A Mechanism for Sinkhole Development Above Brine Cavities in the Windsor-Detroit Area

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ABSTRACT

The development of three sinkholes of unexpected size and depth in the Windsor-Detroit area is briefly described and previous ideas on their formation are summarized. The roles of the Sylvania Sandstone—a unit of unique mechanical properties—and of the high in situ horizontal stresses are evaluated. Results of geomechanical testing and observations on the Sylvania are presented. It is proposed that the Sylvania fails under high horizontal loads, converts into sand, flows downward through cracks towards deeper solution mine caverns, and creates a shallow void that generates the sink-holes. Linear-arch theory is used to evaluate subsidence-induced horizontal stress increments. It is concluded that sinkholes are likely to occur in other areas where the Sylvania is close to the surface (less than 200 m) and active subsidence bowls have surface gradients of a few millimeters per meter.

INTRODUCTION

Salt has been extracted from the Silurian-age Salina formation of the Michigan basin for many decades. In the southeast Michigan-southwest Ontario area, the mining of evaporites dates to the last century and has been carried out at many locations. The mining technique most commonly used is solution mining, although rock salt mines have been and are important producers. The association of surface subsidence features with solution mining operations is well established. At solution mine sites near Windsor, Ontario and on Point Hennepin, Michigan, rapid subsidence events caused the formation of large, steep-sided surface depressions, or sinkholes, up to 40 m deep in 1954 and 1971, respectively. The locations of these and other relevant solution mining sites are shown in Figure 1. Since these events, variations on a mechanism of sink-hole formation for the area have been suggested (Terzaghi, K., 1954; Terzaghi, R., 1970; Nieto and Hendron, 1977). However, none of the proposed ideas satisfactorily explains the way in which a void of relatively small height could migrate more than 400 m upward in competent rock without bulking up or arching and could create such deep depressions.

This paper summarizes the work conducted in the last several years by the Engineering Geology Program of the University of Illinois at Urbana-Champaign, and more recently by the Ontario Geological Survey, in cooperation with solution mine operators of the area (see Figure 1) and the U.S. Geological Survey. The main purpose of the paper is to demonstrate the important role of the Sylvania sandstone in the mechanism of sinkhole formation. Details on the production history of the brine fields, geology and subsidence evolution can be found elsewhere (Landes and Piper, 1972; Nieto and Hendron, 1977; Russell, 1982).

EVENTS

Brine production at Windsor started in the first decade of this century from single-cavity wells but developed rapidly in the 1930s into a gallery system where fresh water was injected into the salt beds through one well and brine pumped from another. Rapid post-war production by this method was halted on February 19, 1954 when rapid subsidence caused the adjoining plants of The Canadian Salt Company and Canadian Industries, Ltd. to be evacuated. Warning signs had been noted six years previously when cracking was observed in several buildings. Monitoring of survey points between then and 1954 had shown existence of a bowl of subsidence of approximately 450 m in diameter with a maximum depth of 400 mm just before col-

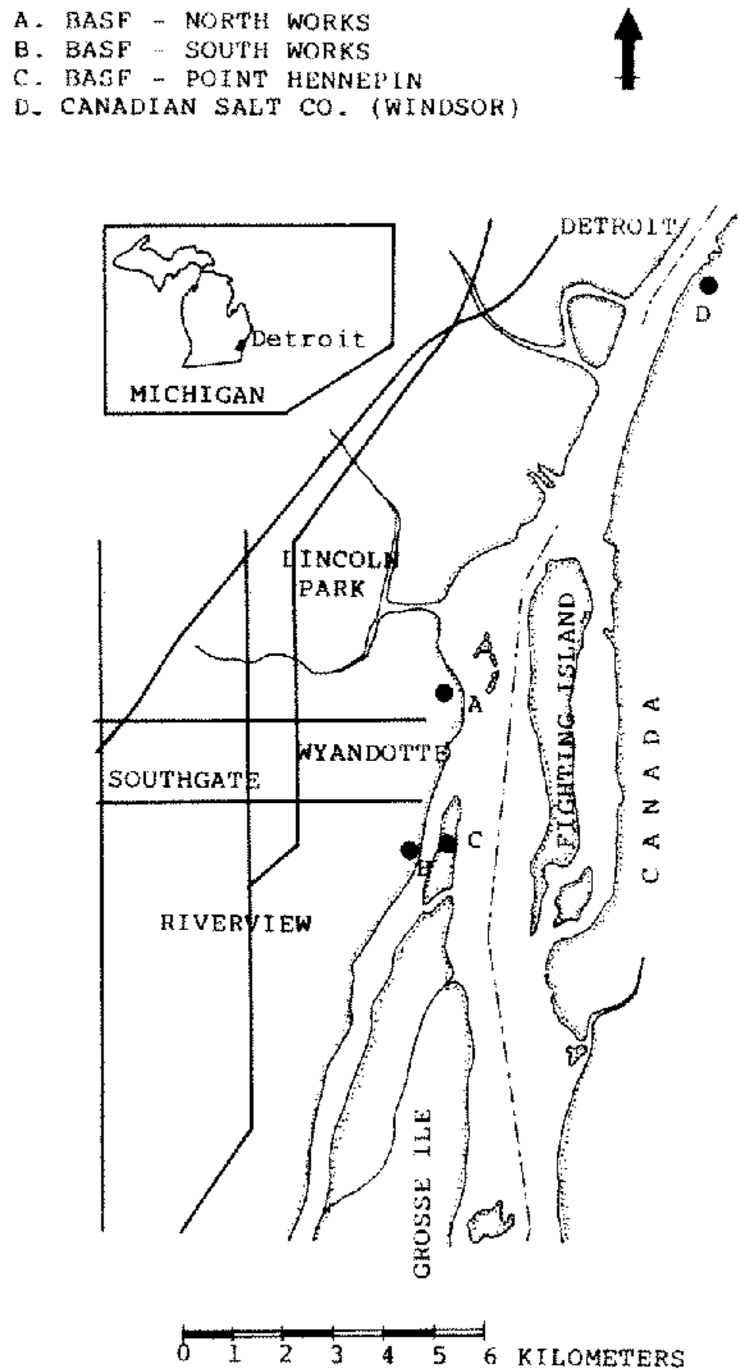

Figure 1. Location map showing Windsor, Point Hennepin, and other relevant brine field sites.

lapse. This monitoring also showed a rapidly accelerated rate of subsidence in 1952 and 1953. The sinkhole that formed was located in the center of this bowl and was up to 150 m across and 8 m deep.

A similar sequence of events characterizes the sinkholes at Point Hennepin. Salt production started in 1943 by a number of single-cavity wells, but these rapidly coalesced into large galleries known as the North and Central Galleries. Surveying of observation points on this site (from 1960 onward) showed steady subsidence until late 1967 when subsidence rates accelerated. The ensuing steep-walled sinkholes again formed in the center of the bowls defined by contours of equal subsidence (Nieto and Hendron, 1977). On January 9, 1971 a sinkhole began to develop over the North Gallery and stabilized after a few months at about 65 m in diameter. A second sinkhole developed over the Central Gallery in April and May, 1971 (Figure 2). This was a larger feature than the North Gallery sinkhole, having a diameter of about 120 m and a depth of about 35 m; an ancillary sinkhole 60 m in diameter developed next to it.

The similarity in the sequence of events, geological setting and scale of the sinkholes clearly dictates that a common mechanism of void migration from salt bed to surface be propsed. The differences in sinkhole depths (deeper at Point Hennepin) suggests that some subtle differences exist, however. The stratigraphic sequence for both sites is quite similar, as shown in Figure 3. The main producing horizon at the two sites is a 60-m thick salt unit (unit B of the Salina formation in Landes, 1945, terminology), which is about 335 m deep at Point Hennepin and about 425 m deep at Windsor.

PREVIOUS WORK AND BACKGROUND FOR PRESENT STUDY

The engineering geological reports on the area prior to the Windsor event were concerned with general subsidence and the effect of localized zones of subsidence (bowls with maximum depths of tens of millimeters and diameters of several tens of meters) on the surface structures existing over the brine fields. In the mid and late forties, K. Terzaghi and R. B. Peck concluded in a series of reports to the solution mine operators that general subsidence was caused by the sagging of the rock strata above the solution cavities as the dissolution of the salt removed the support of those beds. Sagging caused beds to separate from the roof rock and eventually collapse into the cavern, thus reducing the thickness of the remaining roof plate, hence increasing the sag. This mechanism of bed sag and collapse would migrate upward (stoping) and eventually could reach the surface. However, the roof collapse in the center of the sags could be precluded from reaching the surface if the space between the roof of the cavern and the top of the pile of rubble would close because of the increase in volume created as the material changed from the original rock into rubble (bulking). Terzaghi also discussed the general relationships of stoping in various materials that bulk at different rates. He invoked bulking as the reason for subsidence stoppage with termination of solution mining. These ideas prompted the termination of brining and subsidence at the North

