Closure and Collapse of Man-Made Cavities in Salt

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ABSTRACT

Three case histories of cavity closure and collapse are presented to elucidate mechanisms that initiate and control cavity instability. The importance of incorporating these mechanisms in models that assess the stability of cavities in salt is discussed. Because complete data bases are not available for these three events, precise definition of the mechanisms is not always possible. Excessive closure of deep cavities is controlled by large strains produced over time in the salt, especially during periods of low cavity pressure. Cavity collapse and concomitant surface subsidence involves more complex mechanisms that are related to slaking and cracking of the non-salt rocks above the cavity.

INTRODUCTION

The increasing demand for cavities in salt for both the production of brine and the storage of fluids is causing development of new cavities that are sited closer together and deeper than in the past. The greater cavity density and depth results in high stress in the surrounding salt and non-salt rocks and the effect of higher temperatures that are encountered at the greater depths. These higher stresses and temperatures increase the potential for cavity instability substantially above that of shallower, more sparsely sited cavities. Both cavity closure and collapse are greatly increased by modest increases in stress and temperature. Closure and collapse result not only in loss of storage volume and, possibly, stored fluids, but can also precipitate surface subsidence that can damage structures and piping networks, as well as subsurface subsidence that can sever well strings, or more seriously, breach fresh water aquifers.

Sophisticated models are required to assess the potential for cavity instability. In addition to incorporating irregular geometries, large geometry changes, in situ stress, and non-linear constitutive behavior, these models must also include the mechanisms that lead to and control the instability. Some of these mechanisms are fairly straightforward, such as the large strains that can be produced over time at constant stress and temperature in a viscoelastic material such as salt. Some mechanisms, however, are not so fundamental and can often be deduced only by detailed investigation of several cases of cavity instability.

This paper gives a brief description of capabilities required of numerical models and lists the kind of input needed for analysis of cavity stability. Attention is focused on instability mechanisms and conditions for which they are likely to be active. In particular, the excessive cavity closures at Eminence, Mississippi, and the cavity collapses at Grosse Ile, Michigan and Windsor, Ontario, are discussed in detail to illustrate the action of several instability mechanisms. The descriptions of these events are taken from a larger collection of documented cavity instabilities (Coates et al., 1981). Finally, the possibility of incorporating these mechanisms into numerical models is discussed.

MODELS

Analysis of cavity closure and collapse requires a very complex mathematical model. Irregular geometries, non-linear constitutive laws and large geometry changes require use of numerical solution techniques such as finite element and finite difference methods.

The model must be able to simulate cavities of arbitrary shape so that in most cases a three-dimensional analysis is required. Occasionally, the geometry of the problem permits a simpler axisymmetric or plane strain analysis. A large-displacement, large-strain formulation that includes rigid body modes is required to predict a collapse sequence. The model must handle several different constitutive laws because of the different geological media that surround the cavities; both time-dependent and time-independent material behavior usually need to be modeled. Simulation of geological phenomena such as joints, fractures, and interfaces is also required. Additionally, the model must contain closure and collapse mechanisms that are known to produce and control cavity instabilities.

When such a model is constructed, it should be validated by predicting (*a posteriori*) failure events before it can be accepted for stability and failure analysis of existing and proposed cavities.

A number of inputs to the model are required to analyze cavity stability and to simulate cavity instabilities. The input factors required are cavity size and shape, cavity location, proximity to other cavities, in situ stress, stratigraphy, construction and operating histories, and constitutive laws for the salt and surrounding materials. Each of these input variables is important for accurate modeling, but the relative importance of these input factors depends on the specific cavity modeled. For example, stratigraphy above the salt is not significant when modeling cavities are located very deep in the middle of a salt dome.

Cavity Size and Shape

Cavity size and shape control the perturbations of the in situ stress that result in stress concentrations around the cavity. Cavity size is important for two reasons. First, stresses around large cavities are usually larger than stresses around small cavities, primarily because large cavities have large roof spans. Second, if stoping contributes significantly to collapse, large cavities can accommodate more rubble and thereby allow the cavity to migrate further toward the surface. Cavity shape is important because short, wide cavities tend to produce larger stresses than do high, narrow cavities of equal volume.

Cavity Location

Cavity depth, nearness to the salt boundaries and proximity to other cavities influence the stress in the salt and other rocks around the cavity. For example, deep cavities must support a greater overburden than do shallow cavities, cavities near salt boundaries usually induce large stresses in the more brittle rock outside the salt, and cavities in close proximity influence the stress fields around one another.

In Situ Stress

The in situ stress is probably the most significant factor controlling the stability and deformation of the salt cavity. Generally, the magnitude and direction of the principal stresses are unknown. In many cases where tectonic forces are small, however, it is adequate to assume that the in situ stress in the salt is lithostatic, i.e., that all three principal stresses are equal and have the same value as does the overburden. In materials that flow less readily, the in situ stress is often assumed to be a gravitating stress field; i.e., the largest (compressive) principal stress is vertical and equal to the overburden, the two horizontal principal stresses are equal and have a magnitude determined by the overburden and Poisson's ratio. That is, the horizontal principal stress $\sigma_H = (\nu/1 - \nu)\sigma_V$ where ν is Poisson's ratio and σ_V is the vertical principal stress (equal to the overburden). Other assumptions regarding the in situ stress can be made based on tectonics or stress measurements.

Stratigraphy

The material above and below the cavity influences the stability, as well as the closure and collapse sequence for that cavity. The thickness and density of material above the cavity determines the overburden. More importantly, the different layers have different strengths and deform differently, and therefore give rise to different failure mechanisms.

Construction and Operating Histories

Construction and operating histories are important, especially for deep cavities in which a fluid pressure must be maintained to prevent large closure of the cavity. The size and shape of storage cavities are often changed by filling and emptying cycles, and occasionally these cycles cause adjacent cavities to coalesce.

Constitutive Laws

Constitutive laws define the strength and relate the stress, temperature, strain, strain rate, etc., for a material. Strength is the maximum stress a material can sustain and is usually expressed in terms of stress and material properties. An example is the Mohr-Coulomb criterion for shear failure. The relationship among stress, temperature, strain, strain rate, etc., is usually not well determined, but approximations can be made that are adequate for engineering analysis. Very little data are available to construct time-dependent constitutive models for geological materials. The most notable exception is salt, whose creep behavior can be characterized adequately by several different empirical laws.

CAVITY CLOSURE AT EMINENCE SALT DOME, MISSISSIPPI

Transcontinental Gas Pipe Line Corporation (TRANSCO) constructed the first natural gas storage facility designed specifically for dry natural gas storage in a Gulf Coast salt dome in 1970. Fenix & Scisson, Inc. (F&S) was selected as the design/construction contractor. The facility has been successfully operated for over ten years and has stored over 150 billion standard cubic feet of natural gas. The only unexpected problem resulting from the operation has been the large cavern closure rates. F&S anticipated an initial closure rate of 10 to 15 per cent per year; whereas, the actual initial closure rates were between 20 to 30 per cent per year. Recent operating data (1980–1981), however, indicate that closure rates have decreased to nearly zero. The early high closure rates were offset by leaching additional storage space during the off-peak storage summer months.

Based on the experience at Eminence, the second natural gas storage project in a salt dome was constructed in 1973 and has experienced no recognizable cavern closure. This facility was constructed for Texas Utilities Fuel Company, by F&S, in the Bethel Salt Dome near Palestine, Texas. The basic design changes (from Eminence) were: (1) cavern interval was located at a shallower depth; (2) cavern shape was changed; and (3) the minimum operating pressure was increased.

Stratigraphy

The Eminence Dome is located in Covington County, Mississippi, about 20 miles north of Hattiesburg. The top of the salt is at a depth of 2400 feet with an overlying caprock consisting of 500 feet of limestone and anhydrite. Figure 1 illustrates the stratigraphy of the dome. During drilling of the first well, the salt was cored continuously at the interval of 5700 to 6700 feet. These care samples were used to determine the quality of the salt and the insoluble content. Anhydrite insolubles, ranging from 0.09 to 7.42 per cent and averaging about 4 per cent, were discovered. (See Allen, 1971, p. 278.)

Site Selection

Eminence salt dome was selected as a suitable site for the storage of natural gas because: (1) the dome is at a relatively shallow depth and is large enough to allow for future expansion; (2) wells could be constructed in the Wilcox Formation on the flank of the dome for brine disposal; (3) land for surface facilities was available; and (4) the site was only 1.5 miles from the company's main transmission pipeline (Allen, 1971, p. 276; Oil and Gas Journal, 1971, p. 67). The design criteria that were established for the first two storage cavities are shown in Table 1.

Cavern History

Four storage caverns were leached at Eminence using the bottom injection method. In this technique, fresh water was pumped down a central 7-inch tubing string to a

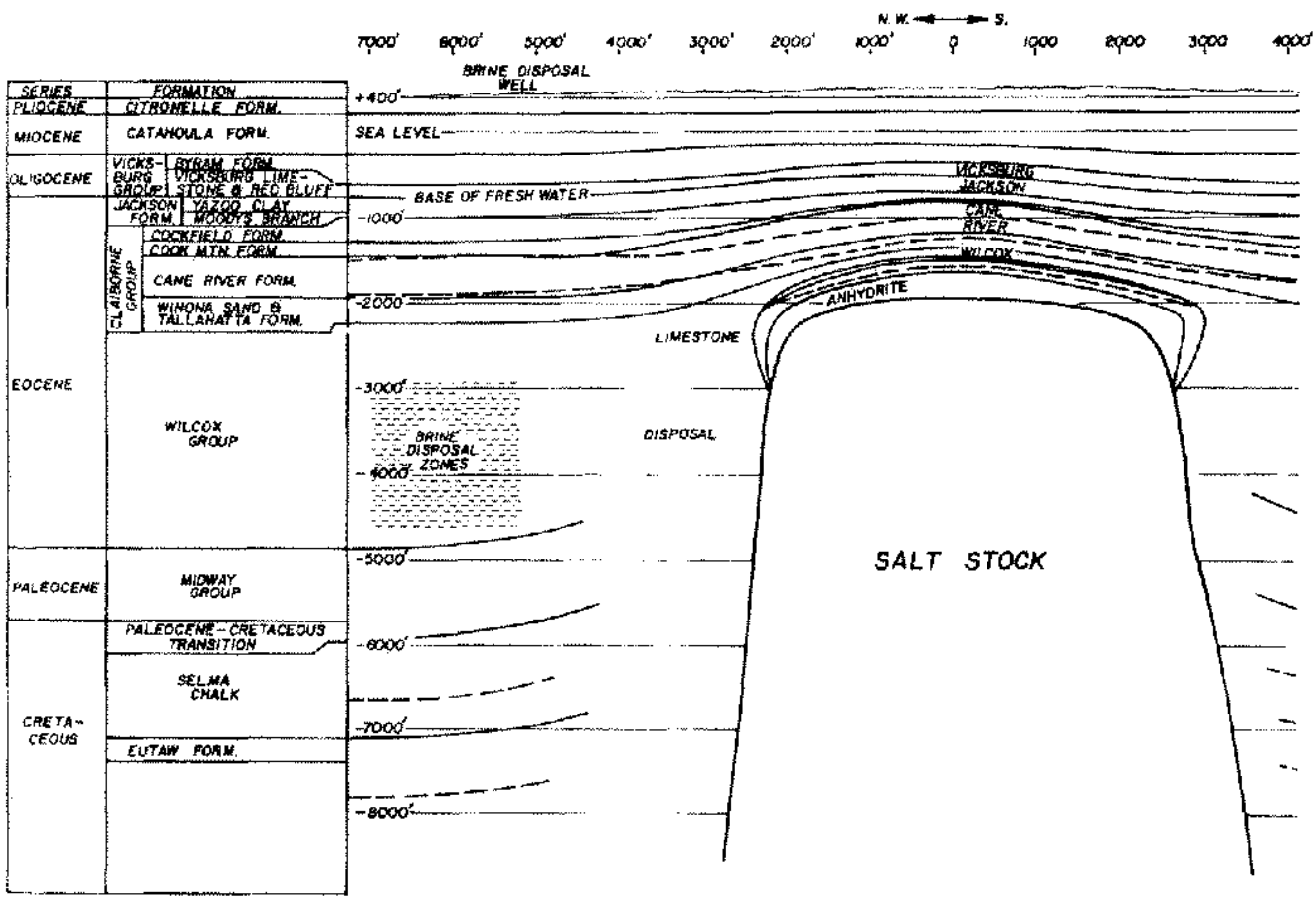

Figure 1. Stratigraphy of Eminence salt dome (after Fenix & Scisson, 1980).

