

MINE CONFIGURATION AND ITS RELATIONSHIP TO SURFACE SUBSIDENCE¹

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Abstract.--Careful evaluation of mine maps has been of considerable aid in understanding subsidence failure mechanisms above active and abandoned underground coal mines. This, in turn, aids the investigator in: (1) predicting what might happen in the future, and (2) designing proper corrective action to prevent additional subsidence events. Factors to be considered include accurate orientation of the mine map with surface features; pillar shape, size, alignment, and strength; percent coal extraction; overburden thickness and composition; location and orientation of barriers and unmined coal reserves; entry and haulageway size and alignment; water conditions in the mine; geologic structure; the presence of retreat mining in adjacent or nearby panels; and pillar alignment in association with retreated panels. Field investigations, including drilling programs, based on the evaluation of available mine maps have established clear relationships between surface effects of mine subsidence events and specific underground conditions causing the subsidence. These include: (1) coal barriers acting as fulcrum points causing massive surface cracks due to transfer of overburden loads (Graysville and Willow Bend, AL); (2) pillars incapable of supporting overburden loads (Graysville, AL); (3) alignment of pillars left to protect the surface, creating residual stress fields that fail in a catastrophic manner (Fairmont, WV); and (4) natural fracture systems, such as faults and joints, providing conduits for movement of unconsolidated sediments (piping) into the mine void and subsequently, movement of the surface (Arnold, PA and Shinnston, WV). These events have occurred with overburden thickness ranging from 20 ft to over 700 ft. Surface damage ranged from minor cracks and no vertical displacement to vertical displacement of 2.5 ft and cracks up to 6 ft wide and 200 ft deep.

INTRODUCTION

Underground mining creates a void system which disturbs the existing stress field established by

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natural processes. The overburden responds with the first cut into the coal and continues until the applied stress reaches a new equilibrium within the overburden. These stress changes result in deformation and displacement of the surrounding overburden material. The magnitude of the change takes place is controlled by the size of the cavity and the strength characteristics of the affected strata. Figure 1 is a simplified illustration of the forces acting on a stratigraphic section as a result of a mine void. The force vectors above the void are deflected toward the void proportionate to the distance from the center of the void. Below the coal seam an upward component of force also acts towards the center of the void. As the cavity increases in size, fractures develop in the overburden which may result in subsidence of the surface and sometimes heaving of the mine floor.

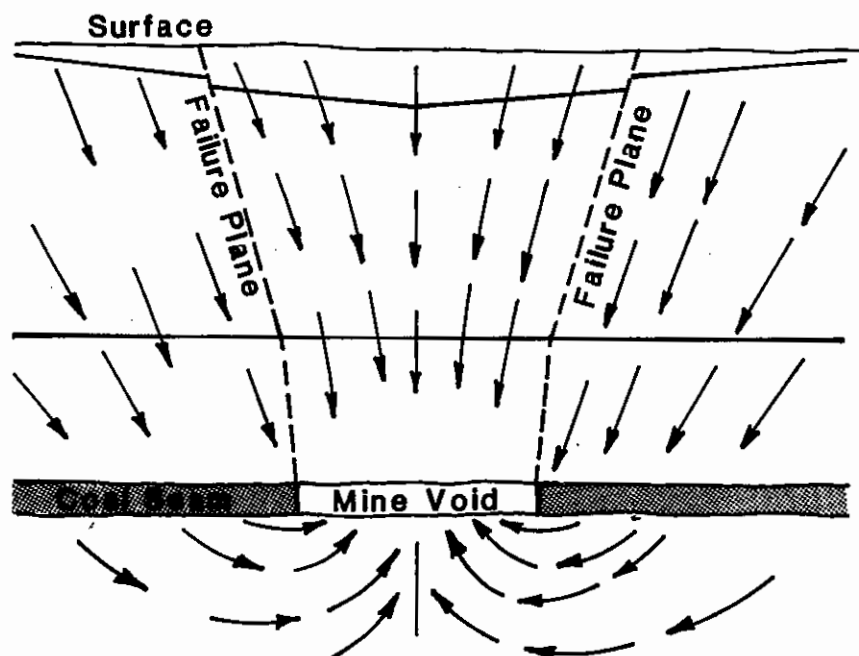


Figure 1.--Schematic representation of ground movement due to subsidence of overburden into a mine void (Grond, 1957).

Since 1979, the Office of Surface Mining Reclamation and Enforcement (OSMRE) has conducted 848 abandoned mine-related subsidence investigations in the 12 coal states east of the Mississippi River (table 1). These preliminary investigations established 572 situations as subsidence emergencies. Remedial action was implemented by OSMRE with project costs ranging from \$200 (to fill a hole in a yard adjacent to a house), to approximately \$3 million for ground stabilization in a large housing area. Overburden thicknesses above the mined-out areas ranged from less than 20 ft to over 700 ft.

Table 1.--Subsidence-related investigations and emergency projects conducted by OSMRE between October 1979 and July 1987.

