Brinefield Subsidence at Windsor, Ontario

Ruth D. Terzaghi
Research Fellow in Engineering Geology
Harvard University
Cambridge, Massachusetts

ABSTRACT

In 1948, settlement cracks were noticed in buildings within the Sandwich brine field area of Windsor, Ontario. Thereupon about 85 reference points were established on structures in the area. Changes in elevation of these points were measured at yearly intervals. The results of the second annual survey indicate that a shallow bowl of subsidence with a radius of about 1000 feet had developed at the time of the survey. Its depth had increased by about 2.5 inches since the initial survey. The results of subsequent surveys show that the bowl continued to deepen at an accelerating rate. During the fifth year its depth increased by 10.5 inches to a total value in excess of 16 inches.

In 1954, about four months after the fifth annual survey, a rapid subsidence took place in the central part of the bowl. Within a few hours, a water-filled depression, about 500 feet in diameter and more than twenty-five feet in maximum depth, was formed. Structures located within the area of rapid subsidence were damaged beyond repair.

Subsequent investigations indicated that sudden important subsidence was the culminating event in a progressive failure of strata overlying a solution cavity produced by brine extraction from salt deposits located at depths in excess of 1000 feet below the surface of the ground.

INTRODUCTION

In February, 1954, the sudden subsidence of the central portion of a brine field in the Sandwich district of Windsor, Ontario, produced a bowl-shaped, water-filled depression with a maximum depth of about twenty-five feet and width of 400 to 500 feet. Unlike many of the surface depressions associated with brine extraction, the Windsor depression, locally called the *sinkhole*, was centered neither about a single well nor about a group of wells. It appears rather to be the result of subsidence of rock strata into extensive cavities in underlying salt deposits. The roof of the uppermost cavity was located at a depth of about 1000 feet below the ground surface.

At the time of the subsidence, the brine field was owned in part by Canadian Industries Ltd., and in part by the Canadian Salt Co. I am indebted to both organizations for permission to publish an account of the interesting and relatively well-documented series of events connected with the subsidence. The account is based almost entirely on information contained in unpublished reports by Carl A. Bays, Ralph B. Peck, and Karl Terzaghi, who were retained under a co-operative agreement between the owners to investigate the subsidence. Mr. J.D. Mair, Vice President of Canadian Salt Co., has kindly made additional data available to me.

GEOLOGICAL CONDITIONS[1]

The Sandwich brine field is underlain by unconsolidated Pleistocene deposits consisting chiefly of stiff silt and clay, known in the area as "Lake Erie Blue Clay" (T.B. Piper, personal communication, 1969). Locally, the clay rests on lenses of sand or gravel with a maximum thickness of a few feet. Well logs indicate that the total thickness of the

1. Unless otherwise noted, the sections on geological conditions and brine production are based on Dr. Bays' report (1954), and on the well records included therein.

unconsolidated material ranges between 85 and 104 feet within the area subject to gradual subsidence prior to the formation of the sinkhole.[2] A thickness in excess of 99 feet was encountered in only two of the twenty wells for which data are available, and the log of only one of them indicates a thickness of less than 91 feet. These data suggest that the thickness of the clay underlying the subsiding area, was, with minor exceptions, between 91 and 99 feet.

The Pleistocene sediments are underlain by sedimentary rocks of Devonian and Silurian age (Bays 1954, Caley 1945 and Landes 1945). As shown in Figure 1, the uppermost part of this sedimentary series consists of several hundred feet of limestone, referred by Bays (1954) to the Norfolk (Canada) or Dundee-Detroit River (U.S.) Formation. On the basis of drilling records, Bays described the formation as follows: "The Norfolk is . . . a predominantly brown limestone 335 to 350 feet thick. Large yields of water, and mud losses during drilling, in the Norfolk indicate it is extensively jointed and fractured."

The Norfolk Limestone rests on sandstone belonging to the Sylvania Formation of Devonian age. According to Bays, "The sandstone is usually in two benches split by a gray and brown limestone. The three units total 175 to 200 feet in thickness. Cementation in the Sylvania is highly variable; some beds are well cemented with carbonate or silica and others are very loose."

Carbonate strata of Upper Silurian age, commonly about 300 feet in total thickness, underlie the Sylvania. Their general relationships suggest that they belong to the Bass Island Formation, encountered in brine wells in the Detroit area. In that region, the uppermost two hundred feet of the formation is reported to be sound, strong and competent, and capable of bridging cavities with a span of several hundred feet without any indications of stoping (Terzaghi 1950). This observation indicates that the joints are in general far apart, the blocks between joints well interlocked, and the bond across bedding planes fairly strong.

The uppermost evaporite bed was commonly encountered in the Sandwich wells at depths ranging between 975 and 1000 feet. This bed, together with the underlying approximately 800 feet of dolomite, shale, gypsum, anhydrite and salt, has been referred to the Salina Formation of Silurian age.