TABLE 1

Design Criteria for Eminence Storage Facility

Number of wells	4
Cavern interval, feet	5500 to 6200
Formation temperature, °F	150
Specific gravity of gas	0.584
Maximum storage pressure, psia	3950
Minimum storage pressure, psia	1000
Minimum deliverability per well, MMscf/D*	280
Product casing size, inches	13⅜
Total gas storage volume, MMscf	8892
Cushion gas volume, MMscf	2127
Usable (top) gas volume, MMscf	6765

*Million standard cubic feet per day.

location near the bottom of the planned cavity. Brine was returned to the surface through the annulus between the 7-inch tubing and a second string of 10¾-inch tubing placed near the top of the planned cavity. During later stages of leaching caverns No. 3 and 4, a modified reverse circulation procedure was used. By doing this, a brine of a higher salinity was produced, thereby leaching faster and shortening construction time. In addition, a diesel oil blanket was maintained at the top of the cavity through the annulus between the 10¾-inch tubing and a 13⅜-inch casing cemented into the hole. This process preserves the cavern neck and prevents any leaching above the 10¾-inch tubing. (See Allen, 1971, p. 278.) Figure 2 shows current profiles of the leaching process.

The storage facilities at Eminence are dry-type (brine-free) gas storage caverns. The caverns are operated between a maximum and minimum gas storage pressure, with the gas volume between these two pressures being usable storage gas. This method of pressure storage allows free-flow of the gas from the caverns as needed and the water content of the produced gas is kept at a minimum. (See Allen, 1971, p. 277.)

The initial volume of each cavern was determined by measuring the volume of fresh water pumped into the cavern during leaching and the salinity of the brine returned. Subsequent measurements were made by metering the amount of brine or fresh water needed to fill the cavern or by measuring the amount of brine displaced when filling the cavern with gas. Sonar surveys were also run in each cavern to confirm the cavern shapes and volumes. These surveys were taken when the leaching was 50 per cent complete and again upon completion. (See Allen, 1971, p. 278.) Solutioning of cavern No. 1 began on November 24, 1968. This first cavern was completed in 393 days and had a volume of 1,100,805 barrels on December 21, 1969. Figure 3 shows the cavern volume data through April, 1981. A sonar survey on March 21, 1970, indicated that the volume had diminished to 971,597 barrels. Experience with sonar

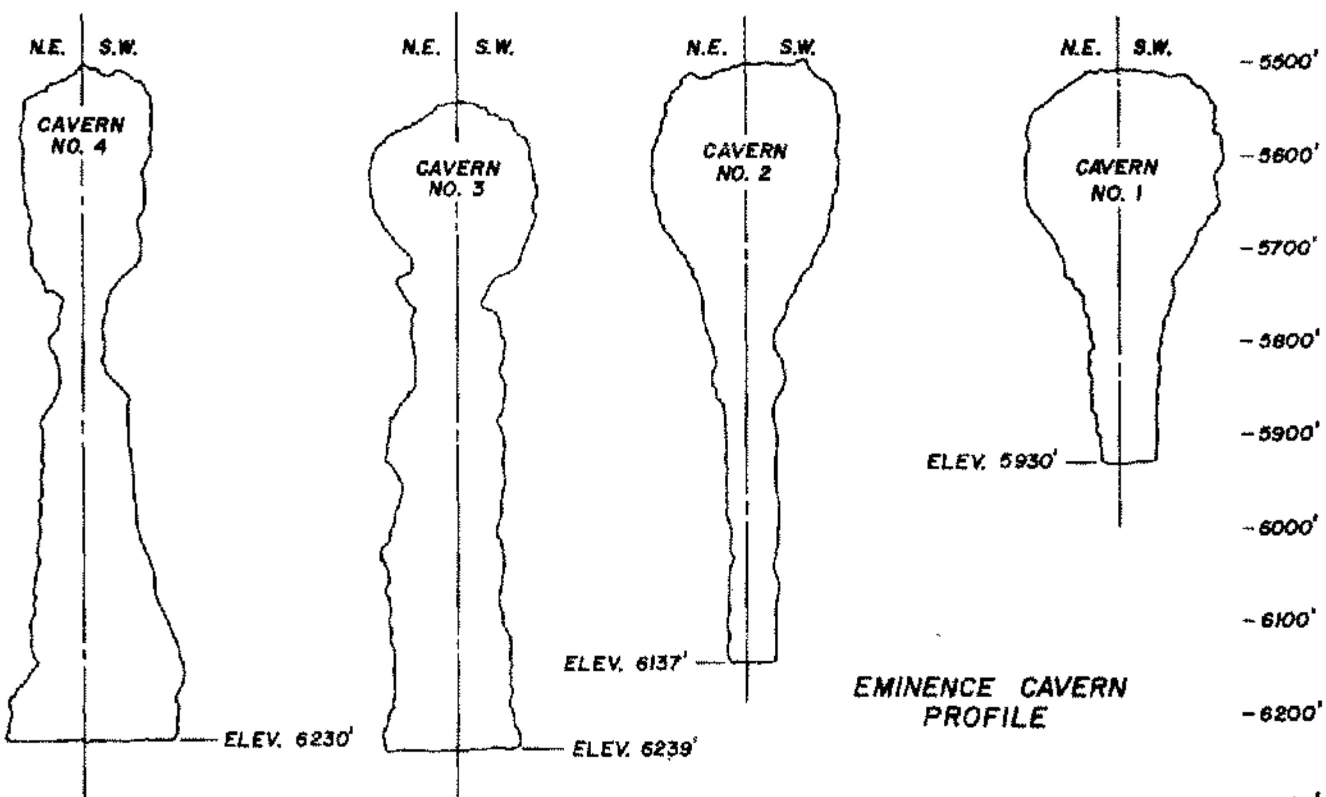

Figure 2. Eminence cavern profile (after Fenix & Scisson, 1980).

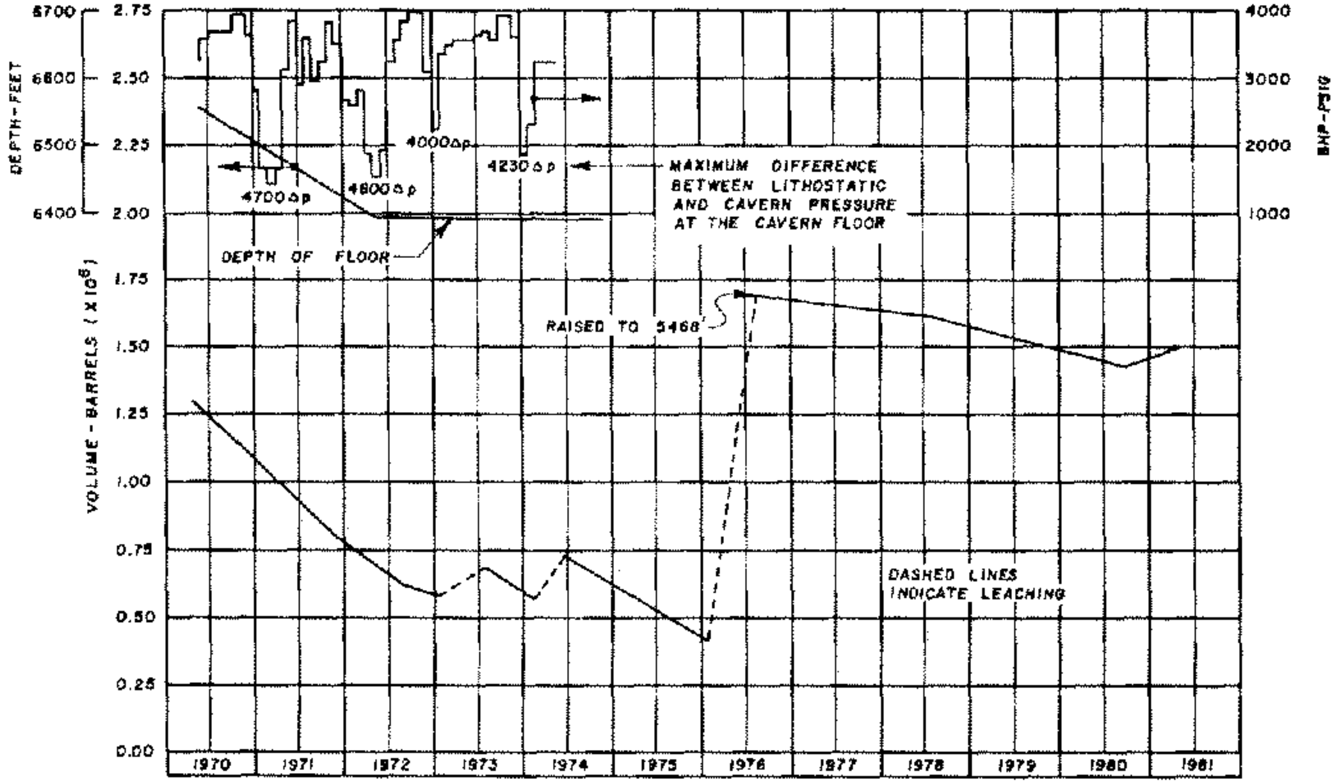

Figure 3. Volume and pressure as functions of time for Eminence cavern no. 1 (after Fenix & Scisson, 1975).

surveys of SPR caverns shows errors in volume as large as 25 per cent if the cavern shape is irregular. This decreased volume of 129,208 barrels does not indicate that the cavern had experienced closure under a full hydrostatic head of brine due to the accuracy of the sonar survey tool. On May 25, 1970, dewatering of the cavern was begun and gas was injected. Sonar measurements show that the depth to the cavern floor was 6560 feet. When the dewatering process was finished October 8, 1970, the volume estimated by metering the displaced brine was 1,047,480 barrels. When the cavern was refilled with brine from June 7, 1972 to June 23, 1972, only 637,583 barrels were required to fill the cavern; a loss of about 40 per cent of the original volume (24 per cent annually). During the period between October, 1970 and June, 1972, the pressure in the cavern was allowed to drop to between 2000 and 1500 psig for two periods of about three months each. The next dewatering and gas injection cycle, completed on August 24, 1972, revealed that the cavern volume had decreased slightly to 615,438 barrels, a loss of less than 4 per cent. At the completion of the gas injection, the cavern pressure was raised to over 3500 psig.