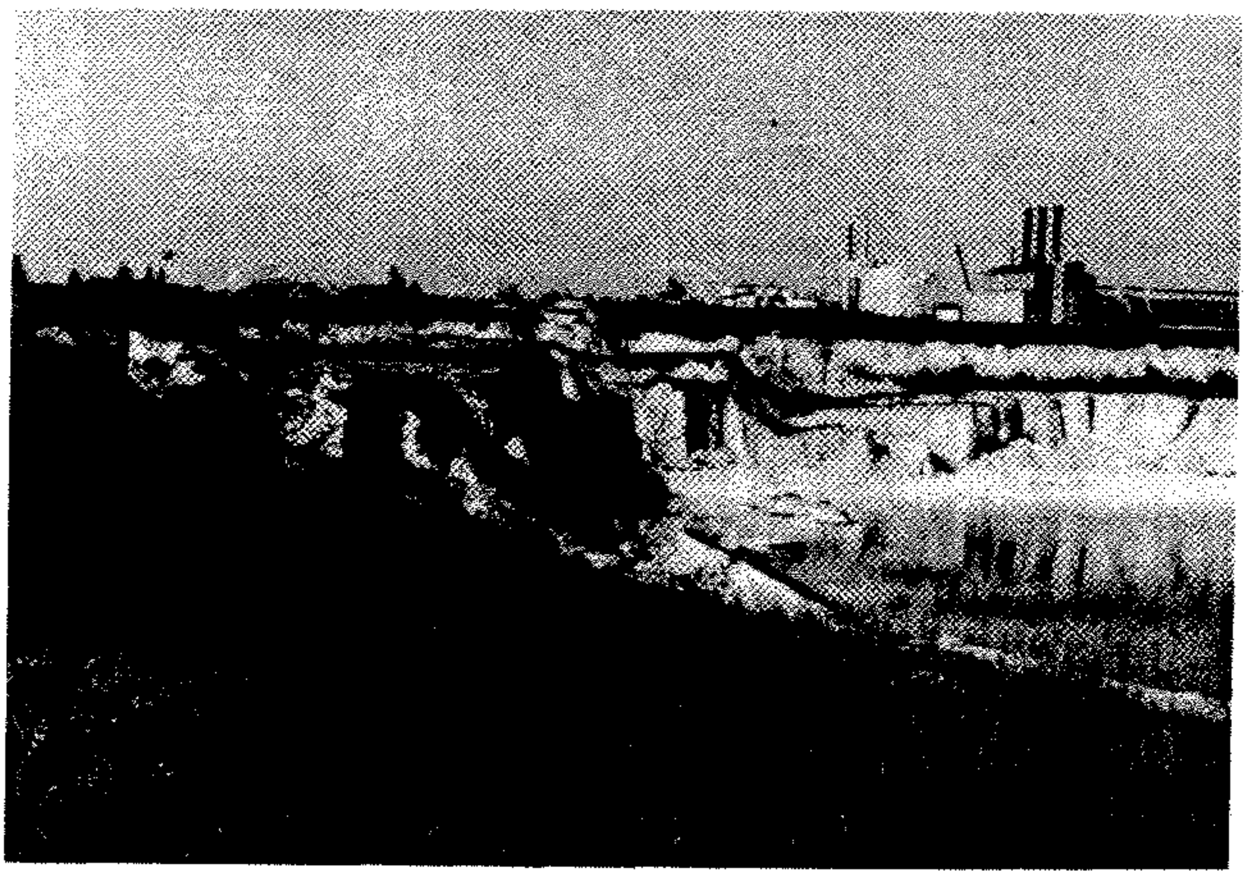

Figure 2. Sinkhole over Central Gallery at Point Hennepin; material on sinkhole walls is plant waste; photograph taken looking west in 1979.

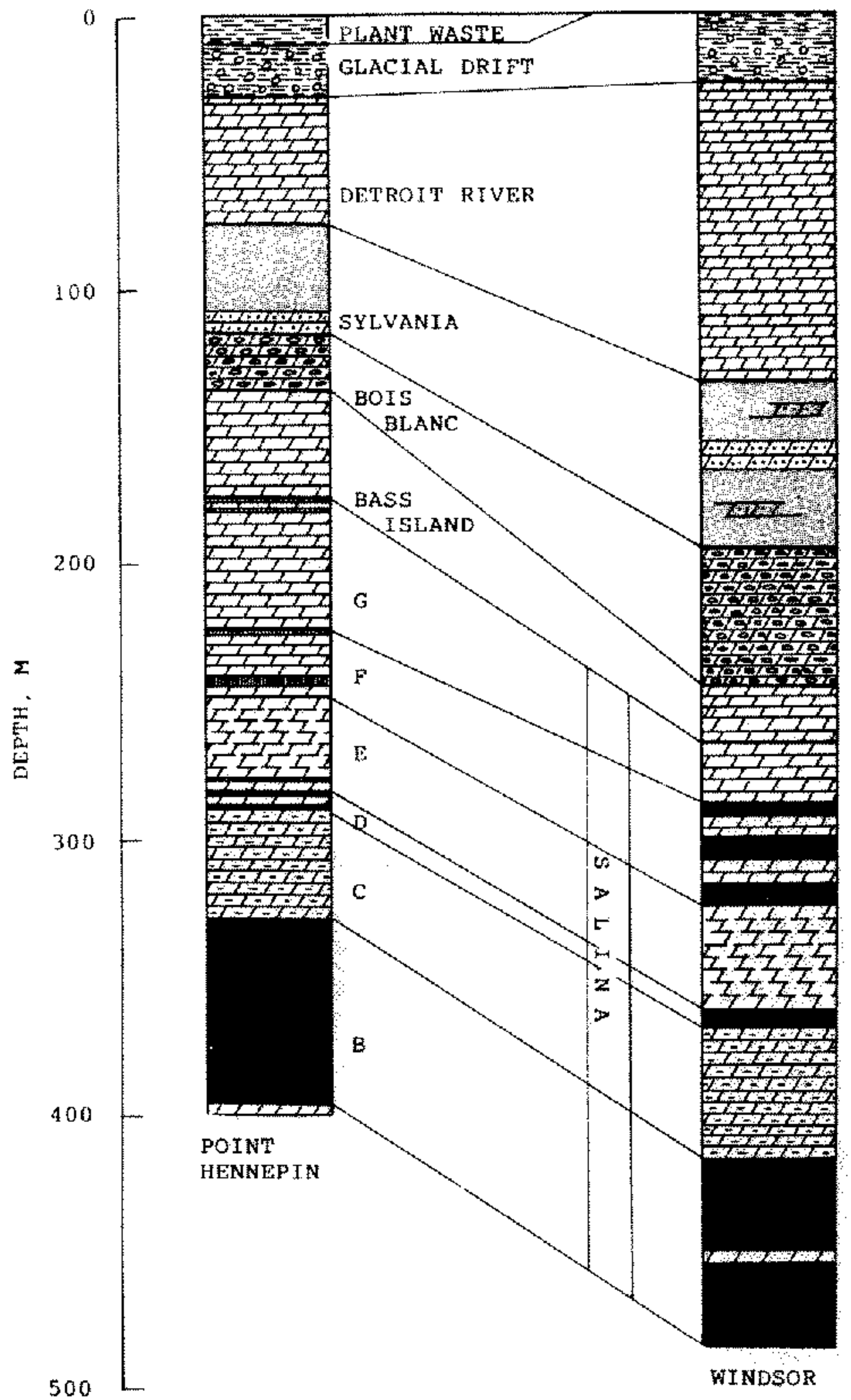

Figure 3. Stratigraphic sections at Point Hennepin and Windsor.

and South Works of the former Wyandotte Chemicals Corporation plant and the relocation of the brine fields at Point Hennepin on Grosse Ile, Michigan (Figure 1).

Terzaghi (1954) concluded that the Windsor sinkhole was caused by stoping. He presented examples of stoping from European brine fields and indicated that the propagation of stoping to the surface through the hard dolomite at Windsor probably assumed a cylindrical shape (Figure 4). His observations from European fields indicated that cylindrical shapes occurred in competent rock and that conical shapes tended to develop in incompetent rocks. Bulking was not evaluated in his discussion, since his main concern was to determine whether ground subsidence was caused by the lateral migration of glacial clay to the depression formed by the collapsed top of rock, or whether surface subsidence simply reflected the configuration of the subsided top of rock. R. Terzaghi (1970) published an account of the Windsor sinkhole development and included new data and a reappraisal of the subsidence mechanism. This author concluded that the sinkhole was the result of a rapid increase of subsidence within an area of general subsidence. Further, she postulated a gradual slumping of more or less intact beds to explain the ineffectiveness of bulking in preventing surface collapse over such considerable thickness of rock (over 400 m).

After the two occurrences at Point Hennepin, Piper and Landes (1972) gave an account of the development of the sinkholes and their environmental impact. Nieto and Hendron (1977) examined the production records and subsidence measurements at Point Hennepin and evaluated the required bulking factors for stoping to migrate through a cylindrical chimney to the surface. They also established that for all three sinkholes, surface gradients of about 2 mm/m developed a few months prior to collapse

