SALT MINE SUBSIDENCE AND ASSOCIATED DAMAGE: A CASE HISTORY[1]

by

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Abstract. Based on case data a subsidence and the associated damage is reported. The subsidence occurred over a room and pillar salt mine in the U.S. The mine was approximately 305 m (1,000 feet) deep, and sustained a massive collapse resulting in approximately 2.7 m (8.8 ft) of surface settlement. Because of the size of the subsidence it resulted in damage to about 20 surface structures and significantly modified drainage on the ground surface. This paper presents the results of an engineering investigation performed on this subsidence event.

Additional Key Words: salt mine subsidence, subsidence damage.

Introduction

The subject of this paper is a subsidence from room and pillar mining of salt. The subsidence occurred in a relatively flat topographic region. It damaged residential structures, greenhouses, warehouses, a wood-framed office, flatwork and an in-ground pool. Approximately 20 structures were affected.

This paper first presents case history information regarding the geological and mining conditions. The subsidence characteristics are then discussed followed by a description of the associated damage. The resultant damage is related to the attendant ground movements. A summary and conclusion section follows.

Geologic Conditions

The site consist of approximately 21.3 m (70 ft) of till soils. The till is underlain by sedimentary rocks consisting of shales, limestone, siltstone, and silty sandstone. The hard rocks make up only about 15 percent of the rock profile.

The sedimentary rocks in this area are fairly flat lying with the mined-out salt deposit being an integral part of the gently westerly dipping Permian-Pennsylvanian rock strata. This mined-out deposit consists of a series of salt, anhydride and shale beds. Above the mined-out salt deposits is a fairly thick formation of shales. This formation contains gray shales with some evaporites towards the base and red to green shales and clay with interbedded silts and some evaporitic material (primarily gypsum) higher up.

Mining Conditions

The salt pillars were reportedly 15.2 m (50 ft) square and 4.9 m (16 ft) high with 12.2 m (40 ft) wide mine rooms below the main area of subsidence. Mine depth is about 305 m (1,000 ft). In the area of question the mining was basically done going south to southwest from 1987 to about 1991. From about 1991 salt extraction has proceeded west to about mid-1993. At this point the width of the mined-out area in the area of subsidence was approximately 580 m (1,900 ft). In other words, the panel width to depth was close to 2. The sag subsidence which occurred over the salt mine was caused by the yielding of the salt pillars.

The mining occurred in the lower part of the salt deposit. The mined-out horizon contained 2.5 to 15.2 cm (1 to 6 inch) layers of relatively pure sodium chloride, separated by clay and shale laminae less than 1 mm thick. Several 2.5 cm (1 in.) thick shale beds are 4.6 to 5.5 m (15 to 18 ft) apart and are above and below the mined out horizon. The floor of the mine was typically 0.15 to 0.6 m (0.5 to 2 ft) above the underlying shale bed. The original extraction heights in different areas of the mine were 2.75 and 4.9 m (9 ft and 16 ft). When mining proceeded at 2.75 m (9 ft) heights the salt roof tended to break to the overlying prominent clay seam at 4.25 to 4.9 m (14 to 16 ft).

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Floor heave and pillar spalling in the mine were also observed. The floor heave was probably exacerbated by the underlying shale bed. The failure of this room and pillar mine appears to be the result of increasing the mine height to 4.9 m (16 ft) which in turn resulted in a pillar width to height ratio from 5.6 to 3.1 combined with an increase in overburden load on these taller pillars. Increased pillar loads in the central area of the mine are postulated to have resulted from broadening of the mined-out area and transfer of abutment pressures at the south limit of the mine where unexpected structural complexity was encountered. Also adversely affecting pillar stability was the clay seam at the top of the pillar which reduced the development of confinement stress in the pillar.

Subsidence Conditions

Based on the available topographic information the magnitude of the subsidence was estimated with time. Figure 1 is a map of approximate subsidence contours for 1993. These contours were mainly determined from a 1966 topographic map and a subsequent survey conducted in August 1993 after subsidence commenced. Another subsidence contour map was also prepared for 1995. This map is based on a topographic survey done in 1995 and the profile elevations given on construction plans for a north-south highway. Using the contour lines across the highway, pre-subsidence and post-subsidence profiles were drawn on Figure 2. Also included on this profile drawing were elevation shots taken in January 1994 along a portion of the highway. The subsidence profile data for 1995 along the highway in Figure 2 as well as the 1995 topographic survey were used to construct the subsidence contour map for 1995 depicted in Figure 3.

