EVALUATION OF THE APPLICABILITY OF SUBSIDENCE MODELS TO HAZARDOUS WASTE SITES

by

PEI Associates, Inc.
11499 Chester Road
Cincinnati, Ohio 45246-0100

Contract No. 68-02-3963

Task Officer

Ronald D. Hill
Land Pollution Control Division
Hazardous Waste Engineering Research Laboratory
Cincinnati, Ohio 45268

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-02-3963 to PEI Associates, Inc. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments, and the needs of both large and small business in handling their wastes responsibly and economically.

This report reviews the available information on subsidence phenomenon and available predictive models. It will be useful for designers of hazardous waste facilities, Federal and State hazardous waste permit reviewers, and planners of hazardous waste remedial actions.

For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

William A. Cawley, Acting Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

EPA has discovered a number of uncontrolled hazardous waste sites in close proximity to abandoned underground mines. Further, several Resource Conservation and Recovery Act permit applications have been received for treatment, storage, or disposal facilities located in areas where abandoned underground mines are known to exist. The potential exists for subsidence under a hazardous waste facility to result in uncontrolled release of hazardous constituents to the environment.

The investigation was approached in two phases. Phase I involved a literature review and data compilation to gather information on the subsidence phenomenon, available predictive models, and on the adverse effects that can result from mine-related subsidence; and Phase II consisted of an evaluation of available equations and models used to predict subsidence and an assessment of the applicability of these models to predict subsidence problems at hazardous waste sites.

Predictive models of subsidence fall into two broad categories: empirical and analytical. In order to use the empirical approach, two major requirements must be met. First, the model must be used in an area for which a large data set has already been gathered. Second, the investigator must have an accurate account of the dimensions of the mine, including height of the overburden, width of the coal seam, location and condition of all remaining pillars, and percentage of coal removed. A large data set has not yet been collected for the American coal fields but, regardless, meeting the second requirement would be difficult. It is not possible to obtain necessary measurements to verify pillar dimensions and locations. Therefore, the empirical approach is not applicable.

The analytical approach is derived from deformation mechanisms and strength parameters of rock. The elastic theory and finite element models are applicable only to longwall mining.

Despite the difficulties inherent in modeling subsidence from room-and-pillar operations, every effort should be made to gather as much information as possible. Using all available data, subsidence prediction should be attempted using a model recommended for use in this report or elsewhere. It is important to evaluate the adequacy of the results with a clear understanding that failure of the model to accurately represent the system could, if a hazardous waste facility were disrupted, have a detrimental effect on the environment. Therefore, if it cannot be said with certainty that subsidence will not occur, then one should be hesitant to place a hazardous waste facility in the location under consideration.

CONTENTS

FIGURES

TABLES

SECTION 1

INTRODUCTION

EPA has discovered a number of uncontrolled hazardous waste sites in close proximity to abandoned underground mines. Further, several Resource Conservation and Recovery Act permit applications have been received for treatment, storage, or disposal facilities located in areas where abandoned underground mines are known to exist. The potential exists for subsidence under a hazardous waste facility to result in uncontrolled release of hazardous constituents to the environment.

Subsidence is defined as a lowering of ground surface which occurs as a result of the deformation caused by removal of subsurface mineral deposits. Coal extraction is responsible for more than 90 percent of all subsidence-related problems.[1] Subsidence has the potential to create hazardous conditions for structures situated both above and beneath the ground. Subsidence has already affected more than 2 million acres of land across the United States.[2]

The purposes of this study are to evaluate the currently available models that predict subsidence and to determine the applicability of these models to predicting potential subsidence problems at hazardous waste sites throughout the Appalachian coal fields. These models may serve as tools for the selection, cost analysis, and design of remedial actions at hazardous waste sites.

The investigation was approached in two phases. Phase I involved a literature review and data compilation to gather information on the subsidence phenomenon, available predictive models, and on the adverse effects that can result from mine-related subsidence; and Phase II consisted of an evaluation of available equations and models used to predict subsidence and an assessment of the applicability of these models to predict subsidence problems at hazardous waste sites.

The intent of this report is 1) to present an overview of available predictive models and 2) to provide the user community (e.g., EPA inspectors, permit application reviewers, permit writers, and EPA contractors) with a basic understanding of the subsidence phenomenon and its potential impact on hazardous waste facilities.

This report contains five main sections (Sections 2 through 6), a list of references, a list of contacts, and a glossary. Section 2 contains a description of the subsidence phenomenon, including the actual mechanism of subsidence and the geological aspects. Section 2 also contains a discussion of the potential impact of subsidence on hazardous waste facilities. Section 3 describes the factors affecting subsidence that arise as a result of human activity. Sections 2 and 3 have been included to provide basic definitions and background data that will enable the user to better understand how the models work and how they can be used to assess potential problems at hazardous waste sites.

Section 4 is divided into two parts. The first part provides background information on categories of predictive subsidence models, the state of the art, and some commonly-held assumptions. The second part describes the characteristics and limitations of the individual models that were investigated for this study. Section 5 gives general cost estimates for utilizing selected models. Section 6 contains conclusions and recommendations regarding the applicability of the investigated subsidence prediction models to hazardous waste sites.

The information in this report is based on a review of subsidence literature provided by representatives of the Bureau of Mines, West Virginia Geological Survey, United States Geological Survey, Office of Surface Mining, the National Research Council Committee on Ground Failure Hazard, West Virginia University, and West Virginia Institute of Technology, and on conversations with the persons who provided the literature.

For those who are interested in obtaining more details on subsidence and its potential impact on hazardous waste sites, this report includes a list of references and a list of contacts who are involved in ongoing research.

SECTION 2

DESCRIPTION OF SUBSIDENCE PHENOMENON AND ITS IMPACT ON HAZARDOUS WASTE FACILITIES

The excavation of a subsurface mineral deposit causes a progression of underground changes, the end result of which may be a lowering of the ground surface, or subsidence. This section describes the progression of events that results in subsidence and presents a discussion of the associated geological aspects of subsidence. This section also contains definitions for several common subsidence terms. They are useful for understanding the subsidence phenomenon and models.

2.1 MECHANISM OF SUBSIDENCE

The creation, by mining, of an underground void disturbs the equilibrium of the layers of rock, or strata, that comprise the overburden above the mine. This disturbance results in a redistribution of rock stresses. Stress is defined here as the resistance of the rock to compressional, tensional or tortional force, and is measured as force applied per unit area.

When stresses in a selected area build up to a point where they exceed the strength of the surrounding rock, the rock strata above the cavity fracture and fall into the mine void.[3,4,5] To release pressure, strata can move inward toward the excavation from all directions.[5] Therefore, the surface area affected is often larger than the area of extraction. The pattern of fracture and collapse may extend upward to the ground surface. Thus, subsidence results from a time-dependent redistribution of forces.[2] However, "the length of time over which significant movements occur depends upon the mechanism by which subsidence is [sic] taken place."[6] The redistribution of forces is affected primarily by physical and chemical properties of the rocks that comprise the overburden and by the presence or absence of water.[4] The geological and mining conditions related to various types of subsidence are illustrated in Figure 2-1.

Mine cave-ins cause the underground formation of a dome-shaped section of fractured rock. Above such a dome-shaped section, self-supporting strata sag like a long beam. These sagging strata may result in the formation of a subsidence trough at the surface. The trough's magnitude is a function of the thickness of the coal seam, depth of the seam from the surface, and the total extraction area.[4]

The trough, a shallow, broad depression, forms as a result of a sagging overburden whereas a sinkhole, identified by an abrupt boundary between its edge and the ground surface, forms more often as a result of a fractured, collapsed overburden.[7] Sinkholes are more often associated with shallow mines.

Strain is the deformation that results from applied force. Within elastic limits, strain is proportional to stress. It is measured as change in length per unit length in a given direction. Strains transmitted through strata have horizontal as well as vertical components.[1] Although vertical shift is the striking feature of a subsidence trough or sinkhole, horizontal strain also plays a prominent role in trough formation. It is considered the primary cause of structural damage to buildings affected by subsidence.[8] In evidence of the prominent role played by horizontal strain, horizontal stress may exceed vertical stress by a factor of 1.5 to 4.[7]