On January 15, 1973, the cavern pressure was reduced to below 2000 psig and injection of fresh water was started. The amount of fresh water metered in was 567,504 barrels, measured on February 1, 1973. The volume loss of 47,934 barrels indicated that some closure was still occurring. Sonar readings in the filled cavern revealed that the bottom of the cavern was at a depth of 6393 feet, 167 higher than the May, 1970 depth.

The next cycle of the brine displacement and gas injection showed that the cavern volume was 691,058 barrels on July 18, 1973. Part of (about 16 per cent) this increase in volume of 123,556 barrels was produced by leaching of the cavern by the fresh water that was put into the cavern during January, 1974. The remainder of the increase, however, is unexplained. The cavern was once again filled with fresh water, and the volume was 566,597 barrels on February 20, 1974. The loss of the volume of 124,461 barrels occurred when the cavern pressure dropped below 2000 psig. Subsequent brine displacement and gas injection at an increased cavern pressure disclosed a cavern volume of 739,980 barrels on June 24, 1974.

Solution of salt for development of Eminence cavern No. 2 was started on January 31, 1969 and completed in 423 days with an initial volume of 1,102,045 barrels. Figure 4 illustrates cavern pressure and volume through April, 1981. The pressure and volume history is similar to cavern No. 1. When brine displacement and gas injection was completed in December, 1970, the amount of volume lost was less than 2 per cent. By the end of March, 1973, fresh water metered into the cavern showed that about 44 per cent (corrected for sump fillup) of the cavern volume had been lost. During this period, the pressure in the cav-

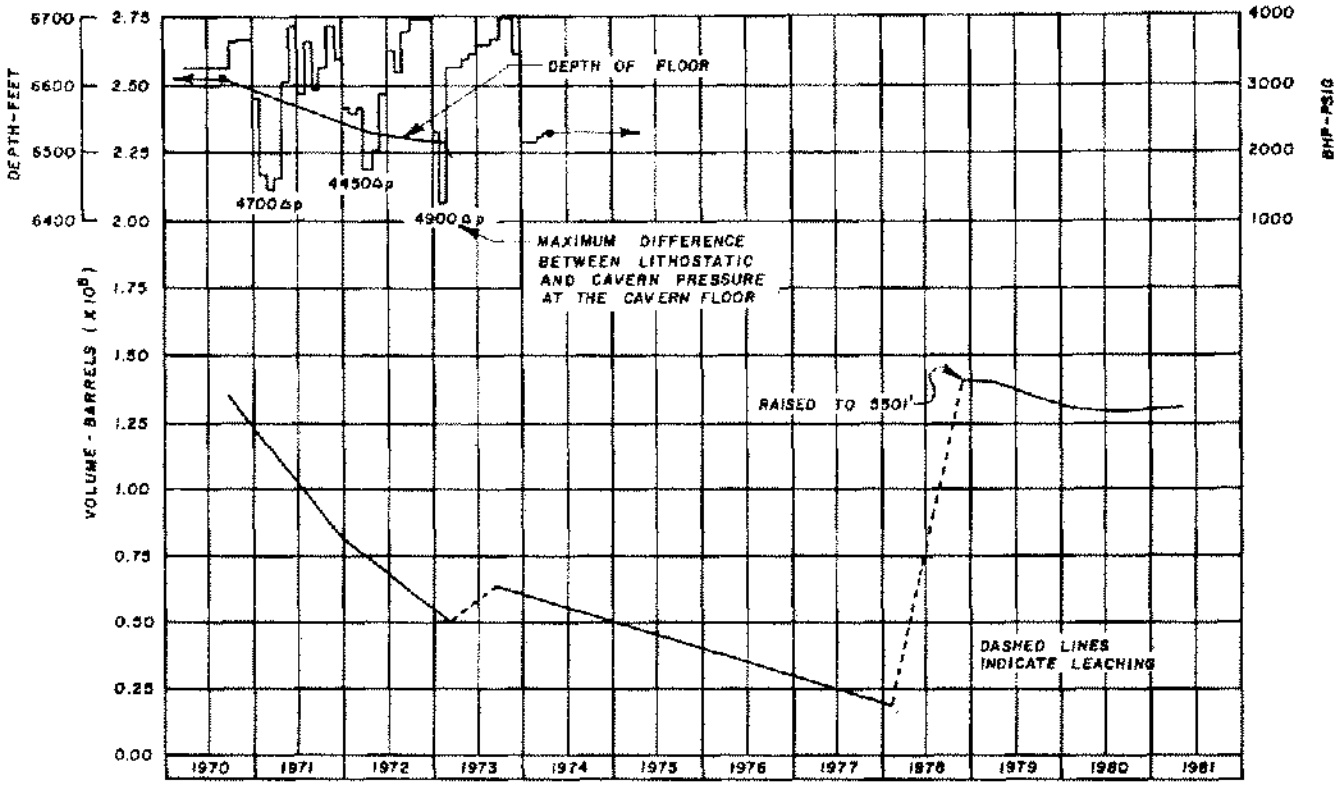

Figure 4. Volume and pressure as functions of time for Eminence Cavern no. 2 (after Fenix & Scisson, 1975).

ern had been allowed to drop to between 1800 and 1300 psig for three periods of three, two and one month, respectively.

Subsequent filling of the cavern with fresh water caused some leaching of the cavern. The final volume, after brine displacement and gas filling in September 1973, was 648,249 barrels.

Cavern No. 3 had a metered volume of 2,178,872 barrels when placed into service August 27, 1972. Cavern No. 4 had a volume of 2,119,738 barrels upon completion of leaching on January 16, 1972. Figures 5 and 6 show the pressure and volume data through April, 1981 for these caverns. Both caverns experienced maximum closure during periods of low pressure.

All of the caverns constructed in the Eminence salt dome are presently different in size and depth, as shown in Figure 2. Since the completion of the caverns, major closure was initially experienced in each cavern. The wellhead pressures of the four caverns at Eminence are normally the same; however, at times they are different. Each cavern experienced its greatest amount of closure during the periods of low pressure. The pressure and volume curves also show that the floor of each cavern decreased in depth with time due to upward movement of the salt in the floor or sluffing of the salt walls. Subsequent leaching also occurred in each cavern when fresh water was injected.

The most recent data reflect a dramatic decrease in losses, as can be seen in the Figures 3 through 6. The diminishing of these losses can be attributed to: (1) maintaining a higher minimum cavern pressure over extended time periods; (2) the sphere-like* cavern configuration of caverns No. 1 and 2 which reduced the ratio of vertical to horizontal diameter, making these caverns more stable; and (3) the installation of additional injection gas cooling.

The last survey run to verify inventories shows a volume gain of some 4.5 per cent; however, this may be somewhat masked by the fact that the downhole pressure and temperature instruments were used for the first time since recalibration. Additional testing will be needed to confirm this trend.

Overall, recent data, technique of operations and inventory calculations and procedures point to future losses that would be classified as minimal.

The closure percentages and closure volumes reported in this article are not actual cavern closure rates, i.e, they are a combination of actual cavern closure and water volumes remaining in the bottom of the cavern that are unrecoverable. The bottom portion of each cavern is filled with salt, anhydrite and brine. In the past, it has been determined that it is not economical to attempt to drill to the original cavern total depth, displace the water in the "rub-

*The initial stresses in rock salt are hydrostatic; therefore, the best shape from the standpoint of stability is a sphere. Hence, reducing the ratio of vertical to horizontal diameter will make the cavity more stable.

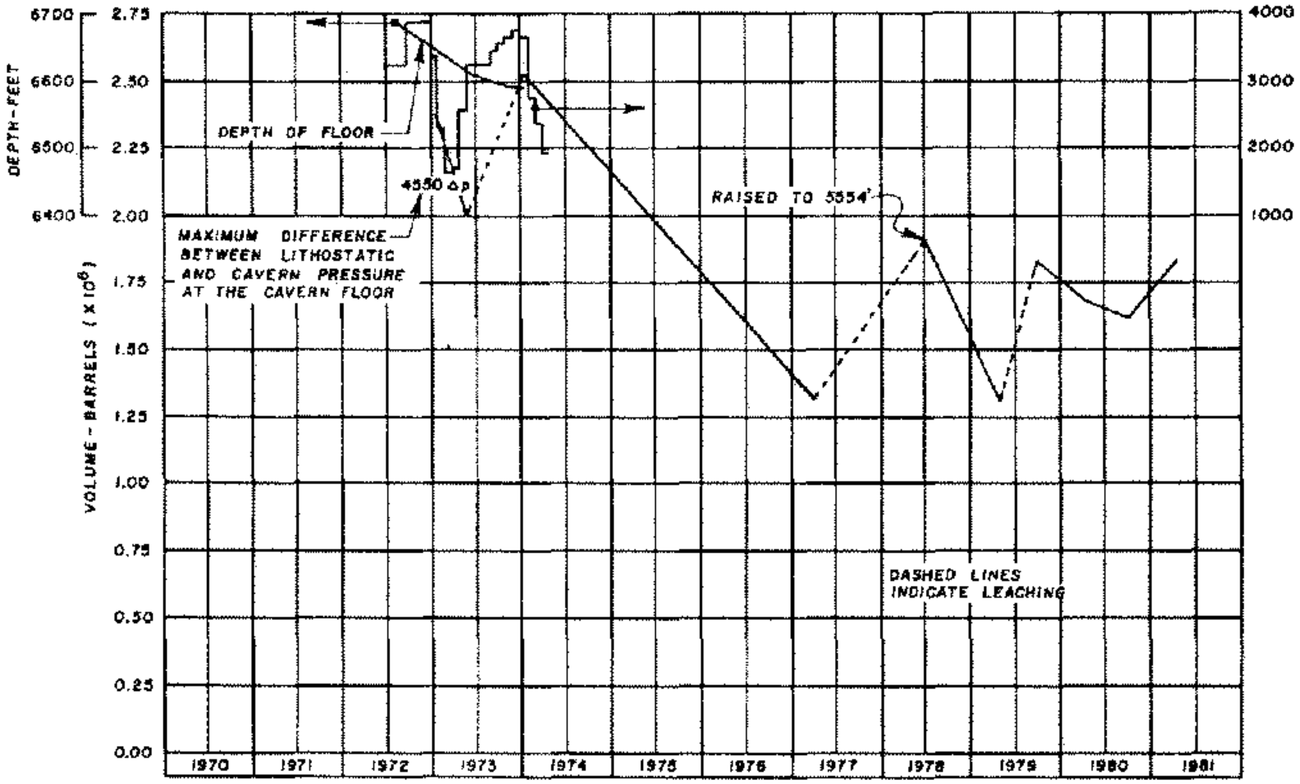

Figure 5. Volume and pressure as functions of time for Eminence cavern no. 3 (after Fenix & Scisson, 1975).

