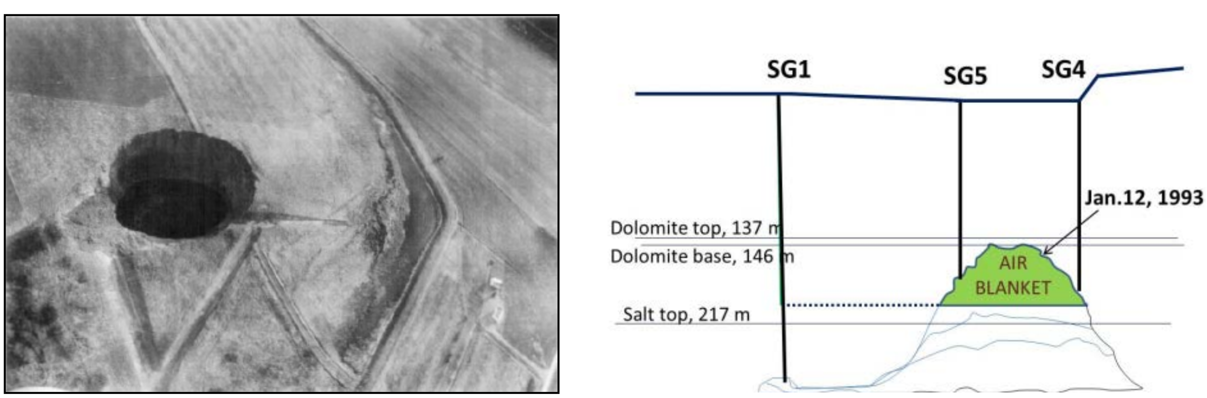

Figure 3. Vertical cross-section of SG4-5 after air injection (left); the crater on March 29, 25 days after the collapse (right) [after Buffet, 1998].

In the Cerville-Buissoncourt field, operated by Solvay, two parallel lines of wells were drilled. Water was injected in the first two boreholes, and brine was withdrawn from wells located several hundreds of meters away from the injection wells. A cavern developed up to the salt roof. When it reached the “critical” horizontal dimensions (determined by experience), injection stopped. Stoping took place until, several years later, the cavern roof reached the Beaumont Dolomite. The brine level then was lowered in the boreholes to decrease cavern pressure by pumping, which led to cavern collapse (Figure 4). Gisos, a scientific consortium, monitored the evolution and collapse of a cavern created during the 2002-2003 period (Klein et al., 2008; Daupley et al., 2013). Collapse occurred when the air/brine interface was still in the access boreholes. In sharp contrast with the La Rape and Gellenoncourt cases, where the collapse was abrupt, the Dolomite layer sagged by 0.5 m (and subsidence increased accordingly at ground level) twenty hours before the final collapse.

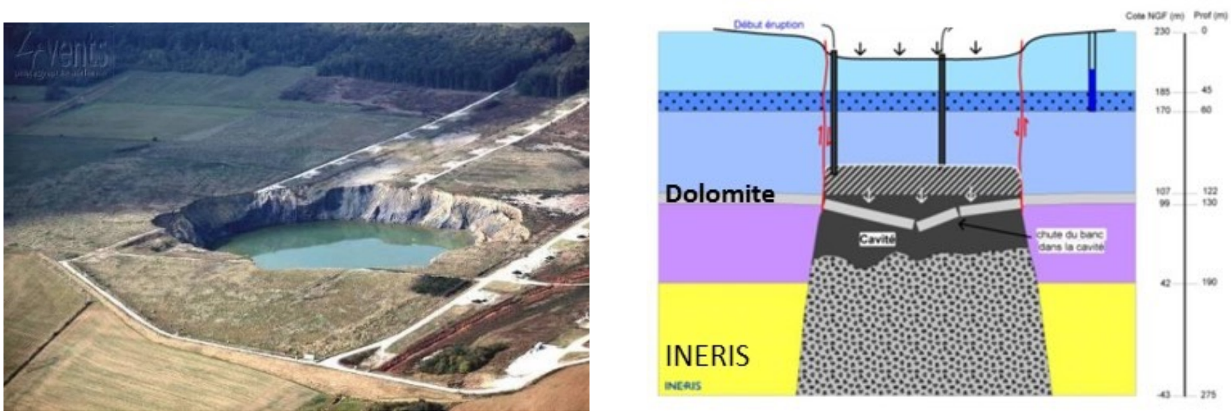

Figure 4. The crater at Cerville-Buissoncourt six months after the collapse. (Ackn. Solvay)