By comparing the subsidence contour maps for 1993 and 1995 it can be seen that the maximum subsidence increased from about 1.7 m to 2.5 m (5.5 ft to 8.1 ft). Also, the sag subsidence became less irregular, more symmetrical, and more developed. Based on Figure 3 the angle of draw measures to be from 31° to 42° to approximate zero subsidence to the south. The areas in which the contours are most closely spaced (i.e., the maximum slope zone) is just inside the ribs. In other words of the areas measured the most abrupt subsidence profile features are on the east side where a solid salt mining limit is present. In this area the maximum profile slope, tensile curvature and compressive curvature are 5.0 percent, 6.56×10^{-4} m^{-1} (2.0×10^{-4} ft^{-1}) and 5.74×10^{-4} m^{-1} (1.75×10^{-4} ft^{-1}) respectively. These profile measurements were taken over a horizontal distance of 12.2 m (40 ft).

Subsidence measurements along the northern part of the highway appear to indicate that the subsidence is propagating northward. This outward progression of subsidence is caused by overburden loads being transferred from yielding pillars to less yielding pillars resulting in the less yielded pillars now becoming overstressed. The mine area to the north was not mapped, however.

As mentioned above, in the center of the subsidence sag there is an estimated maximum of 2.5 m (8.1 ft) of settlement by about June, 1995. From additional survey data from June 1995 to February 1996 an additional 0.2 m (0.7 ft) of settlement occurred in the area of maximum subsidence. Therefore, the maximum subsidence to February 1996 is estimated at 2.7 m (8.8 ft). The time rate of settlement in the maximum subsidence area is shown in Figure 4. Figure 4 also depicts similar time rate displacements for sag subsidence over room and pillar coal mines. Note, as expected, the salt mine subsidence has significantly greater time dependent movements than those from coal mining. This is due to the significantly greater creep properties of salt compared to coal measures.

The potential maximum subsidence that can occur at the surface can also be estimated. This value would be the extraction ratio times the extraction height. In other words, 70 percent times 4.9 m (16 ft) or an upper limit of 3.4 m (11.2 ft) of ultimate subsidence. Even for supercritical subsidence conditions (for which this case is), in full extraction mining the potential maximum subsidence is usually not realized but is something less. Assuming 95 percent of the potential maximum subsidence is realized, or 3.24 m (10.6 ft), only an additional 0.52 m (1.7 ft) would be expected in the future in the maximum subsidence area.

Subsidence Damage

Of the approximate 20 structures affected by this subsidence 16 were mapped for damage and are shown on Figures 1 and 3. The construction characteristics and the associated damage conditions for each structure mapped are summarized in Table 1. Also, the associated sag profile characteristics for each of the mapped structures are given in Table 2.

Structure Nos. 1 to 3 are houses with appurtenances. Structure Nos. 4 to 16 exist on one property and consist of 11 separate buildings, flatwork, and an in-ground pool. Most of the buildings on the property support an on-site nursery business. In addition to the residence, there is an office/garage building, five