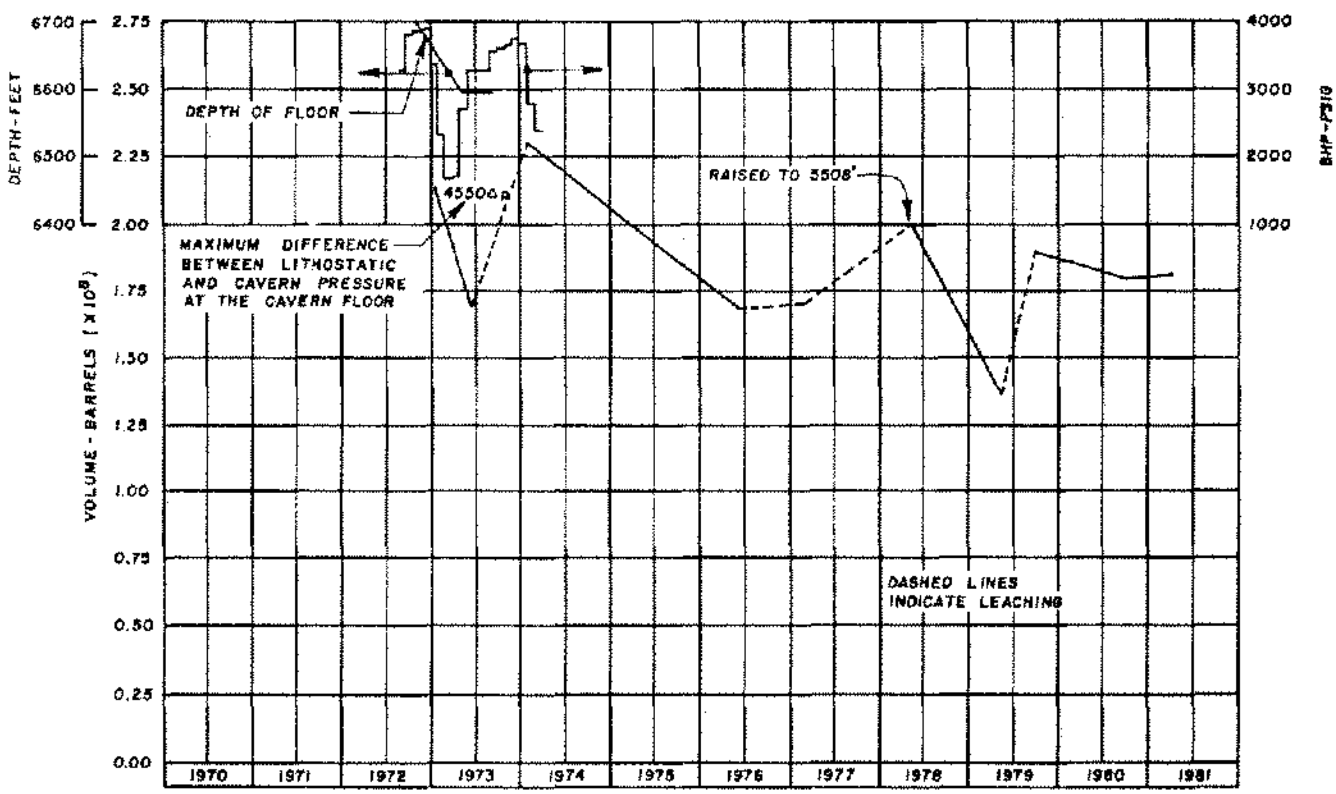

Figure 6. Volume and pressure as functions of time for Eminence cavern no. 4 (after Fenix & Scisson, 1975).

ble pile," and reutilize this volume as usable gas storage space.

SUBSIDENCE AT GROSSE ILE, MICHIGAN

Introduction

In early 1971, two sinkholes formed rapidly on the Grosse Ile brine field of BASF Wyandotte Corporation. The collapse features were the result of solution mining over a period of about 30 years. Surveys of surface settlements had been conducted for 18 years prior to the development of the sinkholes. Two separate reports detailing the events relating to the subsidence were published by the Solution Mining Research Institute. The environmental effects of the subsidence were reported by Landes and Piper (1972), and the mechanisms of the collapse were discussed by Nieto-Pescetto and Hendron (1977). The following sections are based on these two reports.

History

Solution mining operations for the production of salt began in the Detroit area in 1895. Limited brine production on the perimeter of the Grosse Ile brine field at the Point Hennepin location began in 1941. Prior to this, brine was produced on the mainland. Before salt wells were developed on the rest of Point Hennepin, this area was used for the disposal of tailings from the manufacture of soda ash. These tailings were piped to the island, ponded and allowed to settle. During the period 1948 to 1950, when disposal was stopped, the tailings were accumulated to about 30 feet above the natural land surface. The main constituents of these tailings are calcium carbonate, calcium sulfate and calcium hydroxide. Silica and other insoluble impurities from the original limestone raw material used in the production of soda ash are also present. Most of the well operations of BASF Wyandotte Corporation are located on top of the tailing plateau. (See Landes and Piper, 1972, pp. 6–7, 9.)

Beginning in 1943, brine wells were operated on Grosse Ile by the conventional single-well method of injecting water down a tube and forcing brine up through the annulus between the tubing and the well-casing. The single-well cavities formed by this procedure later coalesced into two major galleries, labeled North and Central in Figure 7 and several minor galleries. (See Landes and Piper, 1972, p. 19.). Table 2 gives the production history of 73 wells shown in Figure 7. These data, coupled with assumptions

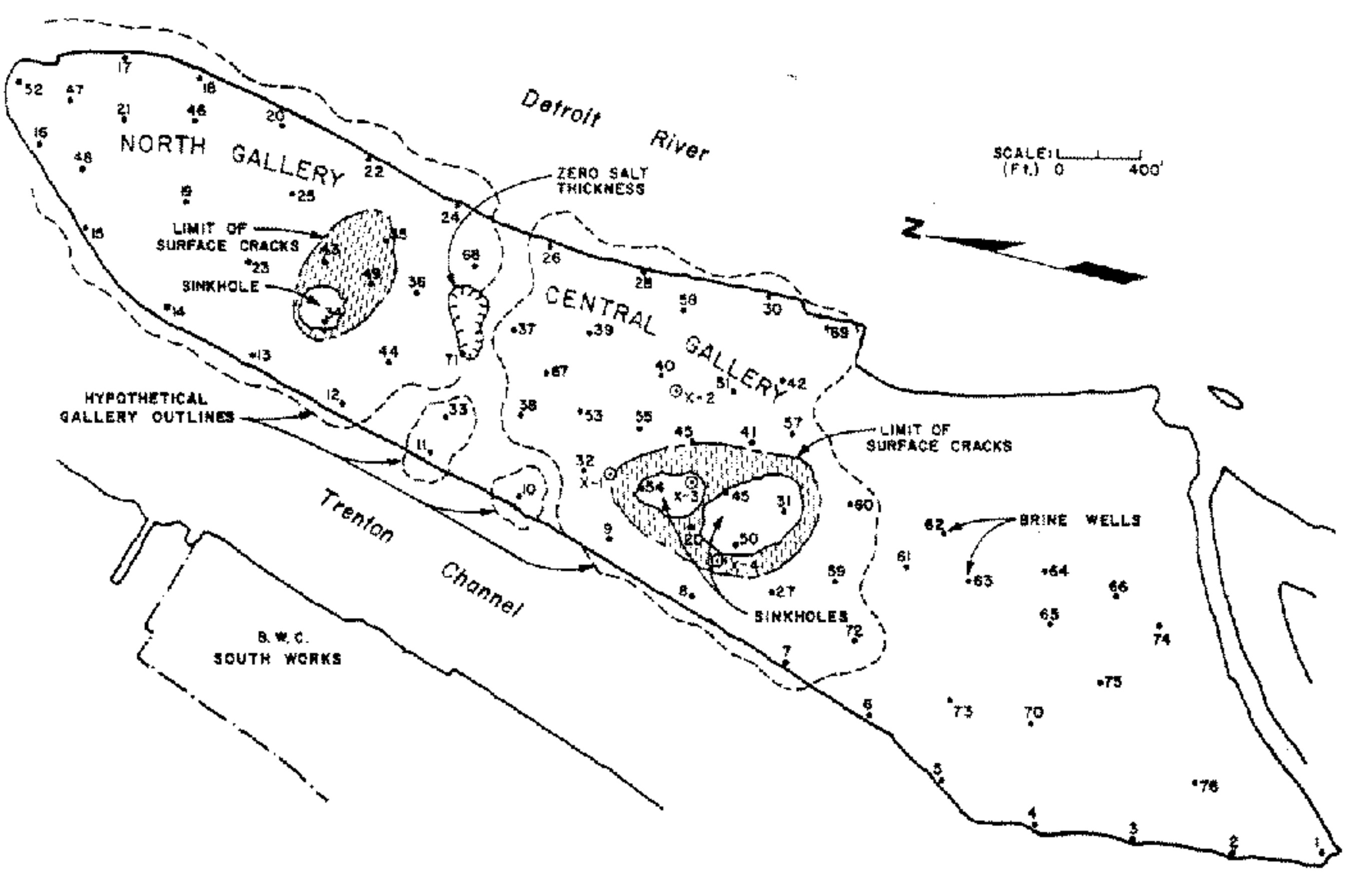

Figure 7. Location of sinkholes, galleries, and brine wells at Grosse Ile, Michigan (after Landes and Piper, 1972).

regarding initial cavity shape, could be used to estimate an effective extraction ratio in the galleries.

Location and Stratigraphy

The brine fields of the BASF Wyandotte Corporation are located on Point Hennepin, on the northern tip of Grosse Ile. The island is in the Detroit River, adjacent to the city of Wyandotte, a suburb of Detroit, Michigan. Point Hennepin is 1¼ miles long and ¼ mile wide, covering about 200 acres, and is separated from the rest of the island by a lagoon.

A typical core log of the sediments underlying the Point Hennepin brine field is shown in Figure 8. Below the 30 feet of man-made tailings on the surface of Point Hennepin is about 60 feet of glacial drift consisting mostly of clay. Detroit River dolomite, having a thickness of 150 feet, underlies the glacial drift. This layer of rock contains water-filled cracks and joints which have a high hydrogen sulfide content. A 150-foot-thick layer of saturated Sylvania sandstone lies beneath the dolomite layer. Cementation is present in different degrees from moderate to tight. (See Landes and Piper, 1972, p. 9.)