The uppermost bed of salt is generally 10 to 30 feet thick. Separated from this bed by a few tens of feet of carbonate rock, the underlying salt

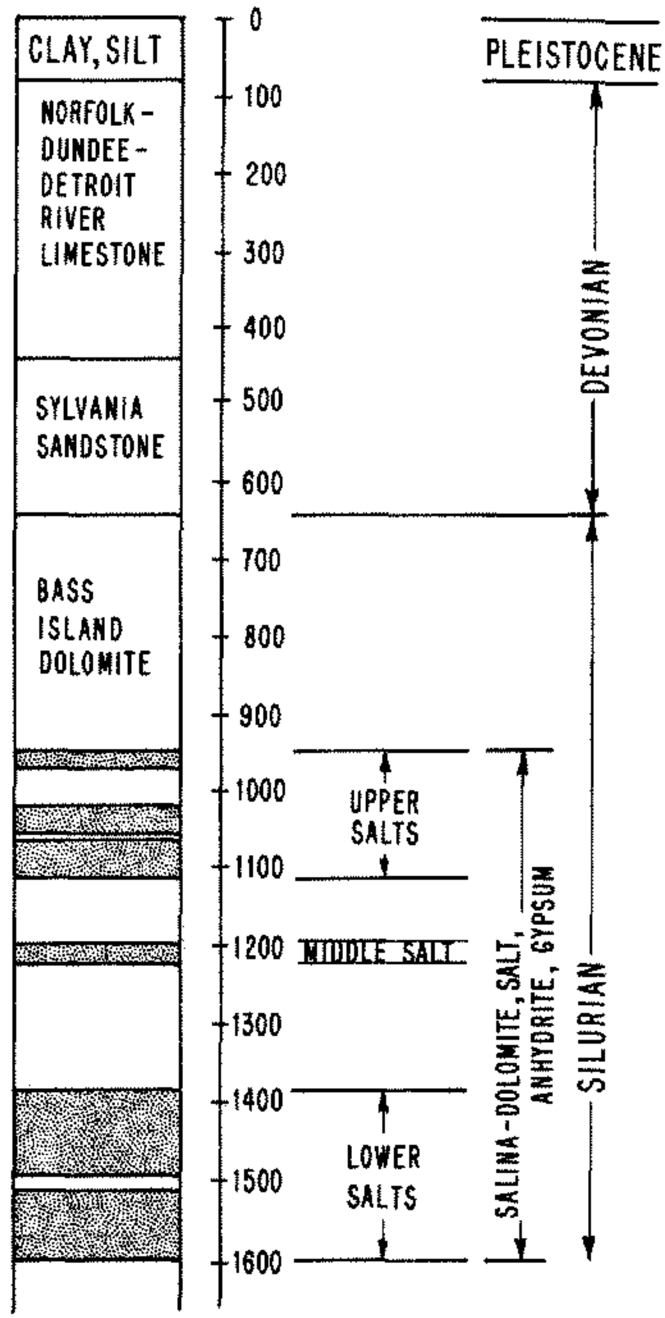

Figure 1. Typical section, Sandwich brine field.

2. Estimates of thickness of Pleistocene deposits are based on length of drive pipe, consisting of 10- or 12½-in. casing, which was, according to Dr. Bays (1954) "set on the bedrock or into it a few feet." Hence the data may exaggerate the thickness of the clay by a few feet.

consists of one or more strata with an aggregate thickness of eighty to one hundred feet in the Sandwich area. Together these beds constitute the "Upper Salt." At a depth of about 1100 feet, the base of the Upper Salt rests on rock called limestone by the drillers.

At depths between 1200 and 1250 feet, one or more strata of salt were encountered in many of the wells. Unnamed in brine field practice, they will herein be called "Middle Salt." These thin, discontinuous strata cannot have made a notable contribution to the total salt production, but rockfalls associated with them seem to have caused a disproportionate fraction of the tubing and casing breaks experienced during the operation of the brine field. Failure to distinguish between rockfalls in the Middle Salt and those in the Upper Salt has apparently led some observers to overestimate the relative amounts of solution in the Upper Salt. In order to avoid such an overestimate, it appears useful to recognize the separate existence of the Middle Salt.

During drilling of some of the wells, cavities with a maximum height of 20 feet were encountered in both the Upper and the Middle Salts. Some, possibly all, of these were of natural origin.

The Lower Salt consists of two beds separated, according to the well logs, by a few feet of limestone. Occurring between depths of about 1400 and 1600 feet, they have an aggregate thickness close to 200 feet.

Formations penetrated by brine wells of the area have undergone little or no deformation. According to Bays (1954), regional dips vary from slightly west of north to northwest. They average 60 to 70 feet per mile and rarely exceed 100 feet to the mile.

BRINE EXTRACTION

The first brine well was drilled in the Sandwich field in 1902, but relatively intensive development did not begin until 1922. Between that year and 1953, 25 wells were drilled to a depth of about 1600 feet, to the base of the Lower Salt. The casing appears generally to have extended to a depth between 1237 and 1290 feet, that is, below the Middle Salt, and the tubing, to the bottom of the well. All of the wells drilled before 1928, and most of those drilled later, were operated initially as water-forcing wells. Sooner or later, most of the wells became connected through solution channels to one or more of the others, and finally to a "general cavity," which, according to Dr. Bays, was in the Lower Salt.