STATE	FIELD INVESTIGATIONS	EMERGENCY PROJECTS
Alabama	11	5
Georgia	1	0
Illinois	35	32
Indiana	43	34
Kentucky	63	26
Maryland	1	0
Michigan	5	4
Ohio	82	45
Pennsylvania	505	360
Rhode Island	2	2
Virginia	5	3
West Virginia	95	61
TOTAL	848	572

In general, mine subsidence problems develop where post-mining pillar support systems and coal barriers ultimately fail. Many interrelated factors control when, where, and how failure will occur. These factors include:

- Thickness of coal mined;
- size, shape, and distribution of pillars and rooms;
- percent extraction of coal;
- thickness and physical characteristics of the overburden;
- method of mining (e.g., longwall, shortwall, room and pillar, room and pillar with full or partial retreat);
- dry or flooded conditions in the mine;
- actual or potential level and degree of fracturing in overburden; and
- mineralogy of overburden (e.g., clay minerals that swell when water is added, sulfide minerals that chemically and physically change in the presence of oxygen and moisture, and minerals that react with water to form new minerals).

Many of these factors can be determined through drilling, geologic mapping, or other technical data previously gathered for specific areas. However, data from mine maps are invaluable in determining subsidence failure mechanisms and provide information otherwise not available during a subsidence investigation. Once the failure mechanism has been determined, selection of the appropriate stabilization technique is possible.

USE AND DEVELOPMENT OF MINE MAPS

The importance of obtaining a mine map when investigating a surface disturbance believed to be associated with underground mining cannot be overemphasized. The mine map shows where mining has occurred and assists the operator in determining how to safely and effectively continue development to achieve maximum productivity. Mine maps identify entry, haulage, and escape systems. Mine maps also show the type of mining, coal barriers and reserves, and limits of underground mining activity up to the date of the map. They indicate the presence of retreat mining in adjacent or nearby panels and pillar alignment in association with retreated panels.

The investigator must, however, be aware of the following basic problems in working with archived mine maps:

- a. The map may not represent the final mine configuration. There is always a time lag involved between mine surveying and the drafting of the information on the map. Many archived maps are obtained from sources other than the official files of the mine company (e.g., consulting companies and private individuals), and therefore may not be the final detailed map.
- b. The scale of the map may be distorted due to the paper's stretching during copying or due to the photographic copying and reproduction process.
- c. If the original print is not of very good quality, a reproduction may be very difficult to read. This is especially true of maps reproduced from microfilm.

MINE MAP ORIENTATION

The key to using a mine map in a subsidence investigation is accurate orientation of the map with surface features. This can be done in several ways. The simplest is to identify the coordinates used for control during the underground mine survey and to re-establish those controls on accurate surface maps. On OSMRE projects where survey control was re-established, drilling was 98 percent successful in confirming mine geometry and intersecting desired drilling targets.

When the control points no longer exist, it is not possible to re-establish the original survey control associated with the mine map. However, many surface features that existed at the time of the mining, such as air shafts, houses, railroads, roads, and property lines, are

represented on the mine map. When these features can be located on the surface, a new coordinate system can be generated and used to orient surface and mine maps drawn to the same scale. On OSMRE projects where this technique was applied by a professional surveyor, drilling was about 90 percent successful in verifying mine geometry.

Despite re-establishment of survey control, drilling targets are sometimes missed. An example of this occurrence was in Belleville, IL, where OSMRE conducted a large subsidence stabilization project (The Canterbury Manor Project). A mine map was available (scale: 1 inch equals 100 ft), and OSMRE secured aerial photography to produce a topographic map at the same scale. The coordinate system used on the mine map appeared to be the township and range survey lines; therefore, the two maps were oriented using the local township and range corners established by the city. When initial drilling in the area indicated the orientation of the mine map was incorrect, the mine map was reoriented with the surface based upon the intersection of voids and pillars defined by eight drill holes. A total of 77 vertical and 23 angle construction holes were eventually drilled for this project. The map orientation phase of the project saved at least \$43,000 in drilling costs, since 22 holes would have intercepted coal pillars and been unsuitable for remedial grouting if the original map orientation had been used to locate the holes.

The required adjustment of the surface mine map orientation was 5 degrees west of north - the magnetic declination of the Belleville area in 1903 when the mine map was prepared. It was concluded that the mine survey was done with a magnetic compass. The project clearly demonstrated that proper map orientation paid off in the overall success of a project. Drilling costs were reduced and adequate support ensured.

EVALUATION OF MINE MAP INFORMATION

Surface subsidence associated with past or present mining activity can occur through many processes taking place in the mine. Some of these processes can be interpreted directly from the mine map, and others only inferred from results of other aspects of a site investigation. Map interpretation of failure causes is possible when roof collapse, pillar crushing, or failure associated with reserves left in place occurs. Sometimes, evaluation of the mine map indicates adequate coal was left to protect the surface, and the subsidence is associated with other factors. Such failure mechanisms, identified by OSMRE investigations, are piping of unconsolidated sediments into the mine through fractures in the overburden; mine closure resulting from squeeze of underclays, middle clays, and roof clays; and disaggregation of highly broken overburden due to flooding of the mine. Because these factors are not related directly to the mining configuration, it is more difficult to identify these failure mechanisms using a mine map. Information indicating the potential for the latter types of events is more likely found by investigative drilling than through mine map interpretation.

Subsidence Types and Their Relationship to Mine Plan

The surface expression of subsidence associated with rock failure in the mine is often characteristic of how the failure occurred. OSMRE has identified three major types of subsidence events. These subsidence types are defined on the basis of the surface expression of the subsided area.