The dolomite layers that underlie the sandstone layer are interbedded with anhydrite, gypsum, shale and minor chert. Proceeding down the sequence there is 70 feet of Bois Blanc cherty dolomite overlying 370 feet of Bass Island dolomite and Salina evaporites (designated G and F in Figure 8) which contain interbeds of anhydrite and gypsum. The lower 270 feet (designated E and C in Figure 8) are argillaceous. Core samples reveal that the dolomite layers are massive but fractured. (See Nieto-Pescetto and Hendron, 1977, p. 7.)

The salt beds are first encountered at a depth of about 810 feet. The principal salt bed, however, is located approximately 1150 feet deep and is 200 feet thick. Interbeds up to several feet thick of dolomite, anhydrite and salt-impregnated, shaly dolomite compose 20 per cent of the thickness of the units.

A local structural and erosional feature is responsible for causing the B salt (Figure 8) to be discontinuous beneath the Point Hennepin brine field between the North and Central galleries. The location of the "pinchout," a zone of nearly zero salt thickness, roughly along a line which connects wells 11, 33, 71, and 68, as seen in Figure 7. Jaron (1966, p. 425) describes this feature as a solution-collapse structure which occurred when the B and C units (Figure 8) were deposited. Apparently the B unit of salt was dissolved by water soon after deposition. The resulting cavity was replaced by the bulking of collapsed insoluble ledges from the B salt section, roughly 50 feet of the overlying unit C roof rock, and by the thickening of the remainder of unit C as it was deposited. This solution and collapse sequence during Salina time dates the discontinuity in the salt structure prior to subsequent deposition

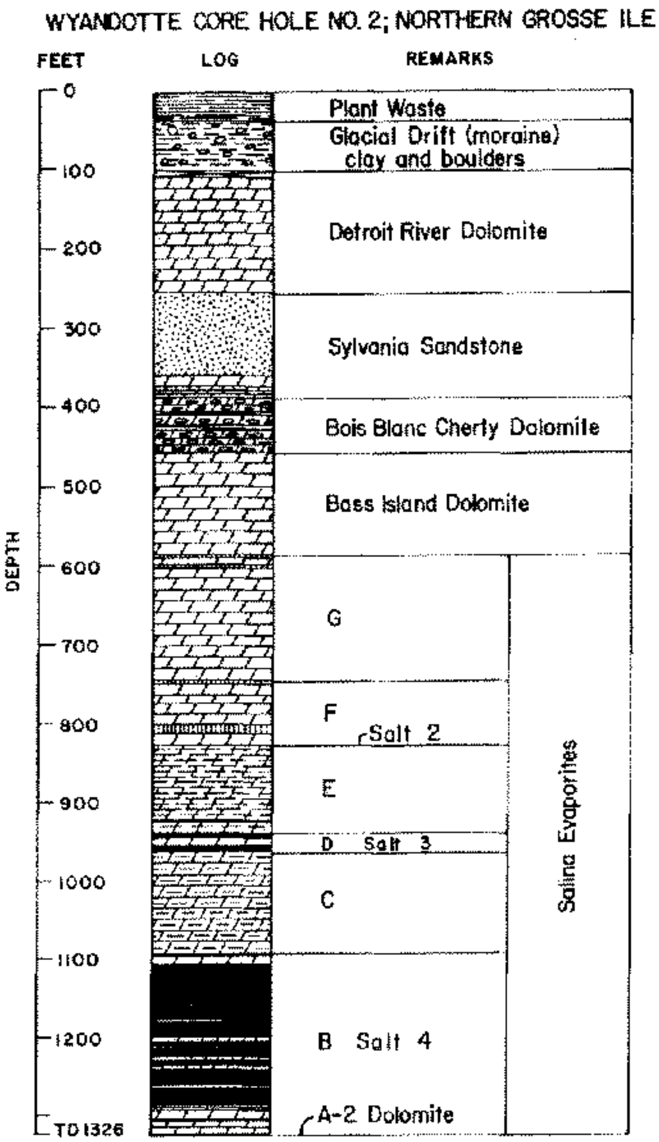

Figure 8. Typical core of Point Hennepin brine field, Grosse Ile, Michigan (after Landes and Piper, 1972).

of the undisturbed overlying beds. This solution feature, which physically separates the North and Central galleries (Figure 7), may be an important factor contributing to the Grosse Ile sinkholes.

Subsidence Activity

Beginning in 1954, elevations were recorded at reference points on the Point Hennepin brine field. Downwarping up to one-quarter inch per year was considered acceptable in this area. Total subsidence measurements of several feet over the entire area were also acceptable as long as the downwarping did not cause tension breaks in brine pipe lines or other major structural damage. It was estimated that the subsidence in the brine field would be limited to only several feet, and repairs to equipment were made accordingly. (See Landes and Piper, 1972, p. 21, 27.) Subsidence profiles along a section taken roughly through the center of both sinkholes are shown in Figure 9. This figure also shows the extent of the two sinkholes, limits of surface cracking, thickness of the salt, and the location of wells along this section. The last profile plotted shows the displacement in December, 1970, only one month before the sinkhole formed in the North gallery and

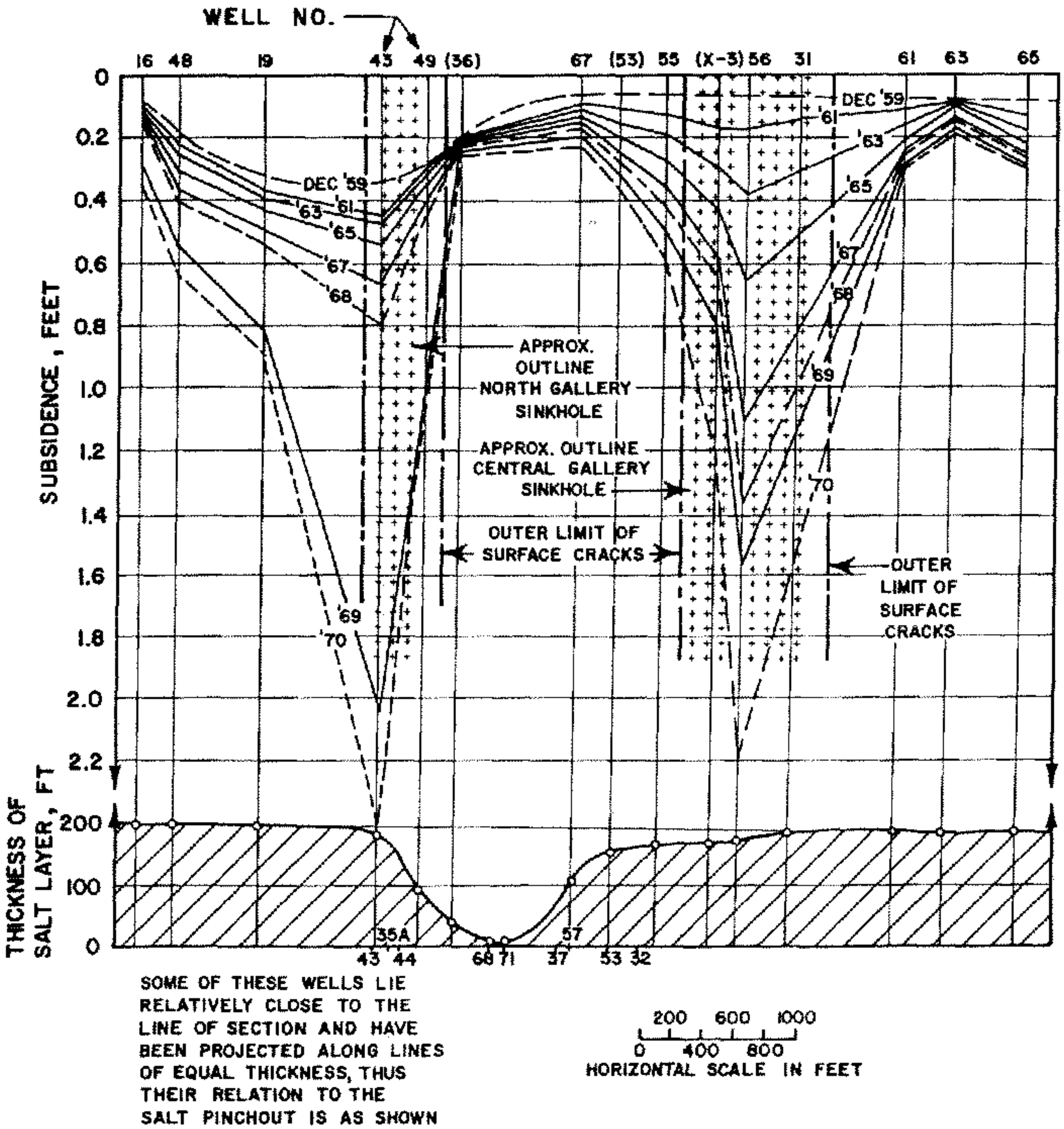

Figure 9. Subsidence profiles along a section through both sinkholes at Grosse Ile, Michigan (after Neito-Pescetto and Hendron, 1977).

four months before the sinkhole formed in the Central gallery.

Northern Gallery Sinkhole

In October, 1969, when abandoned well No. 49 was about to be plugged, it was discovered that the casing had parted at 260, 370 and 700 feet. Quarter-inch wide cracks were observed in the roadway near well 49 in November, 1969. No vertical displacement was indicated by these tensile cracks and they were arranged circumferentially to the subsequent depression.

From March to October, 1970, several breaks and leaks in pipes that serviced the North gallery were found and repaired. On November 10, 1970, cracks several inches wide in the surface of a road near well 49 were observed. There was also an increase in injection pressure in well 71 and observation well 44 showed a rise in its static fluid level of about 20 feet. At well 48, water containing sulfur flowed from the casing of a surface pipe. At this time a smooth, basin-shaped depression formed south and east of well 43, measuring 100 feet in diameter and approximately 2.5 feet deep. By November 12, 1970, the settlement around well 43 totaled 6 feet 1 inch since the September reading. Water and brine mains continued to break as the sinkhole continued to widen and deepen. On January 27, 1971, water began filling the sinkhole, equal to the river level. A sulfurous odor was detected. On April 22, 1971, the steep scarps of the hole were excavated in an attempt to make them less of a safety hazard. The depth at this time was estimated to be 100 feet. Other than minor additional settlement, the sinkhole appeared to have stabilized by May, 1971. (See Landes and Piper, 1972, pp. 27–34.)

Central Gallery Sinkholes

In May, 1970, the wells within the Central gallery were largely retired, in advance of retirement of this entire gallery. The formation of the sinkhole was not preceded by cracking and downwarping as noted before the North gallery sinkhole formed. The only indication at this time that anything unusual was happening was an influx of water containing sulfur into wells 51, 55 and X-2 which was noted when the feed water was out of balance with brine production. The area was inspected on a daily basis, and other than the normal subsidence measured from the leveling of reference points, no unusual subsidence was observed. (See Landes and Piper, 1972, p. 35.) A developing sinkhole was discovered southwest of well 29 at 7 p.m. on April 28, 1971. The rapid ground subsidence was marked by the flow of sulfur water from wells 9, 29, 41 and 42. On April 29, 1971, the sinkhole had developed to about 200 feet in diameter with a depth about 15 feet below the original road grade previously crossing the sinkhole area. By late afternoon on the same day, the hole was an ellipse about 400 × 150 feet, with the major axis running northwest to southeast. Collapse continued through May 22, 1971, when several feet of additional settlement was noted near well X-3. Three days later on May 25, 1971, a satellite sinkhole, approximately 200 feet in diameter, developed in the area of wells 29, 54 and X-3. This sinkhole continued to develop until June 1, 1971. After this date, the two sinkholes appeared stable, with some self-filling by collapsed material from the side walls. (See Landes and Piper, 1972, p. 35-36.) A typical time-versus-settlement curve is shown in Figure 10. This curve shows that subsidence increased rapidly in the two years prior to sinkhole formation.