The available data concerning the design, construction, and operation of the wells indicates that brine was drawn from all three salt horizons. With the exception of three wells drilled prior to 1918, all were designed to extract brine from the Lower Salt. The high incidence of recorded rock falls at or below the level of the top of this horizon (30 out of a total of 50) indicates that the 200-foot thick Lower Salt was, as intended, a major source of brine. In addition, an unknown but doubtless large quantity of brine must have been derived from the Middle and Upper Salts, owing to the introduction of water into these beds through defective well casings and around inadequate packers.

In view of the fact that the total thickness of the source beds underlying the brine field is about 300 feet, it is evident that the total height of cavities underlying the field may have been unusually large. However, because of impurities in the salt and the irregularities of the solution process, the total height of cavities beneath any one point on the surface was doubtless much less than the possible maximum of 300 feet.

The total volume of the cavities due to brine production at the Sandwich field can be roughly estimated from information concerning production. According to Bays, the total production of the Sandwich field was about 71 million cubic feet. He concluded that the quantity of injection water greatly exceeded that of the brine recovered, and he estimated that more than 150 million cubic feet of salt had been removed from the deposits underlying the plant area when production ceased in February, 1954.

If salt extraction had produced a single large cavity in the form of an inverted cone with a diameter of 2000 feet, instead of a considerable number of originally separate but ultimately connected morning-glory-shaped cavities, the cavity would have a maximum height of 150 feet.

The well records given in Bays' report provide scant information regarding the real shape, size, and location of individual cavities or of the "general cavity" to which most of the wells ultimately became connected. The earliest wells so connected were in a centrally located zone extending from the northerly side of the brine field to the southerly side (wells no. 7, 6, 5, and 9). It would not be surprising if maximum solution had taken place in those parts of the salt beds that underlie this zone. The area of maximum surface subsidence is located in the southerly part of this zone.

SETTLEMENTS PRIOR TO MAJOR SUBSIDENCE

Various observations indicate that differential settlement of the surface of the brine field had become appreciable by the late 1940's. The earliest of these observations was recorded in 1948, when it was noticed that cracks had become conspicuous in a number of the plant buildings. At this time, the management initiated an investigation of the cause of the cracking. On the advice of consultants, some 80 reference points were established within the area of the plant. All were located in the westerly part of the area involved in what appears to be a roughly circular bowl of subsidence.

In October, 1948, the elevation of these points was determined with reference to a bench mark located at the east end of the plant (BM 92, shown near the bottom of Fig. 2). The March, 1954, survey showed that it had not participated in the general subsidence since 1948 (Peck, 1954). Annual surveys were carried out on the points located in the northwesterly quadrant of what later became the bowl of subsidence. Points located in the southwesterly part of the area were not re-surveyed until 1950; owing to a change of ownership, observations on these points were discontinued until March, 1954, after the major subsidence. Since 1954, changes in elevation of most of these points have been determined at regular intervals, whereas observations on the points in the northwesterly quadrant were discontinued after 1954. Hence only Figure 2 showing settlement from 1948 through 1950 represents data for all reference points.

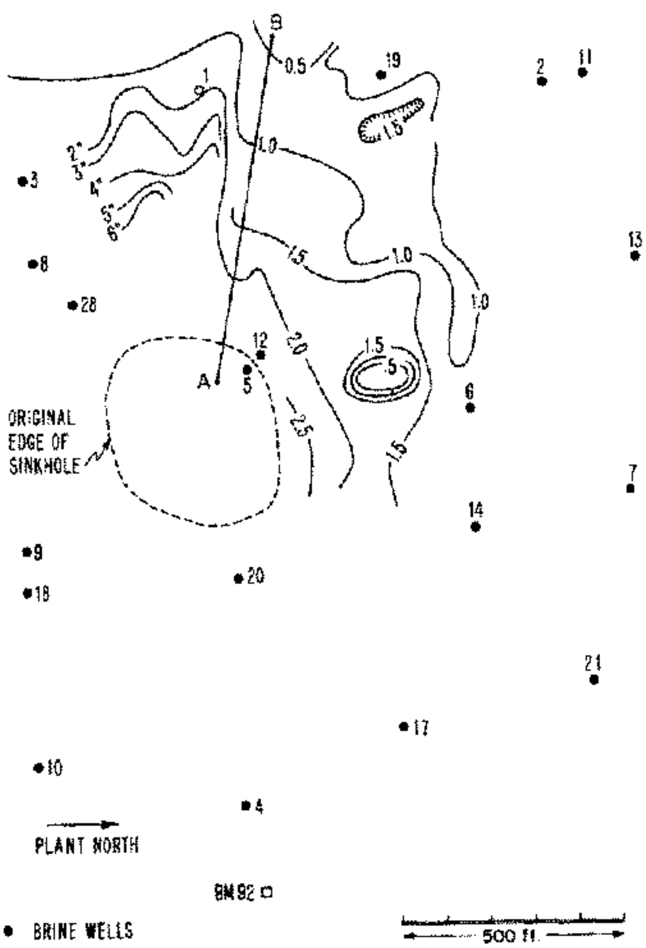

Figure 2. Location of brine wells and total subsidence in inches, measured from Oct. 1948 to Oct. 1950.