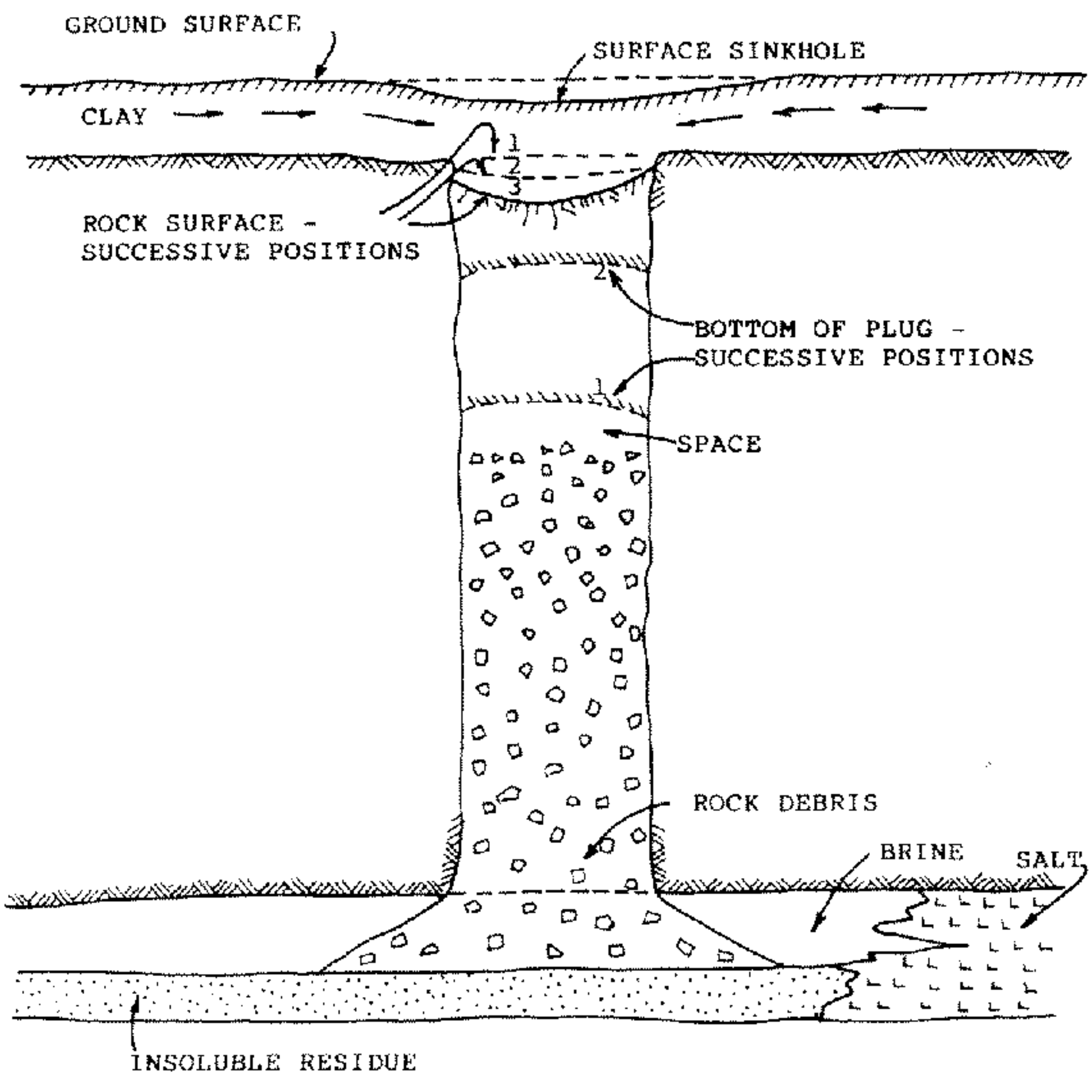

Figure 4. Terzaghi's conception of sinkhole development at Windsor; after R. B. Peck based on reports from K. Terzaghi.

and that the diameter of the bowls within which all three sinkholes developed was about 450 m approximately.

Persons with experience in solution mining in the Windsor-Detroit area (A. J. Robinson and T. B. Piper, oral communication, 1978) expressed doubt that the stoping mechanism—chimney fashion—could fully explain the development of deep sinkholes. Further, they suggested that the relatively shallow Sylvania Sandstone may be directly responsible for the sinkholes (Figure 3). They suggested that broken casings adjacent to the Sylvania could induce water flows that would enable the "loose" Sylvania Sandstone to form a slurry of sufficient density to be washed down cracks, joints or abandoned well casings. This activity would create a new, shallower cavity within the Sylvania Sandstone that would eventually result in a surface sinkhole. Spalling, running sand and large water inflows during excavation of a shaft (Robinson, oral communication, 1978) and the spontaneous loss of cohesion of Sylvania cores with time were cited as evidence of the "loose" nature of the Sylvania Sandstone.

The migration of uninterrupted stoping to create surface collapse from depths of more than 400 m can be further questioned. First, the volume relations derived by Nieto and Hendron (1977) for propagation to surface require that the entire B-salt unit be completely dissolved. However, exploratory drilling in the sinkhole area over the Central Gallery at Point Hennepin just before collapse indicated that the B-salt was virtually intact. Second, the propagation of stoping just to the surface (formation of a sinkhole of negligible depth) requires bulking factors (about 40%) shown to be too small by down hole photographs of the rubble taken in a recent exploratory hole at Point Hennepin. Third, sinkholes with vertical faces are found around Midwestern mined-out coal areas only when the ratio of mined-out material to depth is 1/5 or greater (Figure 2). For smaller values of this ratio subsidence creates sags or bowls, not sinkholes. At Windsor and Point Hennepin the ratios are probably smaller than 1/20 if one considers that no exploratory hole drilled in these areas has found more than a small fraction of the salt dissolved. None of these issues taken separately will negate the hypothesis, but taken together they cast doubt on the validity of a stoping chimney.

This study critically examines the role of the Sylvania Sandstone in sinkhole development in the Windsor-Detroit area. Although not entirely as originally proposed, the Sylvania seems to play a very important role in sink development. This study indicates that under normal conditions the Sylvania will not turn into a slurry and flow in a massive fashion, even in the presence of large water flows from broken casings, because the sandstone possesses some cohesion throughout its depth. No flow out of a casing can produce the necessary velocities to dislodge the sand grains a few meters away from the casing rupture. However, a mechanism is proposed that could allow the Sylvania to fail in compression and lose its cohesion. This failure can be caused by high horizontal stresses that are the result of the deformation accompanying bowl subsidence and of past geologic processes. In this context, high flows of water from broken casings are seen perhaps as triggering compressive failure in the Sylvania by reducing effective stresses, and perhaps initiating the downward flow of the failed, now cohesionless sand.

ENGINEERING GEOLOGICAL CONSIDERATIONS

General

The description that follows considers rock units grouped according to their engineering geological characteristics rather than according to their stratigraphic classification. The reader is referred to Landes (1945) and Landes and Piper (1972) for stratigraphic details of the sequence. The rocks of interest are of Devonian and Silurian age.

Both sites are underlain by 18 m to perhaps 27 m of Pleistocene glacial drift which consists mostly of clay with some boulders. At Point Hennepin, approximately 9 m of plant-waste solids have been deposited on the Pleistocene materials. The underlying unit is the Detroit River Group. The thickness of this unit is about 45 m at Point Hennepin and about 100 m at Windsor. It is principally a dolomite with minor amounts of shale and anhydrite. The dolomite is generally porous and vuggy and fractured in places. Underlying this unit is the Sylvania Sandstone, which is a quartzose sandstone with highly variable degree of cementation. The Sylvania is about 35 m thick at Point Hennepin and about 55 m at Windsor. A more detailed description of this unit is given in the next section. The rock from the base of the Sylvania to the top of the B Salt can be described as approximately 227 m of dolomite layers with interbeds of anhydrite, gypsum, shale, salt, and minor amounts of chert. Any type of interbed can be found throughout the sequence. The upper section of this sequence is predominantly cherty (Bois Blanc cherty dolomite). The middle section (Bass Island Dolomite and Units G and F of the Salina formation) contain interbeds of calcium sulfate (anhydrite and gypsum) and, at the Windsor site, a fairly thick, predominantly salt-bearing Unit (F) over 33 m thick. The lower section (Units E, D and C of the Salina formation) tend to be argillaceous. The Unit D is about 12 m thick and also contains some salt layers. The principal salt producer at the two sites is the 60-m thick Unit B of the Salina. The greater depth of Unit B at the Windsor site reflects greater thicknesses of the Detroit River Group and Sylvania Sandstone.

The dolomite sequence described is fairly massive although fractured in places. The bedding planes are essentially horizontal. At Point Hennepin there is a pinch out of the B Salt which is believed to be an ancient dissolution-and-collapse feature (Landes and Piper, 1972) and to have been critical in the localization of concentrated solution (Nieto and Hendron, 1977) and therefore to the development of the bowls of subsidence.

Sylvania Sandstone

The Sylvania Sandstone is typically a remarkably pure, well-sorted, medium-grained, cemented to very slightly cemented, very densely packed quartz sandstone. In large portions of this unit, lumps of the sandstone can be more or less easily crumbled between the fingers; in others, the material is a dolomitic sandstone and has high resistance. Interbeds of dolomite can be found throughout the unit. A wind-laid mode of deposition of the Sylvania is widely accepted. The Sylvania is really extensive in southeast Michigan and northwest Ohio. Descriptions by various investigators (e.g., Reavely and Winder, 1961; Carman, 1936) indicate that the cementation in the Sylvania is highly variable from one location to another. The cement is believed to represent the carbonate slimes deposited near shore along with the wind-transported sands. Retreat of the seas is believed to be associated with a decrease in dolomitic cement and advancing seas with deposition of dolomitic layers. Because of the rapidly variable conditions associated with near-shore and subaerial environments, it is not surprising to find a high variability in the thickness or even the disappearance of individual beds and in the overall thickness of the Sylvanian.

A description of a section of the Sylvania from NX-sized cores from experimental hole No. 2 adjacent to the Central Gallery sinkhole at Point Hennepin was given by Stump, et al. (1982). The cores were described a few years after recovery. The sandstone is described as massively bedded, very slightly cemented in its central portion and progressively more cemented toward the top and bottom. Centered around 10 m from the top is a 6 m thick zone of extremely poorly cemented sandstone; it was observed to be a mixture of sand and irregular sandstone fragments with average dimensions from 10 to 30 mm. The presence of the fragments of sandstone among the sand indicates that in the subsurface the Sylvania possesses very slight but still tangible cohesion. Thus, there is no evidence that truly cohesionless Sylvania sand exists in any significant amounts in a natural state.