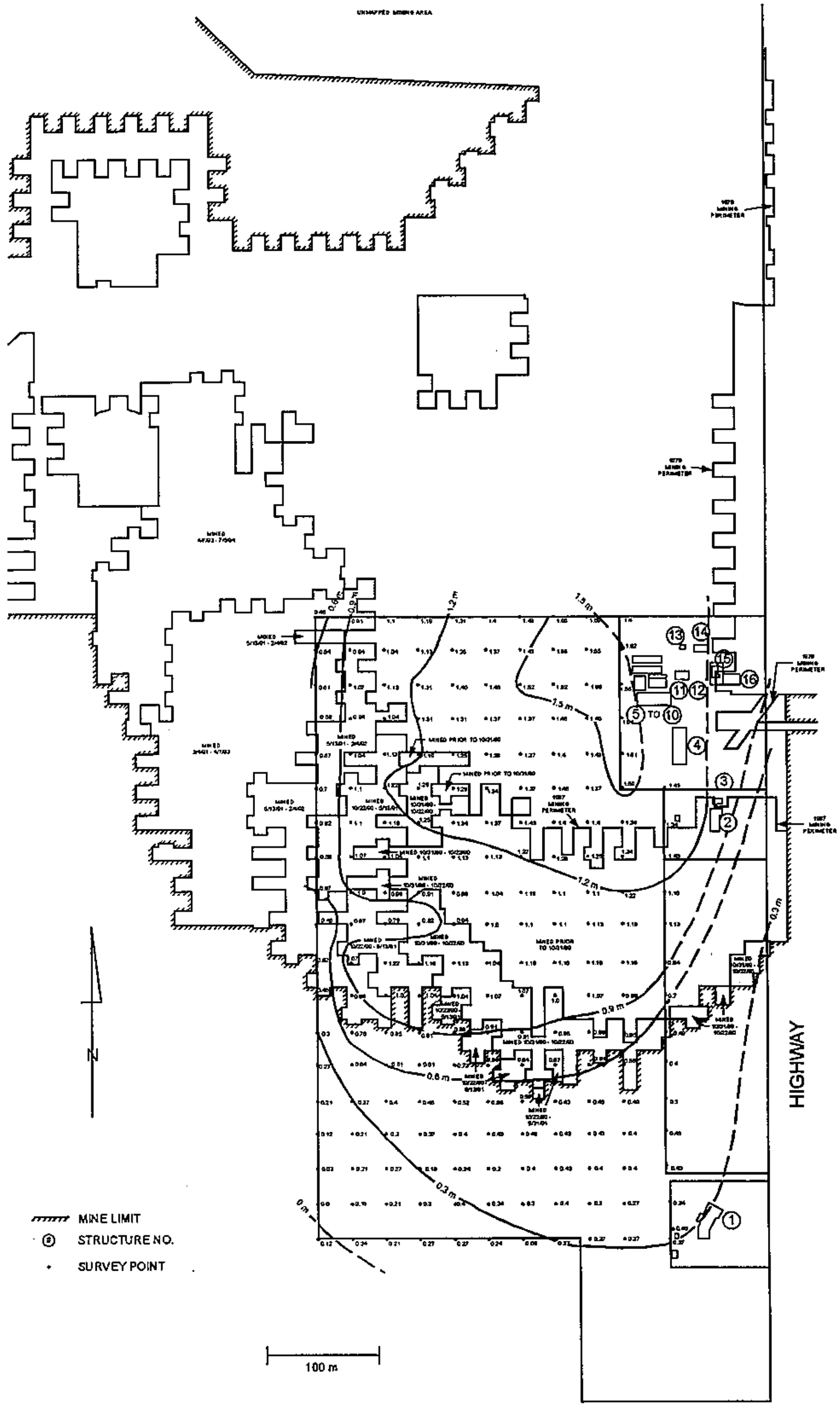

FIGURE 1 APPROXIMATE SUBSIDENCE CONTOURS IN 1993 OVER SALT MINE

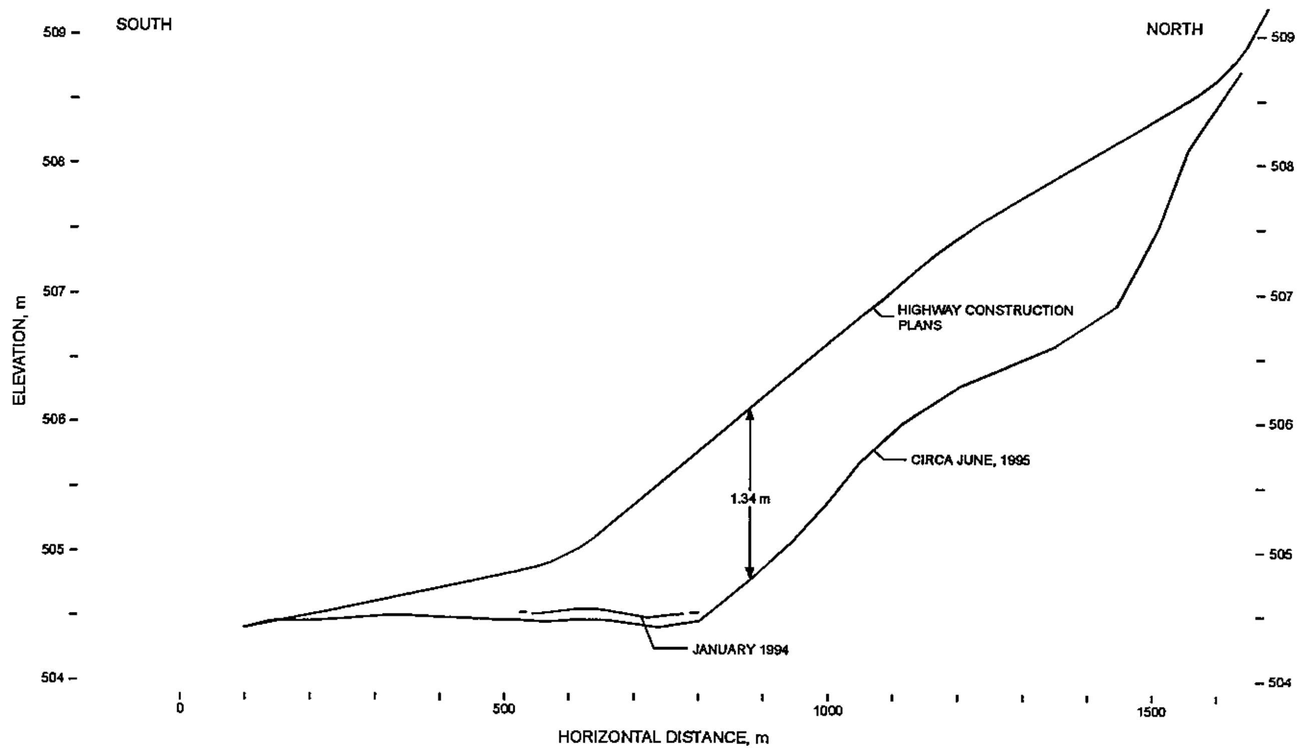

FIGURE 2 PRE-SUBSIDENCE ELEVATIONS AND POST-SUBSIDENCE ELEVATIONS (1994 AND 1995) ALONG HIGHWAY

green-houses, two smaller sheds, and two larger warehouse-type structures. Figure 5 is a plan view of these structures and exterior flatwork. The first evidence of subsidence in this area was in 1993 with the pooling of water. The accumulation of flood water at this time reached 6 in. over the floor of the "Big Shed" and spread into the greenhouses.

Although the amount of settlement observed on the ground surface was impressive (about 2.7 m) the distortion related severity of the ground movements was comparatively low. Even in the locations of the most severe tensile and compressive curvatures distortional damage to residential structures would typically be only slight to moderate with Relative Repair Cost, RRC, of 10 to 40 percent for residential structures on either crawl-space or basement foundations (Marino, 1985). The RRC is defined as the ratio of estimated repair cost to the total replacement cost.

For this reported case the most severe ground movement characteristic is the profile slope. Even with gentle sag curvatures, however, a structure which rotates to the grade in the maximum slope zone of 5.0 percent is unacceptable and would require significant repair. Typically floor tilts of 0.5 to 1.0 percent become noticeable by occupants. In fact even though the maximum tensile and compressive profile curvatures are mild the average profile slope in these locations are significant at 1.8 and 1.2 percent, respectively. An example of this is Structure 2 which is located in the zone of greatest compressive sag curvature. Although the angular distortion is mild along Structure 2 the profile slope is still significant at 1.6 percent (see Table 2). This house was found to have aesthetic, functional and structural damage, however, the most costly element of the damage was the noticeable floor tilt despite the house being significantly outside the maximum slope zone (see Table 1). The effect of the sag slope was also significant for structures 15 and 16 (see Table 2).

Several of the structures mapped exhibited no or very nominal observable damage. These structures had fairly flexible frames (e.g. warehouses and greenhouses) and were exposed to milder small sag slopes and angular distortions.