Lessons drawn from the Lorraine craters

Stoping

In these three cases, even when cavern roof reaches the top of the salt formation, cavern size and depth cannot lead to a sudden collapse, as the overburden is reinforced by the Beaumont Dolomite (and by several thinner anhydrite layers below the Dolomite), which prevents failure from propagating to ground level. The cavern roof must rise before the overburden is able to drop. This happens after the cavern roof reaches the top of the salt formation, allowing direct contact between brine and marls or argillites, which are abundant in the overburden. Boidin (2007) described the lithology of the 60- to 70-m thick interval separating the top of the salt formation from the Beaumont Dolomite. It is composed of a dozen interbedded anhydrite and argillite layers, through which the cavern roof rises incrementally. The argillite layers weather when in contact with saturated brine and the thin anhydrite layers sag and break, a progressive process which is both physico-chemical and mechanical. This process lasted 10 years at Gellenoncourt, and more than 3 years at La Rape and Cerville-Buissoncourt.

Ultimately, the cavern roof reaches the competent Dolomite layer. The areas cleared below this stiff layer were 1875 m^2 (Gellenoncourt), 4000 m^2 (La Rape) and 8-10,000 m^2 (Cerville-Buissoncourt). Stress conditions were not severe enough for the Dolomite to break. Brine pressure, which supports the Dolomite from below, must be lowered through brine withdrawal. In both cases, when a large enough area is cleared below the Dolomite layer, this stiff layer sags and tensile stresses develop, ultimately leading to Dolomite failure. When a breach is created in the Dolomite layer, a cylinder of rock above this hole can drop into the cavern. Remarkably, the mechanical behavior of salt plays no role in these collapses. (At such depths, cavern creep closure is exceedingly slow.)

The role of fluids during cavern collapse

In the La Rape and Gellenoncourt caverns, a large amount of air had entered the cavern before the collapse, although brine had been left at the cavern bottom (see Figures 2 and 3). The collapse was fast and abrupt. When the overburden collapsed, air pressure increased. At Gellenoncourt, rocky blocks, whose weight could reach several kilograms, were found at ground level near the crater edge (Buffet, 1998); they had been carried away by the air flow expelled from the cavern.

When a cavern is filled with brine rather than air, one can expect that an overburden collapse would be less abrupt. When the cavern is tight, or almost perfectly tight, an abrupt collapse of the overburden is highly unlikely. For a collapse to occur, some kind of hydraulic connection between the cavern and ground level or a permeable aquifer layer must be created. In the case of the Cerville-Buissoncourt borehole lines, which were opened to atmosphere, on April 4, 2008, ten months before the final collapse, a swarm of seismic events was recorded, it "*led to a spectacular variation in the brine level of more than 13 meters downstream from the cavern, i.e., more than 1200 m away*" (Klein et al. 2008, p. 143). The brine level "*returned to its initial value nearly 8 hours later*". It is likely that, in March-April 2008, the overburden over the cavern roof became deeply disturbed, and the cavern was no longer tight. It also must be noted that, before the collapse, which took place in February 2009, the water head in the Rhetian aquifer was decreasing consistently, clear proof of a hydraulic connection with the cavern (Xavier Daupley, personal communication). During the final collapse, piston drop was slowed by the increase of cavern brine pressure, and by the viscous and friction shear forces generated by the cylinder drop, which apply on the cylinder edge. It is likely that, in most cases, transient brine pressure increases to high values.

Why the crater contour is circular

A striking feature of the "piston" collapse is that crater contour after the collapse is almost perfectly circular (Figures 2, 3, 4 and 5).

Figure 5. Examples of circular craters above caves and caverns: The Guatemala City 2010 Sinkhole; The Great Blue Hole, Belize; A crater on Mars (NASA, JPL, U. of Arizona); Craters above salt caverns: Denver, Texas; Solimansk, Russia; Jim's water services well, New Mexico (Griswold, 2017).