Because of the dangerous access to the North gallery and satellite sinkholes, soundings were possible at the Central gallery sinkhole only. These soundings indicated that the Central gallery had a flat bottom and was 100 to 120 feet deep below the water level.

Mechanism

The mechanism of the Grosse Ile sinkholes is postulated by Nieto-Pescetto and Hendron (1977, pp. 38–39):

> "Removal of roof support by the coalescence of conventional cavities was evidenced early in the development of the field. For the North gallery, a bowl of subsidence had already developed for the period of 1954 to 1959.... This removal of roof support induced roof sagging and concentration of vertical stresses around the periphery of the gallery. This in turn accelerated the creep of the salt forming the walls of the gallery and caused further subsidence of the roof rock. Pillars that were left inside the gallery probably tapered up and had small areas of contact with the roof rock; these pillars also yielded by creep to the weight of the overlying rock. The sagging roof rock reacted elastically at very small strains, but as sagging continued to develop, the roof beds developed concentric tensile cracks or existing ones opened up. For each bed these cracks propagated downward from the top of the beds around the periphery of the gallery and upwards from the bottom of the bed in the center of the gallery. The tensile strains at the bottom of the bed in the center of the gallery were greater than the corresponding strains at the top of the beds around the periphery. Thus, fracturing in the center was probably more intense and the fractures were more closely spaced.
>
> As production, removal of support, and sagging proceeded, the fracturing described above propagated upwards. These concentric vertical fractures probably accommodated most of the inelastic vertical displacements detected at the surface. Thus even though genetically they were tensile fractures, they operated as vertical shears to accommodate the large

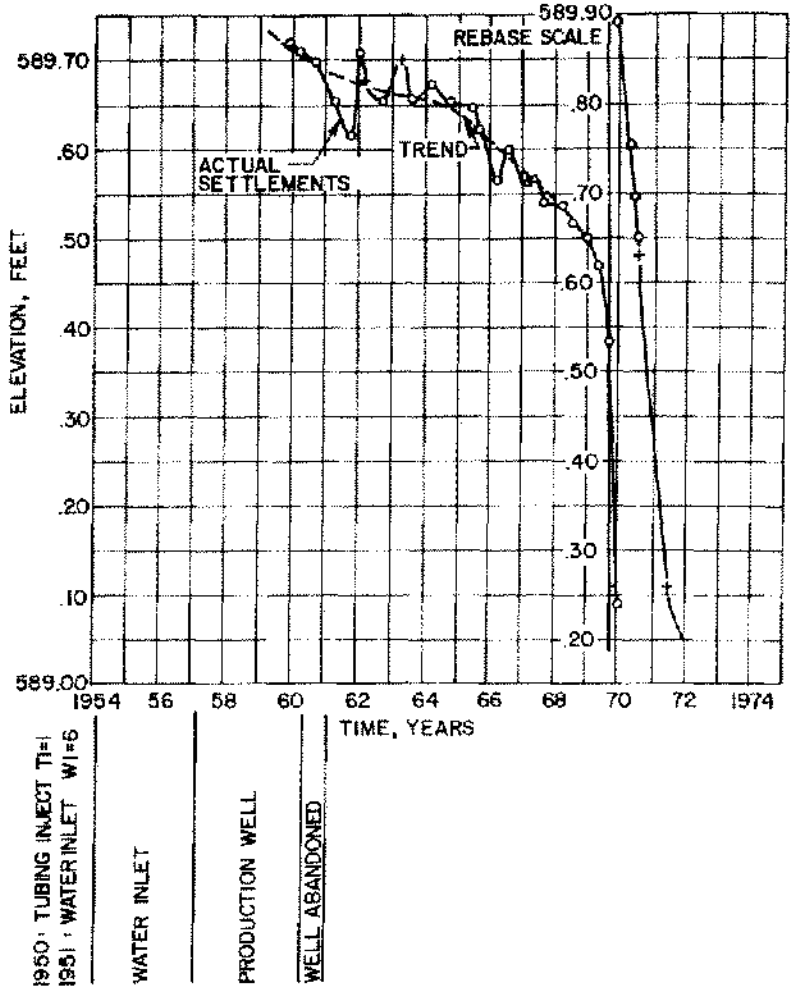

Figure 10. Typical settlement versus time curve (well 35 A), Grosse Ile, Michigan (after Nieto-Pescetto and Hendron, 1977; source: BASF-WC).

strains induced by salt creep within the gallery. This resulted in a surface bowl of subsidence of approximately the same size as the area of heavy production. Since the initial undermining activity had effectively removed a great part of the salt under the roof rock and this rock was fairly well fractured, stoping could easily begin. This could happen more easily in the center of the gallery where fracturing was more intense. At this point it should be mentioned that removal of salt under the roof of a gallery not only allows subsidence but it also permits the loosening of the rock. In this respect, salt against the roof behaves similarly as rock bolting; it prevents the blocks of the roof rock from losing interlocking along rough fractures."

More than one cause probably contributed to the sinkhole formation at Grosse Ile. In the first phase of salt solutioning, in which single cavity wells were used, a large amount of roof support was removed relative to the volume of salt that was extracted. This occurs because the highest rate of salt extraction is at the top of the cavity immediately under the roof. Later, the technique of connecting the wells by undercutting was meant to alleviate this problem by forcing lateral dissolution, but these measures were implemented after some roof support had already been lost. A salt pinchout is believed to have contributed to the formation of large cavities by causing concentrated extraction on either side of its axis. The extensive use of inlet wells, which accounted for almost 45 per cent of the total production in the North and Central galleries, was responsible for the concentrated extraction in the area adjacent to the pinchout. Bowls of subsidence formed on both sides of the pinchout, and when the settlement in the center of the bowls reached about 2 feet, sinkholes formed. The relocation of inlet wells in 1961 and 1968 in the Central and North galleries, respectively, did reduce subsidence rates but did not halt the eventual formation of the sinkholes. (See Nieto-Pescetto and Hendron, 1977, p. 48.)

SUBSIDENCE AT WINDSOR, CANADA

Introduction

On February 19, 1954, a rapid subsidence occurred in the Sandwich brine field area on land owned by The Canadian Salt Company and Canadian Industries Ltd. in Windsor, Ontario. Salt was being produced in this area by conventional gallery solution mining techniques, which involve pumping fresh water into the salt beds through input wells and removing the brine through production wells (Landes and Piper, 1972, p. 17). This production method results in a merging of the individual salt cavities into a common gallery. Inadequate roof support above the gallery probably caused the resulting localized subsidence.

History of Brine Extraction

Brine wells were first drilled in the Sandwich brine field in 1902. Between 1922 and 1953, 25 active wells were in production. These wells were drilled to the base of the Lower Salt (Figure 11), about 1600 feet in depth. Most of the wells were operated as water-forcing wells, which eventually coalesced into a common gallery. The gallery lost its pressure-tight properties about 1934, after which time brine was recovered by using deep well pumps. (See R. Terzaghi, 1970, p. 300.)

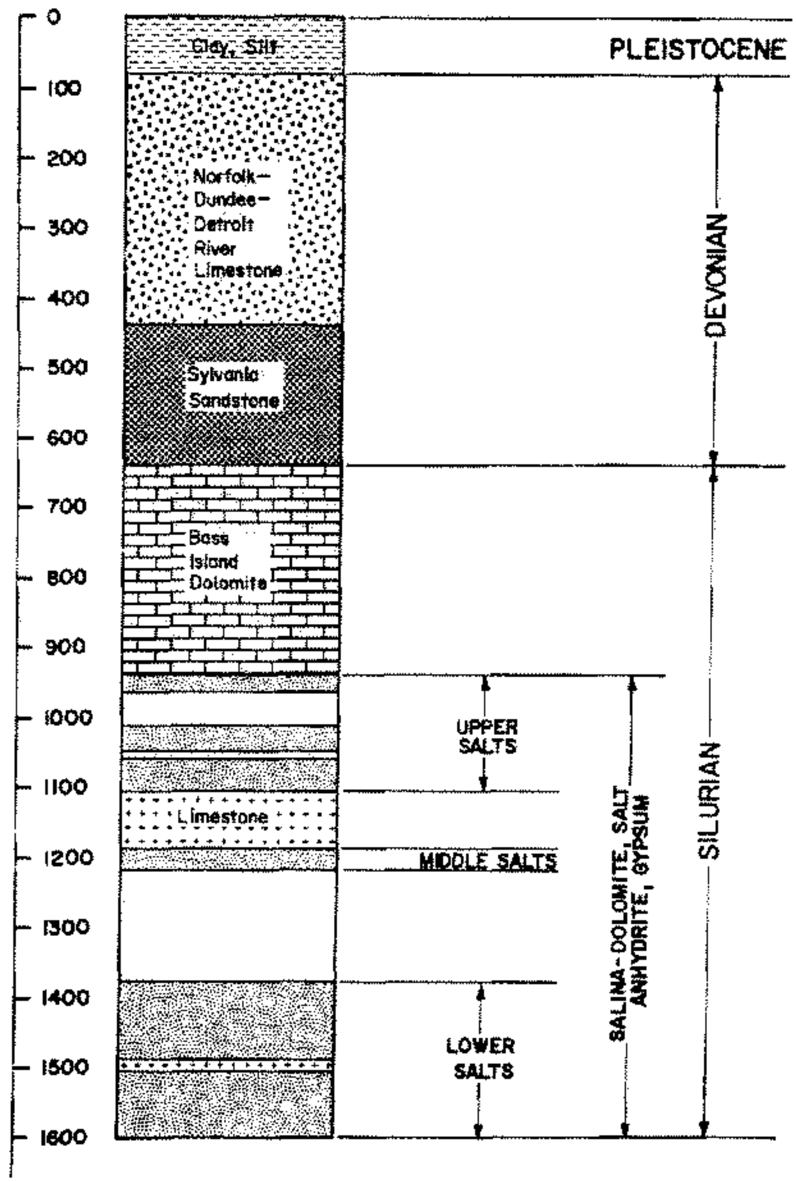

Figure 11. Typical geologic section underlying the Windsor brine field (after R. Terzaghi, 1970).

All wells drilled after 1918 were designed to produce brine from the 200-foot-thick layer of Lower Salt. Rockfalls, caused by the removal of supporting layers of salt from this region, indicate that this layer was the major source of brine produced. Data on design, construction and operation of the wells, as well as faulty well casings and inadequate packers, indicate that a large quantity of brine was removed from the Upper and Middle Salt layers, too. (See R. Terzaghi, 1970, p. 300.)