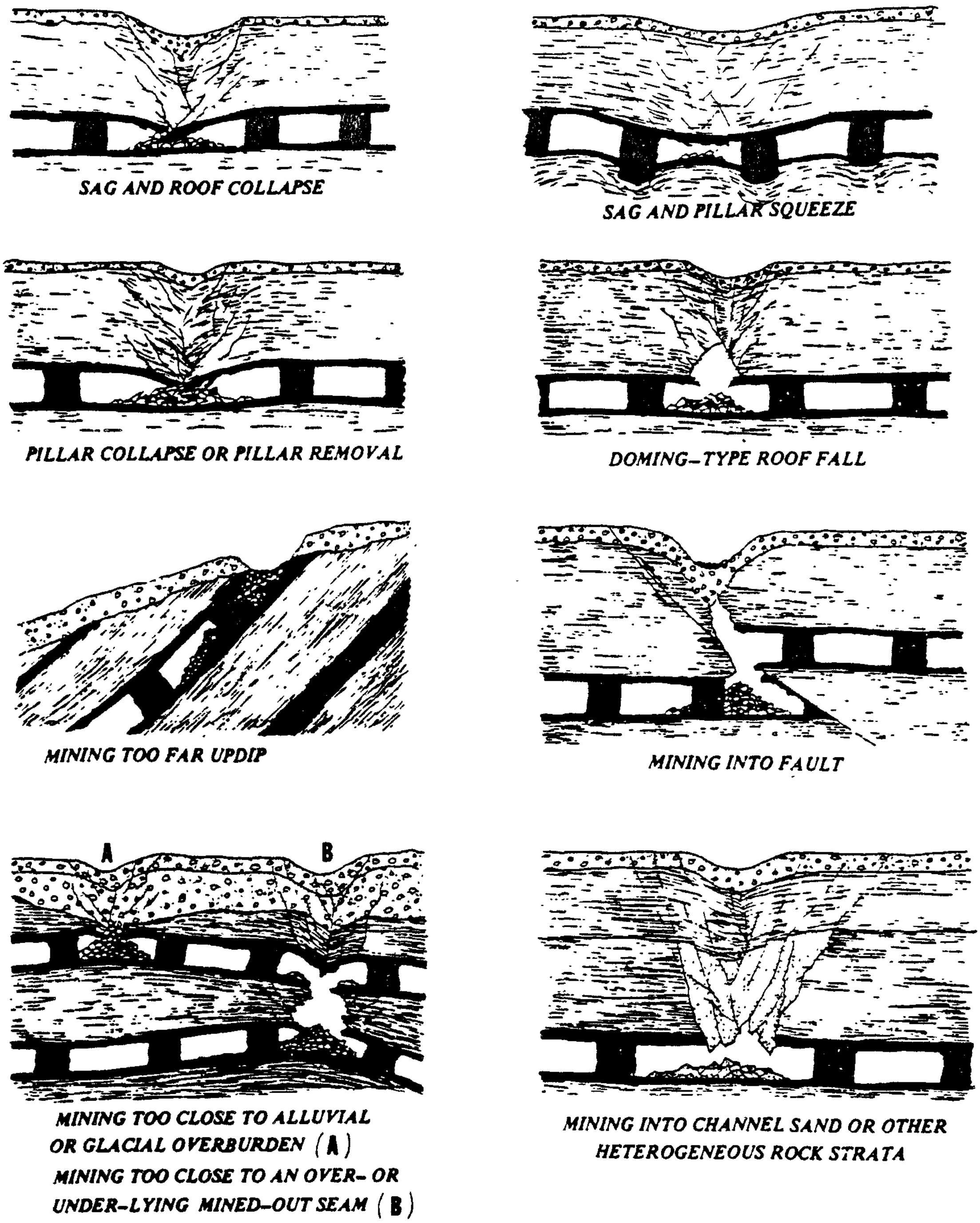

Figure 2-1. Geological/Mining conditions related to underground mine roof failures and resulting surface subsidence.[9]

The curvature of the ground surface due to differential downward vertical movements results in horizontal displacement toward the center of the subsidence trough. If vertical displacements were uniform, no horizontal strain would be produced; however, vertical displacements are non-uniform, and they result in horizontal displacement per unit length. These differential displacements cause the strain that actually produces structural damage.[10] Subsidence models are not yet able to accurately predict horizontal displacement.[5]

A subsidence trough consists of areas of compressive strain, which causes an elastic body to shorten in the direction of applied force, and tensile strain, which causes a body to lengthen in the direction of applied force. At the ground surface, tensile strain occurs outside the extraction area, while compressive strain occurs over the extraction area.[10]

2.2 GEOLOGICAL ASPECTS OF SUBSIDENCE

The geological factors that affect subsidence can be divided into two major areas, stratigraphic and water-related. A number of these factors are illustrated in Figure 2-2.

Stratigraphic factors include the material properties, types, and structural features of the rocks that comprise the strata above and beneath the mined space. More specifically, rocks are characterized by their elastic properties, strength, degree of fracturing, moisture content, homogeneity, degree of compaction, and permeability.[3]

The overburden, which consists of the rock material above the coal seam, is characterized by the unique site-specific interaction of the rock layers, including joints, faults, surface and sub-surface fracturing, tension cracks, bedding and foliation planes.

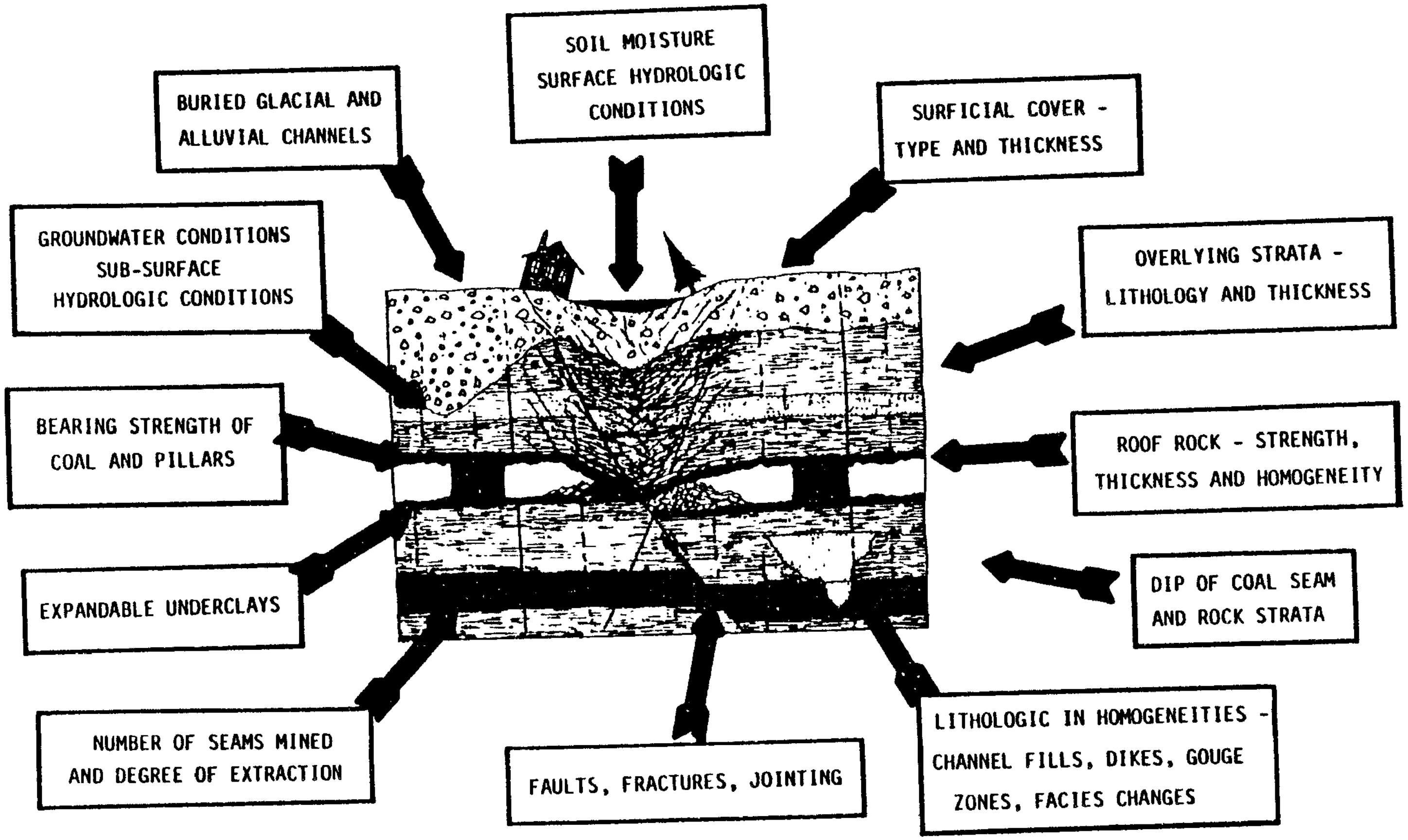

Figure 2-2. Summary diagram of geological factors related to underground mine collapse and resulting surface subsidence.[9]

Structural features affect the timing and the extent of subsidence. When strata above the mined space are strong and hard, such as massive sandstone or limestone, subsidence is minimized.[1,3,5] When strata are soft and weak, such as thin bedded shales, mudstone, siltstone, or unconsolidated deposits, incidences of subsidence increase.[1] Thick, or massive, sandstone above the roof of a mine acts as a rigid beam.[3,11] Because strong rocks, such as limestone and massive sandstone, tend to break at a steeper angle, the area affected by subsidence in an overburden consisting of harder rock is normally smaller than it would have been had the overburden consisted of softer rocks, but it is still larger than the caved area in the mine.[3,5]

Subsidence associated with strong rocks is usually characterized as violent, sudden, and delayed. Subsidence associated with weak rocks is usually characterized by a gradual lowering of the surface.[1]

The amount of clay in the overburden is also an important factor. Clay has the ability to reseal after fracture, thereby keeping man-made structures, such as buildings, perched above it.[12] The presence of clay on a mine floor, however, has its own unique set of problems. These will be examined shortly.

The length of time required for rock deformation to spread from the mine to the ground surface is proportional to the depth of the mine. This is because rocks deform as jointed, layered media, and not as uniform, intact bodies. Therefore, subsidence does not occur all at once. Rather, deformation progresses upward in stages until it reaches the ground surface, at which point it is termed subsidence. Also, the duration of surface movement is proportional to the depth of the mine. The deeper a mine is, the greater volume of overburden rock will be deformed. Deformation in the various involved sections of overburden rock will progress at different rates and will therefore reach the surface over an extended period rather than all at once.

