Loss of the Retsof Salt Mine: Engineering Analysis

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1. INTRODUCTION

The Retsof salt mine was operated successfully in western New York State, U.S.A., for 109 years by extracting approximately 3.7 meters (m) of salt from a gently dipping bedded salt seam using room-and-pillar mining methods. The mine, which was being operated by Akzo Nobel Salt Company (U.S.A.), was the world's largest underground salt mine. Approximately 175 million tons of salt had been extracted from a 26 Km^2 (6,500-acre) area.

The Retsof Mine was initiated with the sinking of the Retsof Shaft in 1885 under the direction of the company president, William Foster (Foster's name spelled backward is the source of the Retsof name (Werner, 1917)). The Greigsville Mining Company started salt extraction in a short distance west of the Retsof Shaft. The Greigsville Mine was subsequently obtained by the Retsof Mining Company, which was eventually purchased by International Salt Co (Werner, 1917). The Barbara ("B") Shaft was completed and mining operation was initiated at the Sterling Salt Mine in 1907 by the Sterling Salt Company. The Sterling Mine was shut down in June of 1930, subsequently purchased by International Salt Company, and connected to the Retsof Salt Mine in 1956 for ventilation and emergency egress (Paul, 1980).

Geology of the Retsof Mine area consists of a thick sequence of salt-bearing shale and dolomite of the Upper Silurian Salina Group overlain by carbonate and shale of the Middle and Upper Devonian. The mine is located at a depth of about 330 m (1,100 feet). The western two-thirds of the mine is under a full sequence of the carbonates and shales. The eastern one-third of the mine, however, is under the Genessee Valley where most of the overlying Devonian was removed by geologic processes and replaced by glacial and alluvial deposits, which are up to 150 m (500 feet) thick. Therefore, that part of the mine under the valley has less than 200 m (600 feet) of rock overburden between it and the glacial and alluvial fill in the valley. The B6 salt bed (Retsof Bed) of the Vernon Formation is the salt unit extracted at the Retsof Mine. Several other salt layers exist in the Salina both above and below the B6. These salt layers include two horizons in Unit D at the base of the Syracuse Formation approximately 50 m (160 feet) above the B6 salt level.

The Retsof Mine experienced a magnitude 3.6 earthquake on March 12, 1994, at 5:43 a.m. U.S. Eastern standard time. The earthquake was associated with a roof fall and an inrush of gas and brine within a recently mined area near the active faces. Brine entered initially at a rate of about 0.34 m^3/second (5,400 gallons per minute (gpm)), and the flow gradually changed over to fresh water and increased to a rate of 1.3 m^3/second (20,000 gpm). The inflow completely flooded the mine in 21 months. The mine flooding resulted in the direct loss of 250 mining jobs and the indirect loss of employment in the community. The collapse and inflow also created two sinkholes at the land surface which destroyed a state highway bridge, damaged a farmstead, and disrupted local utilities (Van Sambeek, 1999). Since then, the bridge was replaced and the highway raised to accommodate the surface subsidence; the highway was reopened in 1997. Surface subsidence in the immediate area of the inflow was >3 m; within about 3 Km of the inflow, the subsidence decreased to <0.3 m. Over the vast majority of the mine area, the surface was unaffected by the flooding.

The loss of the Retsof salt mine to flooding was a total surprise. The mine had operated for 109 years with relatively minor and manageable incidents of structural instability, water inflow, and gas occurrences. A substantial database of geological information was also collected throughout the history of the mine. It was this relatively uneventful mine history and the technical database that provided support for the preinflow opinions that there was no significant potential for collapse and inundation of the mine.

2. SIGNIFICANT ASPECTS OF THE COLLAPSE

The water inflow occurred through the broken roof above a small yield-pillar panel. The yield-pillar mining method was being reestablished in the mine in an attempt to mitigate pillar punching and roof slabbing, which were associated with the use of large rigid pillars. The yield-pillar panels were established beneath a deeply scoured- and sediment-filled glacial valley in early 1993.

The earliest mining at Retsof had been done with small pillars and that part of the mine stood open and accessible for 100 years. Later, with mechanization of mining, the rooms became wider and pillars became correspondingly larger to maintain an extraction ratio of about 70 percent. The vast majority of the mined area had large pillars (nominally 20- to 23-m square).

Yield-pillar panels in salt are characterized by ultralarge abutment pillars bounding a highly extracted area where only structurally insignificant pillars (yield pillars) remain. The 100-m-square abutment pillars were designed to support the full weight of overburden above the panels. The 7-m-square yield pillars were intended to provide just enough support to avoid shallow falls of roof rock. The strength and stiffness of the overburden rock determine the allowable yield-pillar panel width.