Pit or "Pothole" Subsidence

This type of subsidence is usually associated with roof failure under shallow overburden or piping of unconsolidated sediments into the mine through subsidence-induced or naturally occurring fractures. The size and character of the hole in this case is related to the physical character of the unconsolidated sediments being piped into the mine. When the entire overburden is rock, a shallow depression will develop. The depression is usually circular in shape and conforms approximately to the size of the collapsed room in the mine. Pit subsidence is often marked by rows of depressed areas corresponding to the room and pillar distribution in the mine. Once the fall occurs and propagates to the surface, the ground is usually stable and no further subsidence takes place unless the broken overburden is disturbed by water.

Sag Subsidence

Sag subsidence is generally associated with crushing of pillars or squeezing of underclay, middleclay, or top clay. The focus of subsidence is directly over the crushed pillars or displaced clay. Depression outlines are circular to oval in shape and range from a couple of hundred to a thousand feet in width and length. The size of the depressed area is determined by a domino-type failure of additional pillars which can take place following the initial failure. Ground movements associated with sag subsidence can extend over a long period of time because of the gradual transfer of overburden loads to adjacent pillars. High volumes of methane gas are commonly associated with the subsided area when pillar crushing is associated with the subsidence event.

Cantilever Beam Subsidence

This type of subsidence occurs where a portion of the overburden is adequately supported along the edge of a panel and failure of pillars occur within the panel. The overburden contains a cohesive rock unit that does not easily fracture, but functions as a lever. The overburden above the support section (fulcrum) bends as the pillar area fails, lowering the cohesive rock unit until the rock fails and cracks occur at the surface directly above the edge of the fulcrum block. This type of subsidence can affect large areas. The surface expression of the subsidence forms long, continuous, straight-line fractures that parallel barrier pillars or unmined coal reserves. Overburden thickness is usually greater than 300 ft. Crushing of the coal occurs along the edge of the support block, and methane gas may be encountered during the drilling program. However,

drilling into the mine workings usually intercepts open voids close to the support block. Open voids usually exist because the roof is supported by the block of coal, since only the outer edge actually crushes.

This type of subsidence has also been found in the shadow area between two mines. It is especially pronounced in areas where an active pillar retreat mine is separated by a common barrier from an older retreat-mined operation.

Other

There are other frequent site-specific situations that cause surface damage. Such situations include flooding or dewatering of the mine, which causes adjustments of rock materials especially in retreat portions of the mine and/or failure of a bridged or hanging roof. These types of events can sometimes be recognized from information presented on the mine map. When flooding of the mine occurs, surface subsidence can recur due to breakdown of rock immersed in water and movements of the disaggregate rock away from the failure area. Dewatering causes a realignment of pillars and roof especially in retreat mined areas with corresponding overburden movements.

CASE STUDIES

The following case studies involve several of the above subsidence mechanisms and illustrate how mine maps were utilized to identify them.

Bridged Roof/Pillar Failure - Fairmont, WV

The Country Club Road project in Fairmont, WV is an example of subsidence associated with a mine plan that was designed to protect a surface structure. The site is located along a main access road (Country Club Road) to a rural farming area outside of Fairmont. The mining company left support under Country Club Road in the area where pillar retreat mining was occurring (fig. 2). The road meanders to conform with surface topography and the unmined pillar lines are consequently offset so as to parallel the center of Country Club Road.

The subsidence incident began when residents of the home marked "1" on the mine map (fig. 2) heard a loud "explosion" followed by shaking of their homes. Cracks developed in the interior walls of the structure and continued to enlarge over the next few months until completion of an OSMRE stabilization project. Cracks also began to develop in other houses along Country Club Road following the initial subsidence event. An OSMRE emergency drilling program found that the overburden thickness averaged 275 ft and the mine area was flooded. The pillars between houses "1" and "2", and the smaller pillars between houses "3" and "5" were crushed.