According to Bays (R. Terzaghi, 1970, p. 300), the amount of brine extracted was considerably less than the amount of fresh water injected. This accounts for Bays' estimate of 150 million cubic feet of salt having been removed from the deposits, while total production of brine was only about 71 million cubic feet.

There is little information concerning the size and shape of the individual cavities or the final coalesced cavity in the reports. Wells 5, 6, 7 and 9, located in a zone extending from the north side of the brine field to the south side, are perhaps the location of the greatest solutioning. Surface subsidence was greatest in the southern part of this zone. (See R. Terzaghi, 1970, p. 300.)

Stratigraphy

A typical section of the Sandwich brine field is shown in Figure 11. Unconsolidated Pleistocene deposits, composed primarily of stiff silt and clay, lie at the surface in the brine field. The clay that underlies the subsidence area is between 91 and 99 feet thick and overlies a few feet of sand or gravel. Drilling operations in the Norfolk or Dundee-Detroit Limestone Formation that underlies the Pleistocene sediments have encountered large amounts of water and mud. This suggests that the limestone is extensively jointed and fractured (Bays in R. Terzaghi, 1970, p. 299).

Beneath the Norfolk Formation is the Sylvania Sandstone Formation. Bays (R. Terzaghi, 1970, p. 299) reports that the sandstone is usually found in two benches, separated by gray and brown limestone. Some of the beds are cemented with carbonate or silica and others are loose.

The uppermost 200 feet of the Bass Island carbonate strata that underlies the Sylvania Formation is reported by K. Terzaghi (R. Terzaghi 1970, p. 299) to have widely-spaced joints with strong bonds between bedding planes, yielding a competent rock able to bridge cavities spanning several hundred feet without failure.

Three distinct layers of evaporites lie within the Salina Formation of Silurian age. The uppermost evaporite bed is encountered at 975 to 1000 feet. The three salt beds are separated by varying thicknesses of strata as illustrated in Figure 11. The Upper salts are divided by a carbonate layer. At a depth of around 1100 feet, a layer of limestone rock separates the Upper and Middle salt layers. Well drillings reveal that the Middle salt consists of a thin, discontinuous layer of salt between 1200 and 1250 feet. (See R. Terzaghi, 1970, p. 299-300.)

Cavities in the salt, up to 20 feet in height, were discovered when wells were drilled in both the Upper and Lower salts. Some, if not all, of these cavities may have occurred naturally.

At depths of about 1400 and 1600 feet, two beds of lower salt are found. The total thickness of this salt is about 200 feet, and the two layers are separated by a few feet of limestone. (See R. Terzaghi, 1970, p. 300.)

Events Leading to Major Subsidence

Settlement in the brine field area had been recorded since October, 1948. Cracks in a number of plant buildings had become apparent, and plant officials started to investigate the cause of the cracking. At this time about 80 reference marks were made on buildings in the plant. More points were established in 1949, 1951 and 1953. The buildings on which these marks were placed rest on shallow foundations (K. Terzaghi, 1954, p. 4). From Peck's 1954 evaluation of the settlement data, it is shown that the ground settled up to 1.5 inches between October, 1948 and October, 1950 in an irregular pattern. Between October, 1950 and October, 1951, subsidence slightly greater than 2.5 inches per year was recorded north of the Liquid Chlorine Plant (Figure 12). An increase in settlement of 3 inches was noted east of the Hydrogen Tank (located north of the Liquid Chlorine Plant) between October, 1951 and October, 1952. Contour lines from Peck's (1954, Figure 4) report show that the rate of subsidence started to decrease from the edge of the sinkhole toward its center at this time.

Subsidence at the Liquid Chlorine Plant was 9 inches from October, 1952 to October, 1953. A bowl-shaped depression with a radius greater than 1000 feet could be discerned (K. Terzaghi, 1954, p. 5).

Subsidence prior to the recorded observations of 1949 were estimated by Peck (1954, pp. 6–7) from differential level surveys. Differential settlements between buildings on the plant site show that the maximum subsidence in the plant area did not exceed 3 feet before the major subsidence.

Sinkhole Development

Between 8 a.m. and 9 a.m. on Friday, February 19, 1954, the first indications of the imminent ground subsidence were detected by plant employees. Sounds and vibrations resembling the bumping of rail cars, the rumbling of a small earthquake, blasting and cracking were heard and felt, apparently originating below the offices of The Canadian Salt Company, Ltd. The noises became louder, and the vibrations were severe shortly after 9 a.m. and were noted by employees of Canadian Industries, Ltd.

(adjacent to the Canadian Salt plant) as well. These occurrences were, at the time, attributed to blasting or the switching of locomotives in the yard. (See Peck, 1954, Appendix I.)

At 9:30 a.m., the first physical signs of subsidence could be seen in the area shown in Figure 12. An air line broke at its entrance into the liquid chlorine compressor room. By 10:30 a.m., underground water lines had broken beside the bulk storage building. The new subsidence was now clearly visible in an area between the liquid chlorine storage tanks to a point approximately 75 feet toward the Detroit River. A small crack, approximately 1 inch wide, opened in the ground near the railroad tracks running adjacent to The Canadian Salt Company storage tanks. Top-

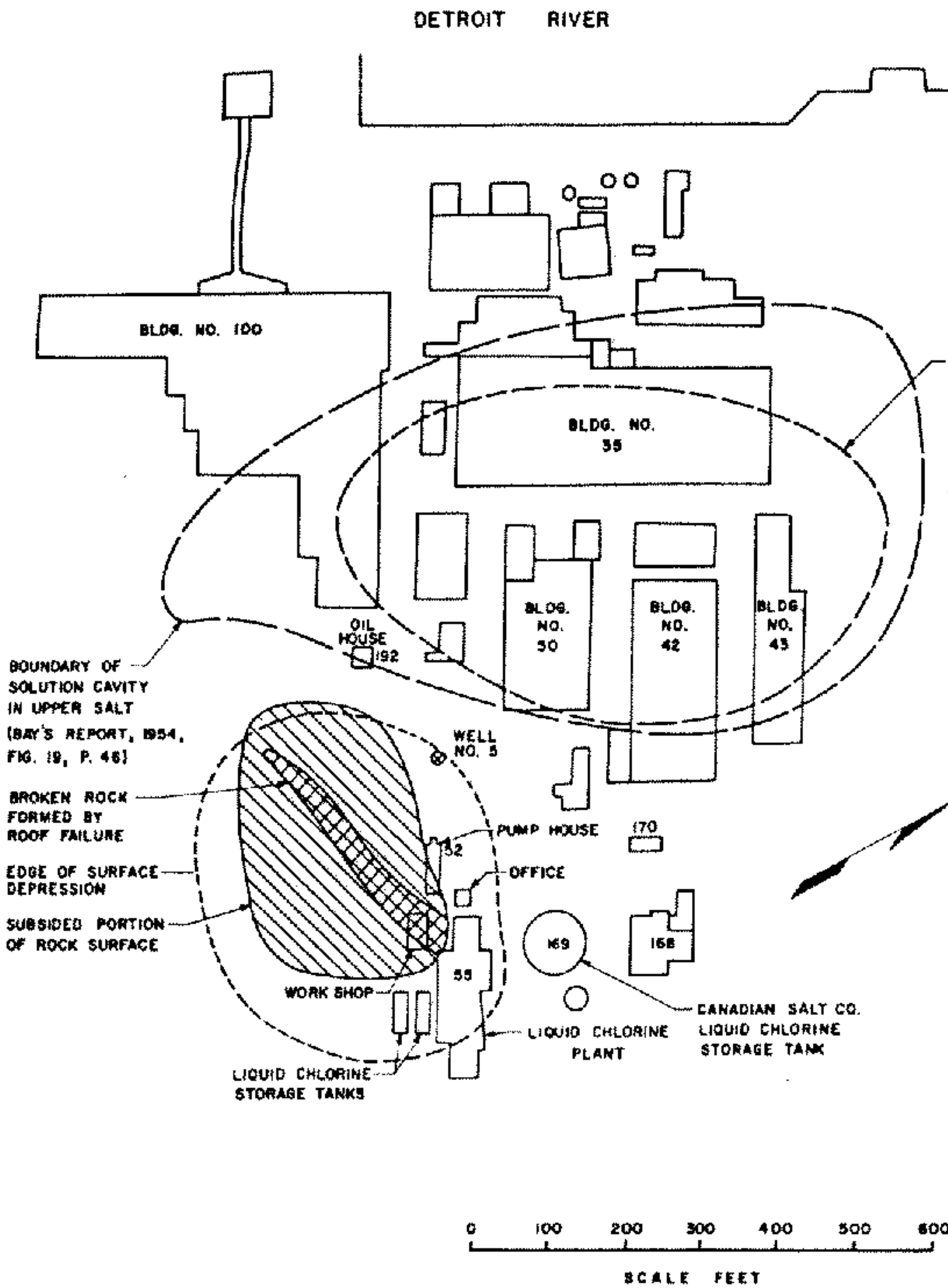

Figure 12. Windsor brine field and operations buildings (after Peck, 1954).

soil began falling into the crack. Water from an adjacent swamp was beginning to fill an approximately 18-inch depression, which had formed in a Canadian Industries road. About noon a ruptured brine line and an underground water main contributed to the flooding. A "gusher" 5 feet in length and lasting five minutes appeared from a fissure which formed near abandoned well No. 5. More gushers and sprays occurred as the ground subsided more rapidly. A rapid subsidence took place around 1:45 p.m., around the north rim of the depression, amounting to approximately 3 feet. A gusher that formed a 4-foot-high, 75-foot-long wall of water accompanied this subsidence. Individual jets of water shot upward, lasting two to three minutes. The water from these jets was black and had a sulfurous odor. This was the last major occurrence, and by 2:30 to 3 p.m., the subsidence appeared stable. The resulting bowl-shaped depression had a radius of roughly 1000 feet. The elliptical lake formed in the center of the depression was 350 feet wide and 450 feet long. The bottom of the lake was surveyed one week after its formation and was found to be 28 feet below the original ground surface. This point of maximum depth was located about 60 feet from the north shore of the lake. (See Peck, 1954, Appendix I.)

Some additional movement was detected until March 23. This movement was local and could be attributed to the mobile clay subsoil adjusting to its new position. During this time the lake bottom rose 5.5 feet, and other portions subsided up to 2.5 feet. (See K. Terzaghi, 1954, p. 6.)

Subsidence Due to Filling of Sinkhole

The Canadian Salt Company began filling the sinkhole on March 31, 1954 with pit run sand and gravel. This backfilling activity caused additional settlement of about 2.5 feet, due to the weight of the fill. (See Peck, 1954, p. 9.)

It was necessary to pump water out of the sinkhole to obtain the proper density of the fill material. Subsequent water seeping into the hole came from the sides and not from the bottom. No sulfur was present in the water. The removal of water caused tension cracks to widen beyond the edge of the crater and the area adjacent to the shoreline subsided. This movement was a result of a shift in equilibrium of the underlying clay beneath the slopes of the bowl of subsidence. (See Peck, 1954, p. 9.)