Most experts agree that preexisting surface topography has no effect on the maximum amount of subsidence, but a small number believe that it does play a minor role.[3,7] This latter group is of the opinion that irregular preexisting topography is indicative of irregular stress distributions within the overburden. They claim that more unstable stress configurations in the overburden enhance the likelihood of subsidence.[1]

Water-related geological factors can affect subsidence in a variety of ways. Water enhances chemical and physical deterioration of mine pillars. Laboratory tests have shown that the amount of water present in an enclosed vessel is inversely proportional to the amount of time required to crush the rock in that vessel under constant stress.[13]

Water also causes the claystone floor of coal mines to soften over time. Once the floor rock becomes significantly softer than the coal pillars, the pillars actually sink, or "punch," into the floor. This causes an overall lowering of the mine roof and the resultant deformation is transmitted through the rock strata to the ground surface.[7,11]

Water may enter a mine directly, as a result of the proximity of the coal seam to transmissive rock strata, or indirectly, as a secondary effect of altered surface drainage patterns. For instance, in a small town in Pennsylvania, a new ordinance calling for installation of gutters and leaders resulted in flooding of the mines beneath the town. Where rainfall had previously filtered through lawns and topsoil to groundwater, it was now collected and drained directly into the underground sewerage system. The local sewerage system was not large enough to carry the increased drainage, and so it overflowed into the mines.[11] Whereas the direct entrance of water into a mine is likely to occur soon after extraction of the coal seam, indirect entrance might not become operative for years after abandonment of a mine.[11] This factor contributes to the difficulty of predicting subsidence for certain types of mining methods, such as 'room-and-pillar' mining. ('Room-and-pillar' mining is described in Section 3.1.2.)

2.3 DEFINITIONS OF COMMON TERMS

This subsection contains definitions for four common subsidence terms. They are useful for understanding the subsidence phenomenon and models.

2.3.1 Angle of Draw

The total ground surface area affected by subsidence is determined in part by the angle of draw, defined as the angle of inclination from the vertical of a line connecting the edge of a workings and the edge of a subsidence area (see Figure 2-3).[10] The average angle of draw is approximately 25°,[3] with a range of 10° to 35°.[1]

2.3.2 Maximum Subsidence, S_{max}

The maximum amount of subsidence possible is directly proportional to the thickness of the mined coal seam. Maximum subsidence, or S_{max}, is equal to 0.9 multiplied by the seam thickness. S_{max} will not be reached until the width of the area of complete extraction (longwall or room length) exceeds a value equal to 1.4 times the depth to the mine. Thinner seams and shorter void spans result in a decrease in the depth of the subsidence basin.[1]

2.3.3 Critical Width

The concept of critical width is fundamental to an understanding of subsidence. Critical width is defined as the smallest extracted width that will result in maximum subsidence at one point on the ground surface.

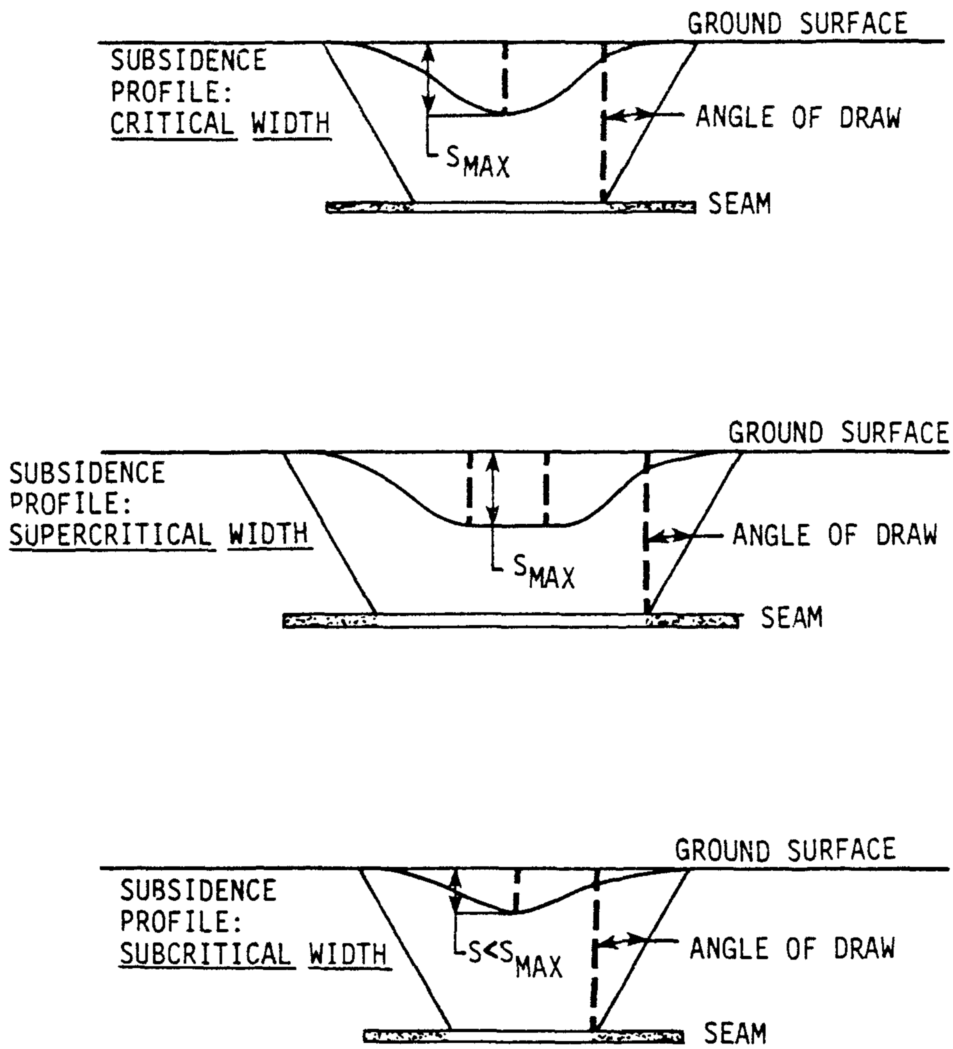

Figure 2-3. Angle of draw and critical width.

Subsidence occurs as a U-shaped trough. It will reach a maximum possible vertical displacement, S_{max}, when the critical width of extraction is reached. Where extraction occurs over an area smaller than the critical width, subcritical width extraction results in formation of a trough whose lowest point is less than S_{max}. Where extraction occurs over an area exceeding the critical width, supercritical width extraction results in formation of a flat-bottomed trough where every point in the bottom section is equal to S_{max}.[7] The stylized drawings in Figure 2-3 illustrate surface subsidence resulting from critical, subcritical, and supercritical width extractions.

2.3.4 Subsidence Factor

The subsidence factor is an area-specific measure for predicting S_{max}. Used primarily in empirical models, it is defined as the ratio of the depth of the subsidence trough to the height of the coal seam. In Appalachia this value ranges from 0.22 to 0.72,[4] with an average value of approximately 0.6.[3] A subsidence factor remains fairly constant within regions, thereby providing a rough estimate of the depth of subsidence troughs, relative to the height of the coal seam, that can be expected in that region.

2.4 POTENTIAL IMPACT OF SUBSIDENCE PHENOMENON ON HAZARDOUS WASTE FACILITIES

Subsidence from abandoned mine workings could affect the structural integrity of hazardous waste facilities located at ground surface above the mine workings through a variety of mechanisms. Cracks that develop in a subsiding overburden may continue to propagate upward into the barriers of a surface impoundment or storage facility. Collapse of stratified layers beneath a hazardous waste site may cause part of a landfill, impoundment, or storage facility to drop into the void created by the collapsing rock. Because subsidence has the potential to cause a breach in the integrity of a liner, containment system, building, or holding tank, hazardous waste facilities should not be located in areas of potential subsidence. A breach in the integrity of a containment system could result in an uncontrolled release of hazardous materials to the environment.

The way in which room-and-pillar mining affects hazardous waste facilities differs from the effects of longwall mining on these facilities. Generally, room-and-pillar mine collapse occurs many years after cessation of mining operations. Moisture, number and size of pillars, depth of overburden, and many other factors (see Figure 2-2) interact to create a unique, site-specific situation. This uniqueness makes the prediction of the extent, location, and time of room-and-pillar subsidence difficult, if not impossible. There is no guarantee that the ground above a room-and-pillar mine will not subside. In fact, if the pillars are too small to support the roof of the mine, and moisture is present, and the overburden is heavy, factors are optimized for subsidence to occur and, given time, it probably will. Therefore, based on the above, it is recommended that hazardous waste facilities not be constructed over room-and-pillar mines, and neither should room-and-pillar mining be conducted under a hazardous waste facility.

The situation is somewhat different for longwall mining. Subsidence resulting from longwall mining occurs virtually concurrently with the mining operation. Ninety-five percent of the total expected subsidence occurs immediately, and the remaining 5 percent occurs in the following one to five years. Therefore, hazardous waste facilities may be constructed over areas that were mined by the longwall method five or more years previously. However, it is recommended that longwall mining not be conducted under existing hazardous waste facilities. This practice would likely result in subsidence, associated disruption of the containment system of the facility, and release of hazardous materials to the surrounds.