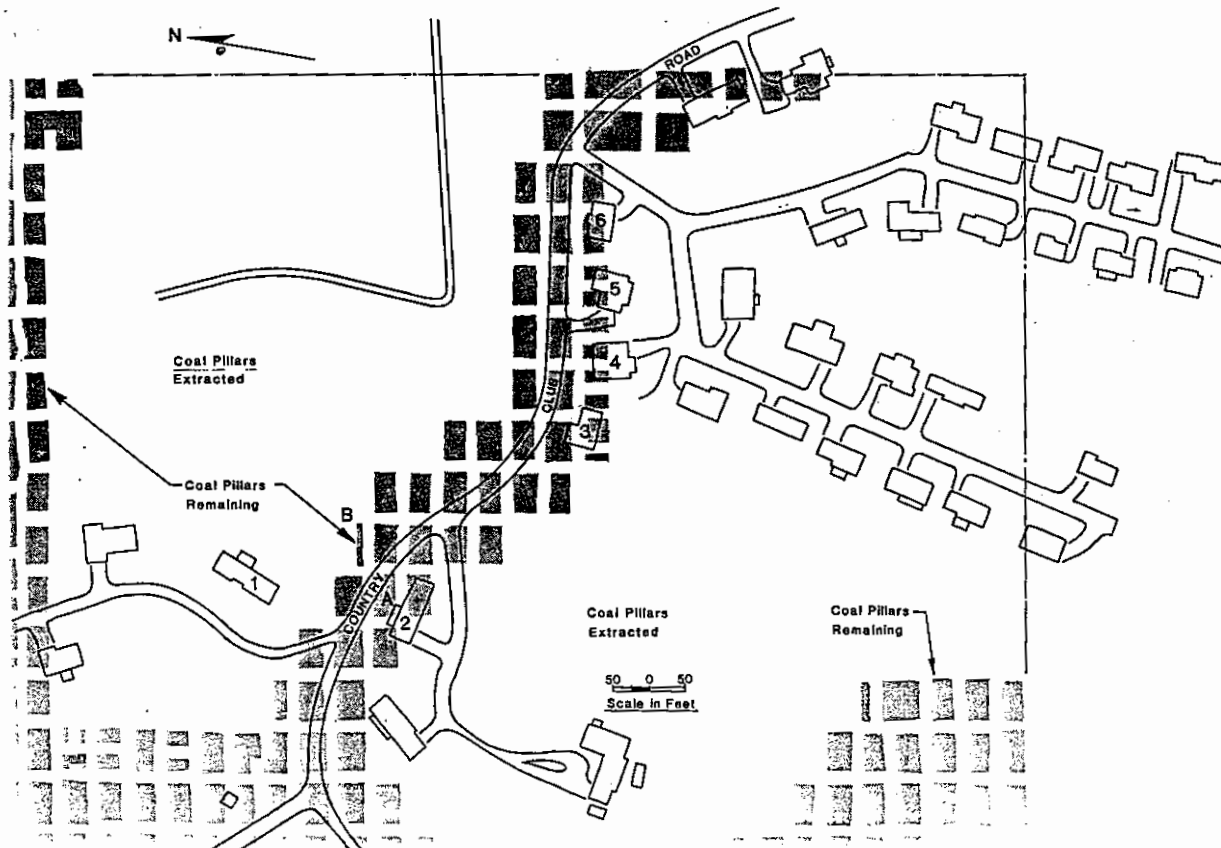


Figure 2.--Surface structures and mine map, Country Club Road Subsidence Project, Fairmont, WV.

Based on the drilling evidence and the configuration of the pillars shown on the mine map, it appears the initial failure is attributable to a "bridged roof" between the offset of the pillars at point "A" and crushing of the thin pillar at point "B" (fig. 2). When the bridged roof failed, it caused failure of the pillars between house "1" and "2" and triggered adjustments of the overburden all along the pillar line. These adjustments resulted in additional pillar crushing, further consolidation or settlement in the already collapsed retreat area adjacent to the pillars, and, thus, considerable damage to the surface structures.

Remedial measures on this project were two-fold. A rock anchor system was installed at House "1" to stabilize the steep hillside (Mates et al. 1986). Cement grout was injected to fill mine voids and stabilize the existing pillars within the subsidence zone.

Cantilever Beam Failure - Graysville and Willow Bend, AL

Subsidence events in the Graysville, AL area illustrate a series of complex subsidence events which through the evaluation of mine configuration were determined to be an example of cantilever beam controlled subsidence. In early 1980, a subsidence event affecting approximately 14 homes, a shopping center, and a service station was investigated by the State of Alabama and OSMRE.

In mid-1980, the U.S. Bureau of Mines, under a cooperative agreement with OSMRE, conducted an in-depth investigation of the site and concluded that the affected area actually encompassed a total of 42 homes, 2 shopping centers, 2 service stations, 2 churches, and a hospital (fig. 3). The areas damaged by surface subsidence were some distance from each other, yet all were related to similar mining and geologic conditions (Morrison et al. 1987).

The Pratt (Blossburg B Mine) and Mary Lee (Flat Top Mine) Seams were mined at depths of 200 and 700 ft, respectively. Of the five distinct subsidence areas identified in figure 3, Areas 1 and 5 were of an emergency nature, and remedial stabilization measures were implemented (Morrison et al. 1987).

The geotechnical investigation focused on Area 1 (fig. 4). The Pratt Seam mine map shows no mining in the most disturbed part of the area. Examination of mine maps in the Mary Lee Seam revealed that mine development in Area 1 (fig. 3) was controlled by faulting, and that reported subsidence events were clustered along the coal left in place along and between the fault zones.

Exploratory drilling confirmed that no mining had occurred in the Pratt Seam. The drilling also established that the overburden was fractured below the Pratt Seam; therefore, the subsidence was initiated by the mining in the Mary Lee Seam.

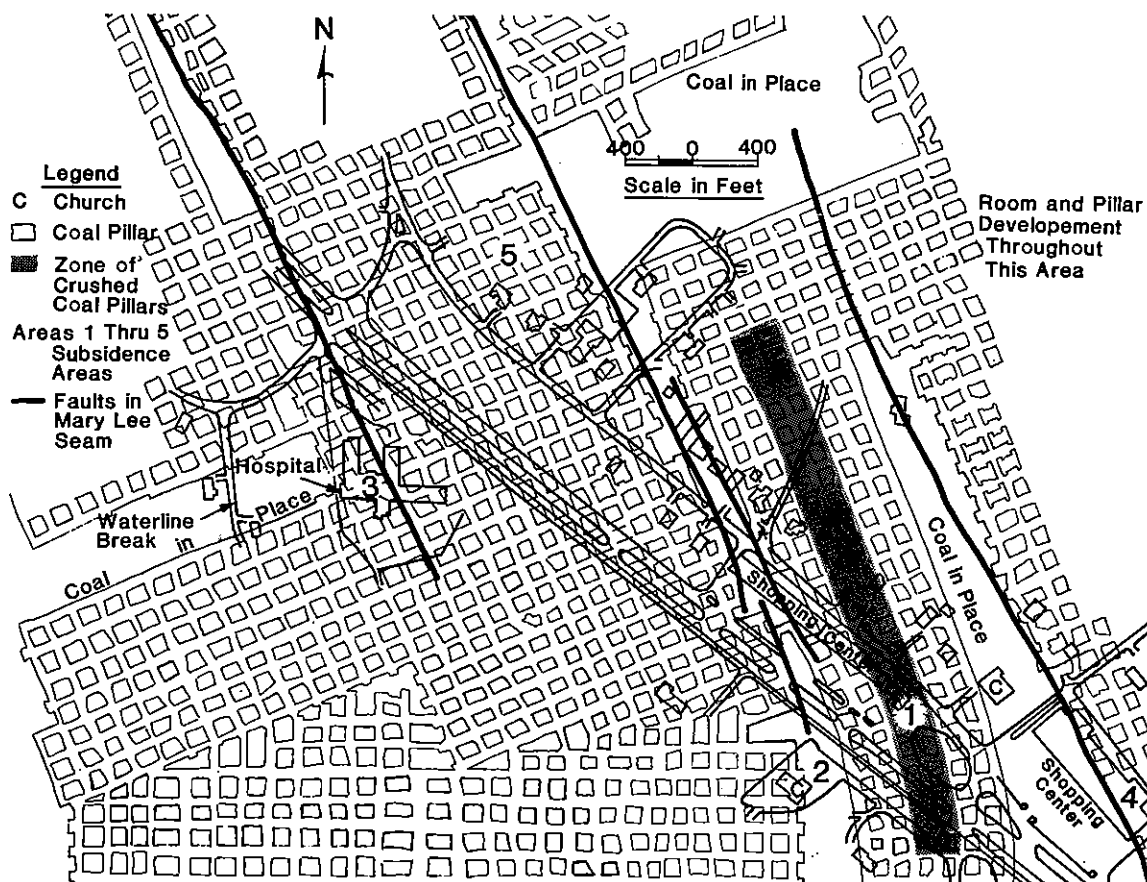


Figure 3.--Surface features and mine map of the Mary Lee Seam, Graysville Subsidence Project, Graysville, AL.

Pillar strength calculations (Morrison et al. 1987) indicated that the pillars within the fault block (table 2) have a safety factor of 1.2 and could carry the overburden load when the entire block of coal contained within the gravity fault block is involved in the support system. However, the calculation of the support within the panel yields a safety factor of 0.6 which indicates the pillars have marginal strength to carry the loads. Pillar strength estimates also indicated that panels on both sides of the faulted area have a safety factor of only 1.0. However, the area to the west of the fault block would be more prone to settlement/subsidence than the area to the east because of the narrower barrier rib and the interrupted panel design (fig. 3).

It was concluded that the barriers associated with the faults, and subjacent to the hospital, are acting much like a pair of fulcrum blocks, with a lever beam extending out over the large panels in both directions. The subsidence associated with Area 1 is the result of the development of a strain arch between the two fault barriers, as the overburden settled over the large panels. Subsidence occurred when horizontal friction at the center of the strain arch between the two fault barriers equaled zero, causing vertical loading and crushing of the center pillars.

Table 2.--Pillar crush analysis for Graysville Subsidence Project Mary Lee Seam (depth, 700 ft) (Morrison et al. 1987).

Pillar location	Extraction (%)	Crush depth (ft)	safety factor
Within the fault block	32	806	1.2
Panel beside fault area	50	710	1.0
Within the panel	62	454	0.6