The Sylvania has been described from the 45-mm core recovered from Borehole W-3 drilled by the Ontario Geological Survey about 4 km south of Windsor (Russell, 1982). Three cycles of upward-decreasing dolomite content are described in the Sylvania. The most notable is the lowest, which contains a dolomite bed 5 m thick at its base. This dolomite grades into dolomitic sandstone and eventually into a poorly cemented sandstone. This cycle takes about one half of the 38-m Sylvania section. Russell has also described a very poorly cemented zone at about the same stratigraphic position (10 m from the top of the Sylvania) that corresponds to the loose "sand zone" described by Stump et al. (1982). This zone also corresponds to the depth at which W-2, another borehole drilled into the Sylvania next to W-3, had to be abandoned because of clogging and caving in the Sylvania.

LABORATORY TESTING

Core samples from experimental borehole No. 2 at Point Hennepin were made available by the solution mine operator (BASF Wyandotte Corporation) for testing at the Engineering Geology Laboratory of the University of Illinois. The program consisted of a limited number of uniaxial, triaxial, direct shear and indirect tensile tests; several thin sections were made also from throughout the Sylvania thickness. Details of the program, procedures and results, as well as of the thin section analysis, have been described by Stump (1980) and Stump et al. (1982).

An extensive geomechanical study of the Sylvania, consisting of uniaxial, triaxial and point load tests, as well as thin-section analysis, was undertaken by the Ontario Geological Survey and some of its results have been reported by Russell (1982). Core samples, mostly from W-3 and some from W-2 were included in that study.

Only the results of the unconfined compression tests, point-load tests and thin section analysis are relevant to the purposes of the present study. Figure 5 shows that the

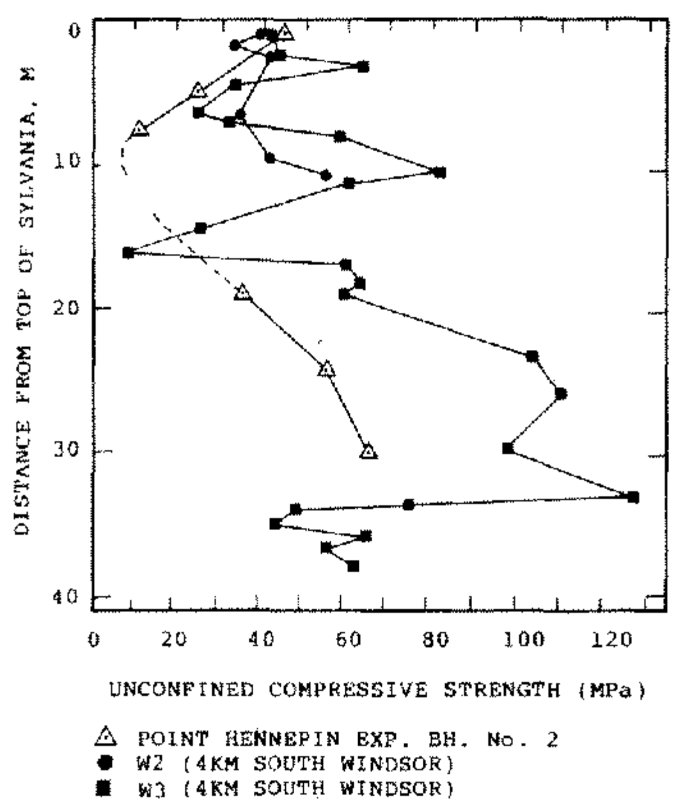

Figure 5. Uniaxial compressive strength of Sylvania.

values of the unconfined compressive strength, q_u, at Point Hennepin (NX-sized samples, conventional testing procedures) vary from about 10 to about 65 MPa with an average of about 35 MPa. The section around 10 m from the top probably has values lower than 10 MPa but, as stated before, could not be tested because it had converted into or recovered as an aggregate of sand and fragments of sandstone.

The samples from W-2 and W-3 (45 mm in diameter, conventionally tested) have q_u values that vary from about 10 MPa to more than 100 MPa. The greater variation in q_u values at Windsor roughly reflects the three depositional cycles described by Russell (1982). In spite of the variation, it can be said that the upper 20 m have values of q_u that fluctuate between 10 and 80 MPa with an average of about 45 MPa.

In addition to their relatively low q_u values, the weaker specimens of Sylvania Sandstone exhibit some remarkable properties as they fail under uniaxial loading. The failure is almost explosive and the material tends to disaggregate into loose sand. The values of Poisson's ratio for these weaker specimens are unusually high. Samples with q_u values of less than about 35 MPa usually have values of Poisson's ratio of 0.5 or greater at 50 percent of ultimate strength. More than 50 percent of these samples convert into sand upon violent failure. The weakest samples (about 10 MPa) display values of Poisson's ratio of up to 0.8 at 50 percent of ultimate strength. In some instances close to 75 percent of their volume are reduced to cohesionless sand. An NX-sized sample from Point Hennepin failed under uniaxial compression and the large amount of sand generated is shown in Figure 6. The stronger samples (35–100 MPa) usually display lower values of Poisson's ratio (less than 0.3) and the amount of sand generated is also considerably smaller. Surface samples of the Sylvania tested at the U.S. Geological Survey Laboratories in Denver confirmed the anomalous properties of the Sylvania (Egge, written communication, 1979). Recent work by Rogers (1982) further corroborates those properties.

The Young's Modulus at 50 percent of ultimate strength for all the Point Hennepin samples and samples from the upper 20 m from W-3 varied from 4 GPa and 15 GPa with an average of 10 GPa. Values in excess of 15 GPa were measured for several of the samples below 20 m from the top at the Windsor site.

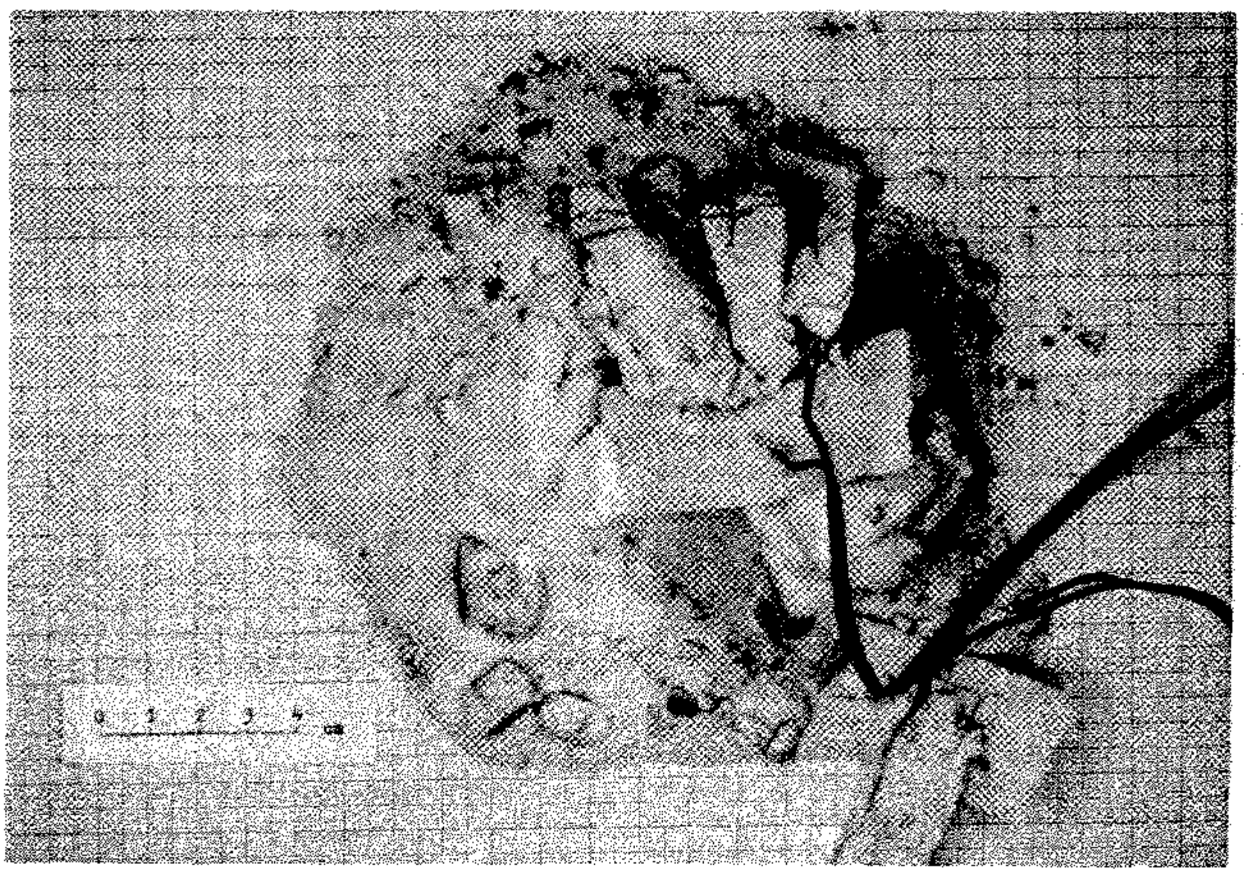

Figure 6. NX-sized sample failed in uniaxial compression (q_u approx. = 35 MPa). Note the paperbacked electrical strain gages, leads, and the large amount of material converted into cohesionless sand.