Closure monitoring was conducted in the yield-pillar test panels and the two full-scale panels during mining to measure panel behavior and to see if the new design mitigated the floor and roof problems being experienced in the large pillar area of the mine. The monitoring initially indicated that the closure rates were slightly greater than expected, but had an overall character (trend) of steadily decreasing rates, which is consistent with stable conditions. This trend changed dramatically to a rapid and unstable rate in the final weeks leading up to the inflow. The change in trend was initially obscured by fluctuating closure rates because of salt extraction between the two yield-pillar panels as the abutment pillar was isolated. Whereas the closure rates were expected to decrease after this mining, they did not; in fact, they increased. This change in panel character has now been interpreted to indicate that a pressure surcharge existed or developed over two of the yield-pillar panels prior to the inflow (Gowan et al., 1999).

Failure of the panel roof accompanied an initial inflow of nearly 100 percent saturated brine, which subsequently changed over to fresh water that entered the mine at a rate of 1.3 m^3/second (20,000 gpm). The inflow of brine was also associated with an inrush of methane gas. Postinflow research indicates that the gas and brine came from a naturally occurring pool approximately 50 m (160 feet) above the mine (Gowan et al., 1999). The existence of such a brine/gas pool directly above the mine was previously unknown.

The brine pool above the mine was formed by the dissolution of salt beds in the Syracuse Formation of the Salina Group. The salt was dissolved by groundwater that was apparently circulating downward through fractures or faults that are vertically connected to aquifers near the top of the rock and in the overlying glacial sediment (Gowan et al., 1999). These overlying aquifers were relatively fresh and sufficiently prolific to sustain the inflow rate.

3. DISCUSSION OF PRECOLLAPSE UNDERSTANDING

Data obtained after the collapse revealed significant physical site conditions that were not previously known, or had been misinterpreted by experts hired by the mining company, Akzo Nobel Salt Inc. (Akzo). These site conditions consisted of (1) a brine/gas pool above the mine, (2) a prolific freshwater aquifer system above the mine, and (3) fractures or faults connecting the prolific freshwater aquifer to at least the brine pool level. The site conditions relating, in particular, to the potential for catastrophic flooding of the mine were unknown and were not foreseeable prior to the collapse. To the contrary, based upon the extensive body of expert opinion and field research obtained by Akzo, prior to the collapse, the possibility of catastrophic flooding was then considered remote. These preexisting opinions and research results had clear and unequivocal relevance to the legal and technical issues raised by the failure of the mine in general, and more particularly, to the issues raised by the catastrophic flooding.

3.1 Brine occurrence and potential catastrophic inflow

Prior to the collapse, it was known that undersaturated brine or brackish water existed in the bedrock units above the mine. A hydrogeologic consultant to the Retsof Mine, in an affidavit, stated that brine pockets over the Retsof Mine were occasionally pressurized, but their volume and interconnected porosity were sufficiently small, such that they dissipated rapidly when encountered (Langill, 1988). Another consultant to Akzo noted that the only large natural pool of pressurized brine within the bedrock existed at the level of the Syracuse Formation and was located north of, and isolated from, the Retsof Mine; consequently, the pool was not considered to be a hazard to any activities in the mine (Dunn/Alpha, 1992).

The concern for catastrophic inflow of brine to the mine was raised by Langill (1986). He ruled out natural brine pockets as significant sources, but opined that man-made pools of brine associated with historic solution-mining wells and localized inflow into a leaking mine shaft (the Sterling Mine B Shaft) posed the greatest potential risk to the Retsof Mine. Langill advised that this threat could be reduced by identifying and avoiding those brine cavities.

Langill identified the historic solution-mining wells located near the mine and expressed the opinion that the greatest threat was from the Phoenix Dairy Brine Well (Langill, 1986), which was located about 0.75 Km (2,500 feet) west of the panels that eventually collapsed. The Phoenix Dairy Brine Well was solution mined in the late 1880s and early 1890s (Werner, 1917). Langill investigated the brine cavity associated with the Phoenix Dairy Brine Well and designed a protective barrier pillar (Langill, 1987a) to prevent interception of the brine cavity.

3.2 High-yield aquifer and the potential for catastrophic flooding

The possible existence of a high-yield aquifer in the Genesee River Valley and the evaluation of the potential for catastrophic inflows to the mine from that aquifer were important issues for the Retsof salt mine. These issues had been raised several times because of (1) concern for inflow to the leaking B Shaft, (2) expressed opinions on the safety of high extraction mining beneath the valley, and (3) interpretations developed during the investigation of the Retsof Mine's suitability for incinerator ash backfill. Several engineering and geological consultants were hired by the mining company to address these issues. All of the consultants recognized the existence of aquifers beneath the glacial valley, but most were of the opinion that these aquifers were isolated from the salt horizons and were not capable of overwhelming the mine.