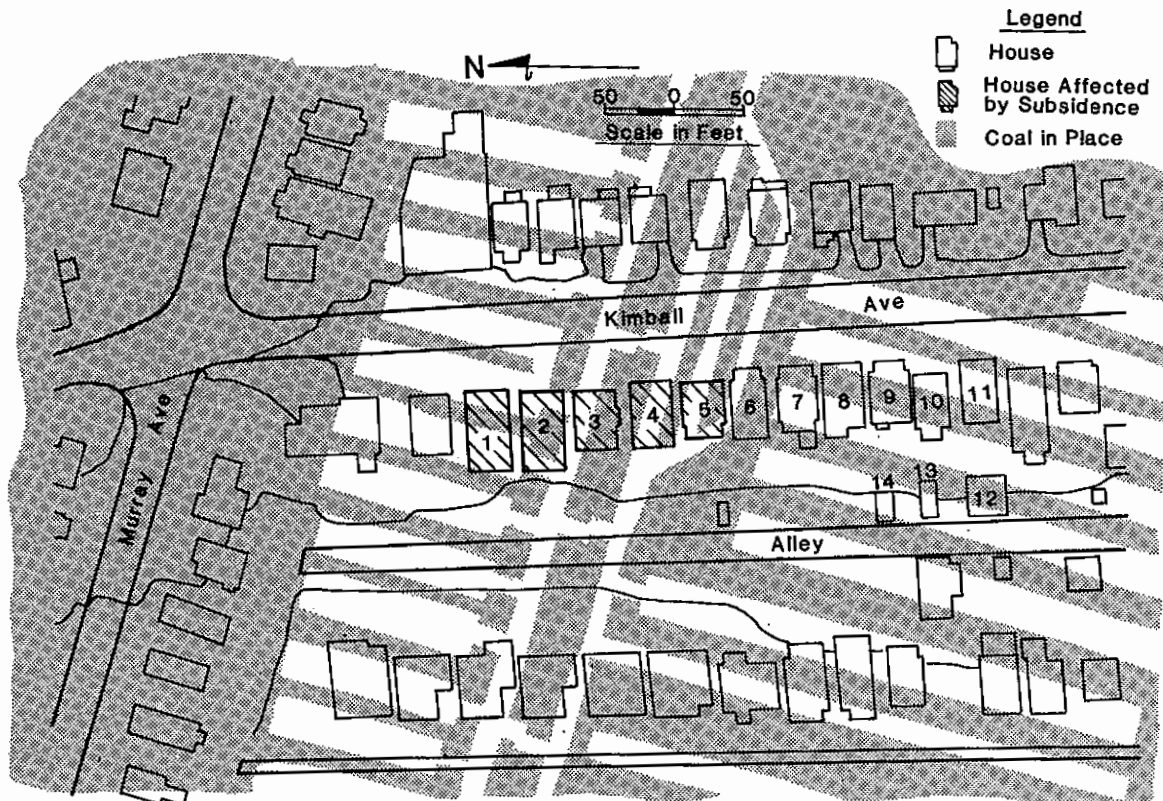


Figure 4.--Surface structures and mine map, Arnold-New Kensington Project, Arnold, PA.

Surface cracks which developed in Areas 2, 3, and 4 were the expression of the tension release over the fulcrums and exhibited very little vertical displacement. Subsidence at Area 5 was most probably the result of failure of the pillar support system due to the redistributed loads created by the settlement taking place over the region. The settlement taking place over the large panels could be due to compression of the "middleman" clay members within the Mary Lee Seam, crushing of the pillars, or a combination of both.

Large volumes of methane gas were encountered during the drilling program and are believed to be the result of pillar crushing within the panel. Gas analyses from boreholes outside the panel between the two faults showed only a trace of methane. The gas trapped within the area between the two faults had to be released during a degasification program because the gas was reaching the surface through the subsidence cracks and threatening public safety and property. Three bleeder holes installed by OSMRE were venting over 300,000 ft³ of methane/day when installed in 1983. The pressure equilibrium is presently being maintained with one bleeder hole.

Another example of a cantilever beam failure occurred at the Willow Bend project in Hueytown, AL, where evaluation of the mine map and use of a drilling program established that mine roof collapse and pillar crushing had taken place on the edge of the barrier pillars supporting main entries and unmined reserves. Surface stabilization consisted of building a series of concrete support

columns extending from the coal barriers. Field monitoring has shown that the movement stopped after the point support columns were installed.

Piping Through Fracture Systems - Arnold-New Kensington, PA, and Shinnston, WV

The Arnold-New Kensington Subsidence project in Arnold, PA is an example of surface subsidence associated with an underground mine that was not caused by mine roof or pillar failure. Initial evaluation of the mine map and the subsequent investigative drilling program determined that sufficient coal was left in the mine to support the surface, yet, the subsidence event destroyed one house and extensively damaged four others. This case study illustrates how OSMRE has utilized mine maps in conjunction with other maps and information obtained during the investigation to establish the true cause of the problem.

Figure 4 is a mine map which also includes surface topography and location of homes. The map shows large coal pillars along a haulageway directly beneath the properties. Drilling authenticated the presence of the pillars and identified 6-ft open voids. Earlier drilling by the Pennsylvania Department of Environmental Resources encountered approximately 3 ft of light brown silt partially filling the void under the alley behind the center house (fig. 4, House 3). This material strongly resembled the Quaternary age Carmichaels Formation, a 90-ft- thick terrace

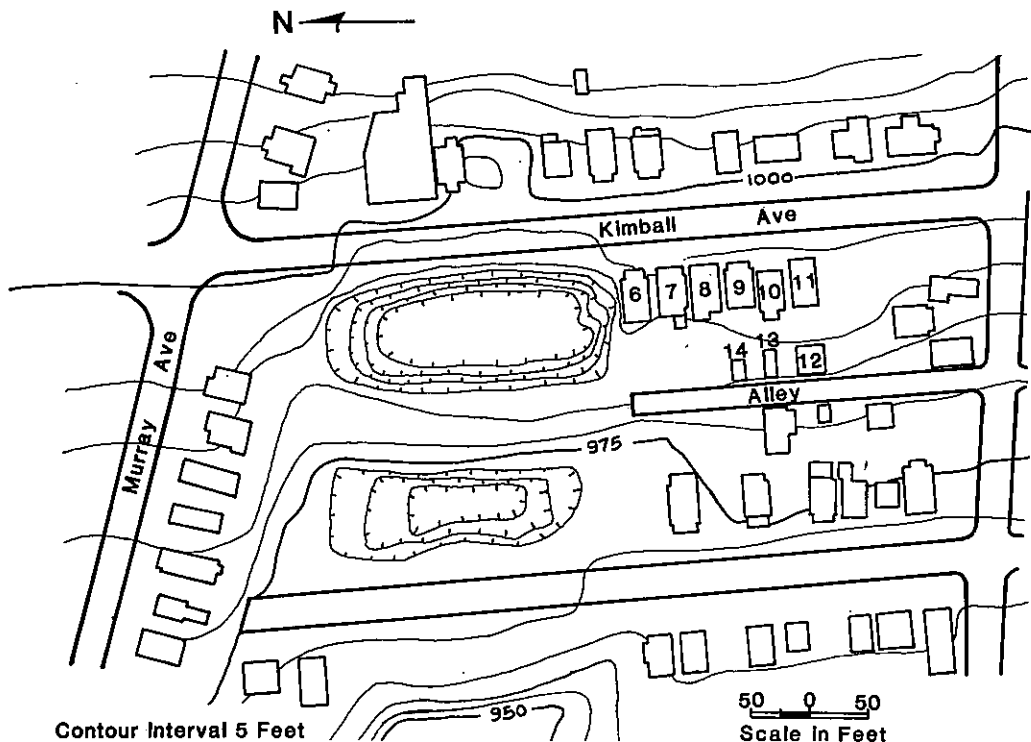


Figure 5.--Topography and urban development in 1952, Arnold-New Kensington Subsidence Project.