Consider an arbitrary vertical cylinder of rocks whose bottom and top are at the cavern roof and ground level, respectively. H, S and P are the height, the horizontal cross-sectional area and the perimeter of the contour of the cylinder, respectively. Three vertical forces act on the cylinder. The weight of the cylinder is a downward force, $S\gamma_R H$, where γ_R is the average volumetric weight of the overburden and typically is γ_R = 22-25 kPa/m. On the bottom of the cylinder, an upward force applies. This force is SP_c, where $P_c = H\gamma_c$ is the pressure of the fluid at the cavern roof. The sum of these two forces must be balanced by the sum of the (vertical) shear stresses, or σ_{nz}, that apply on the edge of the cylinder:

$$(\gamma_R - \gamma_c)HS = P\int_0^H \sigma_{nz}(z)\, dz \qquad (1)$$

Assume, now, that shear stresses σ_{nt} must remain smaller than some upper bound — for instance, $| \sigma_{nt} | < C + | \sigma_{nn} | \operatorname{tg} \varphi$, where σ_{nt} is the shear stress, σ_{nn} is the normal stress, and C (cohesion) and φ (friction angle) are two constants. Equilibrium is impossible when

$$(\gamma_R - \gamma_c)HS > P\int_0^H (C + |\sigma_{nn}(z)|\ tg\varphi)\, dz \qquad (2)$$

An assumption must be made to compute $\sigma_{nn}(z)$. The simplest consists of assuming that it is equal to geostatic pressure, $|\sigma_{nn}(z)| = \gamma_R z,$ leading to

$$(\gamma_R - \gamma_c)\frac{S}{P} < C + \gamma_R\ H\ tg\varphi / 2 \qquad (3)$$

The maximum of the S/P ratio is reached when Ω is a circle, in which form $S/P = R/2;$ and equilibrium is impossible when

$$(\gamma_R - \gamma_c)R > 2C + \gamma_R\ H\ tg\varphi, \qquad (4)$$

and a crater is more likely to appear when the cavern is shallower (H), when its horizontal dimensions are larger (R) and when cavern pressure (γ_c) is lower. Equation (4) allows defining a cone (when γ_c is fixed): a cavern is unstable when it is not contained inside this cone. The values of C and φ in Eq. (4) are difficult to assess. Karimi-Jafari et al. (2008) suggested that no sinkhole can be created above a cavern whose R/H ratio is much smaller than 1/3, a value that is consistent with the cases described above.

Interesting evidence of this is provided by hydrocarbon storage caverns. Hundreds of storage caverns are operated worldwide. No such cavern is known to have collapsed. On one hand, in most cases, the cavern roof is several dozens of meters below the top of the salt formation and stoping cannot take place. On the other hand, the R/H ratio is smaller by one order of magnitude than R/H = 1/3.

Kansas craters

Stratigraphy of the area near the city of Hutchinson, Kansas can be defined as follows (Walters, 1978; Cochran et al., 2005): sands and gravels with a thickness of 18 m are found first; these often are saturated with water. Directly beneath them are the Ninnescah and Wellington Shales, composed of alternating beds of red and light gray shale, silty shale, and siltstone, with some interbeds of limestone and gypsum. Beneath the shales, at depths ranging from 120 to 160 m bgl, is the top of the Permian Hutchinson Salt Member, which has a thickness of approximately 105 m. In this salt formation, there is no equivalent of the competent Beaumont layer described above in the case of the Lorraine Keuper formation.

Brine wells have been operated in this salt formation since the late 1880s. Before the 1979 regulations were enforced, no salt roof was left at the cavern top, exposing the shale layers to water or brine, which resulted in shale layers weakening and sloughing. Stoping can be active for several decades and sometimes results in sinkhole formation.

Two craters

On the morning of October 21, 1974, it was observed that the surface was subsiding in an area south of the Cargill salt plant located in the eastern part of the city. Railroad tracks crossing the site were left suspended in midair (Walters, 1978) [see Figure 6]. By noon, the growing crater had a diameter of 60 m. Settlement continued until the afternoon of October 23. One year later, the Solution Mining Research Institute (SMRI) drilled ten holes, two on the banks of the sinkhole and eight from a barge. The nearly flat bedrock surface (at the top of the Ninnescah Shale) was reached by seven wells at depths near 21 m bgl. Three boreholes near the center of the pond in the deepest water failed to encounter the shale bedrock, which had collapsed in the cavern below. The average diameter of the central collapsed area was estimated to be 33 m, much smaller than the sinkhole diameter. The sinkhole resulted from a *horizontal* displacement of a volume of 68,000 m^3 of loose sands and gravels toward a central hole.