Indication of Subsidence on Buildings

Buildings in the vicinity of the sinkhole were surveyed after the February 19, 1954 sinkhole formed to determine subsidence. All buildings adjacent to the sinkhole leaned in its direction. Cracks were discovered in the walls of the buildings located near the sinkhole and appeared to be mostly random in nature. Most of the cracks appeared to have originated at the foundations and extended upward toward the roofs. Building 100 (Figure 12) exhibited crack patterns, indicating a consistent set of deformations from stretching in the east-west direction. Total width of these cracks was 3 inches. (See Peck, 1954, Figures 18–20.) The east wall of Building 100 tilted 15.5 inches over a length of 270 feet. K. Terzaghi concludes that the cracks must have begun to open up several years before the major subsidence (K. Terzaghi, 1954, p. 7–8).

Mechanics of Subsidence

Two theories explaining the events that led to the formation of the sinkhole are discussed by Karl Terzaghi (1954) and Ruth Terzaghi (1970), based on the work of Carl Bays. The first is the theory of localized rock subsidence in which the surface of the bedrock surrounding the sinkhole area remained stationary and the bedrock area within the sinkhole area settled. The second theory is of general subsidence, in which the ground surface subsidence was approximately equal to the subsidence of the rock surface.

Localized Subsidence

The theory of localized subsidence, as explained by K. Terzaghi (1954, pp. 11–13), is based on the following sequence of events. Before 1951, the intact rock below the subsided area stoped and decreased in thickness from around 900 feet to about 300 or 400 feet over an area of 70,000 square feet. Rock fragments had accumulated on the floor of the solution cavity below the remaining sound, intact rock. The bottom of the cavity was separated from the roof by 20 to 30 feet of water. As the thickness of the intact rock decreased, due to increasing fragmentation, the center of the rock began to subside, and the overlying clay began to flow toward the center of the subsidence. K. Terzaghi (1954, p. 13) states that the average downward movement of the intact rock increased from a few feet to almost 15 feet from 1952 to 1953. He further concludes that movement this great would be improbable unless the thickness of the rock had been reduced to less than 200 feet. The tension cracks discovered in the north wall of Building 100 are explained by radial stretching of the stiff crust above the moving clay. Radial compression of the stiff crust may account for the rate of subsidence in the center of the sinkhole being less than at its edges between 1951 and 1952. (See K. Terzaghi, 1954, pp. 13–14.)

In 1953, before the sinkhole developed, the radius of the area subsiding increased by 7 or 8 feet. Bending and shear along the edges caused the rock to fail in February, 1954. Fifteen feet of water-filled space between the overlying rock and the rock fragments at the bottom of the cavity accounts for the additional 15 feet of subsidence and the large amounts of water which resulted. (See K. Terzaghi, 1954, p. 14.) Karl Terzaghi (1954, p. 15) explains the mechanism of localized subsidence as follows:

"As soon as the process of stoping arrived at a depth of several hundred feet below the surface of the bedrock and the rock foundation of the clay stratum started to disintegrate, water under pressure rose through joints in the rock and started to invade the sandy, glacial sediments located between bedrock and clay. Since the permeability of these sediments is very high compared to that of the clay, the hydrostatic pressure was transmitted from the sinkhole area in the radial direction over long distances and the hydrostatic pressure in the pore-water of the sediments reduced the effective pressure exerted by the clay on the sediments to a value close to zero. At the instant of the sinkhole formation the continuity of the clay stratum was disrupted by tension cracks and the water under pressure shot out of the ground in the form of jets and of sheets of water, as described by the eye witnesses."

The theory of the flow of clay toward the center of the sinkhole area does not seem to be the correct mechanism to explain the rapid subsidence for two reasons. First, R. Terzaghi (1970, p. 305) reports that the clay is actually of a stiff and immobile character. Second, if the clay had actually flowed before the major subsidence event, it should have continued to flow after the event, because the average gradient around the depression was at least as high after the subsidence as prior to the sinkhole formation. Therefore, this theory is considered not plausible unless check borings could prove that the amount of clay above the subsidence area had increased by at least 5 million cubic feet between 1948 and 1953 (K. Terzaghi, 1954, p. 15).

General Subsidence

The Windsor brine field subsidence is thought to have a mechanism similar to the 1971 Grosse Ile subsidences. Salt dissolution, which caused the coalescence of many cavities into one massive cavity, removed much of the roof support above the cavity. The removal of this roof support induced roof sagging and concentrated the vertical stresses around the perimeter of the gallery walls. This roof sagging was first seen as a gradual downwarping of the ground above the brine wells. Further subsidence of the roof rock was caused as the gallery walls began to creep at an accelerated rate as the result of the stress concentration. As the sagging continued, cracking developed downward in the perimeter of the cavity and upward from the bottom of the beds in the center of the gallery. The tensile strains at the bottom of the bed in the center of the gallery were greater than those at the top of the beds around the perimeter, indicating more intense and closely-spaced fracturing in the center. The upward movement of the fracturing and the removal of roof support eventually resulted in sinkhole formation. (See Nieto-Pescetto and Hendron, 1977, pp. 38–39.)

The areas thought to have adequate roof support below the brine field are shown in Figure 12. The subsidence is approximately the same size as the area where the most salt was removed.

Although gradual subsidence was noted far in advance of the sinkhole formation, no attempts were made to arrest the subsidence. R. Terzaghi (1970, p. 303) illustrates the deformation of the bedrock from surface subsidence measurements over a number of years in Figure 13. The illustration is based on profiles through the west part of the sinkhole to the edge of the area where subsidence measurements were made.

Similarities exist between the Grosse Ile and Windsor collapses. The formation of each sinkhole was within well-developed bowls of localized subsidence, all with approximately equal diameters. In addition, the total subsidence over a period of five years before collapse was about the same for each sinkhole. A significant similarity exists among the rock surface gradients of the three cases. Each gradient was about 2.5 inches per 100 feet just prior to sinkhole development. Data from the separate sites at Windsor and Grosse Ile may be used in predicting future subsidence activity in similar geological settings. (See Neito-Pescetto and Hendron, 1977, p. 48.)

The similarities between the Grosse Ile and Windsor sinkhole formations are not surprising in view of the nearly identical stratigraphic sections of the two sites and the similarities in the salt production methods. This implies that structural modeling of sinks and prediction of future sinks will be much more successful in areas where one or more collapses have already occurred. Taken together, the Windsor and Grosse Ile sinks represent one of the best and most complete sets of cavity collapse data available for future model development.

CONCLUSIONS

Model capabilities and inputs are described for the study of stability of cavities in salt. An important characteristic of these models is that they contain or permit the action of the mechanisms that initiate and control cavity closure and collapse. These mechanisms can be identified by studying case histories of events in which cavities undergo large closure or collapse. Three such case histories have been selected for presentation from a larger collection of events. The three, cavity closure at Eminence, Mississippi; cavity collapse at Grosse Ile, Michigan; and cavity collapse at Windsor, Ontario, were selected because they are more completely documented than other events.

Although it is difficult to define the mechanisms precisely because of an incomplete data base, some general statements can be made. First, in cases of excessive cavity closure such as occurred at Eminence, the cavities are

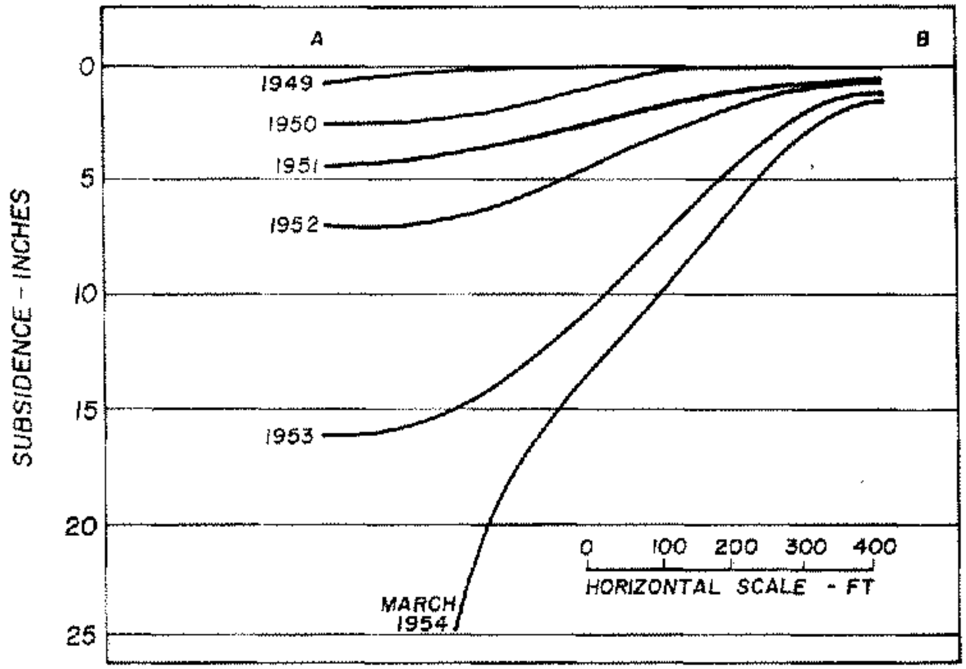

Figure 13. Profile through the westerly portion of the subsidence area at Windsor (after R. Terzaghi, 1970).

sited very deep. The closures were caused by reduction of the cavity pressure to well below the overburden (in situ) stress. When the cavity pressure is less than the overburden stress, the overburden is supported by a shear (effective) stress in the salt surrounding the cavity. The magnitude of this shear stress is proportional to the difference between the cavity pressure and the overburden stress. The salt creeps in response to this shear stress at a rate determined by the magnitude of the shear stress. Typically, the creep rate in salt depends on shear stress raised to a power that lies between three and five. Deep cavities subjected to large overburden stress, then, are more likely to suffer excessive closure because the potential for large shear stress is greater than it is for shallow cavities. These events are suitable for analysis by several state-of-the-art models which incorporate the viscoelastic behavior of salt, and the closures at Eminence have been adequately simulated (Preece and Stone, 1982).

In the cases in which the cavity collapsed and produced surface subsidence, the primary factor contributing to these failures appears to have been the closeness of the cavity roof to the top of the salt. The thickness of the salt above the roof at failure depends on factors such as the length of the roof span and the strength of the strata overlying the salt. As salt is leached from the cavity roof and as the salt creeps under the load of the overburden, load is transferred to the strata above the salt, increasing the stress in these less ductile layers. When the strength of these layers is reached, the cavity roof begins to fail. In some cases, collapse results when all the salt is leached from the roof and is aided by brine intrusion into the overlying argillaceous layers that reduces the strength of these layers. Surface subsidence over these cavities can be the result of the operation of a number of mechanisms such as troughing, stoping, plugging and piping. The relative contribution of each mechanism to the subsidence influences the sink formation sequence and geometry. Because these mechanisms are not well understood, it is difficult to construct models that adequately simulate cavity collapse. Improved knowledge of slaking and cracking of geologic materials is required to gain an understanding of those mechanisms so that they can be incorporated into models.

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