deposit in this area. Local citizens indicated that the subsidence area was an old sand pit that had been filled in with household trash and brush and covered over. A topographic map constructed from 1952 aerial photography showed the sand pits (fig. 5). Drilling also confirmed the character of the fill in these pits. There was some suggestion that the problem was related to this fill area. This fill, however, did not explain the magnitude of the subsidence occurring at the site. At this point in the investigation, there was no evidence of failure in the mine, yet a major depression was continuing to develop on the surface.

OSMRE subsequently implemented a drilling program in and around the problem area. The drilling in the immediate vicinity of the subsidence area identified a normal fault situated directly below the houses (fig. 6) with a vertical throw of 10 ft. The drilling program also established that the coal seam was 260 ft below the surface, and the base of the Carmichaels Formation was 90 ft below the surface. Silts of the Carmichaels Formation were recovered in one core hole at a depth of 245 ft. Borros anchors were installed both in front of and behind the houses at various depths to attempt to identify the zone of movement within the terrace deposits. Inclinator casing was also installed in front of and behind the houses to measure movement in the fill and the underlying Carmichaels Formation.

Information from Pennsylvania Department of Environmental Resources drilling was plotted on a map and the Carmichaels Formation/bedrock contact was contoured (fig. 7). Also plotted on this map is the trace of the near-vertical fault as defined by the OSMRE drilling program. This map

indicates a pre-Carmichaels stream valley located at the center point of the surface depression and a nick point (waterfall) on the fault line. The sum of information indicated the development of surface geomorphology was fault-controlled with a strong possibility of valley stress release jointing exposed at the pre-Carmichaels interface.

Information obtained from the Borros anchors and the inclinometer readings established that movement was taking place throughout the Carmichaels Formation, but not in the bedrock. Water level readings from the inclinometer casing indicated a depression in the water table directly over the projected location of the fault at the Carmichaels/bedrock interface (fig. 8). The drilling established the presence of Carmichaels-like sediments in the mine and in the overburden 15 ft above the mine roof.

From the available information, it was concluded that surface subsidence was caused by the piping of silt from the Carmichaels Formation downward through open valley stress release fractures associated with the normal fault. A grouting program was implemented to seal the Carmichaels/bedrock interface and surface movement subsequently stopped.

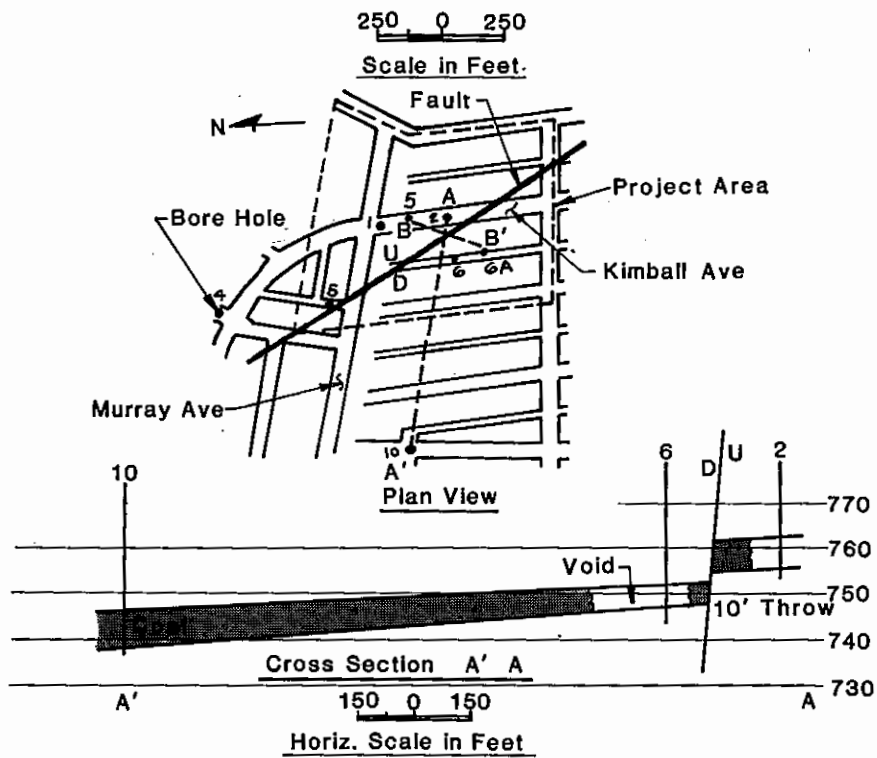


Figure 6.--Plan map and cross-section A-A, Arnold-New Kensington Subsidence Project.