During the 1970s and early 1980s, concerns were expressed for significant water inflows while evaluating groundwater flows to the leaking B Shaft within the Sterling Mine, which had been connected underground to the Retsof Mine in 1956. International Salt Company (ISCO) and its successor, Akzo, retained consultants and contractors to assess the conditions around the leaking shaft. The mining company was provided with reports and held meetings during which several different consultants and contractors expressed opposing views. Initially, these views were pessimistic and expressed the opinion that high inflows were possible (Behre Dolbear, 1976). The viewpoints began to change as more data were collected (Behre Dolbear, 1983; Langill, 1987b and 1989). By 1993, the opinion was expressed to Akzo that inflow to the B Shaft would continue to increase (<0.02 m^3/second), but the mine was not in jeopardy of catastrophic inflow (Gowan, 1993).

A hydrogeologic study was conducted for Akzo in the early 1990s to evaluate the potential use of the mine for incinerator ash disposal (Dunn, 1992). The investigation included the review of data from over 180 holes and mine shafts at and around the mine. The resulting report was a summation of all the available data until 1992. The report concluded that no prolific aquifer was present in the valley fill. While the top of rock was fractured and capable of transmitting water, the glacial fill above the rock was believed to consist primarily of low permeability units dominated by silt and clay. The fractured top of the rock was isolated from the mine level by 120 m (400 feet) of relatively dry and impervious shale, dolomite, and salt (Dunn, 1992).

Explicit opinions regarding inflow potential were also provided to Akzo/ISCO during litigation over cavity ownership in the late 1980s. Langill (1989) clearly states that his investigations show the Onondaga and Bertie Formations (fractured bedrock horizons several hundred feet above the mine) would not catastrophically flood the mine during total extraction or pillar robbing. Langill's opinions were significant since he had conducted subsurface investigation around the Sterling Mine for more than a decade; consequently, he had the knowledge necessary to support such an opinion. An opinion was also expressed to ISCO by Scott (1988) who stated that pillar robbing (high extraction mining) is feasible at Retsof and can be done beneath aquifers, as is the case under Cayuga Lake and the North Sea. These opinions of consultants respected by ISCO/Akzo were more credible to ISCO/Akzo than the opinions of the experts on the other side of the litigation. The opposing experts either did not have direct site knowledge or were not qualified experts relative to the issues.

3.3 Fractures/faults connecting the potential aquifers to the mine

There was no evidence of faults or fractures connecting the glacial valley fill or bedrock aquifers to the mine level. The issue of the existence of fractures and faults was important to ISCO/Akzo and had been the subject of several investigations by the mining company and others. An investigation was conducted for ISCO during litigation with a local gas producer. ISCO contracted Pounder and Harmon (1975) specifically to locate faults and they found no definitive evidence of faulting.

Dunn (1992) evaluated the potential for vertical faults/fractures connecting the fractured bedrock of the basal valley fill with the mine horizon. Dunn (1992) constructed structural contour maps from a database comprised of over 180 shafts and boreholes in the mine area. No faults were identified by that analysis. Dunn concluded that the Retsof salt mine remained dry, except at two leaky shafts, for over 100 years due to the lack of vertical fractures through the more than 120 m (400 feet) of dolomite, shale, and salt layers between mine level and the water-bearing, fractured horizons at the top of the rock.

No faulting was identified by others investigating the area for the state of New York. This included surface reconnaissance mapping in the mine area (Fakundiny et al., 1978) and subsurface mapping for petroleum resource potential (Van Tyne et al., 1980). A careful examination of postcollapse drillhole data still does not provide clear evidence of vertical discontinuities; however, the unusual arrangement of the Genesee Valley does suggest structural control in the valley (Isachson and McKendree, 1977).

4. SUMMARY

The Retsof Mine was lost to an inundation of fresh water that was believed by the mine operators to be impossible. Several engineering analyses had been performed by consultants to the mine operators that essentially erased concerns about the possibility of large inflows. These analyses included:

1. Required separation distances from historical solution-mined cavities.
2. Interpretation of more than 180 boreholes and shafts through the rock over the mine that failed to detect any naturally occurring brine pockets.
3. Hydrological studies for the nearby Sterling Mine B Shaft that showed little potential for catastrophic inflow.
4. Hydrological studies for planning incinerator ash disposal in the mine that concluded no prolific aquifer was present in the valley fill.
5. At least three geological studies that found no evidence of faults or fractures connecting potential aquifers to the mine.

Postcollapse investigations shed new light on conclusions reached in the five analyses listed above. The separation distance was sufficient to shield the mine from known solution-mined caverns, but a natural "brine pocket" that existed west of the mine also extended over the part of the mine that eventually collapsed. The deliverability of the valley aquifer system exceeded everyone's precollapse expectations, both in rate and total volume. The aquifer deliverability was 50 times greater than had been opined. If the inflow had been only as large as that considered possible, the mine could likely have been saved by a combination of pumping and grouting. As it was, the inflow overwhelmed all capacity to pump and dispose of the brine and prevented conventional grouting.

The yield-pillar panel method of mining was in use where the inflow(s) occurred, but its culpability in "causing" the inflow has never been established. This general area of the mine was experiencing ground control problems (including a roof fall with fatalities) and the yield-pillar panels were introduced – after a period of testing – to solve those problems. The yield-pillar panels were located beneath what now appears to have been a natural, high-pressure brine and gas pocket. While the yield-pillar panels were unable to prevent the inflow of brine and gas, we cannot say that a similar inflow would have been avoided had large-pillar mining been continued into the same area.

REFERENCES

Behre Dolbear & Company, Inc., 1976. *The Sterling Mine - A Geologic Overview Related to a Water Hazard and Discussion of Suggested Solutions*, Report to International Salt Company, 32 pp.

Behre Dolbear & Company, Inc., 1983. Memorandum to ISCO, 9 pp.

Dunn Corporation/Alpha Geoscience, 1992. Letter report to Akzo Nobel Salt Inc. from Samuel Gowan, 3 pp.

Dunn Corporation, 1992. *Hydrogeologic Report for the Akzo Ash Processing Project*, Consulting report to Akzo Salt Inc., 35 pp.

Fakundiny, R. H., J. T. Meyers, P. W. Pomeroy, J. W. Pferd, and T. A. Nowak, Jr., 1978. *Structural Instability Features in the Vicinity of the Clarendon-Linden Fault System, Western New York and Lake Ontario, in Advances in Analysis of Geotechnical Instabilities*, University of Waterloo Press, SM Study No. 13, Paper 4, pp. 121-178.

Gowan, S. W., 1993. Oral communication to Akzo Nobel Salt, Inc.

Gowan, S. W., L. L. Van Sambeek, and S. M. Trader, 1999. "The Discovery of an Apparent Brine Pool Associated With Anomalous Closure Patterns and the Eventual Failure of the Retsof Salt Mine," *Proceedings, October 1999 Meeting of the Solution Mining Research Institute*, Washington, D.C., U.S.A.

Isachson, Y. W. and W. G. McKendree, 1977. Generalized Map of Recorded Joint Systems in New York, New York State Museum Map and Chart Series No. 31F.

Langill, R. F., 1988. Declaration of Richard F. Langill in International Salt Company vs. Geostow et al., 12 pp.

Langill, Richard F. & Associates, 1986. *Detecting Subsurface Hazard Near Cuylerville*, Report to International Salt Company, 12 pp.

Langill, Richard F. & Associates, 1987a. *Investigations of the Phoenix Dairy Company Site Near Cuylerville, NY*, Report to International Salt Company, 7 pp.

Langill, Richard F. & Associates, 1987b. *Subsidence and Fluid Movement at the Sterling Mine*, Report to International Salt Company, 29 pp.

Langill, Richard F. & Associates, 1989. *Subsidence and Groundwater Inflow at the Sterling Mine*, Report to International Salt Company, 12 pp.

Paul, D. K., 1980. *Sterling Mine "B" and "C" Shafts Water Entry Problems and Mine Flooding Status Report*, unpublished report to International Salt Company, p. 26.

Pounder and Harmon, 1975. *Preliminary Geological Study, Retsof Area, State of New York*, Report to ISCO, 7 pp.

Scott, J. J., 1988. Affidavit in Support of Motion for Summary Judgement, in the Matter of ISCO vs. Geostow et al., U.S. District Court, Western District of N.Y., 9 pp.

Van Sambeek, L. L., 1999. *Flooding-Induced Mine Subsidence at Retsof, New York, Geo-Engineering for Underground Facilities*, pp. 315-326.

Van Tyne, A. M., D. G. Kamakaris, and S. Corbo, 1980. Structure Contours on Base of the Hamilton Group, METC/EGSP Series 116, New York State Museum Science Service Geological Survey, Alfred Oil & Gas Office, for the United States Department of Energy Easton Gas Shales Project - Contract Number DE-AS21-76 MC05206.

Werner, C.J., 1917. *A History and Description of the Manufacturing and Mining of Salts in New York State*, Tobias A. Wright Press, Huntington, NY, pp. 105-141.