SECTION 3

FACTORS THAT AFFECT SUBSIDENCE

Certain factors that affect the occurrence of subsidence arise as a result of human activity. They include mining method, mine dimensions, multiple seam mining, major surface changes, roof bolting and cribbing, rate of mining, and time of mining.

3.1 MINING METHOD

As this report is concerned with subsidence that occurs as a result of coal mining, the following explanations will be restricted to coal mining only.

Coal is mined underground by two different methods, the room-and-pillar method and the longwall method. The more traditional room-and-pillar mining is more common, less efficient, and less expensive than longwall mining, which requires a substantial investment in costly machinery.

While subsidence due to longwall mining occurs almost concurrently with the mining process, and usually produces a smooth, predictable surface settlement, subsidence due to room-and-pillar mining may be delayed as much as 50 to 100 years, and has been characterized as erratic, intermittent, and delayed.[1] The different timing and character of subsidence from longwall and room-and-pillar mining have different ramifications for hazardous waste facilities built on the surface above longwall and room-and-pillar mines.

This report addresses the mechanisms and predictive models for both room-and-pillar and longwall mining. Because the highly consistent nature of subsidence from longwall mining makes it easier to model and predict than subsidence from room-and-pillar mining, more work has been conducted on developing models for longwall solutions.

3.1.1 Longwall Mining

Deformation of strata due to longwall mining is transmitted through to the surface almost immediately, and results in a smooth subsided area at the ground surface.[11,14] When mining ceases, subsidence ceases; when mining resumes, subsidence resumes.[11] By the time mining is completed, 95 percent of the total eventual subsidence has occurred. Subsidence will be complete within 1 to 5 years maximum,[11,13] the former number being more widely accepted.

Subsidence due to longwall mining proceeds as follows. After the coal is extracted, the roof collapses immediately. When the ratio of the coal seam height to overburden height exceeds some critical value, generally between about 0.1 to 0.5, displacements will then be transferred to the surface. The critical value of that ratio is affected by the strength and structure of the overburden rock. Subsidence will not begin until a critical minimum mine void size is exceeded, resulting in the collapse of a compression arch in the solid rock above the mined area. Subcritical extraction widths produce a relatively small and shallow trough, and supercritical extraction widths produce a deeper trough with a fairly flat bottom.[1]

For longwall subsidence in Appalachia, the angle of draw typically ranges from 12° to 34°.[15]

3.1.2 Room-and-Pillar Mining

In room-and-pillar mining, a series of parallel entries are driven into a coal seam. Interconnecting breakthroughs are driven, at right angles, through pillars into adjoining entries, thus creating "rooms and pillars." The number and size of pillars is determined based on the amount of support deemed necessary to maintain the integrity of the roof during the entire mining operation.[1]

Anywhere from 40 percent to almost 100 percent of the coal may be extracted by this method. The higher number reflects the results of "retreat" mining, where pillars are "robbed" in the final stage before abandonment of the section of the coal seam being mined.[1]

A major difficulty in predicting subsidence from room-and-pillar mining is the inability to know whether reports of the amounts of coal removed are accurate. In some cases, the available maps of mine workings do not accurately portray the size and number of remaining support pillars. This problem is especially pertinent to older, abandoned mines, particularly those from the 1940's and 1950's and earlier.[11] In those years, before the enactment of miner safety laws and surface protection rights, miners took more coal than is taken now. It was not uncommon for coal mine operators to "rob" pillars in their final retreat from the mine. When more coal is taken than is required to support the roof, the remaining pillars are too small to support the weight of the overburden. Over time, the pillars deteriorate, lose strength, and are finally crushed.[1,3,7,11,16] Although additional data could be gathered by a drilling survey, they would not provide sufficient information to determine the stability of the area with regard to subsidence. Underground character could vary greatly over short distances, and ascertainment of the presence and quantity of mined space would not provide information on the strength of the pillars and mine roof or on the imminence of subsidence.

Unlike the immediate subsidence which occurs due to longwall mining, subsidence resulting from room-and-pillar mining is strongly time-dependent. The creep effect of coal in the pillars, the constant load over time, the oxidation and strain all contribute to the eventual buckling of pillars.[11] Water hastens failure of the supports by progressively softening claystone mine floors until pillars gradually sink into the weak underclay.[7,11] This particular kind of pillar failure often results in the development of wide areas of subsidence, as opposed to the limited areas characteristic of the kind of pillar failure caused by deterioration of the pillars themselves.[16]

Due to the aforementioned factors, subsidence from room-and-pillar operations is characterized as erratic, intermittent, delayed, and difficult to predict.[1] In addition, if the percent recovery of a room and pillar operation is unknown, it becomes extremely difficult to predict the occurrence or extent of subsidence.[3] The potential always exists for a room-and-pillar mine roof to collapse and cause subsidence. Irregular room development, non-uniform barrier pillars and poor panel definition further contribute to the difficulty of predicting room-and-pillar subsidence.[1] "Under such circumstances, frequently associated with old mining areas, it is usually impossible to predict the time, magnitude or occurrence of subsidence."[1] Opinions differ as to the length of time required for complete subsidence. One study maintains that 100 years are required.[17] After a mine floods, failure is likely to occur within 10 years. With respect to the Pittsburgh coal seam, if it has not occurred within 30 to 40 years, it is unlikely to begin. Once it does begin, however, it is likely to continue for several years.[16]

Certain patterns specific to subsidence from room-and-pillar mining have emerged near Pittsburgh, Pennsylvania. Where shale overlies the coal seam, the roof usually falls along northeast mine passageways, and parallel to the joint direction in the coal. Where thick sandstone overlies the coal, severe and frequent falls occur in the rock overlying the coal, with no consistent orientation relative to joints or passageways.[1]

3.2 MINE DIMENSIONS

Dimensional factors include depth from the ground surface to the coal seam (equal to overburden height), the thickness of the coal seam, the length and width of the coal panel extracted, and the amount of support provided by the gob,[3,11,13,18] where gob is defined as the coal refuse left in the mine.

Although some experts believe that subsidence will not occur where mines are located more than 500 feet below the surfce, others point, in disagreement, to those instances where the ground has subsided above mines located some 1000 feet below the surface.

What is more clear is that a direct relationship exists between the occurrence of subsidence and the ratio of mined coal seam thickness to the overburden thickness. The thicker the coal seam relative to the height of the overburden, the more likely it is that subsidence will occur.

The entire quantity of coal removed is equal to the thickness of the seam times the area (length times width) of the extracted coal panel. The greater the total amount of coal removed per unit area, the more likely it is that subsidence will occur.

3.3 MULTIPLE SEAM MINING

Where multiple seams are being mined in an area, stress concentrations within the rock comprising the overburden increase beyond those expected as a result of mining a single seam. This increase in stresses, in turn, causes an increased likelihood of subsidence.[1,18] The greatest difficulty in predicting subsidence is in assessing potential subsidence problems associated with horizontally or vertically adjacent mined out areas.

3.4 MAJOR SURFACE CHANGES

Large man-made structures on the ground surface above a mine increase the surface loading. The increased load is transmitted to the overburden strata. Where stress concentrations increase within the overburden, the likelihood of subsidence increases. In other words, the loading acts as additional overburden.

3.5 ROOF BOLTING AND CRIBBING

The practice of bolting and cribbing lends additional support to the mine roof and, therefore, delays or prevents the collapse of the roof into the mine. Where practiced, roof bolting and cribbing decrease the likelihood of subsidence, until the bolts and cribbing deteriorate. Steel bolts corrode under highly-corrosive mine conditions, and the wooden cribbing rots.

3.6 RATE FACTORS

In longwall mining, the time for subsidence to occur is a function of the time required to work the coal face through the critical width (defined in Section II, "Description of Subsidence Phenomenon"), which, in turn, is controlled by factors such as mine depth, angle of draw, and rate of advance. A smooth, consistent advance rate is associated with a consistent, predictable surface settlement. No such clear time relationship exists for room-and-pillar mining.

3.7 TIME

Where a coal seam has been mined by the room-and-pillar method for a period of 50 years or more, a sharp increase is noted in the likelihood of the occurrence of subsidence.[18] Fifty years ago, before the enactment of miner safety laws and surface protection rights, miners removed more coal than they remove now. In mines where coal was removed under those conditions, the remaining pillars are too small to support the weight of the overburden on a long-term basis. Losses in strength that occur as a result of deterioration cause the pillars finally to collapse.

Subsidence in abandoned room-and-pillar mines has occurred as soon as 10 years and as long as 100 years after retreat from the mine.[7] More than half of the cases of subsidence have occurred more than 50 years after the mine was closed.[7] Since it is virtually impossible to know in which mines subsidence will occur, with respect to the situation of hazardous waste facilities above them, it must be assumed that subsidence will eventually occur at all mining sites.

Subsidence from longwall mining occurs virtually concurrently with the coal extraction process. There is a slight additional (5 percent) settlement of the gob with time; however, 95 percent of the subsidence occurs during the extraction process.

3.8 SUMMARY

Table 3-1 summarizes the effect of major factors on increasing or decreasing the likelihood of subsidence.