Figure 7 shows a plot of point-load index values for samples from W-3 throughout the entire Sylvania section. It is apparent that the samples loaded diametrically are weaker than the samples loaded axially. The average reduction for samples loaded diametrically (parallel to bedding) is about 65 percent.

Thin sections taken from samples throughout the Sylvania unit reveal an extraordinary degree of pressure solution. A photomicrograph of a thin section from Point Hennepin is shown in Figure 8. The most notable features are 1) the planar or concave-covex grain contacts, 2) the virtual absence of cement and 3) the apparent low porosity. Porosity values obtained by Stump (1980) from thin sections varied from 8 to 11 percent.

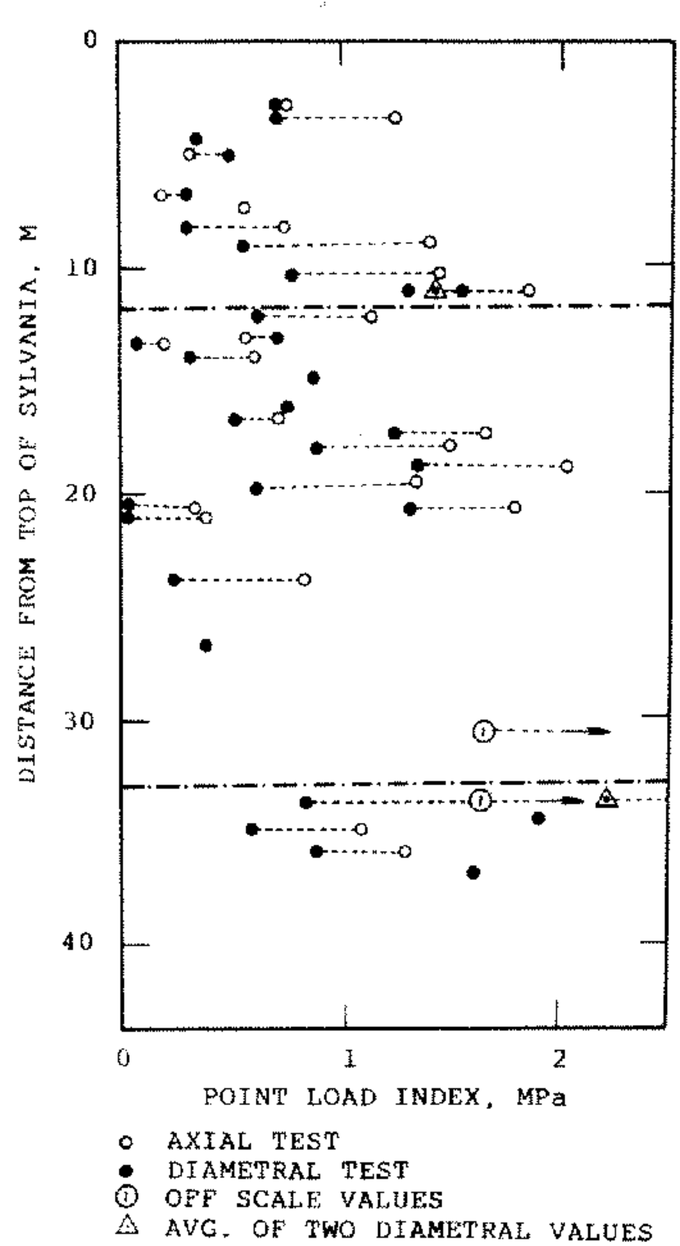

Figure 7. Results of point-load index tests from borehole W-3. Values of samples loaded horizontally (diametrally) are generally a fraction of samples loaded vertically (axially).

DISCUSSION OF MECHANICAL PROPERTIES OF SYLVANIA SANDSTONE

The unique configuration of the sandstone grains is believed to account for the unusual mechanical properties of a substantial portion of the Sylvania Sandstone. As the sandstone is loaded in compression, the dilatant behavior (high Poisson's ratio) of the sandstone indicates that the grains rotate relative to one another with loading, opening cracks at the surfaces of grain contact. As the load increases, a point is reached when failure commences and the stored elastic energy is released with the remarkable consequence that a large percentage of the matrix is reduced to loose sand.

The values of q_u and E obtained on laboratory samples need to be reduced for any field application. The laboratory samples were tested air dried, but the Sylvania is water saturated in the field as it lies below the water table. A reduction to about 65 percent of the air-dry value appears reasonable for these materials (Vutukuri et al., 1974). A second reduction concerns the direction of load application. Samples loaded horizontally are only 65 percent as strong as when loaded vertically (Figure 7). Finally, the well-known size factor should be taken into account (Hoek and Brown, 1980). Therefore, a reduction of 50 percent of the values of q_u shown in Figure 5 should be considered a rather moderate reduction. This reduction will be used in the evaluation of the failure mechanism to be discussed in a subsequent section.

It is well established that whereas q_u values parallel to bedding are smaller than those perpendicular to bedding, the opposite is true for Young's modulus. Further, as discussed in the next section, it is believed that the rock mass in the field is under rather high horizontal load before the onset of any subsidence. Thus, the influence of any discontinuities (joints) on the modulus is probably very small. Because of these considerations an average in situ modulus of 10 GPa will be assumed for the Sylvania.

STATE OF STRESS

Direct measurements (e.g., Haimson and Lee, 1980; Haimson, 1982) as well as indirect evidence (e.g., White et al., 1973; Russell et al., 1982) indicate that a major portion of the mid continent, including southern Ontario, northwestern New York, and probably most of Michigan, Ohio, Illinois and Indiana, is subject to horizontal stresses well in excess of the vertical stresses. In a summary of rock stress data in Canada, Franklin and Hungr (1978) refer to in situ stress measurements taken in Paleozoic carbonate and shale rocks in nearby Ontario and list variations in horizontal stresses with overburden

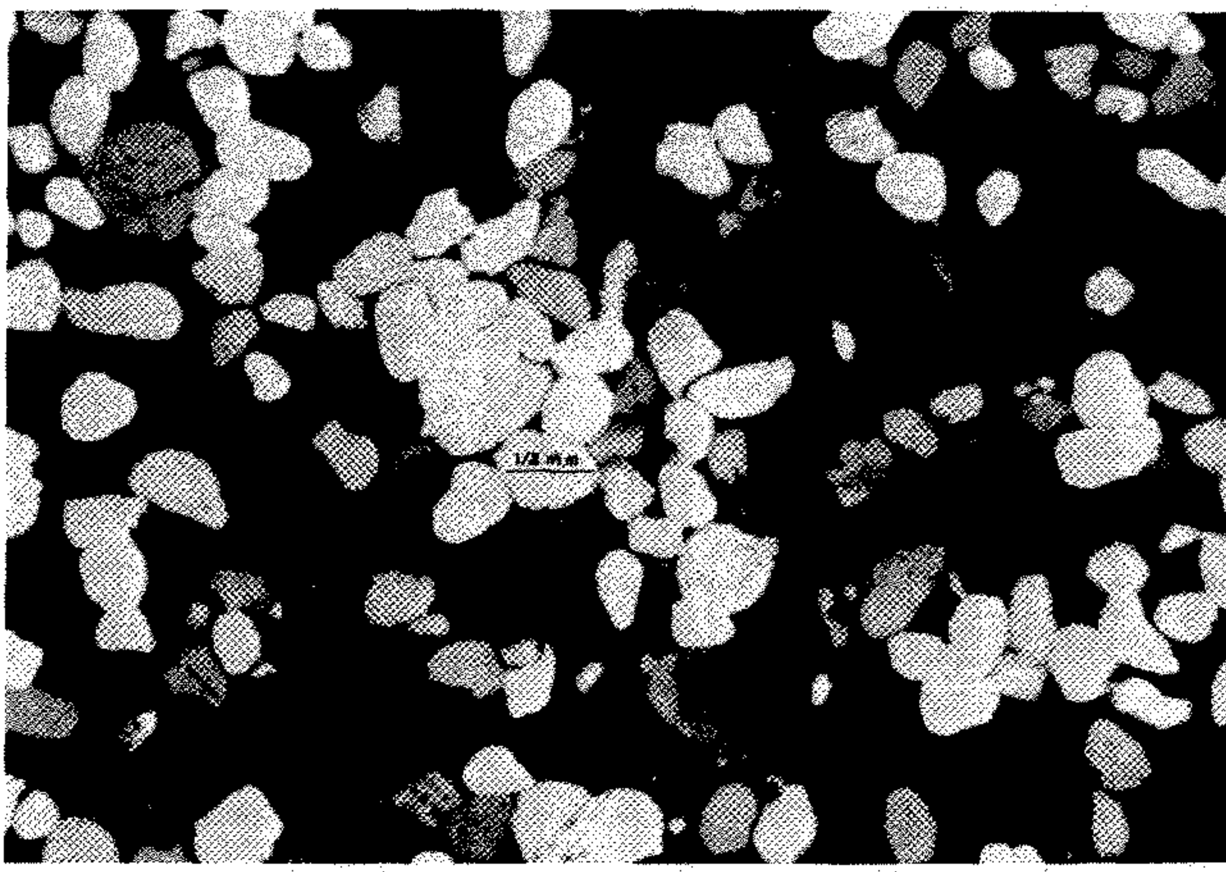

Figure 8. Photomicrograph of thin section of a Sylvania sample from Point Hennepin; crossed nicols. Note the planar or concave-conves contacts of most grains.

depths (p. 28). High horizontal stresses in the range of 1.7–14.7 MPa have been measured at shallow depths between 2 and 37 m within 350 km of the Windsor-Detroit area. Generally only a relatively small difference in magnitude between the two horizontal principal stresses has been found. The major principal stress direction seems to be fairly constant throughout the region, with a northeast to easterly trend. Herget, Pahl and Oliver (1975) have proposed the following empirical equation for relating average horizontal stress to depth below ground surface based on Canadian values:

$$\sigma_H = 8.16\,\text{MPa} + 0.04Z\,\text{MPa} \quad (1)$$

where

σ_H = average horizontal stress, and
Z = depth in meters.

Equation (1) is virtually the same as that recently given by Haimson (1982) for the region under consideration and will be used to obtain estimates of σ_H for the Windsor and Point Hennepin sites. The depth to the midpoint of the upper half of the Sylvania at Point Hennepin is approximately 90 m; for Windsor that depth is about 150 m. Therefore, according to Equation (1), the average horizontal stresses for the upper half of the Sylvania can be estimated to be 12 MPa and 14 MPa, respectively.

If the q_u values of the Sylvania are reduced by 50 percent because of water saturation, anisotropy (horizontal loading) and scale effect, the in situ strength values for Point Hennepin should range from about 5.0 to 32.5 MPa (average: 17.5 MPa) and for borehole W-3 from about 5.0 to 40 MPa (average: 22.5 MPa). Thus, before any subsidence-induced stresses are developed, the Sylvania material with average strength at Point Hennepin is loaded horizontally rather close to unconfined failure (70 percent), and the weaker materials are in fact loaded to levels greater than their unconfined strength. The latter materials are prevented from failing because of the confinement provided by the overburden. No samples were tested from the Windsor site itself, but it will be assumed that the samples from borehole W-3 are fairly representative of that site. The horizontal stresses at Windsor may be close to 60 percent of the average unconfined strength. Here again, the overburden generates the confinement that prevents the spontaneous failure of the weaker material.

PROPOSED MECHANICAL MODEL FOR SINKHOLE DEVELOPMENT

In the following postulated sequence of events, an effort is made to incorporate all of the available information in the development of a mechanical model that explains the presence of sinkholes at the Windsor and Point Hennepin sites. A summary of some of the salient points of this sequence of events is given in Figure 9.

1. A bowl of subsidence is generated by the concentrated dissolution (because of a long history of intense production from one well) of salt from the B salt, where most completions took place, and from the shallower F and D salts (these layers were exposed to undersaturated brine coming from broken casings; c.f. Russell, 1982). This subsidence manifests itself at the surface first as a bowl of gentle gradients and limited aereal extent but then grows to display gradients as much as 2 mm/m and diameters of up to 500 m (Nieto and Hendron, 1977). Increase in subsidence then implies an increase in the flexure and the diameter of the bowl of subsidence.

2. Any layer or group of layers between the surface and top of Unit B undergo a similar deformational sequence as outlined in 1. However, the amount of flexure of the layers increases with depth.

3. The stress-strain history of each layer or group of layers behaving as a single plate can be summarized as follows:

(a) As the underlying layer sags and/or collapses, the layer in question deflects elastically and develops horizontal compressive stresses in its upper half. No tensile stresses develop in the lower half because of existing joints.

(b) It can be demonstrated using elastic theory that if the layer in question has a lower modulus than the underlying layer there is virtually no separation at the contact between the two layers as subsidence continues (provided that the two layers being discussed are of equal thickness). If the layer has equal or greater modulus than the underlying layer, the former separates along a bedding plane or other horizontal discontinuity and "hangs" unsupported.

(c) As subsidence continues (wider bowls and steeper gradients), the stresses in the upper half of the layer, either supported or unsupported, continue to increase until the layer either fails in shear, because the horizontal compressive stresses along the upper half exceed the available strength, or simply collapses ("turns inside out," "snaps") without shear failure. These two modes of failure have been extensively discussed in the applied mechanics literature (e.g., Woodruff, 1966; Wright, 1977).

(d) As subsidence continues the horizontal compressive stresses in the failed or collapsed layer decrease and eventually become tensile. Thus, any failure-induced or preexistent fracture opens up. This change to a net tensile field throughout most of the subsidence bowl is quite different from the strain fields in other types of subsidence profiles such as those developed over wide, mined-out coal areas. There, the center of a mature subsidence profile is virtually under no strain (flat in the center portion). See Terzaghi (1970) for a typical development of a subsidence bowl in the Windsor-Detroit area.

4. In the case of the Sylvania the beds deform following the subsidence shapes of the stiffer underlying Bois Blanc dolomite; however, the Sylvania becomes *separated at or near the top of the bed* from the overlying stiffer Detroit River dolomite. Evidence of that separation has been reported by Dowhan (1976). In a borehole drilled in a rapidly developing bowl of subsidence on the south end of Point Hennepin, he described a 2-m vertical gap in the Sylvania about 8 m from the top. A sonar survey measured lateral extents of up to 60 m at least in one direction.

The Sylvania then continues to deform under *essentially no vertical confinement* until, as will be explained in the next section, the upper half fails under horizontal loading conditions. The horizontal stresses are a combination of the in situ stresses and the stresses generated by subsidence. A significant portion of the Sylvania then becomes cohesionless sand.

5. As the underlying Bois Blanc continues to subside and either collapses or crushes, cracks begin to open up. These cracks (as well as broken casings) allow the cohesionless Sylvania sand to flow unhindered as a slurry downward toward the deeper solution openings. It should be emphasized that the width of these cracks need not be very large. Stump et al. (1982) report experiments on the flow of well sorted sand slurries (St. Peter sandstone) down smooth, tabular fractures in rock. They conclude that when the width of the fracture or fissure is about twice the maximum grain size diameter, an interrupted downward flow of the slurry takes place. The maximum grain size diameter for the Sylvania sandstone in southeast Michigan is about 0.38 mm (Carman, 1936). Thus, a gap of about 0.8 mm will probably allow some downward flow. Of course, if the roughness of the fracture impedes the flow, continuing increase in the width of the gap (as subsidence develops) will cause the flow to resume. It is recognized that after a significant portion of the Sylvania has become cohesionless sand, broken casings could facilitate the downward migration of the loose material. However, if the casings become plugged, as they often do when slurries are poured into them, downward flow through casings should cease.

6. The migration of the Sylvania sand results in the removal of support from the base of the Detroit River dolomite. As the unsupported area increases, a large plate of this formation fails progressively by stoping up to the base of the unconsolidated glacial sediments. These materials, and in the case of Point Hennepin, the plant waste, fail essentially as a plug.

7. The clay and boulders of the glacial material and the plant waste slide from the top of the Detroit River

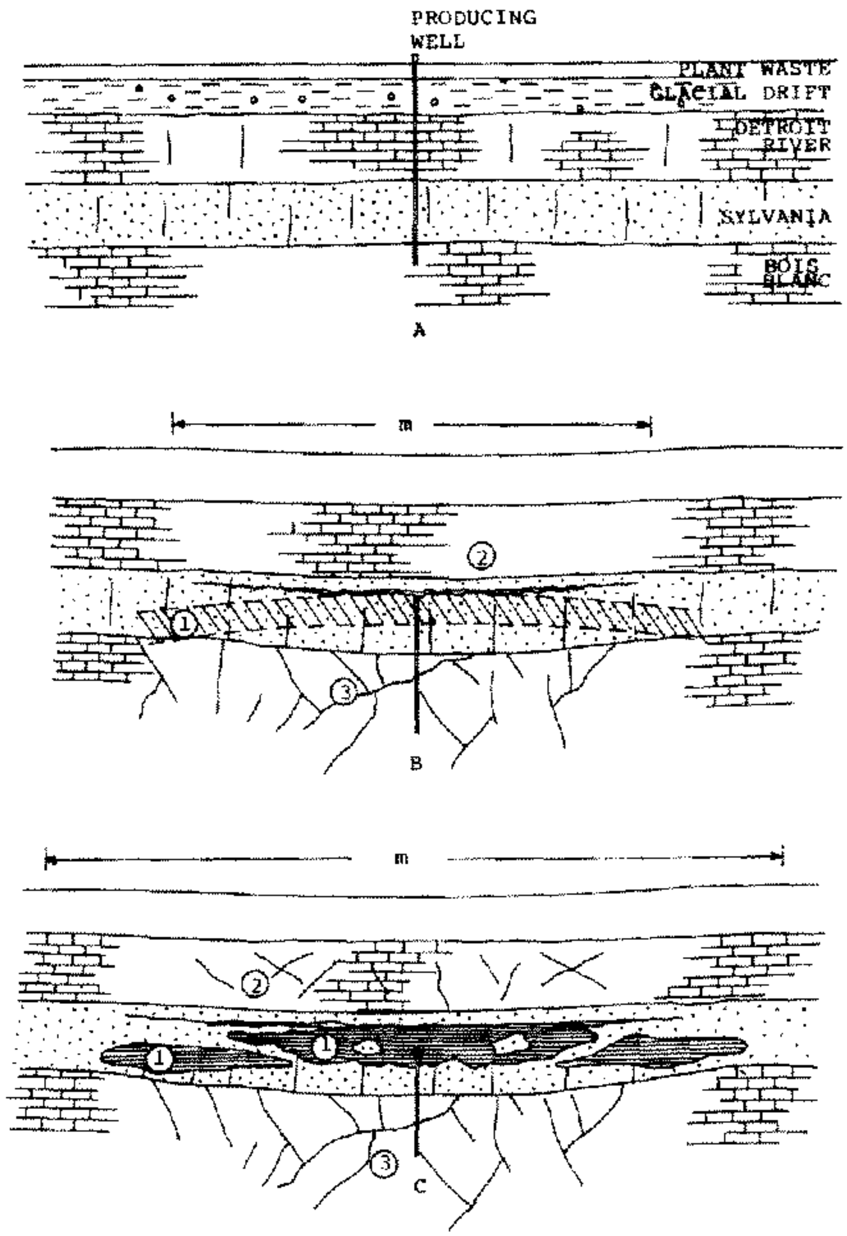

Figure 9. Proposed mechanical model for sinkhole development: A) Pre-solution-mining conditions; upper part of Sylvania is loaded horizontally from 12-14 MPa. B) Surface development of bowl of subsidence with width (m) at location of long producing well; (1) flat arch effect induces additional compressive stresses; (2) Sylvania separates from Detroit River near top (vertically unconfined conditions); (3) pre-existing and subsidence-induced fractures in Bois Blanc. C) Crushing of upper part of the Sylvania; (1) failed Sylvania converted into sand; (2) Detroit River begins to develop steep gradients; (3) fractures from in Bois Blanc begin to open. D) Void development in Sylvania; (1) void created by migration of slurry through open cracks in lower Sylvania and Bois Blanc; (3) Detroit River begins stopping. E) Collapse of Detroit River and surficial deposits; (1) sinkhole; (2) surficial deposits slide into cavity in Sylvania.

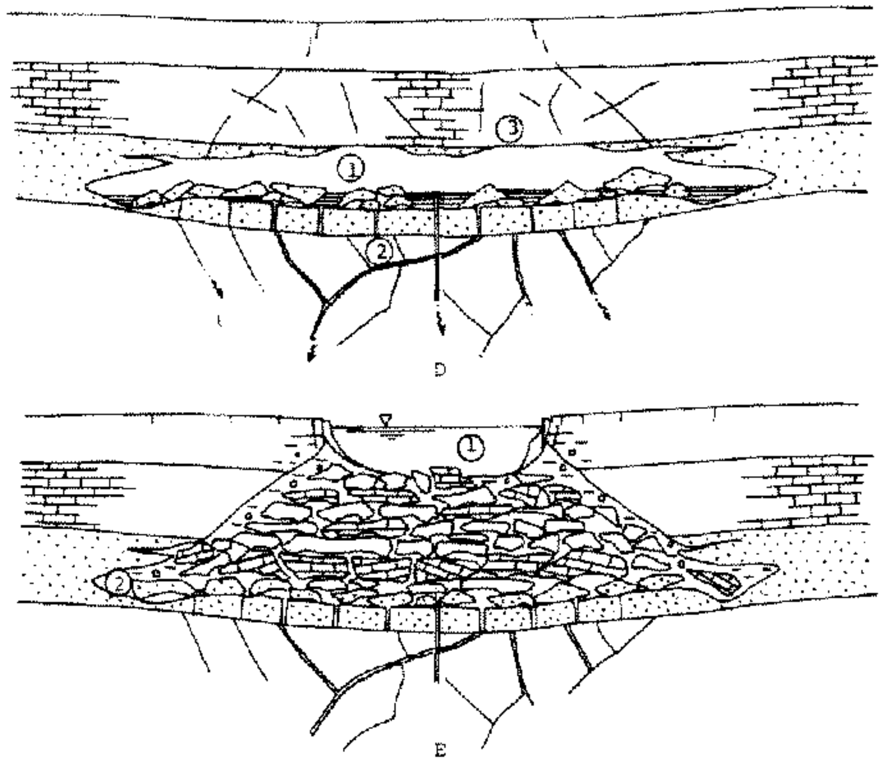

Figure 9. *(continued)*

rubble pile to the sides where large volumes of these materials can be accommodated. In this manner the depth of the sinkholes increases considerably.

EVALUATION OF THE PROPOSED MECHANISM

The most important aspect of this evaluation is establishing, at least in a general manner, whether the Sylvania sandstone can in fact fail under the postulated conditions. The proper way to analyze the stress development in the Sylvania is by the finite element method—an approach that requires a much better definition of material properties, initial stress and boundary conditions than has been thus far generated. For the purposes of this study, it will suffice to obtain a general idea of the levels of horizontal stresses that should be expected because of the development of a bowl of subsidence in the Sylvania and because of the pre-existing stress field. The method of analysis to be used was developed by Evans (1941); it is referred to as linear arch, flat arch or voussoir arch theory and has been extensively used to evaluate the stability of self-supported, cracked (no tension) roofs of mines in flat-lying layered rock. The stability is evaluated in terms of the self-supported span, m, the thickness of the roof layer, t, the Young's modulus and the uniaxial compressive strength of the rock (Figure 10). This method of analysis is not rigorous and should not be used to predict whether the Sylvania will fail at a particular location without further verification. Wright and Kelley (1970) and Wright (1976), using finite element analysis, have shown that the Evans method, in fact, underestimates the horizontal stresses of linear arches. Thus, one can consider

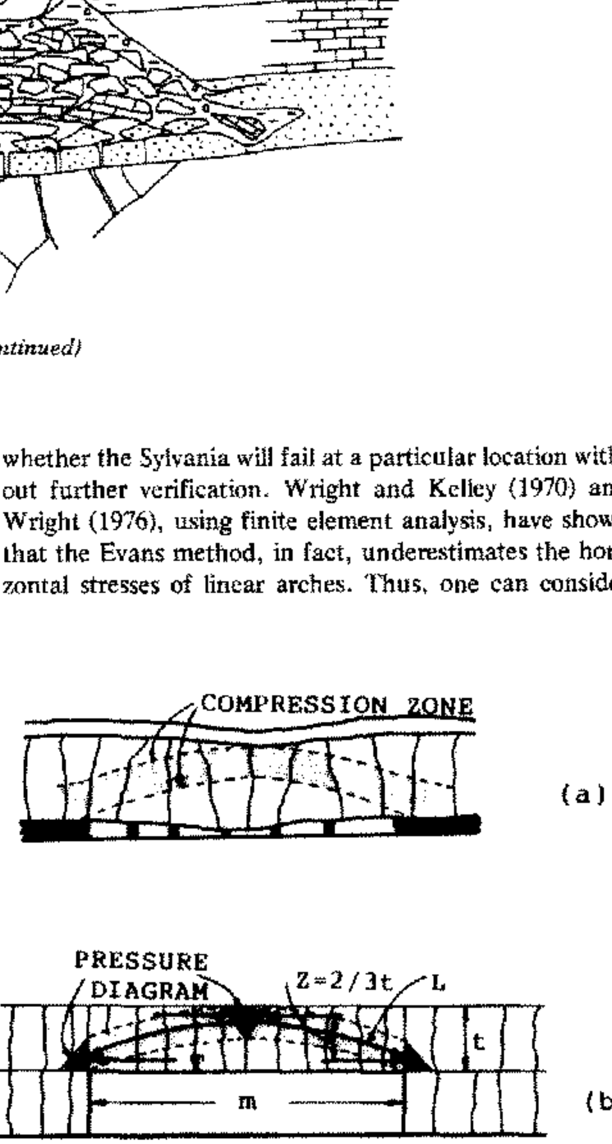

Figure 10. Linear arch (a) and assumptions for analysis in Evans method (b). L, linear arch length; m, free span; t, thickness of layers or group of layers behaving as unit; z, distance between thrust forces (T).

that the stresses obtained using the Evans method are conservative estimates of the horizontal stresses that could be expected because of subsidence. The unsupported span is assimilated to the width of a subsidence bowl developing in any layer or group of layers. Description of the method and sample calculations are included in Stump (1980) and Stump et al. (1982). The geometry of a linear arch, the forces involved and the assumed stress distribution are shown in Figure 10. Not shown are the in situ stresses, as this method does not take such stresses into account. Note the presence of a compression zone shaped as an arch. It is that zone that is believed to fail in compression and a substantial part of it is believed to become cohesionless sand, similar to the laboratory specimens.

It is important to note that linear arch theory predicts two modes of failure: 1) arch crushing, which is a compressive failure of the upper part of the layer, and 2) arch collapse, which is a snapping or turning inside out of the arch. This second type of failure occurs when the strains created in the linear arch length, L, by the induced horizontal stresses reduce the linear arch length close to the length of the unsupported span, m, of the layer (the distance z between the thrust forces, T, tends to 0; see Figure 10).

An array of linear arch geometries was analyzed to simulate different widths of the bowl of subsidence and to include the cases of the Sylvania deforming as a single unit, or as separate layers of smaller thickness. The maximum horizontal stresses generated in a self-supported flat linear arch of Sylvania with a modulus of 10 GPa, thicknesses varying from a few to 25 m, and linear-arch unsupported spans from 60 to 300 m are shown in Figure 11. The oblique line separates the two modes of failure—arch collapse and arch crushing—described above. Also plotted in Figure 11 are the range of corrected unconfined compressive strength values for the Sylvania at Point Hennepin and for the upper 20 m of borehole W-3 (near Windsor).

In the proposed mechanism the base of the Sylvania is probably not unsupported as the Sylvania tends to follow the deflections of the stiffer, underlying Bois Blanc dolomite. However, the Sylvania will undergo the same deformation as if it were unsupported; therefore, the stress development should be about the same.

If the Sylvania behaves as a single layer about 20 m thick, and the bowl of subsidence has a width of 180 m, the horizontal stresses in the upper part of the Sylvania are close to 25 MPa, i.e., higher than the average uniaxial compressive strength of both the Sylvania sites, as illustrated in Figure 11. As the width of the bowl of subsidence increases (free span of the linear arch, m, increases) the stresses also increase, and at 300 m, the maximum horizontal stresses in the upper portion of the Sylvania should be in excess of even the maximum significant q_u values for both sites. If one now recalls that the in situ horizontal stresses before any subsidence were 60 percent (Windsor) and 80 percent (Point Hennepin) of the unconfined compressive strength, one needs to conclude that the Sylvania should fail horizontally.

The question now arises as to how extensive is the failure throughout the Sylvania, because only the upper portion is stressed to the levels indicated above. Laboratory testing showed that during unconfined compression failure, disaggregation not only takes place along the theoretical shear plane of the specimen but also propagates into zones where the shear stresses are relatively small. This occurs probably because of the sudden manner in which the stored elastic energy is released. Thus, a similar situation should occur in the field and substantial portions of the Sylvania should be reduced to sand.

If, on the other hand, the Sylvania does not sag as one or two thick units but separates into a few layers that develop independent sags, the maximum horizontal stresses for comparable widths of the subsidence bowls are greater. If a linear arch thickness of 7 m and a bowl width of 120 m are assumed, the maximum horizontal stress is greater than the average q_u for both Point Hennepin and Windsor. As the bowl width increases, the stresses increase up to a certain value and then the mode of failure changes from crushing to collapse. Thus, if the Sylvania sags as a series of thinner, individual linear arches, the maximum stresses may not exceed the available strength of some layers. This, of course, would result in less sand being formed. It needs to be restated that the Evans method does not include the prestressing effect of in situ stresses. If those stresses are considered, longer spans and higher subsidence-induced stresses could be obtained before collapse of the linear arches. Nonetheless, the thickness of the individually sagging linear arches (made up of one or more layers) and their average strength will determine whether crushing or collapse will take place, and likewise the amounts of cohesionless sand that will be produced.

It should also be kept in mind that the Evans method is two-dimensional, whereas the stresses induced by a subsiding bowl need to be considered in a three-dimensional field. Thus, if one considers a three-dimensional linear arch with a square plane view that is not only supported on the sides but also in front and back, for the same amount of deformation, the stress levels should be greater for this three-dimensional type of linear arch than for a two-dimensional one.

Another point of interest in this discussion concerns the difference in depth between the sinkholes at Windsor and those at Point Hennepin. There are at least three probable reasons for deeper sinkholes at the latter site. First, the Sylvania at Windsor is not as massively bedded and appears to be stronger than the Sylvania at Point Hennepin (see Figure 5). Thus, it could have subsided in

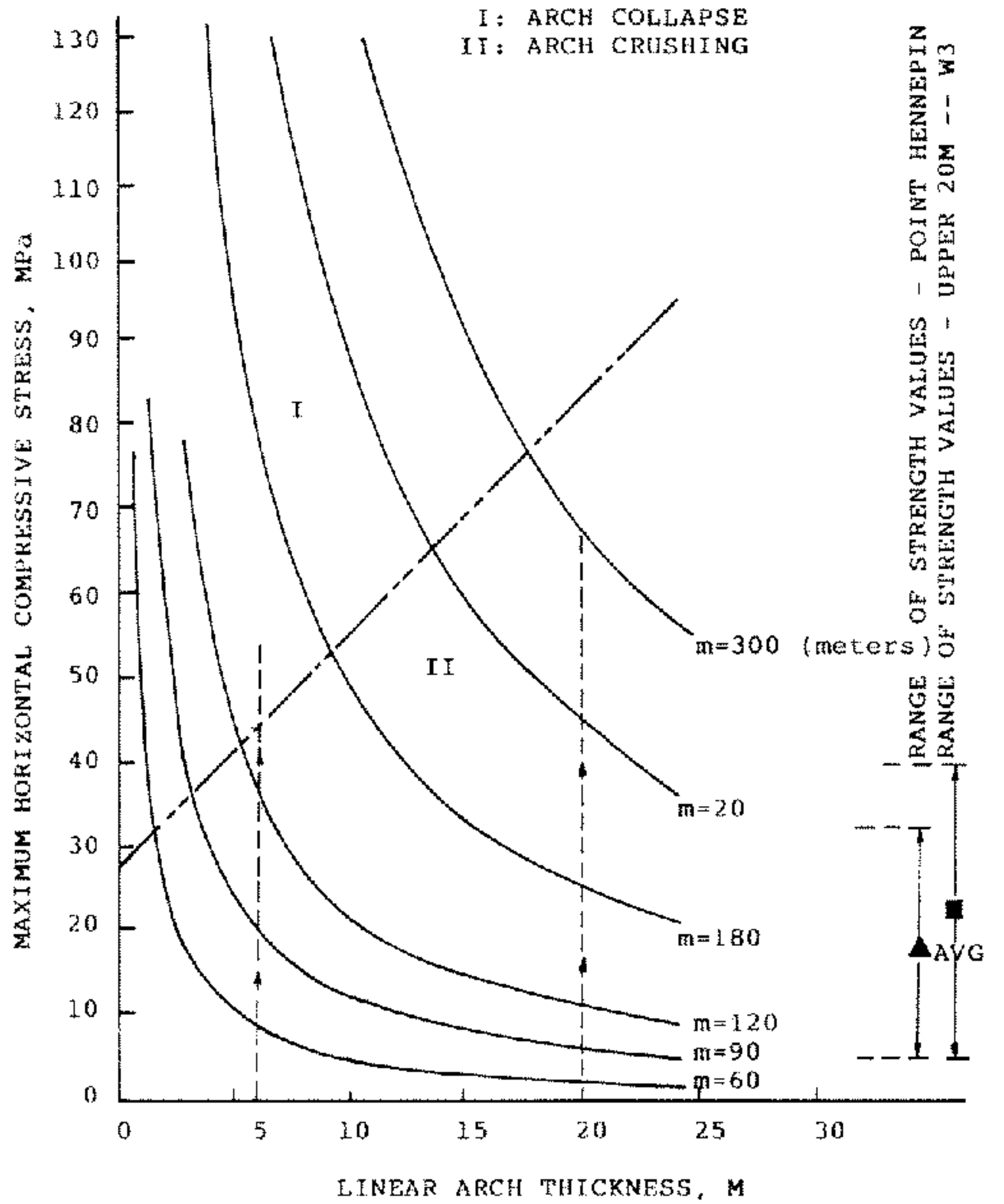

Figure 11. Maximum horizontal compressive stress increments and failure modes because of subsidence (Evans method) for linear arches of different thickness.

a series of linear arches that simply collapsed and did not crush. Second, dolomite and dolomitic sandstone layers exist particularly near the base of the Sylvania at Windsor. These units probably cannot produce cohesionless sand. Third, the Sylvania at Windsor occurs at a greater depth because of a thicker Detroit River dolomite; bulking then has a greater opportunity to fill up the space vacated by the failed Sylvania sand.

In addressing the question of why sinkholes developed at Point Hennepin and Windsor and not at the former Wyandotte Chemicals North and South Works, the observations on critical surface gradients by Nieto and Hendron (1977) are relevant. Those authors noted that the surface gradients at the sites that developed sinkholes were about 2 mm/m a few months before collapse; however, the maximum gradients at the North and South Works were only about 1.4 mm/m. Surface gradients are subdued indicators of vertical deflections or sagging presumably occurring also in the Sylvania Sandstone. Because sag is proportional to an increase in the horizontal stresses in this material, the increase in horizontal stresses at the North and South Works was never sufficient to cause extensive compressive failure of the Sylvania Sandstone.

It can be concluded, therefore, that sinkholes can be expected where the Sylvania is massively bedded and fairly close to the surface and when the subsidence induced by solution mining has fairly steep gradients at the surface (in the order of a few millimeters per meter). However, one cannot predict the occurrence of sinkholes everywhere in the Sylvania, even if fairly shallow and undergoing substantial subsidence, because of the variable nature of this sandstone. A reasonably cautious position is that sinkholes are likely to occur if the conditions of depth and gradient of subsidence bowls are similar to those at Windsor and Point Hennepin.

CONCLUSIONS AND RECOMMENDATION

1. Although not as originally conceived, the origin of three steep-walled, deep sinkholes in the Windsor-Detroit area appears to be related to the unique characteristics of the Sylvania Sandstone.
2. It is proposed that the Sylvania fails under horizontal compression, converts into sand and migrates downward through subsidence-induced cracks creating a shallow void that originates the sinkholes.
3. The failure of the Sylvania and its conversion into cohesionless sand appears possible because of a unique combination of the geological features documented in this study: a) low strength and cementation, b) dilatant behavior and generalized failure under uniaxial loading, c) high in situ horizontal stresses, and d) reduction of vertical confinement and induction of additional horizontal stresses during bowl subsidence.
4. Sinkholes are likely to occur in areas where the Sylvania is relatively close to the surface (up to 200 m) and surface gradients of subsidence bowls are in the order of a few millimeters per meter.
5. It is recommended that a limited number of boreholes be carefully executed, cored and logged with state-of-the-art downhole technology near the edge and possibly within the sinkholes. This information, as well as some seismic surveys, would be used to evaluate the proposed model and to provide the physical basis for a more refined analysis (finite element) of the stress-straom history of the Sylvania Sandstone during subsidence.

ACKNOWLEDGMENTS

Funds for the Point Hennepin studies were provided by the U.S. Geological Survey. The contract was monitored by Mr. John R. Ege, U.S.G.S., Denver, whose encouragement and support are acknowledged.

Messrs. Arthur I. Robinson, The Canadian Salt Company Ltd., and Thomas B. Piper, BASF Wyandotte Chemical Corporation, provided the invaluable insights about the role of the Sylvania on which this work is largely based; the views expressed, however, are the writers' own.

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