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SYNOPSIS: An area in southwestern Illinois has been experiencing surface and subsurface movements with associated damage to surface structures. The area is underlain by an abandoned, partially extracted room-and-pillar underground coal mine. Instrumentation included TDR (Time Domain Reflectometry), Inclinometers, Sondex, Tiltplates, and precision land surveys. This paper presents the results of a 16-month cooperative study between the Department of Mining Engineering at SIUC and a local coal company.

INTRODUCTION

Surface subsidence movements related to underground coal mining in southwest Illinois have been known to cause property damage ever since mining was begun in the region in the late 19th century. Records of mapping areas of subsidence date back as early as 1934. Underground mining of coal, with associated surface subsidence movements, is continuing in the region. Partial extraction room-and-pillar mining method has been the primary mining system in the region, and most mining has been done at less than 60 m (200 ft.) depth. Until about mid 1940's, mining layout and geometry was generally irregular (Figure 1) because of manual loading techniques. Rooms were generally 12 m (40 ft.) or more wide and 60 m (200 ft.) or more long with local extraction ratios exceeding 65%.

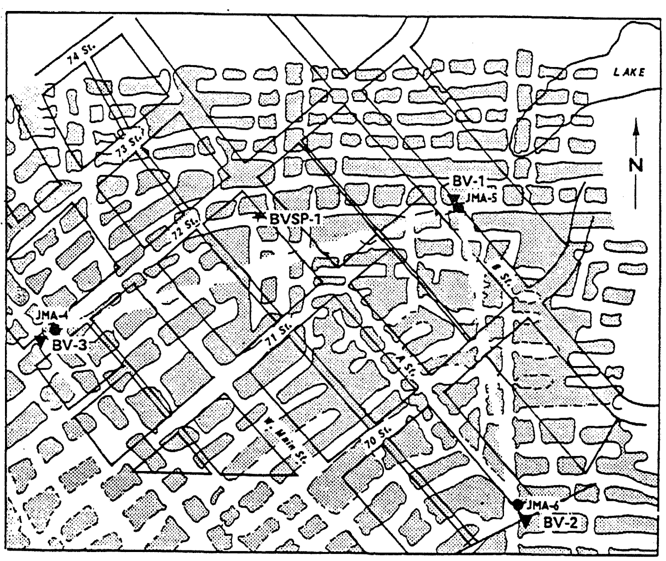

Figure 1. Irregular Mine Workings Prior to 1940, (from DuMontelle, 1978)

Over the last 30 years or so, continuous mining machines have been utilized for coal extraction and the mining layout is more regular (Figure 2). Entry widths are generally restricted to less than 6 m (20 ft.) and roof bolting is used as the primary artificial support.

In spite of a long history of subsidence in the region, very few engineering studies of mine

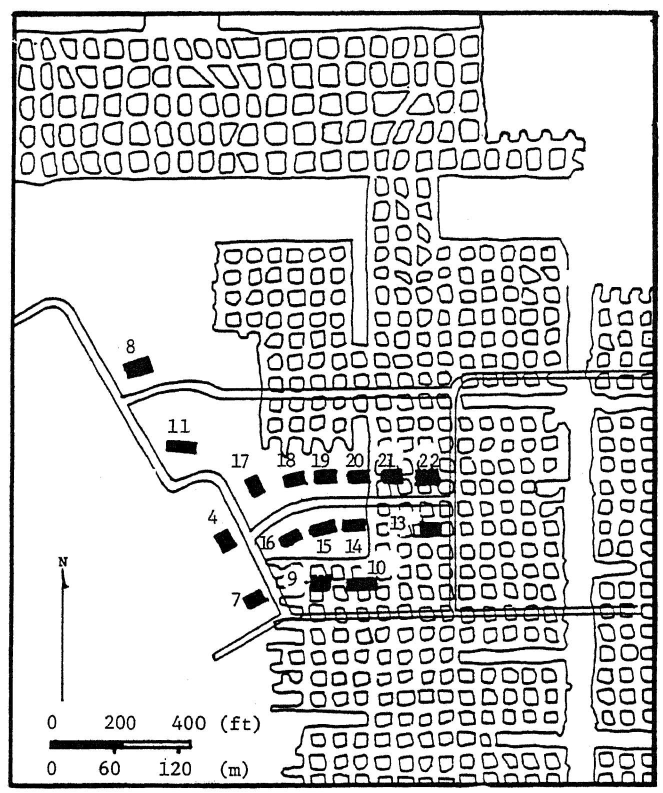

Figure 2. Mine Workings and Surface Structures

subsidence have been conducted in the area. To the best of the authors' knowledge the study conducted by the Illinois State Geological Survey (DuMontelle, 1978) in cooperation with the Bureau of Mines of the U.S. Department of the Interior, is the only study which provides details on geology and hydrogeology of the area, engineering properties of surficial as well as bedrock materials, and progressive subsidence movements. Due to irregular layout of mine workings in the area and limited instrumentation, very few specific conclusions were drawn in this study.

In August 1983, the Department of Mining Engineering signed a 16-month cooperative agreement with a coal company to undertake a detailed study of the causes, mechanisms, and characteristics of surface and subsurface subsidence movements and associated possible damage to surface structures in a 30,000 m^2 (75 acre) area overlying workings mined in late 1970's using continuous mining equipment. Subsidence movements, with associated damage to surface structures, have been experienced in the area since 1977. A detailed discussion of the history of subsidence in the area is provided elsewhere (Chugh et al, 1985). This study area is located about 25 km (15 miles) south of the above mentioned study area.