TABLE 3-1. MAJOR FACTORS ASSOCIATED WITH SUBSIDENCE

Factor	Effect
Overburden height	The greater the overburden height (the deeper the mine), generally, the less likely subsidence becomes.
Overburden material	Subsidence is minimized in overburdens comprised of hard rock such as massive sandstone and limestone. It is more likely in areas of softer rock, such as mudstone, siltstone, and bedded shales.
Faults	Inherent weaknesses in the overburden increase the likelihood of subsidence.
Coal seam thickness	The thicker the coal seam, relative to the overburden, the more likely subsidence is to occur.
Mine age	Older room-and-pillar mines (over 50 years old) are more likely than recent operations to have been robbed of coal meant to support the roof. They are more prone to subsidence than mines with adequate numbers and sizes of pillars. Some younger mines too, however, have also been robbed of sufficient coal to support the roof.
Mining method	1) Longwall method - Smooth, predictable surface settlement; occurs almost concurrently with mining. 2) Room-and-pillar method - Erratic and intermittent surface settlement; may be delayed as much as 50 to 100 years after mining.
Amount of support remaining	1) The larger the amount and/or numbers of gob or pillars remaining, the lower the likelihood of subsidence. 2) Roof bolting and cribbing provide additional support and delay or prevent roof collapse. Therefore, they decrease the likelihood of subsidence.
Multiple seam mining	Causes increased stress concentrations in overburden and, therefore, increases the likelihood of subsidence.
Major surface changes	Placing man-made structures on the ground surface increases surface loading, increases stress concentrations, and therefore increases the likelihood of subsidence.
Moisture	Increasing amounts of moisture in the mine contribute to heightened rates of deterioration and increase the likelihood of subsidence.

SECTION 4

SUBSIDENCE MODELS

4.1 BACKGROUND INFORMATION

Predictive models of subsidence fall into two major categories, empirical and analytical. Empirical models are based primarily on observations of ground movement, and do not take into account principles of deformable body mechanics or the mechanics of continuum.[19] The empirical approach is a descriptive technique. While it is simple and practical, it is area-specific, requires a large data set, and is best applied to areas in which 100 percent of the coal has been removed.[1]

The analytical approach employs deformation mechanisms based on the theory of elasticity, and the strength parameters of rock. The value of the tensile strength parameter assigned to rock varies widely among the analytical models. While analytical models are more widely applicable than empirical models, they are mathematically complex and their idealization of the subsidence phenomenon precludes an exact description. Table 4-1 provides an overview of the investigated models. It categorizes each model by theory, method of analysis, and means of analysis. It is divided into two sections, empirical and analytical.

One major shortcoming of many of the subsidence models that have been developed, both empirical and analytical, is that most models have been tested at only one site.[11] Few have been tested at more than one site. Because of the unique geological environment of each coal mine, models that are developed

TABLE 4-1. INVESTIGATED MODELS

Theory	Method of analysis	Means of analysis	Reference
EMPIRICAL	Graphical	Statistical	1,5,10,20,21,22
	Exponential function	Statistical	8
	Profile function	Statistical	3,5,6,8,19,21,23,24
	Stochastic (random) media	Statistical motion of voids	1,5
	Integration-grid method	Relative influence of sectors comprising critical area	25
ANALYTICAL	Elastic		
	Physical model	Gelatin or urethane rubber	10
	Mathematical	Layered linear elastic continuum	10,20
	Finite element solution	Assumes heterogenity and anisotropy	3,5,6,8,10
	Isotropic	Assumes isotropy and linear elasticity	5,10
	Elastoplastic	Finite elements with constrained plastic flow	5,10,21
	Zone area	Based on theory of influence functions	10,15,25,26,27
	Distinct element	Finite differences at interfaces between rigid blocks	21
	Viscoelastic	Frictionless laminated and multimembrane model, incorporates time	5,13

for use in one specific region are usually not applicable for use in other regions. The National Coal Board (NCB) model, developed for use in Great Britain, is one model that has been tested at more than one site. Predictions by the British NCB model do not coincide with field observations in the Appalachian region. In the Appalachian coal field, 30 to 50 percent more subsidence occurs than is predicted by the NCB model.[11]

Many analytical models require input parameters that are either unavailable, irrelevant, or too cost-prohibitive to gather.[28] Analytical methods are further criticized for the 'arbitrary' way in which the values of certain parameters (e.g., Young's modulus, rock strength) are adjusted to improve correlation of the model with field observations at a particular site.[5,7] "... The predominant obstacle of transforming ... models into predictive methods is the indefinite and subjective process by which the magnitude of the input parameters are [sic] chosen".[21]

In Europe, comparatively uniform conditions and a long history of field measurement have facilitated development of accurate and reliable empirical subsidence prediction models.[1] In the United States, on the other hand, diverse conditions and a comparative dearth of field data have resulted in a subsidence prediction methodology that is less well developed. Attempts are still being made to accurately define such basic parameters as subsurface rock, soil and ground water conditions, and the distribution, duration and intensity of stress changes.[29] Currently available models can predict the degree of expected subsidence, but not the length of time required for it to develop.

No subsidence model yet exists that accounts for the rates of coal oxidation, degradation and creep. Rate is one key to determining the involvement of time in prediction.

A predictive model that accounts for time is in the early stages of development at West Virginia University. In this model, time is linked to the viscoelasticity of rock. Viscoelasticity is a property of rock in which application of a stress gives rise to a strain that approaches its equilibrium value (limit) slowly. As the viscoelasticity of a material approaches its limit, the material is considered failed. Because a certain, fixed period of time is associated with the failure of different types of rock, viscoelasticity of rock may be considered a function of time. Therefore, with prior knowledge about the viscoelastic properties of rock, a model can theoretically be used to calculate the length of time after which subsidence will occur. It is difficult, however, to obtain viscoelastic property values of rocks for use in the time-dependent model.[13]

4.2 DESCRIPTIONS OF INDIVIDUAL MODELS

4.2.1 Empirical Theories

Graphical Method--

The graphical, or National Coal Board (NCB), method best predicts subsidence due to longwall mining of thin seams at moderate depths and in areas where the overburden is composed of soft rock (i.e., marl, siltstone or shale) and contains little or no hard rock (i.e., sandstone or limestone).

The NCB method is based on observed phenomena. It was developed in England, and its existing data base is extensive. Predictions by the NCB method do not correlate well with observations in the Appalachian coal fields.

In order to use this method, values are required for these parameters: width, length, and thickness of the proposed panel, and height of the overburden.[1,5,10,20,21,22]

Exponential Function Method--

Three steps are involved in this method. First, the model determines S_{max} at the center of the proposed mine void space where excavated coal has exceeded the critical width. Next, it determines the extent of subsidence where excavated coal has not exceeded the critical width. Finally, it determines subsidence at various distances from the center of the proposed opening. The thickness of the excavated seam and the overburden must be known in advance.[8]

Profile Function Method--

The profile function is a technique for fitting a curve to measured data. Once the curve fittings are determined, subsidence can be determined along any cross section, in arbitrary positions and orientations, by a mathematical expression of the distribution of displacements over a two-dimensional area. The mathematical equation shows one-half the subsidence profile.

The profile function predicts vertical displacement and surface curvature caused by longwall mining. Its applicability is restricted to complete subsidence over rectangular areas of extraction. Because it cannot explain cause-effect relationships, it is of questionable value for new situations lacking a data base. It can be used only in a region that can provide constants for its development.

The profile function is more accurate and repeatable than the graphical (NCB) method. With slight modifications, it has shown good agreement with field data in the Appalachian coalfield.[3,5,6,8,19,21,23,24]

The hyperbolic function, a profile function developed by Brauner, accurately predicts the depth at the center of a subsidence trough (S_{max}), but not the overall shape of the subsidence trough.[24]

Many researchers have developed profile functions. Knothe's description is applicable for single seam, longwall mining of rectangular panels. It is limited to mines where the area exceeds critical width and is no longer influenced by time. Other profiles, developed for use throughout Europe by Martos, King and Whetton, Marr, and Wardell, differ considerably from Appalachian coalfield data.[5,19]

A computer program for the profile function, developed by Hall and Dowding, is based on an analytically obtained formula of approximation for the subsidence profile curve. It includes empirically obtained factors. The program requires input data for each extraction area and calculation point at ground surface, a characterization of the trough area, coordinates and depths of corner points, the thickness of the seam worked, and a stowage factor.[21] The stowage factor represents the percentage of mined void space that is refilled with other materials (e.g., crushed rock). Normally, only about 50 to 70 percent of the space can be filled in, representing stowage factors of 0.5 to 0.7. Because of operational difficulties, the stowage factor never exceeds 0.8. The practice of refilling is common in Europe only.

Stochastic (Random) Media Theory Method--

The stochastic media theory predicts a subsidence profile using the characteristic bell-shaped, normal distribution curve. It does not incorporate knowledge of material properties, but transfers field measurements from known to new areas by an empirical approach. The only physical principle it employs is conservation of mass.