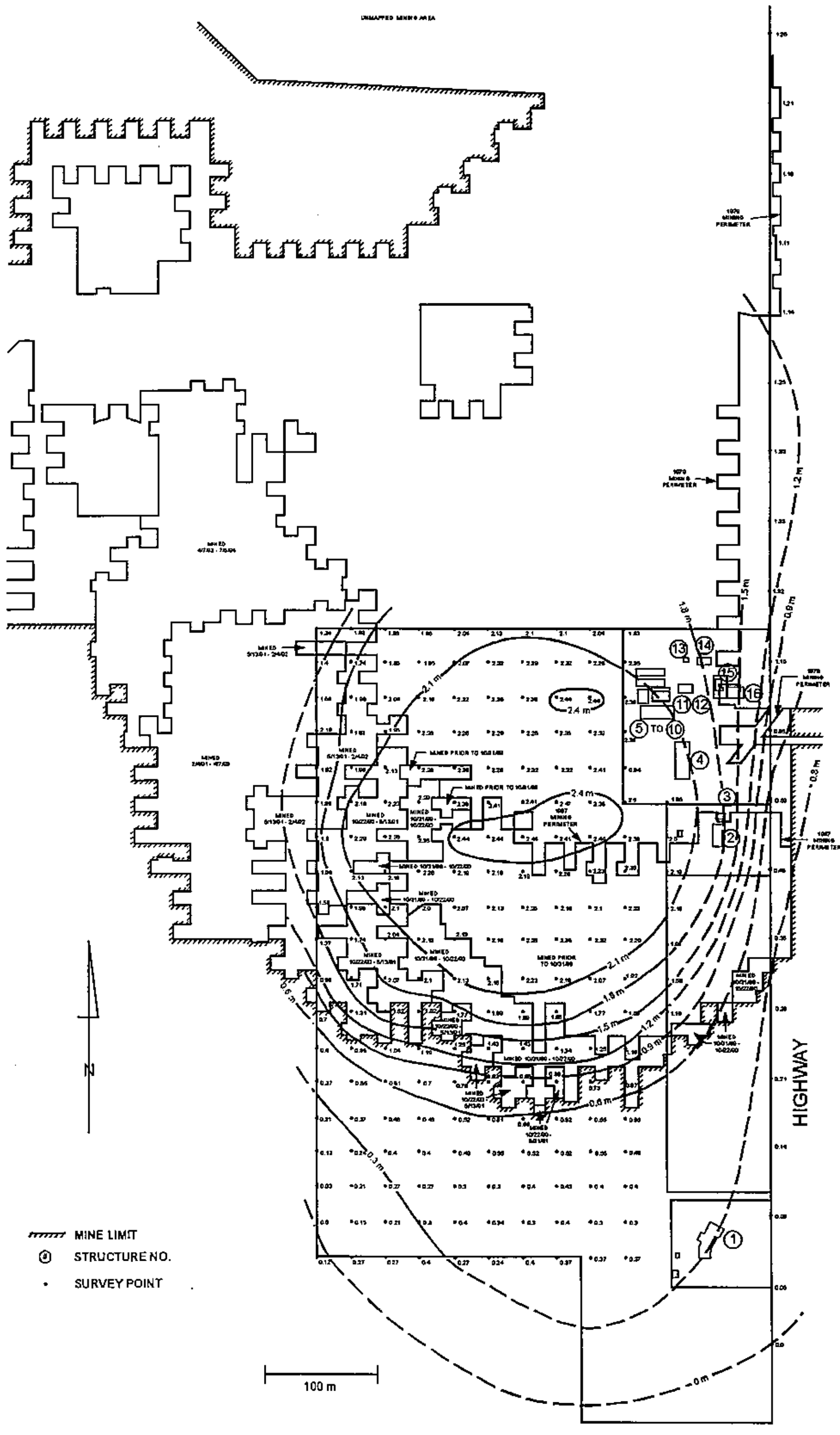

FIGURE 3 APPROXIMATE SUBSIDENCE CONTOURS IN 1995 OVER SALT MINE

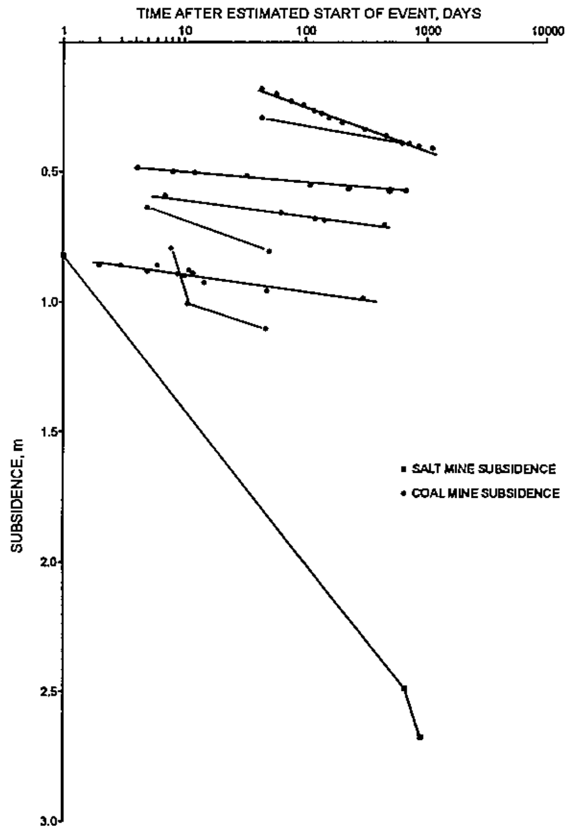

FIGURE 4 TIME RATE OF SETTLEMENT AT THE SAG CENTER AFTER INITIAL MOVEMENTS FOR A ROOM AND PILLAR SALT MINE AND COAL MINES (Marino, 1985, and Marino and DeVine, 1985)

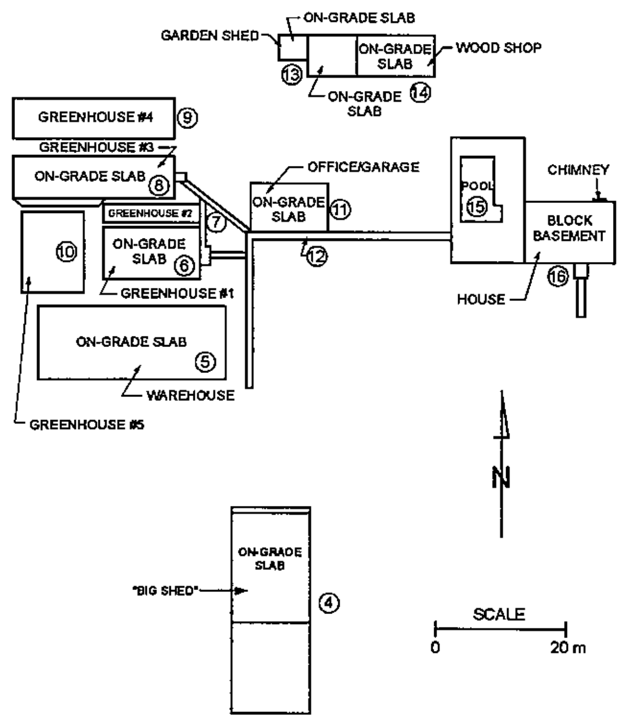

FIGURE 5 PLAN VIEW OF STRUCTURE NOS. 4 THROUGH 16

Summary and Conclusions

This paper describes a salt mine subsidence and the associated damage to surface structures. Approximately 20 structures were affected of which 16 were mapped. The maximum subsidence measured during this investigation was 2.7 m (8.8 ft) after approximately 2.5 years. The measured rate of movement was found to be considerably more time dependent than from coal mine subsidence. Although the amount of settlement on the surface was significant as was the sag slope, the sag curvatures were mild by comparison. As a result the most significant damage from this subsidence is from rigid body rotation of surface structures. The mild curvatures are due to a mine depth of 305 m (1,000 ft) and the plastic nature of the unmined salt areas.

The resultant subsidence damage to the affected structures ranged from none to damage of an aesthetic, functional and structural nature. The observed subsidence damage was found to correlate well with the associated subsidence measured conditions.