Levels were carried out with ordinary rather than with precision instruments. Concerning their accuracy, Dr. Peck (1954) stated, "Studies of the data suggest that the elevation of a given reference point at the time of any one survey may have been determined with an error not exceeding one-half inch. Variations of this order of magnitude in successive readings are probably not significant."

After the program of observations had been set up in 1948, the advice of consultants was not again sought until February, 1954. The following account is based on data which became available at that time.

At the end of the first year (October, 1949), measured settlements ranged between zero and 1.5 inches and exhibited no clear pattern. By the end of the second year (October, 1950) settlement observations indicated that a bowl-shaped depression was developing. As shown in Figure 2, maximum observed subsidence in 1950 had taken place in an area several hundred feet west of the site of the future sinkhole. The reference points located in this area were not again surveyed until 1954, and it is therefore not known whether this area continued to experience the maximum rate of subsidence.

In the following years, (1951 through 1953), settlement increased at an accelerating pace, as illustrated by Figure 3 which shows measured settlement of five reference points located near the site of the sinkhole formed in 1954.

Figure 4 shows the total settlements observed in October, 1953, at the occasion of the fifth annual survey. It should be noted that the maximum settlement of 16 inches refers only to that which took place after October, 1948. Observations of the tilt of plant buildings carried out under the direction of Dr. Peck in 1954, indicated that the maximum total settlement which had taken place prior to the

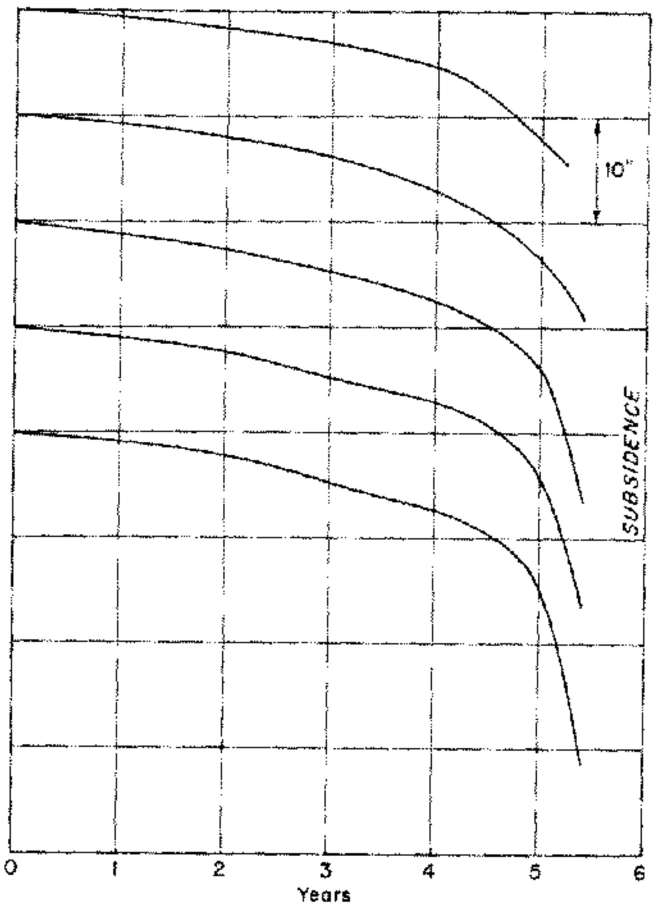

Figure 3. Settlement of five reference points located near sinkhole.

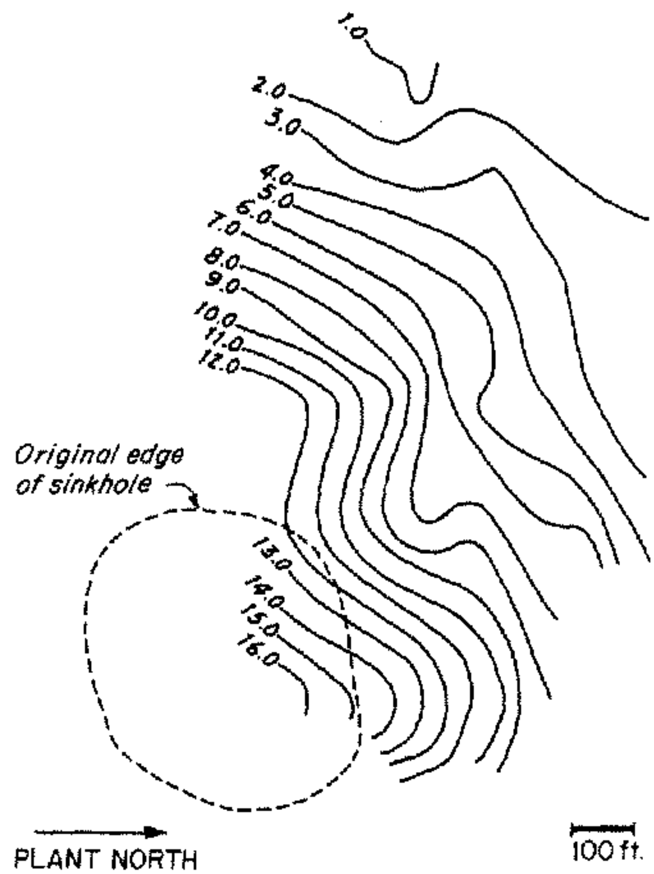

Figure 4. Total subsidence in inches, measured from October 1948 to October 1953.

sudden subsidence was probably as much as two feet, but not more than three feet.