SPECIFIC OBJECTIVES OF THE STUDY

1) Determine the extent to which surface and subsurface movements are complete in the area,
2) Determine the influence of geology and hydrology of the area on subsidence movements,
3) Identify the mechanism(s) of subsidence in the area,
4) Characterize the extent of damage and monitor possible progressive damage to selected surface structures, and
5) Develop recommendations to (a) minimize further damage to surface structures in the area, (b) identify future areas that may be affected by these movements and (c) modify mining systems to minimize these movements.

MINE AND AREA DESCRIPTION

The area covers approximately 30,000 m^2 (75 acres) with a relief of less than 6 m (20 ft.) in surface topography and has 30 residential houses. The area overlies a 540 m x 280 m (1800 ft. x 840 ft.) panel (Figure 2) at a depth ranging from 30-45 m (100-150 ft.). Mining thickness ranged 1.8-2.4 m (6-8 ft.) with pillars at 18 m (60 ft.) centers and 6 m (20 ft.) wide entries and an extraction ratio of about 60%.

Surficial overburden thickness in the area varies from 17-27 m (50 to 80 ft.) and primarily consists of glacial silts and clays (Figure 3). The rocks overlying the coal seam consist of interbedded limestones, sandstones and shales and vary in thickness from 11.7-13.3 m (35-40 ft.). Claystone forms the immediate floor of the coal seam and its thickness varies from 0.3-1.7 m (1-5 ft.). It is underlain by interbedded shales and limestones of varying thickness.

Previous regional hydrological studies (Buchler, 1971) have categorized the study area in the low probability region for large volume water wells. The Mississippian formation lying well below the coal seam, is the best source for bedrock groundwater supplies. Sand and gravel lenses have been found locally but prediction of their presence or extent is difficult.

DESCRIPTION OF THE RESEARCH STUDY

Twenty two (22) boreholes were drilled in and around the study area to study geology and hydrology of the area. Data were collected on surficial as well as bedrock overburden thickness, sequence and thickness of different beds in consolidated overburden, claystone thickness below the coal seam, change in lithology, charge and recharge zones, thickness of impermeable strata and other variables which may influence surface and subsurface movements in the area.

Four (4) boreholes were sampled for surficial overburden and five (5) boreholes for bedrock overburden to characterize overburden geotechnical properties. Soil samples were obtained with shelby tubes and were studied for natural moisture content, Atterberg limits, unconfined compressive strength and shear strength. Rock sampling consisted of core drilling, over mine openings and coal pillars, 54 mm (2 1/8 in.) diameter boreholes below the bedrock surface to about 3 m (10 ft.) below the coal seam. The objective of the boreholes over

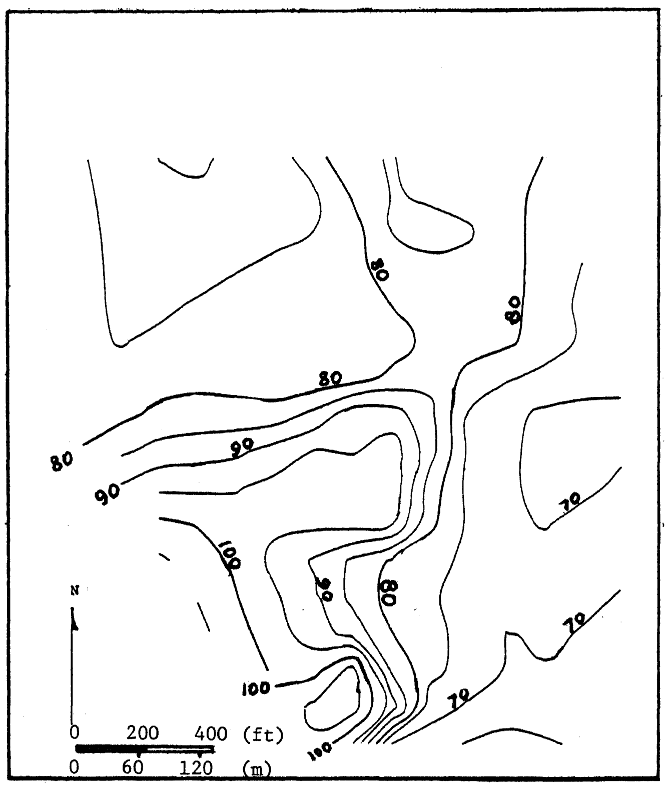

Figure 3. Unconsolidated Overburden Contours

mine openings was to study the extent of fracturing in rock strata above the coal seam due to subsidence movements and also to determine the height of remaining open cavities and extent to which mine openings had been filled by roof falls. Several boreholes were drilled over coal pillars to obtain relatively undisturbed cores of roof strata, coal seam, and claystone below the coal seam. Unconfined compressive strength, indirect tensile strength, slake durability, swelling strain index, water content, Atterberg limits, and clay mineral composition tests were conducted on cores (Chandrashekhar, 1985).

Surface subsidence movements were monitored along six (6) lines consisting of 152 monuments (Figure 4) located at about 18 m (60 ft.) intervals. Subsidence monuments were designed to minimize freeze-thaw associated movements. The monuments were surveyed for vertical and horizontal movements with standards for Second order class II accuracy.