Carey salt well # 19 near the city of Hutchinson, Kansas, was abandoned in 1922. On the evening of January 3, 2005, a sinkhole developed rapidly around the wellhead (Cochran et al., 2005). Its depth was 13 m, and its horizontal maximum diameter was 63 m. Figure 7 (left) is a view to the south that includes the sinkhole, a pre-existing brine pond and a railroad track. The casing of Well #19 can be seen on this figure, standing vertical in the NW part of the sinkhole, clearly suggesting that no rigid rock cylinder had fallen. (The well casing should have dropped accordingly.) This was confirmed by a deviated well and a sonar survey performed in the upper part of the cavern (Figure 7, right). The cavern bottom was 46 m below water (54 m bgl), much higher than salt-top depth, which is more than 130-m deep. Over more than 80 years, the cavern had progressed upward through stoping until it reached water-saturated sands and gravels that flowed into the cavern as through an *hourglass*.

Figure 6. Cargill salt plant, Hutchinson, Kansas, 1974. (From Walters, 1978; Photograph by Hutchinson News, October 21, 1974.)

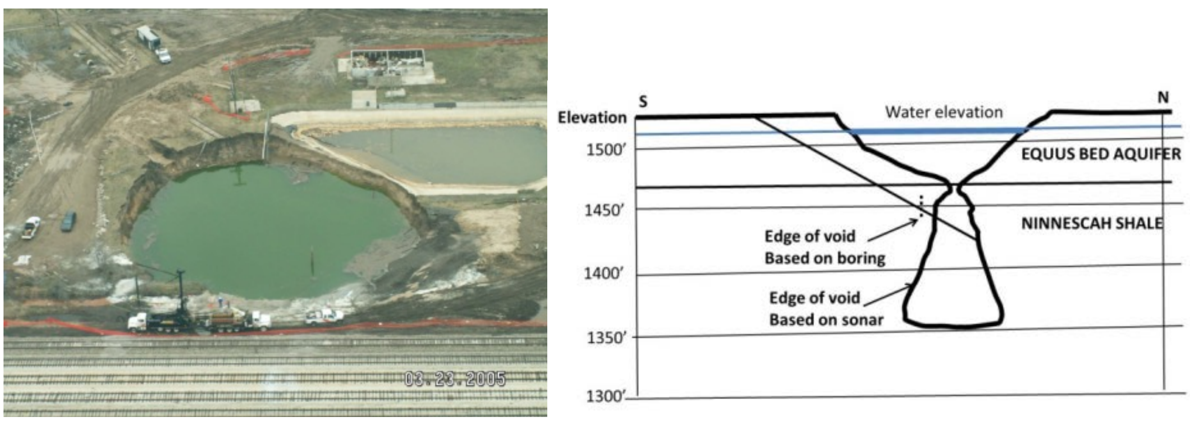

Figure 7. Well # 19 sinkhole view and vertical cross-section (after Cochran et al., 2005).

The role of fluids during cavern collapse

During an hour-glass sinkhole creation, there is no change in cavern volume — in sharp contrast with the piston case. The volume of sediments flowing downward into the cavern must be balanced by an equivalent volume of brine flowing upward from the cavern to the sinkhole. For instance, in the case of the Cargill crater, "*samples of the water in the sinkhole taken October 22, 1974* [the day after sinkhole creation] *… had a chloride content of 89,000 ppm*" (Walters, 1978); two weeks later, the chloride content was 1525 ppm — in other words, a slug of brine was displaced to the sinkhole "*but substantially dissipated within two weeks*".

Conclusion

Several examples of craters formed above salt caverns were described. [Other examples can be found in the literature — for instance, Morisseau (2000) or Bérest (2016).] Cavern roof had reached the top of the salt formation; stoping took place during several years or dozens of years. When the cavern roof is shallow enough, collapse takes place. Two cases must be distinguished. In the piston case, a cylinder of rocks drops abruptly (faster when the cavern top contains air), experiencing no deformation. In the hourglass case, loose sediments at ground level flow to a central hole, a breach created in the bedrock at the top of the cavern. A simple mechanical analysis strongly suggests that the resulting crater contour is circular. This also suggests that, in sharp contrast with brining caverns, hydrocarbon storage caverns (in which the diameter/depth ratio generally is small, and above which a thick salt layer is left between cavern top and salt roof) cannot experience overburden collapse — a notion clearly confirmed by hundreds of examples worldwide.

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