Figure 5 shows successive profiles through the subsiding area, based on the annual surveys of reference points. Reference points surveyed only in 1948 and 1950 are not included.

Figure 6 shows changes in the annual rate of subsidence from 1949 to 1953. In the zone of zero change, subsidence took place at about one inch per year. It may be assumed that this settlement represents slow creep in the remaining "pillars" of salt located at depth beneath the peripheral portions of the bowl of subsidence.

FORMATION OF "SINKHOLE"

On February 19, 1954, several months after the fifth annual survey of the reference points, an alarming series of events took place at the site of the plant. The following account of these events is based on eye-witness reports.

The first precursors of trouble consisted in rumbling noises and minor vibrations noted between 8 a.m. and 9 a.m. These became more severe after 9 a.m. Next, distortions and leakage of various water and steam lines were observed, and by 10:30 a.m. it was apparent that a depression was forming in the originally nearly level surface of the ground. About noon, the depression began to fill with water from a nearby swamp and later from a ruptured water main and a brine line. Another source of water was a short-lived jet of water spurting from a fissure which had opened in the ground within the depression. At about 1:45 p.m., a rapid subsidence, amounting to approximately three feet, took place around one side of the rim of the depression. This event was accompanied by the appearance of a jet of water about four feet high, issuing from the fissure along which subsidence had

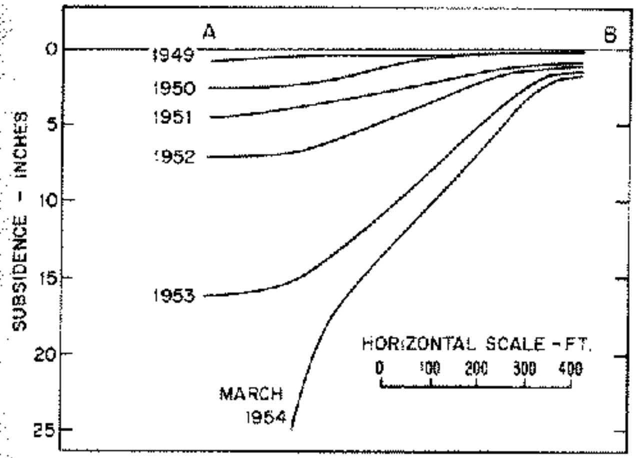

Figure 5. Successive profiles through westerly portion of subsiding area, along line A–B, shown in Figure 2.

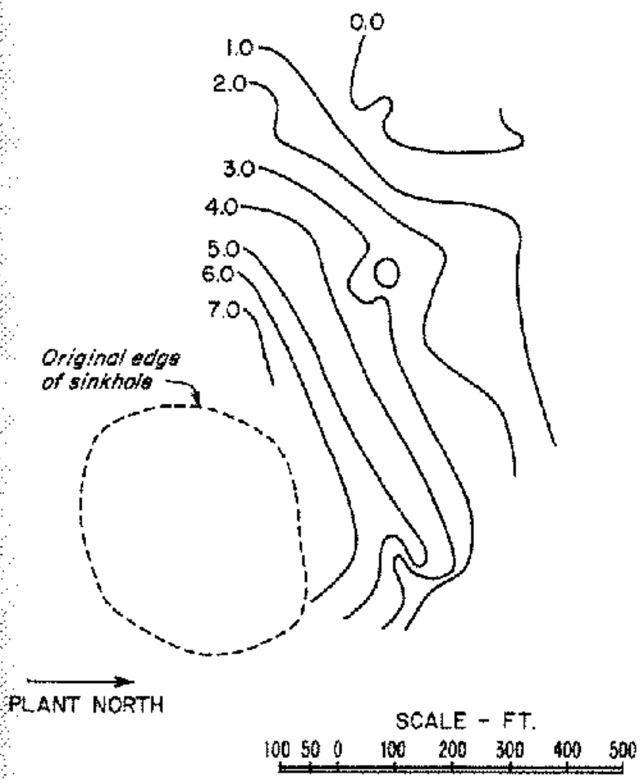

Figure 6. Difference in rates of subsidence of 1953 and 1949, inches per year.

taken place. In the early afternoon, additional jets or "fountains" developed at points which eventually became submerged. One of the largest of these formed a wall of water four feet in height and 75 feet long. In general, individual jets remained active for periods of two to five minutes. The water which thus spurted from the ground appeared black and had a sulphurous odor.

By mid-afternoon, movement had virtually ceased. Figure 7 shows the condition of a part of the plant at this time. There was a water-filled depression, "the sinkhole," roughly elliptical in shape, with a maximum diameter of nearly 500 feet and a maximum depth in excess of 25 feet. The pond occupied the center of a larger bowl-shaped depression with a radius of about 1000 feet. Many of the plant buildings were damaged beyond repair.

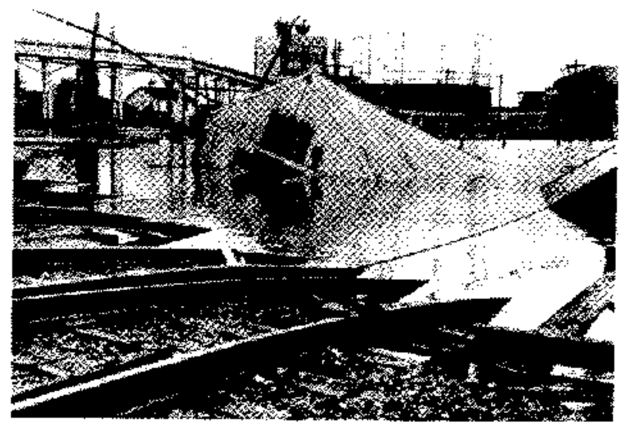

Figure 7. View of sinkhole, 1954.

Brine production at the Sandwich field was permanently discontinued after the sinkhole had formed.

In the months following the formation of the sinkhole, the pond was pumped out and the depression was filled with sand and gravel.

POST-SUBSIDENCE INVESTIGATION

Following the formation of the sinkhole, the Canadian Salt Co. and Canadian Industries Ltd. retained a panel of consultants of which Carl A. Bays, Ralph B. Peck, and Karl Terzaghi were members.

The program recommended by the panel included the determination of the depth to bedrock in the sinkhole area by means of a large number of washborings. Before any borings had been made, a seismic survey was carried out at the suggestion of

Bays. After a contour map of the bedrock surface had been prepared on the basis of that survey, three holes were drilled to bedrock; one of these was near the deepest part of the sinkhole, one on the westerly slope of the depression, and the third, in line with the other two, was slightly east of the westerly shore of the pond occupying the sinkhole area. The results of the drilling indicated that the seismic survey had overestimated the depth to bedrock by sixty to eighty feet within that part of the sinkhole area where the measured depth was 92 to 98 feet. After the results of the borings became available, the results of the seismic survey were recomputed.

Figure 8, an east-west cross section through the sinkhole, shows the results of soundings in the

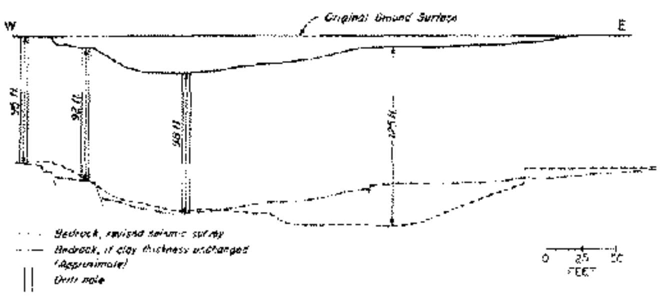

Figure 8. East-West section through sinkhole.

sinkhole pool, the depth to bedrock determined at three points by borings, and the revised results of the seismic survey. According to the seismic survey, the Pleistocene deposits were as much as 25 feet thicker beneath the easterly part of the depression than beneath the westerly part, where the observed thickness of 92 to 98 feet is close to the values recorded in the logs of brine wells in the vicinity of the sinkhole (85 to 94 feet). In the absence of additional borings, the accuracy of the recomputed results of the seismic survey cannot be regarded as established.

Within the period of four months following the formation of the sinkhole, two sets of settlement observations were carried out. Both of these surveys included reference points in the area located to the northwest of the sinkhole, as well as those in the southwesterly section which had not been surveyed since 1950. The results of the levelling showed that rather irregular movements of small magnitude had taken place within this period. Some points went up whereas others settled. In general, additional settlements of as much as one inch had taken place in the zone adjacent to the sinkhole pond; settlements of other parts of the brine field were within the limits of error of the survey.

Because of a change of ownership, observation of reference points in the northwesterly part of the subsiding area was discontinued after 1954. In the southwesterly quadrant, however, the Canadian Salt Co. (J.D. Mair, personal communication, 1969) carried out annual surveys of some thirty reference points, about half of which had been in existence since 1948 (Fig. 9). Most of the points under observation have settled at average rates of less than one-fourth inch per year since 1954, and the settlement of many of them appears to have ceased altogether. The settlement of points located at a distance of 200 to 500 feet from the sinkhole area is scarcely perceptible. Their average annual rate of settlement over the 14-year period following sinkhole formation does not exceed about one-seventh of the average annual rate observed from 1948 to 1950 (the only years for which data are available for this part of the subsiding area), and it therefore appears that the formation of the sinkhole coincided with the end of the process of widespread, accelerating subsidence which preceded it.

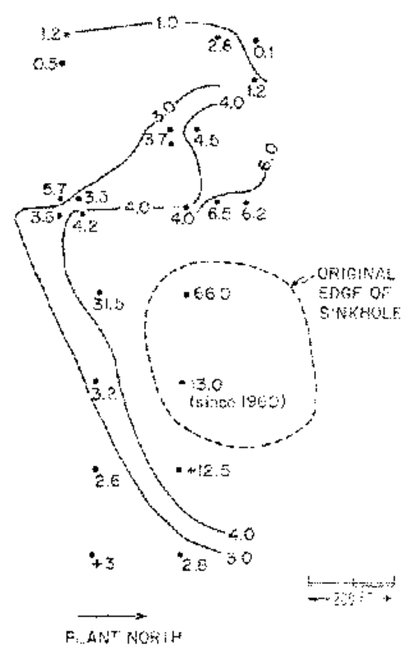

Figure 9. Settlements in inches, 1954 to 1968.

Only four of the reference points in the southwesterly area have experienced a change of elevation in excess of 6.5 inches in the period of observation (1954 to 1968). Of these, two are located within the sinkhole area, and the other two are within 100 feet of it. The data suggest a northwestward or westward tilt involving a subsidence of 66 inches at the westerly end of the tilted area, and an elevation of 12.5 inches of the easterly end. The tilting movement took place at a rapidly decreasing rate until about 1965, when the rate of movement of the three subsiding points seems to have assumed a fairly constant rate of about one inch per year. The reference point which went up had apparently become stationary by the beginning of 1967.

Inasmuch as the notable subsidence in the years following sinkhole formation took place at a rapidly decreasing rate, it is probably attributable to settlement and readjustments in the rock debris underlying the broken rock surface at depth. The apparently constant rate of settlement of about one inch per year presently experienced by three of the reference points in or near the sinkhole area is of the same order as that observed in many areas where salt extraction has been practiced. It appears to result from the slow creep of salt pillars, whether left by design in salt mining or fortuitously during brine extraction. It differs qualitatively as well as quantitatively from the accelerating subsidence associated with progressive roof failure.

MECHANISM OF SUBSIDENCE

After the formation of the sinkhole in February, 1954, it was clear that the gradual subsidence of an area with a diameter of about 2000 feet as well as the rapid subsidence of its central portion were the result of the collapse of the roof of one or more cavities in underlying salt beds. Nevertheless, the data then available left a number of unanswered questions. In his report of October 27, 1954, Dr. Karl Terzaghi suggested two alternative hypothetical models of the events which led to sinkhole formation. One of these involved subsidence of only that part of the rock surface which underlies the sinkhole, i.e., localized rock subsidence. The second involved the more conventional hypothesis of the subsidence of the rock surface underlying the entire subsiding area, i.e., general subsidence.

Concerning the hypothesis of localized settlement, he wrote, in part, as follows:

"If the bedrock surface surrounding the sinkhole area remained practically stationary throughout the years, the observed subsidence can only be explained by assuming that the bedrock surface in the sinkhole area . . . descended through a space with a volume equal to that through which the surrounding ground surface moved down. It must further be assumed that the clay advanced in radial directions towards the sinkhole area, from distances of more than one thousand feet . . .

". . . Yet a flow of clay over such distances . . . beneath an almost horizontal surface is a process without known precedent. Therefore the writer cannot accept it unless check borings show that the quantity of clay located above the subsided portion of the rock surface has really increased . . ."

The recommended check borings were never made, but two other items of information suggest that the settlement of the surface of the ground outside the sinkhole area was not the result of flow of clay toward the center of the bowl of subsidence. The first of these concerns the character of the clay. In the opinion of many who are familiar with it, this clay is a stiff and highly immobile material. The second item is the great reduction in the rate of settlement of points located in peripheral parts of the subsiding area following sinkhole formation. If flow of clay had taken place prior to the major subsidence, such flow should have continued therefore, because the average gradient toward the center of the bowl was at least as high after the subsidence and subsequent filling operation as it was prior to sinkhole formation. It thus appears that the hypothesis of localized subsidence is no longer tenable.

If, as suggested by the second hypothesis, the subsidence of the ground surface was everywhere essentially identical with that of the bedrock, the rock surface underlying a large area outside of the sinkhole subsided at rates which were locally as great as 7 inches per year. Such a rate of subsidence could be explained only if this area were underlain by one or more cavities with inadequate roof support.

If surface settlements did indeed accurately reflect the deformation of the bedrock surface, successive surface profiles provide a valuable clue to the nature of the deformation of the bedrock surface. Figure 5 shows a series of such profiles through the westerly part of the bowl of subsidence, from a point within the sinkhole area to the edge of the area in which settlement observations were made. It will be noted that the profiles for the years 1950 through 1953 exhibit a form similar to that of a loaded, clamped plate of which the clamped edge is subsiding at a rate of about one-half inch per year. The postulated plate consisted of rock strata with an initial thickness of at least 900 feet. The initial deformation of such a plate would be very small but a progressive decrease of its thickness associated with the dropping of strata or packets of strata into the underlying cavity would lead to increasing deformation of the plate and hence increasing settlement of points on the surface of the ground. On the hypothesis that subsidence was the surface expression of the deformation of a roughly circular clamped plate, the episode of rapid and catastrophic subsidence of February, 1954, can be interpreted as the result of the failure of the remaining strata which could no longer carry their own weight plus that of the overlying unconsolidated deposit.

It is not possible to determine accurately the diameter of the area undergoing accelerated subsidence, corresponding to the diameter of the postulated clamped plate, because settlement observations were not made throughout the entire bowl of subsidence. However, available data provide a basis for an estimate of maximum and minimum values. As indicated by Figure 5, the clamped edge of the postulated plate was descending at an approximately constant rate, whereas the remainder of the plate was undergoing deformation at a generally increasing rate. Hence on the map shown in Figure 6 (reproduced from Peck's 1954 report), the location of the clamped edge can be assumed to coincide approximately with the contour representing zero difference between the 1949 rate of subsidence and the 1953 rate. The distance from this contour to the point of maximum subsidence *before sinkhole formation* is approximately the radius of the clamped plate subject to deformation. If this point was located near the center of the sinkhole area, the radius was about 750 feet. However, the center of subsidence preceding failure was not necessarily identical with the center of the sinkhole, because the location of the sinkhole was probably determined by the location of that part of the cavity with maximum original vertical dimension, which was not necessarily at the center of the subsiding plate. As a matter of fact, settlement observations made in 1950 suggest that maximum settlement in 1950 occurred in an area several hundred feet to the southwest of the center of the sinkhole (Fig. 2). If this area was the site of maximum subsidence throughout the years 1951 through 1953, the effective diameter of the clamped plate may not have exceeded 650 feet.

Although it is impossible to determine with precision the time at which the thickness of the cavity roof began to decrease, the records of well abandonment provide some general information. Of the nine wells drilled within the area of the bowl of subsidence or at its periphery, all but two had been abandoned by 1932 owing to severe damage produced by rockfalls. Two survived into the 1940's. One of these, located about 500 feet to the southeastward of the center of the sinkhole, was abandoned in 1940 owing to a rockfall at a depth of 965 feet. The second, located about 100 feet east of the first, was abandoned in 1943 because of irreparable damage at a depth of 1200 feet. Hence it seems that the strata at depths less than 1000 to 1200 feet were still fairly intact in the early 1940's beneath the site of the future bowl of subsidence; otherwise rockfalls would have taken place in the two remaining wells as higher elevations. By 1950, when the bowl of subsidence first became perceptible, progressive failure must have reached a level well above the top of the Upper Salt.

Subsidence like that at Sandwich is commonly attributed to stoping above a large cavity located at depth, followed by the collapse of the remainder of the roof of the cavity. However, if it were assumed that the Sandwich subsidence was due to the presence of a single high cavity, into which much of the roof rock, with a total thickness in excess of 1000 feet, had dropped, it would be virtually impossible to account for the fact that bulking of the debris had not caused the cavity to be filled before major subsidence could take place.

An alternative hypothesis is that early cavities were extensive and locally deep, but contained abundant salt pillars which provided temporary and partial support for a sagging roof. According to this hypothesis, if strata overlying a cavity became separated along bedding planes from the rocks above and sagged into the cavity, they did not descend far before coming to rest at least temporarily on salt remnants. When the next set of strata in turn became detached from the overlying rock, they also came to rest in a nearly intact state and only slightly below their original position. These strata must have been thoroughly fractured and entirely lacking in tensile strength, but the space which they occupied need not have been greatly in excess of their original volume. It can, for instance, be postulated that the 150- to 200-foot thick stratum of insoluble rock between the Lower and the Middle Salts sagged into one or more underlying cavities. More or less simultaneously, it may be supposed, similar sagging took place into the cavity or cavities in the Middle Salt.

The strata of the Bass Island dolomite overlying the Upper Salt were initially thick enough to span a cavity in the Upper Salt without appreciable deformation. Eventually, however, partings along bedding planes must have opened, whereupon one or more strata descended into the cavity, possibly without disruption or notable bulking. As successive strata were detached from the roof and came to lie on the floor of the cavity, the load on the salt remnants at various deeper levels was increased and must have produced failure of some of the salt pinnacles which provided support for the overlying broken strata. Concurrently, solution was taking place in the salt beds, owing to the fact that water was being introduced through well No. 19, west of the subsiding area, while brine was being pumped from wells located east of it. Both the increasing load on salt remnants and their continued diminution by solution must have contributed to a gradual increase in the settlement of the overlying broken strata resting on them, and hence to an increase in the height of the cavity spanned by intact rock. There seems to be no way of determining the stage at which the vertical dimension of this cavity became so great that there was notable shattering and bulking of the strata as they dropped into it. It is only known that when the roof finally failed, the vertical dimension of the cavity exceeded that of the broken rock by twenty-five feet in the deepest part, and by only a few inches at a distance of several hundred feet from the center. The remainder of the cavity was completely filled with broken rock, either at the time of sinkhole formation or in the few months prior thereto. Consequently little or no sudden subsidence took place in the area located more than some two hundred feet beyond the edge of the sinkhole area.

REFERENCES

Bays, Carl A., 1954, Subsurface conditions at the Plants of Canadian Industries, Ltd., and Canadian Salt Co. with reference to the subsidence of February 19, 1954: unpublished report.

Caley, J.F., 1945, Paleozoic geology of the Windsor-Sarnia Area, Ontario: Canadian Geological Survey Memoir, No. 240.

Landes, K.K., 1945, The Salina and Bass Island rocks in the Michigan Basin: Michigan Geological Survey, Div. Oil and Gas Investigations, Prelim Map 40.

Peck, Ralph B., 1954, Memorandum concerning subsidence at Windsor, Ontario: unpublished report.

Terzaghi, Karl, 1950, Memorandum concerning the subsidence of brine fields: unpublished report of Dec. 30.

———, 1954, Report on the subsidence of February 19, 1954, in Windsor, Canada: unpublished report of Oct. 27.