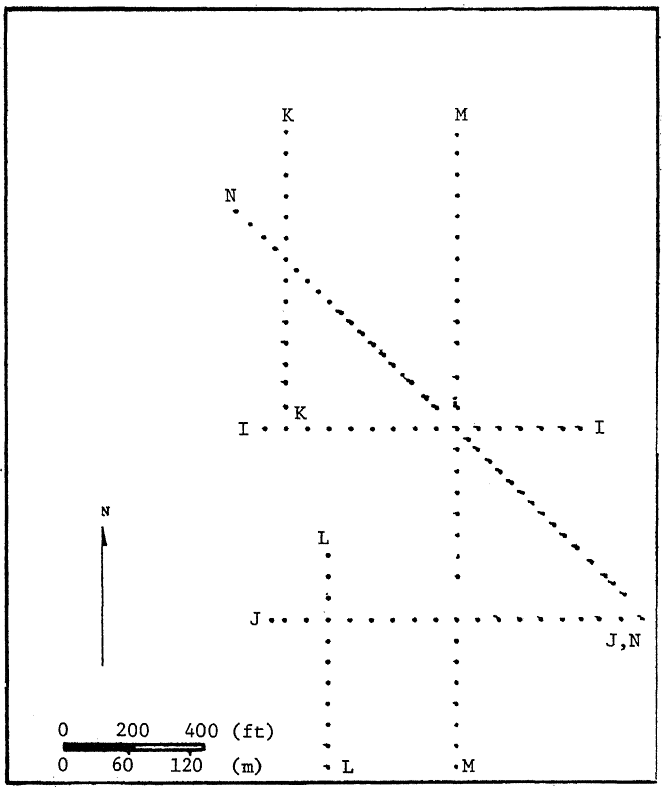

Figure 4. Survey Monuments Along the Subsidence Monitoring Grid Lines

Subsurface vertical and horizontal subsidence movements were monitored using an inclinometer and time domain reflectometry (TDR) instrumentation. Three (3) inclinometer-sondex holes, two through coal pillars and one at an intersection, were instrumented. The casing was installed from the surface to about 6 m (20 ft.) below the coal seam. Five (5) TDR boreholes were located at the center of mine openings.

A total of thirteen (13) tiltplates on foundation walls were installed in four (4) houses critically located with respect to underground mine workings. In addition, carpenter levels (± 0.5 deg) were also installed in houses to determine large movements in the upper structure of the houses.

Ground water levels and flows in surficial (soil) and bedrock (rock) overburden were monitored in six (6) surficial wells and four (4) bedrock wells including the one monitoring the mine pool level. Details on instrumentation and test procedures for these wells are given elsewhere (Chugh et al, 1985). All instrumentation was monitored at intervals of 2-4 weeks.

Selected boreholes in the study area were observed with a borehole TV camera. The borehole walls in bedrock overburden and underground mine workings were carefully inspected with the camera. This was done to determine the 1) amount of overburden fracturing above the coal seam, 2) condition of coal pillars, (intact, sloughing) and mine openings (floor heave, roof falls, presence or absence of water etc.) and 3) height of remaining cavities above roof falls.

STATE OF SURFACE AND SUBSURFACE MOVEMENTS IN THE STUDY AREA

Typical crossection and contour plots of vertical surface subsidence movements over the study area are shown in Figures 5 and 6. Based on an estimated precision of 7 mm (0.3 in.) in elevation surveys, two types of subsidence movements are identified: (1) gradual relatively uniform subsidence of the entire study area, and (2) localized areas (A, B, C, in above figures) of large movements in the form of a trough over a 60-80 m (200-250 ft) area. Movements appear to occur very rapidly in some cases for latter type of subsidence events. Most of the localized subsidence events appear to occur in areas of a bedrock valley (Figure 7) where the proportions of the surficial to bedrock overburden are very large (100:30, 110:20, 120:10 etc.).

MECHANISMS OF SUBSIDENCE

Two mechanisms are hypothesized in the study: 1) slow compressional settlement of coal pillars in the panel over weak claystone floor leading to development of relatively uniform sag subsidence, and 2) localized subsidence events initiated by roof failure over one or more entries or intersections. A brief description of each with evidence from geotechnical studies justifying the hypothesis is given below.

1. Vertical surface subsidence movement data (Figure 5) show gradual downward movement with time over the entire area. Surface movements over mine openings and coal pillars are approximately the same except near the barrier pillars where movements are somewhat smaller. Subsurface vertical movement data from Sondex instrumentation in boreholes over the coal pillars (Figure 8) also show downward movement in lower portions of the pillar near the claystone floor. Over the 16-month study period, approximately 12 mm (0.5 in.) of compressional settlement is noted in the area.

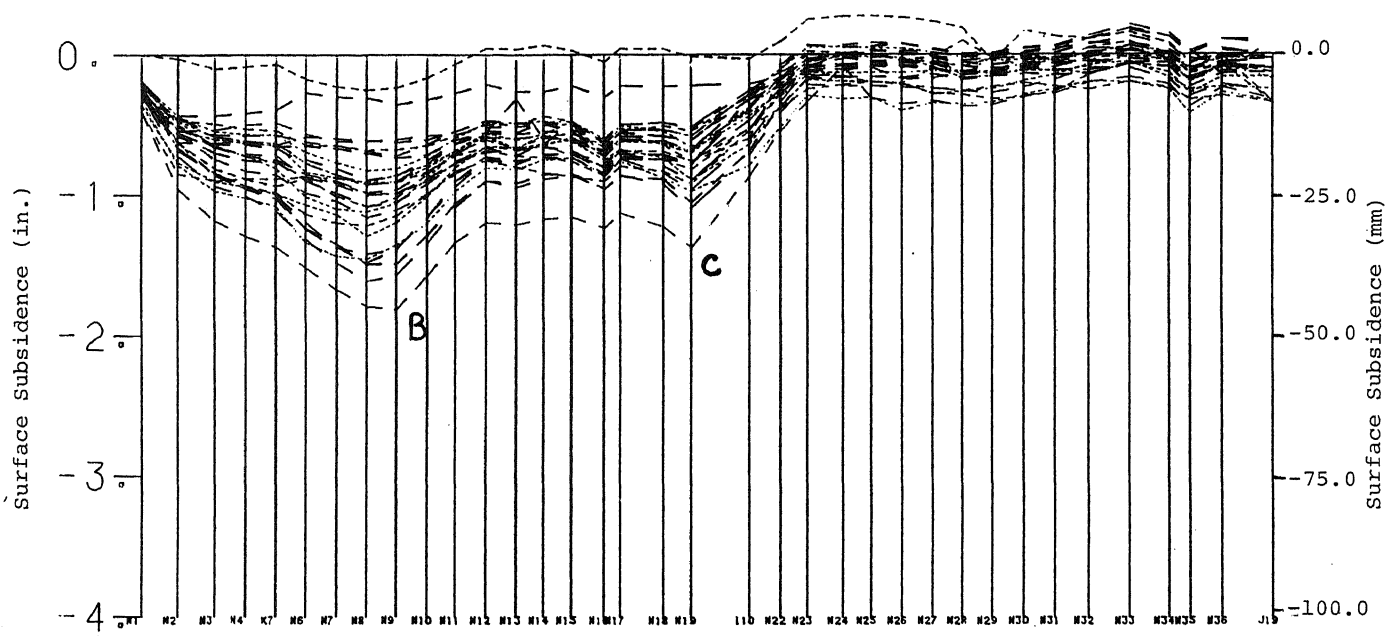

Figure 6. Surface Subsidence Cross Section Along N Grid

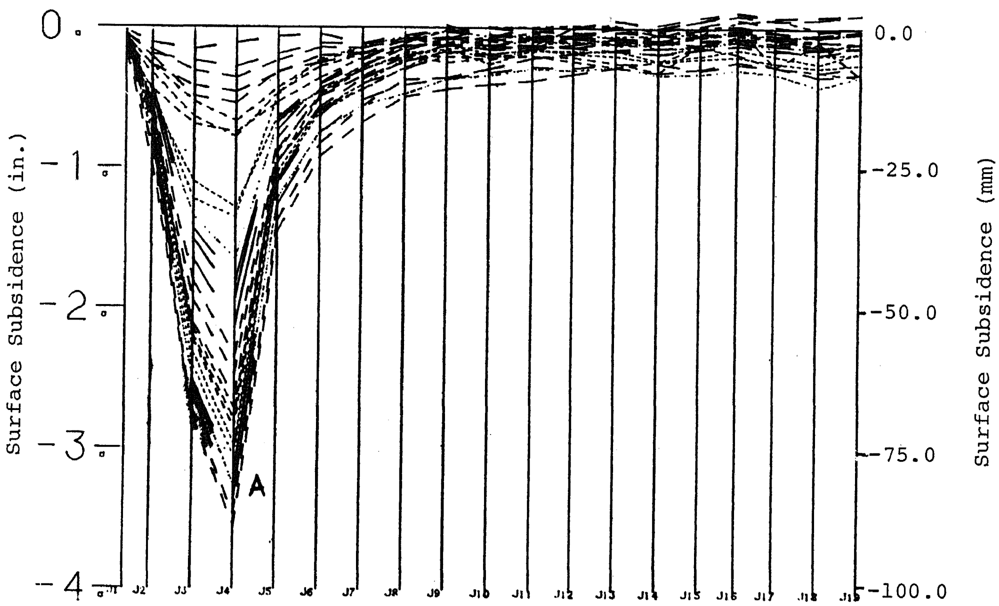

Figure 5. Surface Subsidence Cross Section Along J Grid

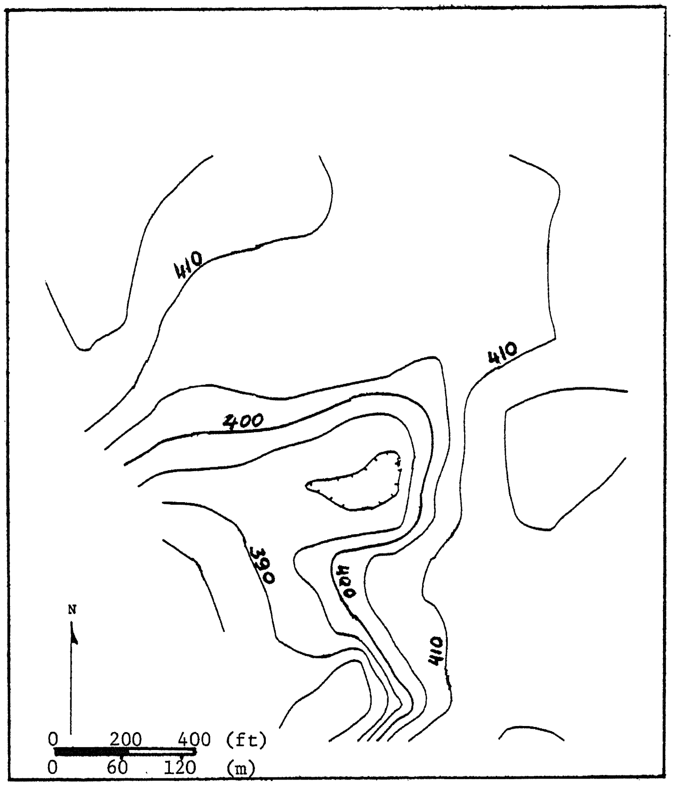

Figure 7. Bedrock Structural Elevation

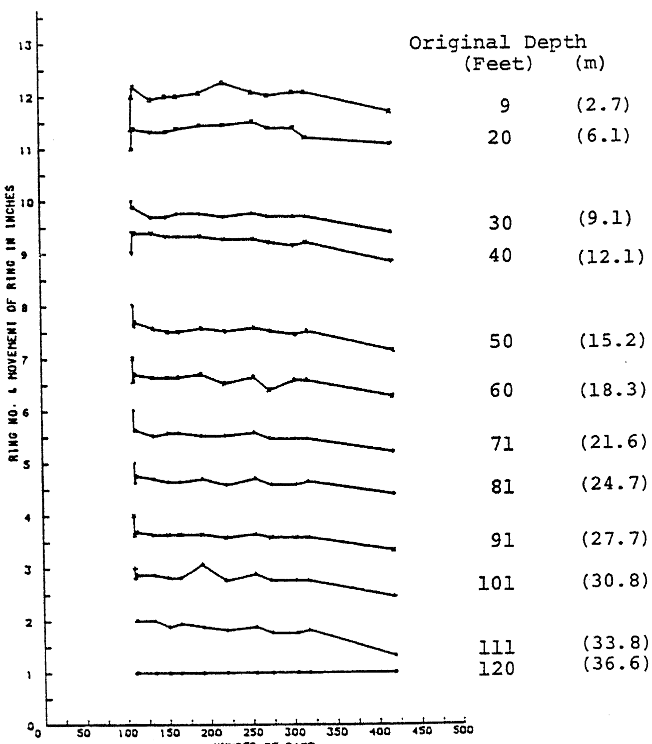

Figure 8. Subsurface Vertical Movements Sondex Hole IS2

The settlement is continuing even after a decade of mining although its rate seems to be decreasing (Figure 9). The expected vertical settlements due to this mechanism will depend upon claystone thickness, overburden pressure, percent extraction, and deformability of claystone. Over a long period of time, these movements may be large enough to cause differential coal pillar settlements and roof falls leading to surface subsidence. Consolidation and compression of claystone floor may be enhanced by the presence of water. In this mechanism, surficial overburden which is at or above its plastic limit (Figure 10) moves downward slowly as pillars settle. No extension strains are expected in the overburden since settlement rates are very small.

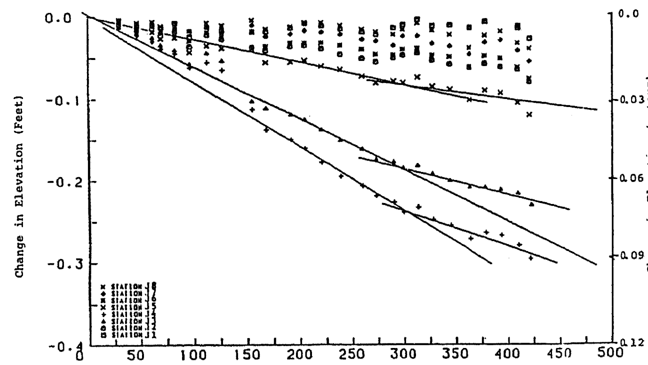

Figure 9. Subsidence Rate of Selected Stations on J Grid Line

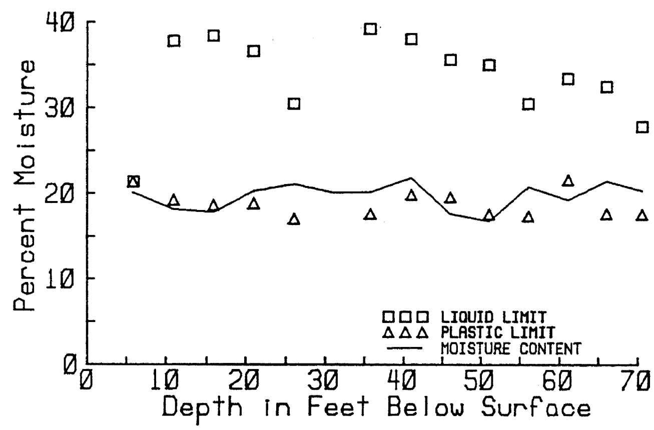

Figure 10. Comparison of Moisture Content, Liquid Limit, and Plastic Limit

2. Fracturing of immediate roof strata due to wide intersections, discontinuities in the immediate roof, and/or prolonged excessive loading of thinly layered and weak overburden may cause the soil overburden to flow into mine voids causing surface subsidence (Figure 11). Differential settlements of pillars on weak claystone floor may also cause initiation or development of such subsidence movements. At least three or four such events (A, B, C, D) with vertical movements ranging from 25-90 mm (1.0-3.5 in.) were observed during the study period. At one such site where access was possible after the subsidence event occurred,

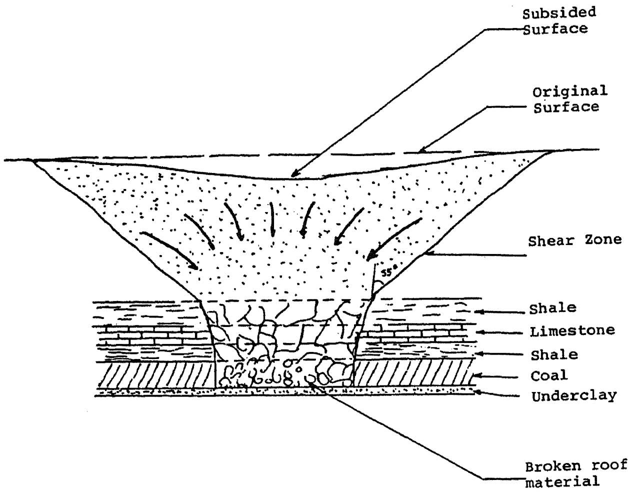

Figure 11. Schematic of Subsidence Mechanism 1

underground mine observations by the Coal Company staff showed flow of surficial overburden into mine voids. No cracks are expected on the surface or subsurface in the surficial overburden in this mechanism also since its moisture content is at or above its plastic limit.

Settlement rate due to sag subsidence appears to vary 5-7 mm (0.2-0.3 in.) per month and shows slightly decreasing trends (Figure 9) over the last six months of the study period. Borehole T.V. camera observations in several of these areas showed relatively intact roof, floor, and coal pillars. It is difficult to predict the maximum possible amount of settlement and the rate at which it will occur. Both will be enhanced in the presence of water. Since there are no indications of floor heave or otherwise filling up of void areas underground, additional subsidence movements are possible. These may or may not, however, result in damage to structures on the surface since movements are small and should occur very slowly in the absence of water. If the area was to get flooded, the magnitude and rates of these movements may result in damage to surface structures.

Borehole TV camera observations in the area of localized subsidence events showed roof falls in entries with dripping water, partially or completely flooded mine workings and highly fractured immediate roof strata. The open cavities above roof falls are common indicating that additional movements in the area are likely to occur. Based on association developed between the presence of the bedrock valley and localized subsidence events observed in this study, it is expected that additional movements of this nature may occur in future and may cause damage to surface and subsurface structures.

EFFECT OF GEOLOGY AND HYDROLOGY

Contours of surface topography, unconsolidated overburden thickness and structural elevation on the top of the bedrock surface (Figure 7) were prepared based on all available data (boreholes drilled during this study and those drilled prior to this study). Pertinent observations are:

1. A bedrock valley approximately 9 m (30 ft) deep is observed in the area (Figure 7). The thickness of the bedrock overburden in this valley is only 3-11 m thick (10-35 ft) while the thickness of the surficial overburden varies 24-34 m (80-110 ft). A cross-sectional map of the boreholes revealed the absence of the Bankston Fork Limestone in the bedrock valley. Thinly bedded immediate roof strata and the absence of the competent limestone bed in the roof together form favorable conditions for roof falls and localized rapidly occuring subsidence events such as A, B, C, and D.

Roof instability may also be induced by differential pillar settlements, prolonged dead load of soil overburden on roof rock and weakening of immediate roof shales due to high swelling strain potential (5-15%).

2. A 1.2-1.8 m (4-6 ft) thick sand bed/sand lens was found at a depth varying from 4.5-7.5 m (15-25 ft) below the ground surface in several soil exploration holes. No trends as to the presence of these confined sand beds were discernible based on available data. Considerable amount of water under low pressure 20-28 kPa (3-4 psi) was observed. Based on available data on water levels in surficial wells and the nearby lake was the east side of the study area it was concluded that the lake was not a water source for the sand bed. Underground roof falls and associated movements in soil overburden may eventually intercept these sand beds. Water from these beds may significantly affect the weak claystone floor because its swelling potential is high. Flow of water from sand lenses sometimes prevented borehole TV camera observations in the bedrock overburden.

3) About 1.8 m (6 ft) of rock below the bedrock surface was highly fractured (RQD < 50%) with a rating of poor to very poor. There is not enough data to verify whether this condition existed prior to mining due to movement of glaciers or resulted from subsidence movements.

4) The immediate roof strata generally had low RQD values (<30%) and high moisture content (8%). The presence of weak thinly layered roof strata would favor localized subsidence events.

5) Immediate claystone floor stratum has high moisture content (10-15%) and contains considerable amount of expandable clay minerals (Table I). Wetting of immediate floor strata may considerably reduce its strength and deformation modulus which may increase total and differential pillar settlements, and may lead to roof falls.

6) Surfical overburden is above its plastic limit, it has an average moisture content of about 20% and it is relatively independent of the depth below the surface (Figure 10). Unconfined compressive strength of soil overburden varies from 75-925 kPa (11-134 psi) and it generally increases with depth below the surface. An elastic-perfectly plastic material behavior is indicated by stress-strain curves.

HYDROLOGICAL STUDIES

Data from monitoring of surficial and deep water wells were compared with the local water table, surface drainage and the water level in the nearby pool.

1) There is no evidence of a hydraulic connection among the surficial wells, bedrock wells and the mine water pool. The water levels appear to follow the local ground elevation and the water table levels follow the local surface drainage pattern.

2) The pressures due to observed water levels in surficial wells are small to be significantly contributing to ground movements in the study area.

3) There is no evidence that a) hydrology in the area has affected mine subsidence and 2) subsidence has had any long-term effects on hydrology.

EXTENT OF DAMAGE TO SURFACE STRUCTURES

The first report of subsidence occurred in late December of 1977. A circular depression formed on the surface bisecting house (Figure 12) in the study area. Even though mining was terminated and supports were installed underground, subsequent surface settlements continued to occur and house 9 had to be moved due to damage to the foundation. Houses 7 and 10 also showed tension cracks in the foundations which were repaired in 1983. To monitor progressive movements of both these houses, tiltplates were installed in the Fall of 1983. In house 7, 3 tiltplates were installed on the foundation walls to monitor the movement on both sides of the major cracks in the foundation and floor. Based on the tiltplate data with a precision of

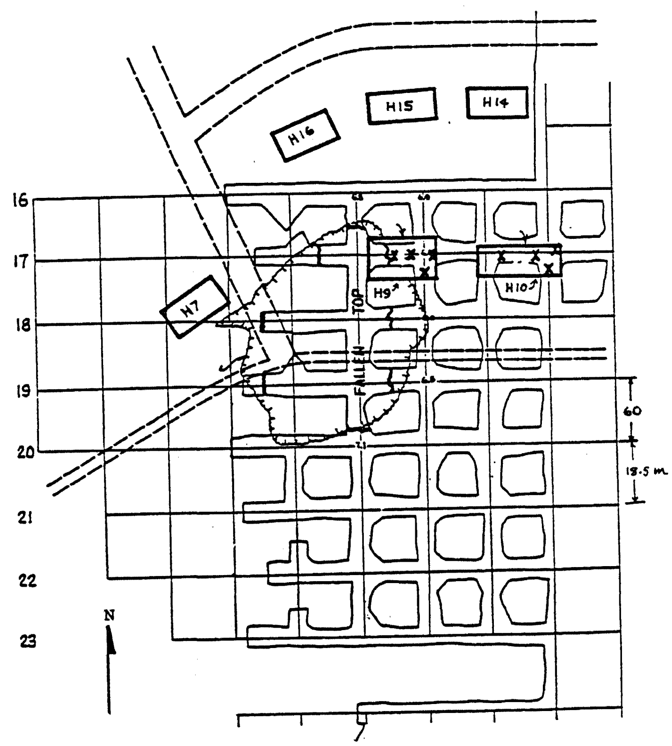

Figure 12. Limits of Surface Cracking from First Report of Subsidence, Dec. 1979

± 4 seconds, the southern portion of the house is tilting most to the southeast, toward the center of the first depression, while the north side of the house is tilting toward the east but its magnitude is less than that of the southern portion of the house. A typical plot of the tilt is shown in Figure 13. A maximum horizontal displacement 2 mm (0.08 in.) is observed in the foundation since the tiltplates were installed. In house 10, 3 tiltplates were installed; one on the west side and two on the east side. The largest movement occurred on the west side of the house, with a tilt of 46 seconds to the west. This corresponds to a horizontal displacement of about 8 mm (0.32 in.).

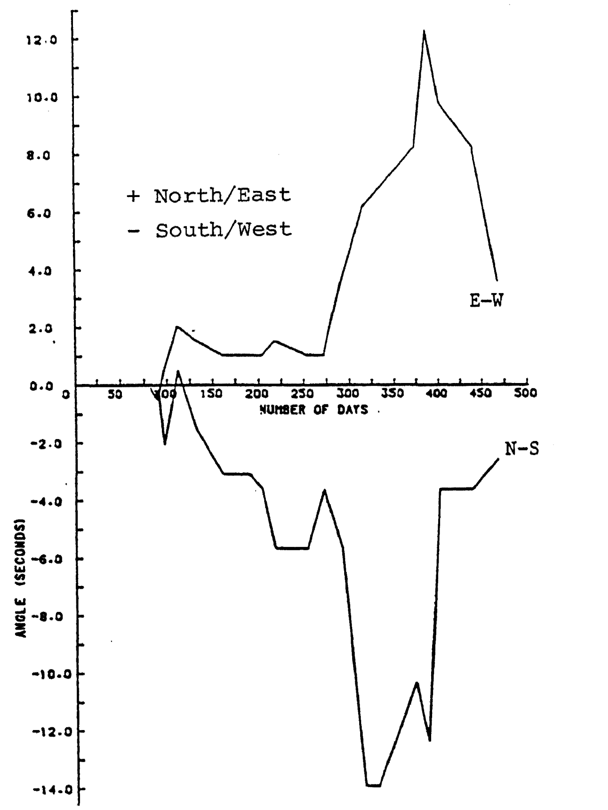

Figure 13. Angular Displacement of Tiltplate H20TP4.

TABLE I. Clay Mineral Analyses

SAMPLE	ILLITE	KAOLINITE	CHLORITE	SMECTITE	*MIXED LAYER	**RATIO S:I	%TOTAL CLAY
C	46	18	--	--	36	37:63	38.0
D	34	2	--	6	58	30:70	33.6
E	14	1	1	37	47	30:70	35.1
F	12	tr	1	60	27	33:67	32.4

* Percentage of mixed-layer illite/smectite present
**Ratio of smectite to illite within the mixed-layer fraction

In addition to the tiltplates, an inclinometer/sondex instrumented hole was located to the south of house 7 to measure the subsurface movements. The maximum horizontal movement 6.8 mm (0.27 in.) in the N 77° E correlates well with the horizontal movement measured from the tiltplates for house 7 since the inclinometer was much closer to the center of the depression than house 7.

Movement in and around houses 7 and 10 are also consistent with the surface subsidence data for survey lines J and L. Since the movements are continuing and decrease only gradually with distance from the center of the depression, it is expected that the tension cracks in both houses will continue to occur for some time in the future.

House 20 had 5 tiltplates installed on the basement walls. Two tiltplates were on opposite sides of a major crack in the north wall. A comparison of the movements in the two tiltplates indicate a twisting of the house along an E-W axis. The movement in this house is complex and indicates probable roof falls to both the north and east causing an overlapping movement.

SUMMARY OF RESEARCH FINDINGS

1) A bedrock valley is located in the study area. At the base of this valley, the thickness of surficial overburden increases to about 34 m (110 ft) and the thickness of bedrock overburden decreases to about 3 m (10 ft).

2) A large number of subsidence events in the past seem to be associated with this bedrock valley. Additional events in the future may also be associated with it.

3) Hydrology of the area does not appear to have either significantly affected or been affected by surface and subsurface movements in the area.

4) The surficial overburden behaves like modeling clay based on its moisture content and plastic limit. Most of the weight of the soil overburden has to be supported by relatively weak and thin rock overburden overlying the coal seam.

5) The immediate floor claystone, 0.3-1.2 m (1-4 ft) thick, is weak and highly moisture sensitive. The mineralogy of the claystone shows high percentage of expandable clay minerals and high clay size content.

6) Strength of the coal is adequate for the mining depth and percentage extraction practiced at the mine.

7) Localized areas on the surface are continually undergoing subsidence (Figure 14). Most subsidence is observed adjacent to House 7 with a total vertical movement of about 89 mm (3.5 in).

8) Inclinometer-Sondex data show subsurface movements in the surficial and bedrock overburden which correlate quite well with those measure by precise land surveys.

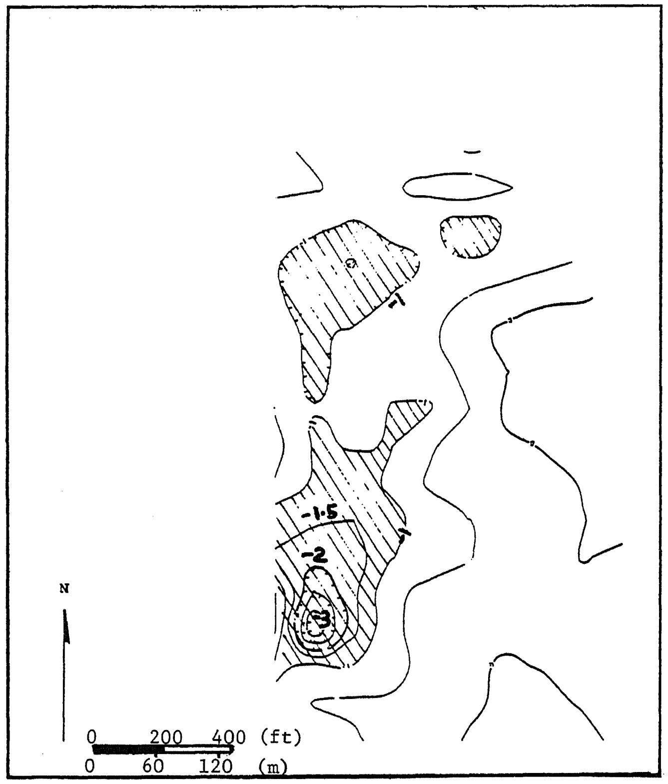

Figure 14. Localized Areas Currently Subsiding

9) Borehole TV camera observations in 10 boreholes show a) the northwest corner of the panel partially filled with water, b) roof falls in two areas around boreholes with open cavities 1.2-1.5 m (4-5 ft) high, c) relatively intact immediate roof, roof bolts and cap blocks, d) little or no pillar sloughing and floor heave, and e) highly fractured rock overburden overlying the coal seam.

10) The major subsidence mechanism causing damage in the area appears to localize roof falls with soil overburden flowing into mine workings. The differential settlement of pillars on weak claystone floor may only be a small contributory factor in causing roof falls and associated surface movements.

11) Residential structures in the study area are undergoing progressive movements and may suffer additional damage. The structures of concern are houses 7, 20, 14, and 10. Over a long period of time, houses 19, 18, 17, and 12 may also be affected.

12) Subsidence in the area is not complete. Slow settlement of the entire study area and localized subsidence events may be anticipated in the future.

13) An angle of draw of 55° in surficial overburden is noted. Based on the angle of draw, a 55 m (180 ft) barrier pillar between two panels is not adequate to eliminate surface subsidence movements on the surface.

14) Maximum tension in a structure appears to occur at about 18-28 m (60-90 ft) away form the edge of mine workings. Major cracks may be anticipated in these areas observed in garages of house 20, house 14, and house 7.

15) Tiltmeters appear to correctly predict direction of vertical movements in relationship to the position of mine structural workings.

16) Slow settlement of pillars on weak claystone floor has been continuing since mining was started in the area almost ten (10) years ago. The authors think that most of the future subsidence events will be related to localized roof falls rather than slow compressive settlement.

17) The influx of water into abandoned mine workings through any source could significantly increase compressive settlement rate, incidence of roof falls and associated surface subsidence.

RECOMMENDATIONS

1) Active mine workings should consider reducing width of mine openings and developing three way intersections wherever possible. The size of the coal pillars may also be reduced.

2) The minimum safe distance to locate a surface structure is 45-60 m (150-200 ft) from the edge of mine workings where similar geology and mining conditions are found.

3) Surface and subsurface movements are not complete. Analysis of current data indicates that houses 7, 10, 14 and 20 may have to be relocated or structurally modified if they are to substain additional subsidence movements.

4) Areas that may be affected by subsidence movements in the future have been outlined in Figure 14. Monitoring of these and other areas should continue at regular intervals to develop a stronger database for future subsidence studies.

5) Future design of mine workings should consider geological and geotechnical data for overburden and immediate floor strata.

6) To minimize damage to surface structures, a study of different methods of stabilization against planned subsidence with high extraction ratios is also recommended.

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