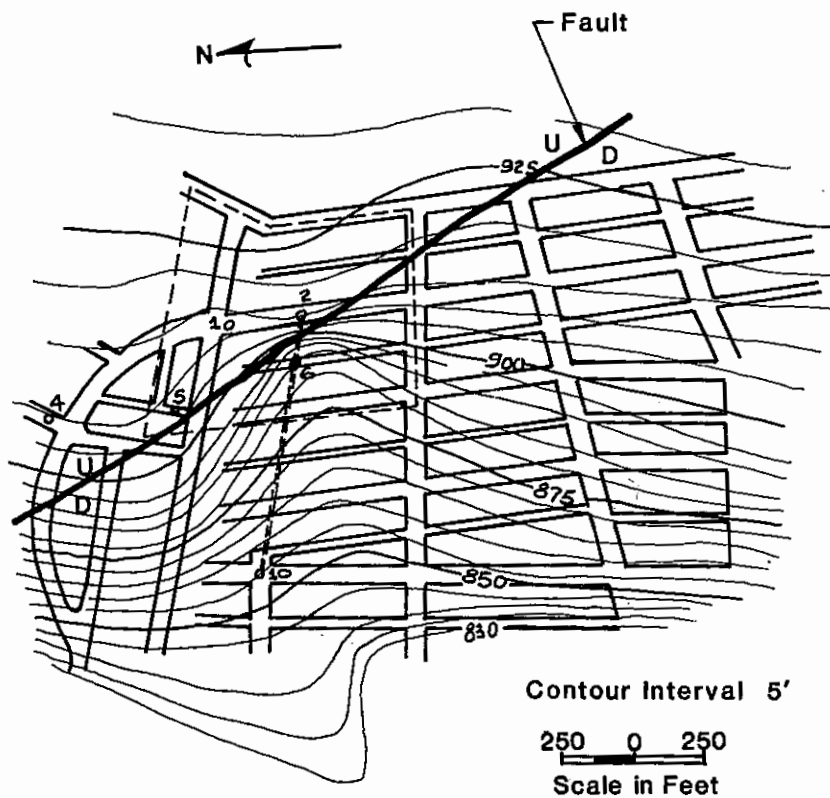


Figure 7.--Bedrock topography underlying the Carmichaels Formation as reconstructed from drilling records, Arnold-New Kensington Subsidence Project (note nick point developed at the fault line).

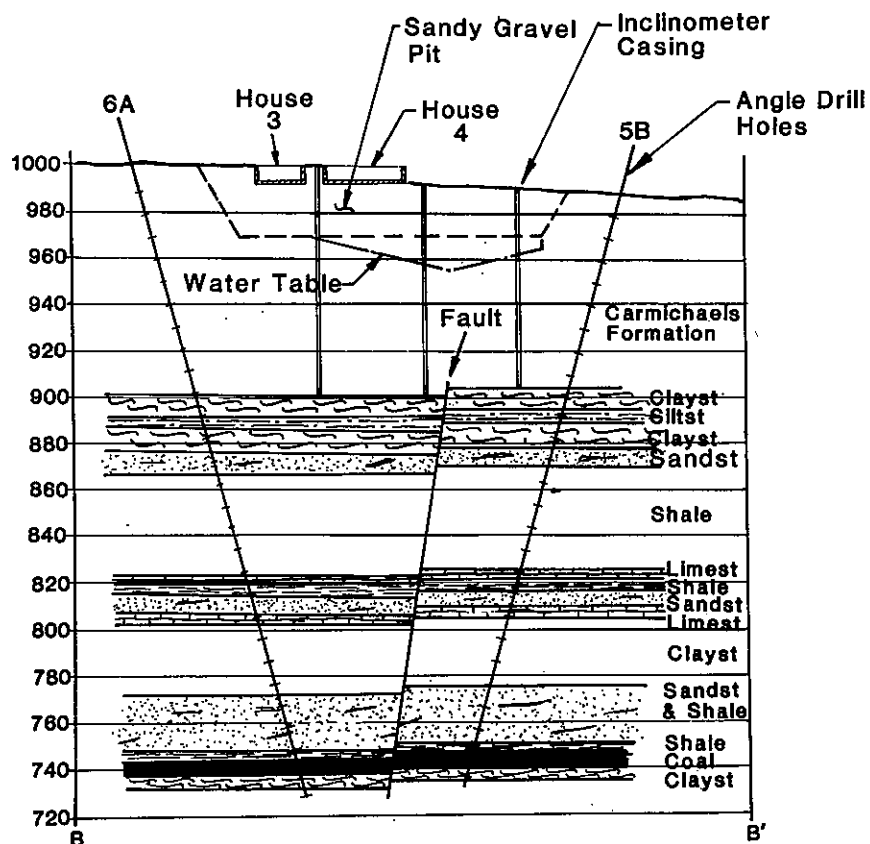


Figure 8.--Cross-section B-B, Arnold-New Kensington Subsidence Project. Cross section location shown on figure 6.

This phenomenon was also observed in an abandoned mine in Shinnston, WV where a thick fan of the Carmichaels Formation was flowing out of an open joint in the bedrock. In this case, the flow was taking place during mining as the fan was partially confined behind a crib wall built by the miners. Over the years piping had created depressions on the surface that homeowners had been filling as they developed.

CONCLUSIONS

Knowledge of the mine configuration is essential to a subsidence investigation and the interpretation of the subsidence mechanism(s). The investigator should obtain all available mine maps in the subsiding area and establish survey control points to accurately tie the mine map to the surface. Once established and confirmed by drilling, mine geometry and the exploratory drilling data can be evaluated to determine the failure mechanism which resulted in the surface disturbance. Only after the failure mechanism has been determined, can an effective stabilization program be implemented.

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