Horizontal strain and displacement can be computed by the stochastic media theory.[1,5]

Integration-Grid Method--

The integration-grid method is applicable to nonrectangular, irregularly shaped extraction areas. It uses a grid derived directly from observed subsidence movements. The critical area is drawn on tracing paper and divided into sectors. Then the relative influence of each sector is determined.[25]

4.2.2 Analytical Theories

Elastic Theory Method--

An early physical model, developed by Berry and Sales, models a mine as a displacement that causes discontinuity in an otherwise continuous elastic rock mass. It uses two- and three-dimensional solutions to represent a longwall panel as a single, rectangular dislocation. The model is applicable only to longwall mining.[10]

Salamon developed a mathematical model based on analog and digital techniques. The model calculates stresses and displacements of complicated excavation geometries in the plane of a single seam. It too is applicable only to longwall mining.[10]

Finite Element Method--

In the multi-layered finite element model, bedding planes are the primary factor affecting subsidence. This model simulates material behaviors and boundary conditions. It incorporates the discontinuities inherent in heterogeneous materials and assumes anisotropy. It creates a stress distribution, and determines the extent of the caved zone based on the mechanical properties of the overburden.[5,6,8,10]

The finite element model is applicable only to longwall mining in deep mines, and the gob area must be settled. Another limitation is that certain parameters for rock strength must be obtained in the laboratory. Since only the more competent samples remain intact for testing, estimates of rock strength are usually overestimated.[5,6,10]

The NASTRAN computer program of the finite element model determines the combined stress on the overburden from mining and body weight. It uses the Mohr-Coulomb Failure Criteria and Young's Modulus to model the progressive collapse of strata, from the mine roof to the ground surface. Those elements that fail are reassigned revised Mohr-Coulomb Failure Criteria and Young's Modulus values, and the stress field is recalculated. The system reaches equilibrium, or complete subsidence, in five to six iterations. NASTRAN is a software package developed at NASA in 1977 by C. W. McCormick. It was originally designed to calculate stresses on homogeneous materials, particularly metals, but has more recently been adapted for use in modeling heterogeneous rock materials.[5]

Isotropic Model Method--

According to Gray et al. (1974), Crouch developed a homogeneous isotropic model for the two-dimensional case of a single seam parallel to the surface. The rock is assumed to be isotropic and linearly elastic. However, the subsidence profiles do not match field observations. Gray et al. (1974) provide no reasons for this.

A three-dimensional transversely isotropic model shows reasonable agreement with field data.[5] No further information was available on this model.

Elastoplastic Theory Method--

Fracturing of strata above a mine roof occurs for some distance. At greater distances, strata deform without fracturing. These strata are accounted for in the Dahl elastoplastic model, a three-dimensional model that represents the development of zones of failure as plastic phenomena.[5,10,21]

The elastoplastic model has been used for modeling longwall and room-and-pillar mine subsidence in the bituminous coal regions of Pennsylvania and West Virginia, and it shows agreement with field measurements. However, if chosen elastoplastic constants yield results that do not correlate with field measurements, constants are 'adjusted' until correlation is achieved. In other words, the model is made to fit the available field data.[5,10,21]

The mathematical model developed at Conoco explains subsidence as a result of rock mass deformation at the mine opening. The deformation is governed by elastic-frictional plastic stress-strain relations where the yield condition is dependent on confining pressure.[20]

Zone Area Method--

The zone area method is based on the theory of influence functions. The theory of influence functions states that the total subsidence is equal to the sum of the individual subsidences resulting from each of the infinitesimal extractions comprising the excavation. It is based on mathematical expressions for summations of the effects of minute extraction elements.[10,15,26,27]

The zone area model requires input of an area-specific zone factor and influence constant. The zone factor is a weighted constant that relates the amount of mined-out area underground to the amount of expected resultant surface subsidence. The influence constant is an exponential value that has been developed to correct for ribside subsidence, described below. The zone area model can be useful in the case of both homogeneous and heterogeneous overburdens. It can handle uniform and nonuniform extraction patterns, and individual sections of an extraction area can be evaluated separately.

This model has a limitation that is called ribside subsidence. Where a surface point is located at the edge of a critical excavation, one-half the zone has been excavated. Therefore, subsidence at this point should equal one-half the maximum value. However, field observations show that subsidence is equal to only about one-fifth the thickness of the seam. Ribside subsidence is corrected for by deducting a 'compensation zone' from the 'extraction zone.' The compensation zone is a zone of incomplete closure at the ribside of the excavation; for purposes of calculation it is treated as if unmined. This lowers ribside subsidence values to less than the original values of one-half the total subsidence, and more closely approximates measured field observations.[27] If a zone factor and an influence constant are available for the region, the zone area model may be useful for modeling subsidence at a hazardous waste site. However, availability of the zone factor and influence constant for a specific area is, in all probability, limited.

The computer program model of the zone area method, developed at Virginia Polytechnic Institute, establishes a series of six annular rings around a surface point, with each zone representing 0.2 of the working depth, given a critical width-to-depth ratio of 1.2.[27] Implementation of the model requires these input parameters:

- coordinates of the area of interest
- rectangular coordinates of panels and pillars
- zone intervals
- draw angle, zone factors, influence constant (representative of area being investigated)
- seam and surface dips and gradients
- extraction height
- graphics input (optional)

Distinct Element Method--

The distinct element model is based on the assumption that the joint system in the overburden is the single most important mechanism in failure of the overburden. Strata over the extracted area are presented as a series of rigid blocks. Deformation occurs at interfaces between the blocks.[21]

Viscoelastic Solution Method--

A viscoelastic model is being developed at West Virginia University. As explained in the first part of this section, viscoelasticity of rock is a function of time. As the viscoelasticity of a material reaches the limit, the material can be considered failed. Therefore, once the viscoelasticity of a material is determined, a relation can be found to time.

The viscoelastic model takes into account local geology and mine geometry, and is applicable to multiple-seam mining. These factors increase its applicability to different areas. Close agreement has been shown between theoretical predictions and observations in the British coalfields. One known disadvantage is that it is of limited use with increasing mine depth.[5,13]

4.3 SUMMARY

Presently, subsidence models exist that can be used to predict the degree of subsidence under various circumstances. Computer programs are available for several of the models.

None of the models that are presently available is able to predict when subsidence will occur. However, one such model is in the developmental stages at West Virginia University.

Table 4-2 provides a summary of the models, their characteristics, and limitations. It is divided into an empirical and an analytical section.

Section 6 provides a discussion of the applicability of these models to subsidence prediction at hazardous waste sites.

TABLE 4-2. MATRIX OF SUBSIDENCE MODELS

Name of Model[a]	Characteristics	Limitations
Empirical theories		
Graphical Method (NCB) (1, 5, 10, 20, 21, 22)	Based on observed phenomena. Extensive existing data base. Developed in Great Britain. Requires values for depth, width, length of proposed panel and height of extracted seam.	Most useful for longwall mining of thin seams at moderate depths of soft rock overburden. Predictions do not correlate with field observations in Appalachian coal field. No emphasis on cause-effect relationships. Does not address time factor.
Exponential Function Method (8)	Three-step determination of subsidence. Requires values for panel width and depth.	Specific to geological context. Does not address time factor.
Profile Function Method (3, 5, 6, 8, 21, 23, 24, 25)	Technique for fitting curve to measured data. Predicts vertical displacement and surface curvature. More accurate and repeatable than the NCB method. With slight modifications, it shows agreement with Appalachian coal field data.	Does not explain cause-effect relationships. Cannot be used in regions without an established data base and constants specific to geological context. Restricted to complete subsidence over rectangular extraction areas. Does not address time factor.
- Hyperbolic function (5, 8, 21, 24)	Predicts maximum subsidence at trough center.	Restricted to rectangular extraction areas where the profile coincides with the centerline. Does not accurately predict overall subsidence trough shapes.
- Knothe's description (19)	See characteristics for profile function.	Applicable for single seam, longwall mining, rectangular panels, excavation area exceeding critical width, area no longer influenced by time.
- Martos' description (Hungarian) (19)	See characteristics for profile function.	Profiles differ considerably from Appalachian coal field data.
- King and Whetton's description (19)	See characteristics for profile function.	Profiles fit only a part of the data; estimates in the critical zone do not match field data.
- Marr's description (British) (19)	See characteristics for profile function.	Profiles differ from Appalachian coal field data.
- Wardell's description (19)	See characteristics for profile function.	Profiles differ from Appalachian coal field data.
- Computer program developed by Hall and Dowding (25)	Based on analytically obtained formula of approximation for the subsidence profile curve. Includes empirically-obtained factors. Requires input data for each extraction point and calculation point at ground surface, characterization of trough area, coordinates and depths of corner points, thickness of seam worked, stowage factor.	See limitations for profile function.
Stochastic (Random) Media Theory (1,5)	Uses *physical principle: conservation of mass*. Predicts subsidence profile with a bell-shaped, normal distribution curve. Uses empirical approach to transfer field measurements from known to new areas. Can computer horizontal strain and displacement.	Specific to geological context. Does not incorporate knowledge of material properties. Does not address time factor.