References

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TABLE 1 STRUCTURES AFFECTED BY SUBSIDENCE AND ASSOCIATED DAMAGE

STRUCTURE NO.[1]	DESCRIPTION	SUBSIDENCE DAMAGE CONDITIONS
1	One-story ranch and an attached garage with a wood-panel custom brick exterior. The reinforced concrete foundation of the house consisted of sections on slab on-grade, a basement, and crawl-space elements. The entire first floor of the house consists of reinforced concrete. This reinforced concrete is 7.6 cm (3 in.) thick and is underlain with "standard corruform deck" above the crawl-space and basement sections. East-west steel truss joists support these slab areas. The on-grade slab portion of the first floor is 10.2 cm (4 in.) thick. The interior walls and ceilings of the house are made of 1.3 cm (½ in.) gypsum board.	Mainly aesthetic damage; however, most of the foundation elements were concealed from view. Cracking and separation on all sides of the exterior of the house range from hairline to having separated as much as 9 mm (0.03 ft) and having horizontal or vertical transverse offsets as large as 9 mm (0.03 ft). Separations also occurred between brick and frame elements (e.g., windows and doors) and were measured to be up to 6 mm (0.02 ft) wide. Relative horizontal displacements between the brick chimney and roof structure on the order of 9 to 12 mm (0.03 to 0.04 ft). At the base of the brick, the cracking extended into the foundation wall and was open 0.9 mm (0.003 ft). All the porch-columns were slightly racked. Exterior slab-house separations of 4.6 to 12 mm (0.015 to 0.04 ft). The main interior damage consists of hairline to 2.4 mm (0.008 ft) wide cracks above and below windows, above doors, and along wall corners.
2	A wood-framed ranch style house with an attached garage. The exterior of the house is made of mainly custom brick masonry and the house rests on a concrete crawl-space foundation. The sill plate appears to be bolted to the concrete stem walls at about every 2.4 m (8 ft.) The interior walls are drywall with some of the walls paneled, wallpapered, or tiled.	Aesthetic, functional, and structural damage. Significantly cracked exterior brick veneer with horizontal to diagonal cracks up to 3 mm (0.01 ft) wide. Also separations were found between the brick and window/door frames up to 9 mm (0.03 ft). Siding above brick as well as the eave consisting of seam splits, nail pops or pulls, separation of molding joints, and slight tears at the end of slats. Foundation wall cracks throughout (mainly vertical) ranging in size from hairline to 6 mm (0.02 ft). Loosened sill anchor bolts. The front porch appears to have old cracks in the concrete slab. Exacerbated cracking in the attached garage slab with offsets less than 6 mm (0.02 ft). With respect to the patio concrete in the back of the house the cracks appear old but were probably exacerbated by subsidence movement. Noticeable floor tilt is present on the exterior of the house at about 1.5 percent. As a result, doors in the house sway open or closed and some doors would not close. Ceiling cracks up to 1.5 mm (0.005 ft) wide with most originating at a window or door opening and in wall or wall/ceiling corners. Noticeable east-west bulges in the ceiling. Nail pops/pulls in ceiling. Racked kitchen cabinets along the walls separated from the ceiling as much as 9 mm (0.03 ft).
3	Detached wood frame garage is covered with siding and rests on a floor slab.	Measurable tilt in the floor slab.
4	Warehouse: An open frame structure with the walls supported on a perimeter foundation. A concrete slab exists only in the northern 16.8 m (55 ft) of the building. Large sliding doors exist both on the north and south ends of the building. The walls of the building are covered with corrugated steel siding.	Cracks and separation in cold joints in the floor open as much as 6 mm (0.02 ft) appear to have been exacerbated or caused by mine subsidence. North and south hay doors are difficult to open and close and may have been exacerbated by subsidence. Tilted to the southwest about a maximum of 0.7 percent.

5	Warehouse which is a fairly large open frame building with a concrete floor. Except for a 15.2 m (50 ft) long, 1.2 m (4 ft) high reinforced concrete wall on the east side of the north wall, the warehouse walls are covered with corrugated fiberglass sheathing. Based on the foundation construction, the western 12.2 m (40 ft) of the building was added on later.	Horizontal cracking and vertical cracks along the concrete wall with most hairline in size but with crack offsets up to 1.5 mm (0.005 ft). One spalled concrete area was noted near the northeast corner. The floor separations along cold joints and cracks were less than 1.5 mm (0.005 ft) in size and appeared to be pre-existing with some additional displacement as a result of subsidence. Warehouse is tilted westward about 0.6 percent.
6	Greenhouse with reinforced concrete floor and perimeter footings.	Slab-footing separations and vertical displacement up to 9 mm (0.03 ft). Footing corners fractured and as a result of this fracturing anchor bolts placed through the sill plate and into the footing probably have lost anchorage. Cracks and separations in floor slab appear to be caused or at least exacerbated by subsidence. Offsets of up to about 6 mm (0.02 ft). The floor of greenhouse no longer drains properly as it is tilted about 0.5 percent to the west from subsidence. The frame of greenhouse has loosened for the differential movement and the west door is severely racked and will not close. The floor of greenhouse no longer drains properly as it is tilted about 0.5 percent to the west from subsidence.
7	Greenhouse with pole foundation and dirt floor.	No damage noted.
8	Greenhouse with reinforced concrete floor and perimeter footings. Partial height reinforced concrete walls are present in the eastern part of the structure.	Significant crack damage exists in the (mid-height) concrete walls in the east part of the structure. Most of this vertical and horizontal cracking was probably exacerbated or caused by subsidence with widths up to 3 mm (0.01 ft). Many cracks in the concrete floor slab appear to have exacerbated openings. Greenhouse is tilted about 0.4 percent to the west.
9	Greenhouse with pole foundation and dirt floor.	No damage noted.
10	Greenhouse with pole foundation and dirt floor.	No damage noted.
11	Office-garage building with basically a wood-frame one room office with an attached garage. The structure rests on a reinforced concrete slab foundation. The interior walls are drywall.	In exposed section of slab foundation subsidence has exacerbated cold joint separations and cracks up to 0.6 mm (0.002 ft). Also, building tilt to the southwest of 0.9 percent. In the superstructure, cracking is present in the walls and ceiling with offsets up to 1.2 mm (0.004 ft). The two door openings appeared to be slightly racked but operate.
12	Concrete sidewalk and patio area. Much of the exterior flatwork is associated with the pool and walking traffic for the nursery.	The sidewalk and patio areas have been strained laterally as well as having been subsided. Many of the cracks and cold joint offsets in all the flatwork appear to be caused by subsidence ground strains, or they are at least to some degree exacerbated by the ground movements. The slab between the garden shop and the wood shop has an east-west cold joint separation open 7.6 mm (0.025 ft) and cracking less than 0.9 mm (0.003 ft). Cracking and separations along cold joints with offsets up to 3.6 cm (0.12 ft) and spalled/buckled concrete in exterior flatwork for nursery traffic.
13	Wood-framed shed with siding exterior resting on a perimeter foundation and on-grade floor slab.	Separation between slab and perimeter footing up to about 3 mm (0.01 ft). North-south crack up to 0.6 mm (0.002 ft wide).
14	A converted chicken shed which has aluminum siding on wood on the south and east sides and corrugated metal on wood on the north and west sides. The superstructure rests on a perimeter foundation and the floor is made of concrete.	A converted chicken shed which has aluminum siding on wood on the soutb and east sides and corrugated metal on wood on the north and west sides. The superstructure rests on a perimeter foundation and the floor is made of concrete.
15	An in-ground pool about 51 sq m (550 sq. ft) in plan surrounded by a concrete patio.	The pool is about 5 cm (2 in.) out of level and the pool filter has become difficult to change.

16	An older one and one-half story wood-framed house with an aluminum siding exterior. The house rests on a block basement foundation and has a fireplace-chimney structure along the north wall. Paneling covers much of the basement walls and the entire first floor is wallpapered or paneled except for some tiles sections in the kitchen and bathroom. Drywall is present on the second floor.	Aesthetic, functional and structural damage. Most of the interior of the house is covered by various materials, consequently making it difficult if not impossible in places to assess cracking damage.

[1] See Figures 1 and 5 for locations.

TABLE 2 ASSOCIATED SUBSIDENCE PROFILE CHARACTERISTICS ALONG STRUCTURES

STRUCTURE NO.	PROFILE SLOPE	PROFILE ANGULAR DISTORTION[1]
1	0.1%	2.1×10^{-4}
2 and 3	1.6%	-1.4×10^{-3}
4	0.6%	-1.3×10^{-3}
5	0.4%	-7.3×10^{-4}
6	0.4%	-4.1×10^{-4}
7	0.4%	-3.2×10^{-4}
8	0.4%	-5.8×10^{-4}
9	0.4%	-5.8×10^{-4}
10	0.4%	-3.3×10^{-4}
11	0.8%	-3.8×10^{-4}
12	0.9%	-2.7×10^{-3}
13	0.8%	-2.1×10^{-4}
14	0.9%	-3.6×10^{-4}
15	1.1%	-1.9×10^{-4}
16	1.2%	-4.4×10^{-4}

[1] Angular distortion, β, along the subsidence profile was measured by taking maximum vertical distance between the subsidence profile and the chord along the structure length divided by half the structure length. A positive number indicates β is associated with tensile strain and hogging curvature and a negative β means compressive ground strains and sagging profile curvature.