(continued)

TABLE 4-2 (continued)

Name of Model	Characteristics	Limitations
Integration-Grid Method (25)	Uses a grid derived directly from observed subsidence movements. Divides critical area into sectors from which the relative influence of each sector is determined. Can be applied to irregularly-shaped, non-rectangular extraction areas.	Specific to geological context. Does not address time factor.
Analytical theories		
Elastic Theories		
- Physical model (Berry and Sales) (10)	Models mine as displacement that causes discontinuity in an otherwise continuous, elastic rock mass. Uses 2- and 3-dimensional solutions to represent a longwall panel as a single, rectangular dislocation.	Applicable only to longwall mining at considerable depths. Does not address time factor.
- Mathematical model (Salamon) (10)	Based on analog and digital techniques. Calculates stresses and displacements of complicated excavation geometries in the plane of a single seam.	Applicable only to longwall mining at considerable depths. Does not address time factor.
Finite Element Model (3, 5, 6, 8, 10)	Multi-layered model with bedding planes as the primary factor affecting subsidence. Simulates material behaviors and boundary conditions. Incorporates the discontinuities inherent in heterogeneous materials and assumes anisotropy. Determines stress distribution. Determines extent of caved zone based on mechanical properties of overburden. Includes geologies from the start.	Does not address time factor. Applicable only to longwall mining at considerable depth. Gob area must be settled. Rock strength parameters, obtained in laboratory, are usually overestimated.
- NASTRAN computer program (5)	Uses Mohr - Coulomb Failure Criteria and Young's Modulus to determine stress on overburden and collapse of strata. Reassigns new constants each time elements fail. Requires 5-6 iterations to reach state of complete subsidence.	See limitations for finite element model.
Isotropic Models		
- Crouch model (10)	Homogeneous, isotropic model for two-dimensional case of a case of a single seam parallel to ground surface. Rock is assumed isotropic and linearly elastic.	Restricted to single seam parallel to ground surface. Subsidence profiles do not consistently match field observations. Does not address time factor.
- Three-dimensional model (5)	Transversely isotropic. Shows reasonable agreement with field data.	Does not address time factor.
Elastoplastic Theories		
- Dahl model (5, 10, 21)	Three-dimensional model that represents development of zones of failure as plastic phenomena. Accounts for those strata at a distance from the critical area which deform without fracturing. Useful for modeling both longwall and room-and-pillar mine subsidence.	Where correlation between predicted and observed values is poor, constants are adjusted to improve correlation. Does not address time factor.

(continued)

TABLE 4-2 (continued)

Name of Model	Characteristics	Limitations
- Conoco mathematical model (20)	Explains subsidence as a result of rock mass deformation at mine opening. Deformation governed by elastic-frictional plastic stress-strain relations. Yield condition depends on confining pressure.	Does not address time factor.
Zone Area Method (6, 15, 27)	Based on theory of influence functions (see text). Requires input of area-specific zone factor and influence constant. Useful in the case of both homogeneous and heterogeneous overburdens, uniform and non-uniform extraction patterns. Can evaluate separately the individual sections of an extraction area.	Occurrence of ribside subsidence (see text). Does not address time factor.
- Computer model (27)	Implementation requires input of numerous parameters (see text). Established series of six annular rings around a surface point, given a critical width-to-depth ratio of 1.2	See limitations for zone area method.
Distinct Element Model (21)	Assumes joint distribution system in overburden to be principle mechanism in overburden failure. Represents strata as rigid blocks. Deformation occurs at interfaces between blocks.	Does not address time factor.
Viscoelastic Solution (5, 13)	Addresses time factor by linking viscoelastic properties of rock to time (see text). Takes into account local geology and mine geometry. Close agreement has been shown between predicted values and observed data in British coal field.	Use becomes increasingly limited with increasing mine depth.

[a]Numbers in parentheses after each model name represent the references from which the information in the columns to the right is taken.

SECTION 5

COSTS OF USING SUBSIDENCE PREDICTION MODELS

Certain factors must be considered in the cost evaluation of running a subsidence prediction model at a hazardous waste site.

First, a site survey must be performed. The site survey includes collection of geological, geotechnical, engineering and environmental data. These data would be collected by various means, including a drilling program, topographical survey, and gathering of preexisting geological records and mining records. Such data would include coal seam thickness, height and character of overburden, amount of coal extracted (i.e, sizes of rooms), and amount of support remaining (i.e., sizes of pillars), as well as other factors summarized in Table 3-1.

Secondly, the cost evaluation must account for a computer-aided analysis of collected data. Included here are actual computer time, and operator time. The operator oversees preliminary data analysis, input of the data into the computer program, and analysis of the computer-generated output.

Estimates for a complete site survey and in-house analysis range from \$150,000 - \$200,000.[17] Of this, the costs for running a computerized subsidence prediction model range from \$250 for a single finite element model or NASTRAN,[5] to \$2,000.[11] This range reflects the costs of computer time only.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

This section contains conclusions about the major factors that affect the likelihood of subsidence, the different effects of room-and-pillar and longwall subsidence on hazardous waste facilities, and the models that will probably be most valuable for predicting the occurrence and extent of subsidence beneath a hazardous waste facility. Recommendations are made regarding the various aspects of subsidence prediction, from collection of data through evaluation of results, as well as the state of the art of subsidence prediction itself.

6.1 CONCLUSIONS

The primary goal of this subsection is to provide a conclusion as to which models are most valuable for predicting the occurrence and extent of subsidence beneath a hazardous waste facility. This discussion will be preceded by a review of those factors that increase the likelihood of subsidence and of the type of subsidence most likely to be problematic for hazardous waste facilities.

Several major factors contribute to increasing or decreasing the likelihood of mine collapse and resultant subsidence. These factors are: height of the overburden, strength of the rock comprising the overburden, extent of geological faults in the overburden, presence of moisture, thickness of the coal seam (relative to the height of the overburden), and percentage of coal removed from the mine. Greater overburden height, stronger rocks comprising the overburden, absence or minimum number of faults in the overburden, increased amounts of moisture, thinner coal seams (relative to the height of the overburden), and smaller percentages of coal removed all decrease the likelihood of subsidence, while the opposite in each case increases the likelihood of subsidence.

Removal of smaller amounts of coal decreases the likelihood of subsidence because the remaining coal acts as a support to the mine roof. The chances of mine roof collapse are diminished with increasing support. Where large amounts of coal are removed from a mine, little or none is left to support the roof and to prevent or delay subsidence. Such is the case with longwall mining, where the percentage of coal removed is fixed at 100 percent and subsidence is intended to occur concomitantly with coal removal. Because approximately 95 percent of the total expected subsidence always occurs at exactly the same time as longwall mining, longwall mining should not be conducted under or near an existing hazardous waste facility. Also, because the remaining five percent of the total expected subsidence requires an additional one to five years for completion, any construction of a hazardous waste facility above an area that has been longwall mined should be postponed until five years after completion of mining. By then, subsidence is reasonably expected to be complete. In review, longwall mining should not be conducted under an existing hazardous waste facility, but a facility may be constructed over an area that has been completely free of longwall mining for five years or more.

Unlike longwall mining, the percentage of coal removed by the room-and-pillar method is highly variable. This is the major factor associated with the difficulty of predicting the occurrence and extent of subsidence over a room-and-pillar mine. As discussed in Section 3, maps of abandoned mine workings often do not accurately represent the size and number of remaining support pillars. Drilling surveys are not a solution. The problems with conducting a drilling survey are several-fold. First, underground character may vary greatly over short distances, so that mine roof collapse may have occurred in one section but not an adjacent section. Second, stresses from mine roof collapse may be in the process of being transmitted to the surface, but not yet have resulted in subsidence at the surface. Third, knowledge of the location of rooms and pillars does not provide data on rates of pillar deterioration that may or may not be occurring within the mine as a result of coal oxidation, pillar creep, presence of moisture, and so on. It is not possible to accurately and dependably characterize the number, size, and condition of support pillars within the room-and-pillar mine; therefore, a hazardous waste facility should not be constructed above any room-and-pillar mine workings, and neither should room-and-pillar mining be conducted under an existing hazardous waste facility. The potential for subsidence to eventually occur over any room-and-pillar mine, coupled with the high risks involved in disrupting the integrity of the containment structure at a hazardous waste facility, lead to the conclusion that no hazardous waste facility should be constructed above a room-and-pillar mine, and that no mining of any kind, longwall or room-and-pillar, should be conducted underneath an existing facility. Although one might use the aforementioned factors as guidelines, the high risks involved preclude any considerations of situating a new facility in an area where subsidence is "probably unlikely."

Certain models may provide rough approximations of the likelihood of subsidence. These models may be used in combination with area-specific information about the aforementioned factors to arrive at a conclusion regarding the likelihood of subsidence in a particular area.

Predictive models of subsidence fall into two broad categories: empirical and analytical. In order to use the empirical approach, two major requirements must be met. First, the model must be used in an area for which a large data set has already been gathered. Second, the investigator must have an accurate account of the dimensions of the mine, including height of the overburden, width of the coal seam, location and condition of all remaining pillars, and percentage of coal removed. A large data set has not yet been collected for the American coal fields but, regardless, meeting the second requirement would be difficult. For reasons discussed previously, it is not possible to obtain necessary measurements to verify pillar dimensions and locations. Therefore, the empirical approach is not applicable.

The analytical approach is derived from deformation mechanisms and strength parameters of rock. The elastic theory and finite element models are applicable only to longwall mining.

Several other models have limitations that may or may not preclude their usefulness. What little information is available about the two-dimensional isotropic model states that its use is restricted to single seams that are parallel to the ground surface. The elastoplastic theory has shown poor correlation between predicted and observed values. Although the zone area model requires development of an area-specific 'zone factor,' it is useful in the case of nonuniform extraction patterns, and can evaluate separately the individual sections of an extraction area.

The distinct element and three-dimensional isotropic models do not have any specific limitations other than those applicable to all analytical models (see Section 4.1). These models may be most useful for predicting subsidence over longwall mines, but the zone area model, taking into account its limitations, is probably more useful in predicting subsidence over room-and-pillar mines.

The viscoelastic solution model, still in the developmental stages, is the only model that addresses the time factor. This is less important than the ability to predict the occurrence or extent of subsidence, but it could be useful in the following way. If the time period of subsidence could someday be estimated for room-and-pillar mining as it now can for longwall mining, it might be possible to plan to construct a hazardous waste facility over a room-and-pillar mine once it had experienced complete subsidence. The viscoelastic model could be used to predict the period of time necessary for subsidence to occur and be completed.

6.2 RECOMMENDATIONS

Despite the difficulties inherent in modeling subsidence from room-and-pillar operations, every effort should be made to gather as much information as possible. Using all available data, subsidence prediction should be attempted using a model recommended for use in this report or elsewhere. It is important to evaluate the adequacy of the results with a clear understanding that failure of the model to accurately represent the system could, if a hazardous waste facility were disrupted, have a detrimental effect on the environment. Therefore, if it cannot be said with certainty that subsidence will not occur, then one should be hesitant to place a hazardous waste facility in the location under consideration.

Subsidence prediction is still in its early stages, and results of subsidence prediction models should not be viewed as completely reliable. Dr. Syd Peng of West Virginia University expressed the belief that the state of the art of subsidence prediction is such that a model providing 30 percent reliability is considered serviceable. In view of this, it should be kept in mind that the results of subsidence prediction models may not reflect future observed conditions.

REFERENCES

1. Lee, F. T. and J. F. Abel, Jr., "Subsidence from Underground Mining: Environmental Analysis and Planning Considerations," USGS Circular 876.

2. Karmis, M. and C. Haycocks, "Computer Simulation of Mining Subsidence Using the Zone Area Method," Office of Mineral Institutes, Bureau of Mines, March, 1983.

3. Jones, T. S. and K. K. Kohli, "Mine Subsidence in West Virginia," Presented at the Annual Fall Meeting of the West Virginia Section of the American Institute of Professional Geologists, October, 1983.

4. Martin, J. S., "The Big Problem Underground," Kentucky Coal Journal, April, 1985, p.45.

5. Kohli, K. K., "Prediction of Surface Subsidence Profile Due to Underground Mining in the Appalachian Coalfield," Ph.D. Dissertation, West Virginia University, 1984.

6. Peng, S. S., "Panel Discussion on Subsidence Prediction," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30-December 2, 1981, p. 288.

7. Gray, R. E. and R. W. Bruhn, "Coal Mine Subsidence - Eastern United States," Man-Induced Land Subsidence, ed. T. L. Holzer, Geological Society of America, Boulder, Colorado, 1984.

8. Peng, S. S. and C. T. Chyan, "Surface Subsidence, Surface Structural Damages and Subsidence Predictions and Modeling in the Northern Appalachian Coalfield," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30-December 2, 1981, p. 73.

9. "Use of Photo Interpretation and Geological Data in the Identification of Surface Damage and Subsidence." Appalachian Regional Commission. ARC-73-111-2554. April, 1975.

10. Gray, R. E. et al., "State of the Art of Subsidence Control," General Analytics, Inc., Report ARC-73-111-2550, December, 1974, pp. II-37-II-45.

11. Personal communication with Drs. Thomas Jones and Kewal Kohli, West Virginia Tech, April 23, 1985.

12. Personal communication with William Hobba, U.S. Geological Survey (Morgantown), April 24, 1985.

13. Personal communication with Dr. Syd Peng and Wen Su, West Virginia University, April 24, 1985.

14. Gentry, D. W. and J. F. Abel, Jr., "Surface Response to Longwall Coal Mining in Mountainous Terrain," Bulletin of the Association of Engineering Geologists, Vol. XV, No. 2, 1978.

15. Karmis, M. et al., "The Potential of the Zone Area Method for Mining Subsidence Prediction in the Appalachian Coalfield," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30 - December 2, 1981, p. 48.

16. "Study and Analysis of Surface Subsidence Over the Mined Pittsburgh Coalbed," GAI Consultants, Inc., Contract J0366047, Bureau of Mines, July, 1977.

17. Personal communication with Bradley Johnson, Bureau of Mines (Washington, D.C.), April 26, 1985.

18. Personal communication with Dr. Lessing, West Virginia Geological Survey, April 22, 1985.

19. Gill, D. E., "Subsidence Associated With the Mining of Bedded Deposits," Subsidence Subcommittee of the Canadian Advisory Committee on Rock Mechanics, Montreal, February, 1971.

20. Choi, D. S. and H. D. Dahl, "Measurement and Prediction of Mine Subsidence Over Room-and-Pillar Workings in Three Dimensions," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30-December 2, 1981, p. 34.

21. Hall, B. M., and C. H. Dowding, "Prediction of Subsidence From Full Extraction Coal Mining," Int. J. Rock Mech. Min. Sci. and Geomech., Abstr., V. 19, No. 3., June 1982, pp 305-312.

22. "Subsidence Engineer's Handbook," National Coal Board, London, 1965.

23. Tandanand, S. and L. R. Powell, "Consideration of Overburden Lithology for Subsidence Prediction," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30-December 2, 1981, p. 17.

24. Hood, M. et al., "Empirical Methods of Subsidence Prediction - A Case Study," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30-December 2, 1981, p. 100.

25. Kratzsch, H., Mining Subsidence Engineering, Springer-Verlag, New York, 1983.

26. Adamek, N. and P. W. Jeran, "Evaluation of Existing Predictive Methods for Mine Subsidence in the U.S.," Proceedings of Workshop on Surface Subsidence Due to Underground Mining, sponsored by West Virginia University, Department of Energy, Bureau of Mines, November 30-December 2, 1981, p. 88.

27. Karmis, M., and C. Haycocks, "Computer Simulation of Mining Subsidence Using the Zone Area Method," Dept. of Mining & Mineral Engineering. Virginia Polytechnic Institute, March 1983.

28. Martin, J. S., "A Problem We Can't Ignore," Kentucky Coal Journal, January, 1985, p.35.

29. "Survey of Ground Surface Conditions Affecting Structural Response to Subsidence," GAI Consultants, Inc., Contract J0295014, Bureau of Mines, June, 1983.

LIST OF CONTACTS

Brad Johnson
Bureau of Mines (Washington)
(202) 334-3312

Dr. Thomas Jones
West Virginia Institute of Technology
(304) 442-3339

Dr. Michael Karmis
Virginia Polytechnic Institute
(703) 961-7057/6671/7918

Dr. Kewal Kohli
West Virginia Institute of Technology
(304) 442-3337

Dr. Lessing
West Virginia Geological Survey
(304) 594-2331

Dr. Syd Peng
West Virginia University
(304) 293-5696

Mike Trebitz
Bureau of Mines (Pittsburgh)
(412) 675-6602

Dr. Barry Voight
Pennsylvania State University
(814) 865-3437

GLOSSARY

Analytical Model - A mathematically complex subsidence prediction method based on the theory of elasticity, mechanics of continuum, and an idealization of the subsidence phenomenon.

Angle of Draw - The angle of inclination from the vertical of a line connecting the edge of a workings and the edge of a subsidence area.

Critical Width - A site-specific value, the exceedance of which results in development of the maximum possible depth of subsidence in the center of a subsidence trough.

Empirical Model - A mathematically simple subsidence prediction method based primarily on field observations and data, a descriptive technique.

Gob - The refuse coal and other minerals that are left in the mine because they are not marketable.

Longwall - A system of mining in which the entire seam is removed in one operation, with heavy machinery, by means of a long working wall.

Maximum Subsidence - A value that is equal to 0.9 multiplied by the thickness of the coal seam.

Overburden - Rock material of any nature, consolidated or unconsolidated, that overlies a coal seam.

Panel - A large rectangular block or pillar of coal; an area or district in which coal is being extracted.

Room-and-Pillar - A system of mining in which the coal is mined in rooms separated by pillars, and about 50 percent of the coal is removed on the first working.

Seam - A stratum or bed of coal. This term is usually applied to a large deposit.

Strain - Deformation resulting from applied force, measured as change in length per unit length in a given direction. Within elastic limits, strain is proportional to stress.

Stress - Resistance of a body to compressional, tensional or tortional force, measured as force per unit area.

Subsidence - A lowering of ground surface which occurs as a result of the deformation caused by removal of subsurface mineral deposits.

Subsidence Factor - The ratio of the depth of the subsidence trough to the height of the coal seam.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Evaluation of the Applicability of Subsidence Models to Hazardous Waste Sites		5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) PEI Associates, Inc.		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS PEI Associates, Inc. 11499 Chester Road Cincinnati, Ohio 45246-0100		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Hazardous Waste Engineering Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA 600/12
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

EPA has discovered a number of uncontrolled hazardous waste sites in close proximity to abandoned underground mines. Further, several Resource Conservation and Recovery Act permit applications have been received for treatment, storage, or disposal facilities located in areas where abandoned underground mines are known to exist. The potential exists for subsidence under a hazardous waste facility to result in uncontrolled release of hazardous constituents to the environment.

The investigation was approached in two phases. Phase I involved a literature review and data compilation to gather information on the subsidence phenomenon, available predictive models, and on the adverse effects that can result from mine-related subsidence and Phase II consisted of an evaluation of available equations and models used to predict subsidence and an assessment of the applicability of these models to predict subsidence problems at hazardous waste sites.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE