THE PREDICTION AND OCCURRENCE OF CHIMNEY SUBSIDENCE IN SOUTHWESTERN PENNSYLVANIA

by

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(ABSTRACT)

Coal mining in Pennsylvania has long been an important factor in the economic development of the commonwealth. However, the mines abandoned before today's strict environmental regulations have degraded over half of Pennsylvania's counties. Subsidence incidents, known as chimney caves, are in the form of sinkholes and develop above abandoned room-and-pillar mines. Chimney caving is the most dominant type of subsidence in southwestern Pennsylvania, yet there are no accurate means available to predict their occurrences. Therefore, an investigation has been conducted in order to develop a set of engineering criteria, or an equation, to predict such occurrences. Through conducting sand model experiments and through the collection of a chimney subsidence incident database, such an equation was derived, and verified using actual field data.

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1. INTRODUCTION

1.1 Background

Subsidence is defined as the settling of the earth's surface caused by a natural or man-induced modification of the underlying supporting structure (Stingelin et al., 1975). In reference to mining, subsidence results from the settling of strata overlying the void left underground from the extraction of a valuable mineral or fuel. The impact of surface subsidence in Pennsylvania, and all of the United States, due to underground mining has long been recognized as detrimental to life and property. However, it was only recently (mid-1960's) that detailed research in the prevention and prediction of subsidence began. This is because previously most mines were located in rural areas where subsidence damage went unnoticed, and because surface subsidence can occur long after mining operations have ceased. Most research so far has been conducted for total extraction (longwall) methods because prediction of subsidence in partial extraction systems becomes much more complex. However, although the number of active longwall mines is increasing, the majority of the country's abandoned underground coal was extracted using the method of room-and-pillar mining, which is a partial extraction system. It is often these abandoned mines that cause subsidence damage.

Although coal mining in Pennsylvania has played a very important role in the economic development of the commonwealth since the mid-1700's, the mines abandoned before the strict environmental regulations of today's mining world have degraded the surrounding land and water in 45 of Pennsylvania's 67 counties (PADEP, 1997). There are more than 250,000 acres of abandoned mine lands, refuse banks, old mine shafts and other remains of past mining – more than any other state in the nation (PADEP, 1997). Subsidence expressions on the earth's surface and undermined areas with subsidence potential are only two of many difficulties associated with abandoned mines. Other abandoned mine land problems include open pits that have not been reclaimed, coal refuse piles, open shafts, and acid mine drainage. These problems must be mended in order to prevent further environmental hazards. Subsidence incidents, known as chimney caves, are in the form of sinkholes and develop above abandoned room-and-pillar mines. Chimney caving is the most dominant type of subsidence in southwestern Pennsylvania. Since chimney caves seem to occur sporadically, steps must be taken to better predict when and where such events will transpire. This requires an understanding of the mechanisms by which the chimney caves form and the conditions that must be present to induce such a form of subsidence. Although several studies have been conducted regarding chimney subsidence in the western United States, very little research has been done concerning this topic in the East. As of yet, there are no accurate means available to predict their occurrences above abandoned mines in southwestern Pennsylvania. Therefore, subsidence should be expected anywhere unless it can be proved that the area is not undermined, that long-term pillar support is in place, or that the mine voids have been fully collapsed (Gray and Bruhn, 1982).

1.2 Literature Review

1.2.1 Types of Subsidence

There are two main types of subsidence: trough and chimney. A trough, or sag, is defined as a gentle shallow depression in the earth's surface over an extensive area. Chimney, or sinkhole, subsidence takes the form of deeper steep-sided pits. According to Gray et al., (1977), after studying 354 incidents of subsidence over abandoned coal mines in the Pittsburgh metropolitan area, the most prevalent subsidence features above abandoned mines are sinkholes, with depths of more than 3 feet, and troughs, usually less than 3 feet deep. Occurrence of subsidence events varies from immediately to more than 100 years after mining has ceased. Subsidence may occur above abandoned mines with overburden thickness between a few feet and 450 feet. However, 450 feet is presumed to be only a temporary upper limit because one could expect, based on present concepts of subsidence mechanisms, that subsidence by pillar crushing or punching will be reported in areas with overburden thickness greater than 450 feet (Gray et al., 1977). Generally speaking, subsidence results from the settling of the earth's surface due to the removal of underlying support. More specifically, pit subsidence is usually a result of roof failure, where trough subsidence may be triggered by roof or pillar failure.

a. Trough Subsidence

These circular or semi-elliptical shaped depressions sag gently over a broad area. Troughs are usually 1.5 to 3 feet deep and range from 30 feet to one-third of a mile in diameter (Peng, 1992). Most subsidence troughs are associated with deeper mines and longwall mining. Tension cracks, formed as the ground is pulled apart, may outline the depressions. There are three main events that will trigger this phenomenon: crushing and deterioration of support pillars (pillar failure), punching of the pillars into the mine floor (floor heave), and roof collapse above the mine opening. The deterioration of support pillars may be attributed to weathering or groundwater fluctuations. This degradation causes the stress concentration to redistribute by arching of the roof. If the adjacent pillars are not strong enough to handle the new loads, they will fail (Gray and Bruhn, 1982). Larger troughs (those with diameters greater than 30 ft.) are thought to be associated with pillar failure and pillar punching, while smaller troughs are credited to roof failure (Peng, 1992). Most troughs above abandoned coal mines in the Pittsburgh coal are dish-shaped in profile, and are 30 feet or more in diameter and 3 feet or less in depth at the center (Gray and Bruhn, 1982).

b. Chimney Subsidence

Chimney subsidence, often referred to as pit, sinkhole, or pothole subsidence, is the most common form of surface subsidence associated with room and pillar mining. A shallow overburden phenomenon, it usually occurs over abandoned mines less than 165 ft. deep (Hunt, 1979). According to Gray et al., (1977), after studying 354 cases of subsidence in Pennsylvania, sinkholes in the Pittsburgh coal region are between 1.5 and 45 ft. deep (mean 14 ft.) and 1.5 to 45 ft. in diameter (mean 9 ft.). Most are less than 15 ft. across and 20 ft. deep. More than half of the subsidence events occurred more than 50 years after mining had ceased. Figures 1.1 and 1.2 are photographs of an actual chimney cave prior to reclamation in Pittsburgh, PA.

Figure 1.1 (a) A sinkhole that developed at the edge of a local resident's driveway

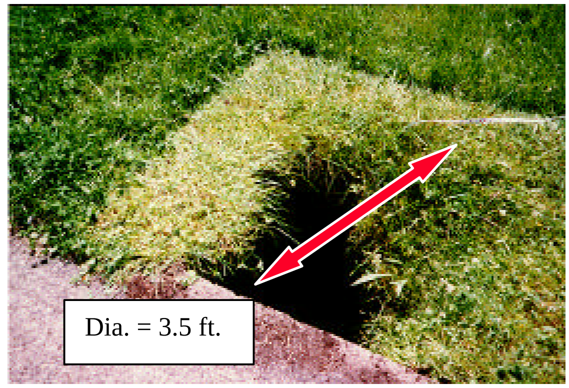


Figure 1.1 (b) A plan view of the sinkhole showing its approximate size

A sinkhole due to chimney caving usually bells out at the base of the hole, taking the shape of a bottle with the cap off. However, if the topsoil erodes away or collapses, the top portion will widen creating an hourglass shape hole. Several different circumstances may cause the formation of this type of subsidence. The most probable cause of the development of a sinkhole is the collapse of a mine roof, especially over mine junctions. This is because mine room intersections are the locations with the largest expanses of exposed roof. This leads to high-induced stresses in the immediate roof beds (Whittaker and Reddish, 1989).

It is possible for the propagation of a collapse-chimney to be arrested before it reaches the ground surface. If the upward movement of the chimney were to intersect a more competent roof layer, such as a massive sandstone deposit, the movement would be halted. The chimney could also be stabilized by self-choking; the natural bulking of the caved rock allowing the upward collapse process to cease. The movement could also be arrested by the formation of a new, stable, self-supported linear arch (Whittaker and Reddish, 1989; Karfakis, 1986).

If, however, there is very shallow depth of cover or if the overlying strata is very weak or wet rock allowing caved material to flow into the mine, the chimney cave is likely to penetrate through to the surface. The presence of wet unconsolidated strata can result in a “slurry” run into the mine giving rise to large pothole forms of subsidence (Misich, 1993). Tension cracks or fractures in the overburden can also serve as weakness planes allowing caving to reach the surface. These cracks may be created by the mining operation or may have already existed. Pit subsidence is frequently deeper than the thickness of the extracted coal seam, contradicting the idea that swelling of the caved material will limit subsidence to some fraction of the extracted seam thickness. This is due to flow of caved material throughout the mine.

According to Dunrud et al., (1980), subsidence pits often occur within depressions (troughs) in the Sheridan, Wyoming area. Most pits located within the depressions are not as deep as pits outside the depressions. The pits located within the troughs generally form several years to decades after the depressions; therefore, local depressions may serve as warnings to possible future pit collapse within them. Small troughs, in the 30 to 50 feet diameter range, overlap with sinkholes in Pittsburgh coal and it is presumed that some will eventually collapse to form sinkholes (Gray and Bruhn, 1982).

According to Hao et al., (1991), after developing and studying a database of past subsidence events, pit subsidence results from mines at depths of less than 100 ft., and is not likely to be produced by mines abandoned since 1960. This is because the majority of coal located in close proximity to the surface has already been extracted, or is currently being removed by surface mining methods. Therefore, underground mines abandoned post-1960 are most likely too deep to induce pit subsidence. It was also found that pit subsidence has a greater incubation period, or delay before surface appearance, than trough subsidence. Mining depth is the most influential determining factor for whether a subsidence event will be a pit or a trough. Again, chimney subsidence is a shallow overburden phenomenon. According to Piggott and Eynon (1978), sinkhole development will normally occur at intervals in rock up to 3 to 5 times the height of the extracted seam with the maximum interval up to 10 times the height of the extracted seam. After conducting a study of coal mine subsidence in Wyoming, Dunrud and Osterwald (1980) agree with the upper limit of sinkhole development suggested by Piggott and Eynon (1978) except where the caved material moves laterally. This happens when material flows through cracks and fractures within the sinkhole, or into adjacent mine entries. In western Pennsylvania, most sinkholes develop through cover less than 50 feet (Bruhn et al., 1978).

Although most theories of subsidence suggest that some sort of roof failure is required in order to produce a chimney cave on the surface, Dr. Jesse Craft of the U. S. Department of the Interior's Office of Surface Mining (OSM) has found through research that such a failure is not necessary. According to Craft, pit subsidence seems to occur in three geologic settings: areas of seasonal water table, areas of thin-bedded shale overburden, and areas of unconsolidated overburden with a perched water table. Sediments can move through tension cracks or fractures in the overburden into the mine void if the unconsolidated overburden becomes water saturated. These fractures may be already existing or may be mine-induced. This phenomenon is known as piping. In such areas of seasonal water tables, roof collapse is not necessary for a pit to form. When small areas of the mine roof collapse, caving will slowly work its way upward in areas of thin-bedded shale overburden. In regions where the ground water table is located within the unconsolidated overburden and the mine-induced fractures reach the base of the unconsolidated overburden, extensive piping can occur causing a wider surface expression of subsidence. This is because the water drains into the mine creating a cone of depression directly over the fracture zone of water loss. Investigations in the mine will show that, again, no roof collapse has taken place.

1.2.2 Mechanisms of Chimney Caving

As discussed in section 1.2.1 (b), the most probable cause of the formation of a chimney cave is a roof fall underground, especially over mine junctions. During the extraction process, the overburden load which had previously been supported by the coal seam is transferred to the nearby pillars. This causes a high state of stress in the material directly above the mined-out room. According to Karfakis (1986), tensile stresses in the immediate roof and/or high compressive stresses at the upper corners of the opening may develop depending on the initial state of stress. If the roof contains vertical fractures or joints, tensile stresses will not develop; however, the creation of fractures may occur. In either case, the roof will deflect downward slightly, and a self-supported linear arch, or Voussoir arch, will form. Compressive stresses will develop on the upper part of the arch-forming layer and at the abutments.

Changes in the state of stress are likely to occur through deterioration of pillars and roof over time. However, the opening will remain stable while the strength of the roof rock exceeds the stress upon it. Karfakis (1986) indicates that the changes in stresses and strength may be due in part to ground water fluctuations, creep, and other factors. The presence of water may deteriorate the strength of rock. The strength of the rock may also be reduced by fluctuations in ground water changing the hydrostatic head and the pore pressure within the rock mass. The variation in relative humidity and weathering of unstable minerals will cause slaking. This will affect the stress distribution by modifying the boundary conditions of the mine opening. Finally, deformations due to creep could modify the stresses by stress relief, and creep deformations may also exceed the plastic limit of the rock and cause failure (Karfakis, 1986).

According to Karfakis (1986), there are two basic modes by which the roof may fail: shear failure and flexural failure. Assuming that the roof behaves as a continuous beam, it will fail flexurally due to: a) loading in a vertical plane, b) low ratio of horizontal to vertical stress, c) thinly bedded or separated roof layers, and d) bending generates tensile stresses which exceed the modulus of rupture of the rock. It may fail in shear when: a) there are high horizontal and vertical stresses, b) the pillars are stiffer than the roof, c) softer layers overlay the immediate roof, and d) the sheer strength of the roof rock is exceeded by the shear stresses generated at the pillar-side abutments. If the roof is considered to be a Voussoir beam, it may fail in shear or by rotation of blocks. If the beam is formed by blocks bounded by joints or cracks, it will fail in shear. The blocks will slide along weakness planes when the vertical stress exceeds the shear resistance along the discontinuity planes created by the joints. If the upper portion of the arch is crushed due to compressive stresses, or when deflections reduce the linear arch line beyond the limiting length, rotation may result (Evans, 1941 and Woodruff, 1966).

Once the initial failure of the immediate roof has occurred, caving simply continues upward until it reaches the surface unless it is arrested by one of the means discussed in section 1.2.1 (b). The sides of the pit are often vertical or overhang when it first intersects the ground surface. If the hole is not reclaimed soon after, the walls of the sinkhole will erode away as a result of water draining downward, deepening and enlarging the size of the pit. Erosion at the ground surface will cause the diameter to widen creating an hourglass shape. After an even longer period of time, the pits may become more shallow as the sides start to slump over into the hole (Karfakis, 1986).

1.2.3 <u>Factors Influencing Subsidence</u>

Many parameters affect the surface expression of subsidence. It seems that the most predominant factor influencing the extent and magnitude of subsidence is overburden depth. Chimney subsidence is limited to relatively shallow mining depths. Other influencing factors as they relate to chimney caving include, but are not limited to, mining method, thickness of seam (mining height), geologic features of overlying and underlying strata, climate, extraction ratio, intact strength of the rock, state of stress, topography, and time. Some of these factors are discussed below.

a. Overburden Depth

It is generally agreed on that the deeper the excavation, the less effect subsidence will have at the surface. The literature has conflicting opinions regarding the length of time required for rock deformations to reach the surface at different depths. Much of the literature states that the more shallow the excavation, the shorter time period it will take for subsidence to reach the surface. However, this is not a valid statement. The majority of chimney caves are formed more than 50 years after mining has ceased. Longwall operations, which are much deeper, produce subsidence effects on the surface simultaneously with mining.

b. Mining Method

Room-and-pillar and longwall mining produce different surface effects of mine subsidence. Generally speaking, subsidence features produced by longwall mining are predictable in active mines and occur during the mining process. Most subsidence troughs are associated with deeper mines and longwall mining. The effects of room-and-pillar mining may not be seen for many years after mining operations have ceased.

c. Mining Height

Opinions differ about the effect of seam thickness on the magnitude of subsidence. It was once thought that the depth of a subsidence formation could not exceed the thickness of the extracted coal seam, or the height of the underground “room”. However, because the caved material can flow through to the void and into other areas of the mine through cracks and fractures in the rock, the depth of a subsidence formation can actually be greater than that of the void. This is especially true in the case of chimney subsidence occurring above room-and-pillar mines. The relationship of seam thickness and overburden depth to vertical displacement of the ground surface is well established in other areas. For example, according to the National Coal Board (1975), a compilation of more than 150 measurements made above longwall mines in the United Kingdom showed that a maximum depth of the subsidence basin of 0.9 times the seam thickness is reached when the span of the void exceeds 1.4 times the depth of the deposit.

d. Geologic Features of Overlying and Underlying Strata

Geologic conditions of an area should be well known prior to mining so that necessary precautions may be taken to predict and monitor any subsidence events that may occur. However, in dealing with coal mines abandoned many decades ago, such precautions may not have been taken. Hard rocks may delay subsidence through their self-supporting action. These rocks may settle with minimal disruption if subsidence takes place (Chen et al.,1985). As discussed in section 1.2.1 (b), very wet or weak rock may flow through fractures and cracks in the overburden forming chimney caves above abandoned coal mines. However, if a roof fall initiates the propagation of a chimney cave and it eventually intersects a massive bed of rock, the formation of the cave will arrest and remain unnoticed on the surface. The process of rock mass movement is accelerated along a plane of geological discontinuity through the subsidence strata (Chen et al.,1985).

e. Time

The time of occurrence of subsidence is related to the deterioration rate of the supporting roof and pillars. Subsidence events in western Pennsylvania have occurred as early as a decade after mining and as late as a century (Gray et al., 1977). Most chimney subsidence events seem to occur more than 50 years after mining. Most subsidence associated with longwall mining is concurrent with mining.

1.2.4 Damage Caused by Subsidence

Surface subsidence events caused by the subsurface void left from the extraction of coal from the earth cause extensive damage every year in the United States. Besides leaving scars on the earth's surface such as craters, cracks, and sags, subsidence causes physical damage to structures and vegetation. The economic impact of subsidence may also be significant in many cases. Damage from surface subsidence can be caused by changes in surface slope, differential vertical displacements, and horizontal strains (Lee and Abel, 1983).

a. Hydrologic Impacts

Both surface and underground water flow may be disrupted by subsidence events. In many areas aquifers overly abandoned underground mining operations. In the event that a roof fall were to begin propagating upwards in the creation of a chimney cave, the intersection of the aquifer with the formation of the cave could cause flooding of the abandoned coal mine. Such flooding may lead to the subsequent blowout of a sealed mine opening. This situation has proved to be life-threatening due to the sudden burst of water on the surface. A similar scenario could occur if a body of surface water seeped into an underground mine through cracks or fractures in the earth caused by mining. Diminished well production is another effect of mine subsidence. According to Sossong (1973), a mine face passed within 30 m of a 20-m deep well which went dry in Pennsylvania. The well was then deepened by 12 m and a good water supply was encountered. Fractures, fissures, and pits on the earth's surface provide a means for contaminants to seep through down to the aquifers that lie above the mined zone. Such contaminants may react chemically with each other or with the rocks. According to Mead et al., (1978), the underground coal gasification process and in situ retorting of oil shale can also affect ground-water supplies. When ground water reenters a gasified coal bed, coal ash, tars, and gases (the residual reaction products) may undergo leaching, dissolution, and hydrologic transport.

b. Structual Damage

Buildings and roads are frequently damaged by subsidence events. In buildings the structural damage may include cracking or failure of foundations, vertical displacement, buckling, misalignment of doors, and complete structural failure. Usually the owner is left paying for the repair work if the damage is caused by an abandoned coal mine. Roads that are damaged must be regraded or backfilled. Damage to sewage and drainage systems, and water and gas lines is also possible. Gas lines may catch fire and explode if ruptured (Lee and Abel, 1983). Gray et al., (1977) found that of the 354 incidents of subsidence examined in western Pennsylvania, nearly 1 in 3 involved damage to property.

c. Impacts on Vegetation and the Living World

Fractures in subsidence features allow methane and other dangerous mine gases to leak out causing trees and plants to die. These same gases could present a hazard to animals or people on the surface. Shallow trough depressions on the surface may fill with water if a proper drainage system is not provided. This creates swampy conditions that may kill vegetation and change wildlife habitats. Finally, chimney caves, or pits, are traps that offer potential for unsuspecting people or animals to fall into.

d. Coal Mine Fires

Coal mine fires may at times be caused by mine subsidence. According to Dunrud and Osterwald (1980), coal mine fires seem to start by spontaneous ignition when air and water enter through subsidence cracks and pits. The drawing in of oxygen and the exhaustion of smoke, steam, and noxious gases through these cracks helps support combustion. As the coal burns, more cavities are created causing more cracking and collapse which allows greater access for air, thereby accelerating coal burning. This process not only destroys the valuable commodity, but it pollutes the air and kills nearby vegetation.

e. Economic Impacts

Economic impacts of subsidence may include direct structural damage, loss of the value of renewable resource lands (ie. farmland), land value depreciation, loss of "sterilized" resources where underground resources must be left to support surface development, and adverse effects on economic growth (HRB-Singer, Inc., 1977). The Bureau of Mines estimated that underground coal mining will cause surface damage costs in excess of one billion dollars from 1973 to 2000 (Comptroller General of the United States, 1979). In Pennsylvania, about $500 million in state and federal funds have been spent since 1967 to clean up pollution problems from abandoned mines. They receive about $20 million a year from the federal government to do reclamation projects (PADER, 1997). This may seem like a lot of money; however, it does not begin to fully illustrate the amount of money needed. According to the Pennsylvania Department of Environmental Protection, at their current rate of reclamation, it will take Pennsylvania

50 years or more to clean up the detrimental effects of past mining at an estimated cost of $15 billion. As of November 12, 1996, the Bureau of Environmental Protection (Bureau) had reclaimed 2263 acres of subsidence.

1.2.5 Reclamation of Subsidence

The reclamation of sinkhole subsidence in the Pittsburgh metropolitan area usually consists of either excavating the hole and filling it with stone, or pumping a concrete mix to backfill the hole. Excavation of the hole consists of removing all collapsed and overhanging material within the void. Generally, the concrete mix is used to backfill the hole when access to the site is limited. The cavity is filled to a specified distance from the surface (usually 1 to 3 feet), and then soil is placed in the remainder of the hole. The areas are often graded, seeded, limed, fertilized, and mulched with straw. Any surface disturbed by the reclamation process is also restored. This includes things such as regrading of tire ruts, cleanup of dirt or mud on roadways, and repair of damaged sidewalks. Sinkholes should never be filled in by property owners with random, available materials. This may furnish a "quick fix," but could provide a channelway for water percolation which may trigger future subsidence.

If reclamation is not performed properly, the subsidence will worsen due to the weathering process. The walls of the sinkhole will erode away as a result of water draining downward, deepening and enlarging the size of the pit.

Reclamation of subsidence occurrences and other damage caused by abandoned underground mining may be performed by or contracted out by either the federal or state (Pennsylvania) government. The federal agency responsible for such projects is the

Department of the Interior, Office of Surface Mining Reclamation and Enforcement (OSM). The state agency in Pennsylvania that administers the abandoned mine lands (AML) projects is the Department of Environmental Protection (DEP) Bureau of Abandoned Mine Reclamation (Bureau). Normally, OSM is responsible for the emergency situations and the Bureau is responsible for all others. An emergency situation is one that occurs suddenly, is life-threatening, and demands immediate attention (PADEP, 1997). The funding of such projects comes from two sources. According to Title IV of the Surface Mining Control and Reclamation Act of 1977 (SMCRA), active coal operators must pay a 35 cents per ton fee for each ton of surface-mined coal and 15 cents per ton for each ton of underground-mined coal. Part of these collected fees are used to fund reclamation of high priority abandoned mines if the problem resulted from pre-August 3, 1977 mining. This is part of a federal grants program. The second source of funding is forfeited reclamation bonds. All mining operators are required to post bonds to ensure reclamation of the mine site. If the site is not reclaimed, the bonds are forfeited and the Bureau uses the money to reclaim the mined area appropriately (PADEP, 1997).

1.2.6 Prediction of Chimney Subsidence

Many of the proposed theories on chimney subsidence prediction apply only to active coal mines. Various theories predict the roof stability of mines since chimney subsidence is a roof stability problem in most cases. The theories require detailed information on mine geometry and geology; information that is readily available for working mines. However, in abandoned mines, subsurface conditions are difficult to obtain. There is currently no accurate means available to predict when and where subsidence will occur above abandoned coal mines. Therefore, subsidence should be expected anywhere unless it can be proved that the area is not undermined, that long-term pillar support is in place, or that the mine voids have been fully collapsed (Gray and Bruhn, 1982).

Whittaker and Reddish (1989) have proposed a theory on calculating the height of caving of the collapse-chimney above room intersections. This theory utilizes the room geometry, bulking factor of the caved rock, and angle of repose of the caved rock to predict the height of the collapse-chimney. Similar approaches have also been proposed by Price et al., (1969), Piggott and Eynon (1978), and Dunrud (1984). Simple relationships between height of the collapse-chimney, thickness of extracted material, and swell factor of the roof material were developed to predict if caving would reach the surface before self-choking. They state that the greater the volume of the underground opening, the higher the collapse is likely to develop. They also determined that the smaller the bulking factor, the higher the propagation of caving. However, theories such as this are idealistic in assuming constant bulking, no lateral movement of the rubble, and perfect geometries (Karfakis, 1986).

It seems that the most accurate means of predicting chimney subsidence is to examine the sites where it has already occurred.

1.2.7 Subsidence Prevention and Control

Several different measures are currently used to prevent or mitigate subsidence events. According to Gray and Bruhn (1982), contractors in some areas of Pennsylvania are now using subsidence resistant designs in their homes and buildings. The goal of these designs is to minimize damage since prevention of damage is not always cost effective. Subsidence resistant designs may include measures such as continuous footing reinforced at top and bottom, so as to take negative and positive bending (Gray and Meyers, 1970). Land use controls, such as zoning of areas subject to subsidence, is also practiced (U. S. Government Accounting Office, 1979). There is also a mine subsidence insurance policy offered to homeowners in Pennsylvania through the Bureau of Mining and Reclamation and the Bureau of District Mining Operations. This is available so that the homeowner is not responsible for paying for the repairs of damage from subsidence of an abandoned coal mine. Coverage is available from a minimum of $5000 up to $150,000 for a residential structure and $250,000 for a nonresidential structure (PADEP, 1997).

There are two categories of measures commonly implemented to prevent or reduce subsidence: 1) those providing general filling of mine voids to support the overburden; and 2) those providing only local support of the overburden or surface structures (Gray and Bruhn, 1982). Some of the filling methods for voids include hydraulic backfilling, pumped slurry injection, pneumatic backfilling, controlled flushing, remote backfilling, grouting, over-excavation and backfill, and blasting. Local support methods may include grout columns, deep foundations, drilled piers, and piles (Gray and Bruhn, 1982).

Subsidence abatement measures generally reduce, but do not eliminate, future incidents of subsidence. They require much time and money to properly plan and implement; therefore, sometimes they are not a practical solution.

1.3 Objectives of Study

The objective of this investigation is (i) to study the factors contributing to the occurrence of chimney subsidence above abandoned coal mines in southwestern Pennsylvania and (ii) to develop engineering criteria that can be used to predict the occurrence of such subsidence. A sand model used to attempt the simulation of chimney subsidence was built, and a database of case studies was collected and analyzed. Currently, there is no accurate technique to predict when and where chimney caving will transpire above abandoned mines in southwestern Pennsylvania, and very little research has been conducted on this phenomenon in the eastern United States. Due to the sudden and destructive nature of these frequent occurrences, it would be quite beneficial to be able to predict their happenings accurately. Therefore, the ultimate goal of this study is to develop an equation that may be used to predict the occurrence of such a subsidence event in southwestern Pennsylvania.

2. THEORETICAL MODELS

2.1 Derivation of a Prediction Equation

As mentioned briefly in the literature review, some of the methods for predicting the occurrence of chimney caves rely mainly on the geometry of the abandoned mine to predict the height of caving. Consider one such equation developed by Whittaker and Reddish (1989) (see Equation 2.1.3 and Figure 2.1). This expression utilizes the bulking factor and angle of repose of the caved material, the width and excavated height of the mine rooms, and the assumed diameter of the collapse-chimney to predict the height of the collapse-chimney. In order to determine whether or not there is a possibility of developing a sinkhole on the surface, one would compare the thickness of the overburden in the area of interest to the calculated height of the collapse-chimney. If the thickness of the overburden were to exceed the height of the collapse-chimney, the hole would not propagate all the way to the earth's surface.

Although several assumptions are made in the calculation such as constant bulking, no lateral movement of the rubble, and perfect geometries, the equation still provides some basis for predicting the development of a sinkhole. One could assume the worst case conditions and obtain the safest, most conservative estimate of collapse-chimney height.

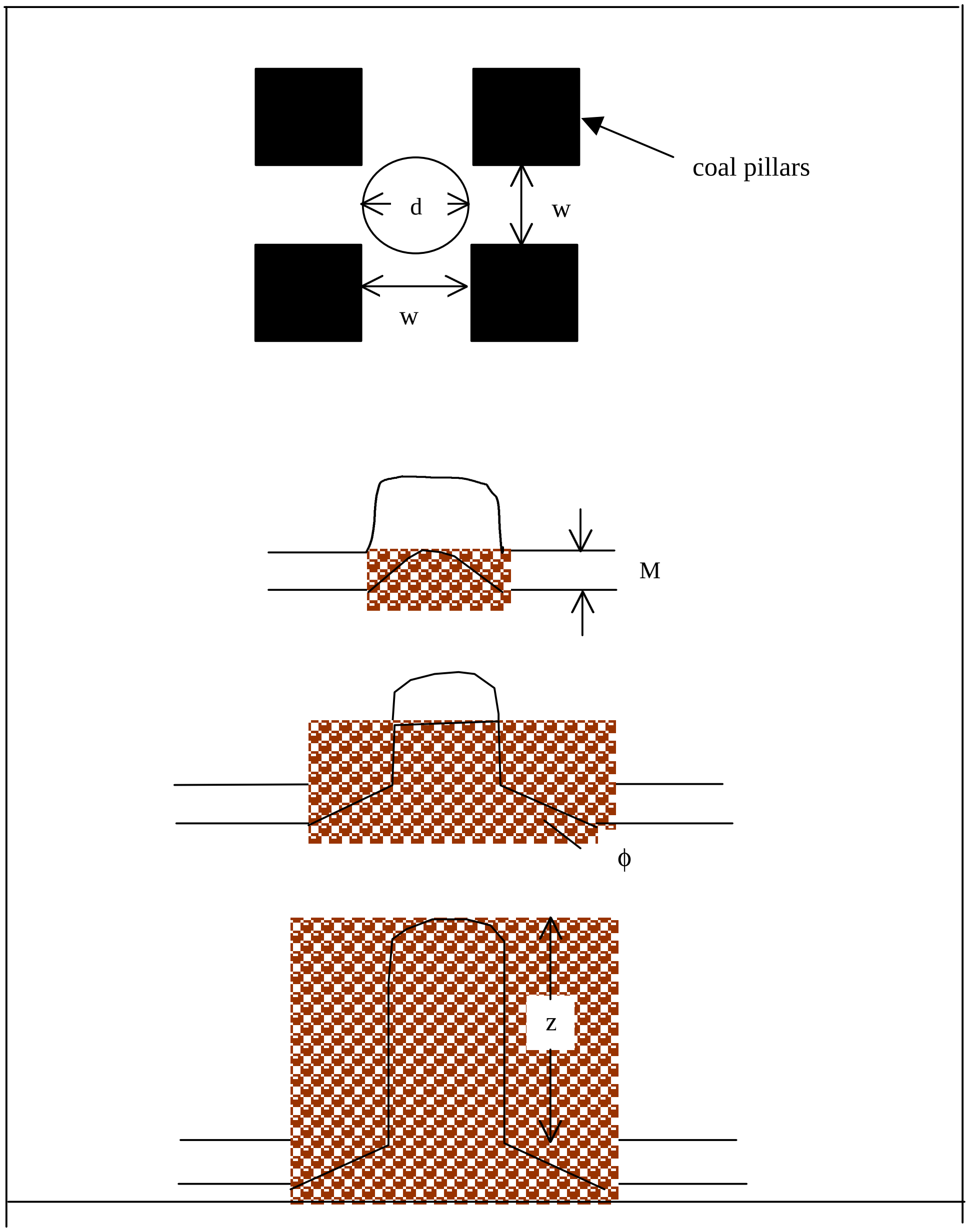


Figure 2.1 A Graphical Representation of the Caving Process

$$V_{caved} = k\, z\, \pi\, D^2 / 4 \tag{2.1.1}$$

$$V_{space} = 4\,(1/2\; w\, M^2 \cot\phi\,) + M\, w^2 + z\, \pi\, D^2 / 4 \tag{2.1.2}$$

Equating (2.1.1) and (2.1.2)

$$z = 4 / ((k - 1) \pi D^2) (2 w M^2 \cot \phi + M w^2) \qquad (2.1.3)$$

where, V_{caved} = volume of caved rock from collapse-chimney
V_{space} = volume of available space to receive caved roof rock
k = bulking factor (1.33 to 1.5)
z = height of collapse-chimney
D = diameter of collapse-chimney
w = width of mine rooms
M = excavated height of mine rooms
ϕ = angle of repose of caved rock within mine rooms adjoining collapse area

In these equations, according to Whittaker and Reddish, the rock density in its solid state is assumed to remain uniform and the bulking characteristics are also assumed to be consistent and remain unaffected by loading created during the extension in height of the collapse-chimney. Also, it is considered that the increased loading on broken material at the base of the chimney will produce insignificant change in volume during the process of caving to the full height of the chimney. Whittaker and Reddish have considered the diameter of the chimney to be in the range of $D = w$ and $D = w\sqrt{2}$, because that is what they have observed the cave diameters to be in their experience. The equation also assumes the shape of the collapse-chimney to be a cylinder.

However, the applicability of this equation in southwestern Pennsylvania is limited. In this vicinity, the diameters of chimney caves are often smaller than the width of the mine rooms. In fact, many of the documented cases of chimney subsidence in southwestern Pennsylvania have chimney diameters a small fraction of the width of the mine rooms. Also, although some of the sinkholes in the region may be cylindrical in shape, many of the sinkholes (as discussed previously) widen at the base of the hole, creating a truncated cone shape. The Whittaker and Reddish equation grossly overestimates the height of the collapse-chimney for cases where the chimney diameters are smaller than the room widths since the calculation for available space to receive caved rock (V_{space}) does not accurately accommodate chimney diameters (D) less than the room widths (w). Their equation only takes into account those cases where the entire section of roof over the junction has collapsed to produce a chimney subsidence expression on the surface. In addition, the equation does not accurately calculate the volume of available space to receive caved rock (V_{space}) even for those holes where D does equal or exceed w. It assumes that the material caving into the abandoned mine room falls in a truncated square pyramid shape rather than in the shape of a truncated cone.

Therefore, a new equation has been developed that serves chimney diameters of all sizes, accommodates the possibility of sinkholes with a wider base, and also considers the shape of the fallen material to be that of a truncated cone rather than a truncated square pyramid.

Consider Figure 2.2 to be used in conjunction with the subsequent equations:

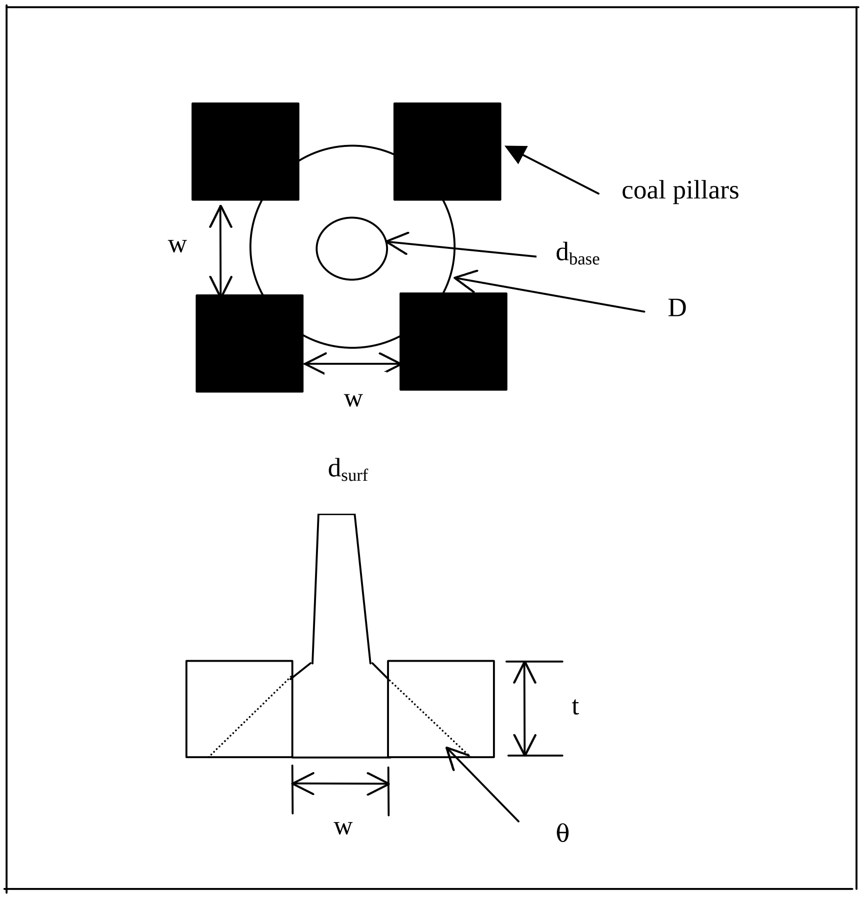


Figure 2.2 Explanation of Variables in Equation 2.1.6

$$V_{caved} = \pi/12\ z\ (d_{base}^2 + d_{surf}^2 + d_{base}d_{surf})\ k \qquad (2.1.4)$$

$$V_{space} = \pi/12\ t\ (d_{base}^2 + D^2 + Dd_{base}) - \qquad (2.1.5)$$

$$((D - w)/6 \tan\theta)\ (D^2 \arccos(w/D) - D^2/2 \sin(2\arccos(w/D)) - \pi D^2/4 + w^2) +$$

$$\pi/12\ z\ (d_{base}^2 + d_{surf}^2 + d_{base}d_{surf})$$

Equating (2.1.4) and (2.1.5)

$$z = 12/(\pi\ (k-1)\ (d_{base}^2 + d_{surf}^2 + d_{base}d_{surf}))\ (\pi/12\ t\ (d_{base}^2 + D^2 + Dd_{base}) - \quad (2.1.6)$$

$$((D - w)/6 \tan\theta)\ (D^2 \operatorname{arcos}(w/D) - D^2/2 \sin(2\operatorname{arcos}(w/D)) - \pi D^2/4 + w^2))$$

where, D $= d_{base} + 2t \cot\theta$
V_{caved} = volume of caved rock from collapse-chimney
V_{space} = volume of available space to receive caved roof rock
k = bulking factor (1.33 to 1.5)
z = height of collapse-chimney
d_{base} = diameter of collapse-chimney at base
d_{surf} = diameter of collapse-chimney at earth's surface
w = width of mine rooms
t = excavated height of mine rooms
θ = angle of repose of caved rock within mine rooms adjoining collapse area

The complete derivation of these equations may be seen in Appendix A.

2.2 Validation of a Prediction Equation

Equation 2.1.6, the modified equation, used to calculate the height of the collapse-chimney, was verified using the results obtained from the chimney caves contained in the database. In each documented case of pit subsidence, the height of the collapse-chimney calculated from the modified equation should equal or exceed the actual thickness of the overburden since all of the documented collapse-chimneys propagated through to the surface. There are 79 documented case studies in this database; however, because many of the files are missing one or more pieces of pertinent information, only about half of the cases could be used to verify the equation. The following is a table showing the calculated height of the collapse-chimney for Equations 2.1.3 (original equation) and 2.1.6 and the actual overburden thickness. In each case, width of the mine rooms (w) was assumed to be 20 feet, angle of repose of caved rock (θ) was assumed to be 25°, and bulking factor (k) was assumed to have a value of 1.4.

Table 2.1 Calculated Height of Collapse Chimney for Equations 2.1.3 and 2.1.6

Site No.	Overburden Thickness (ft.) H	Calculated Height of Collapse-Chimney, (z) (ft.) Equation 2.1.6	Does Calculated Height Equal or Exceed Actual Overburden Thickness?	Calculated Height of Collapse-Chimney, (z) (ft.) Equation 2.1.3	Does Calculated Height Equal or Exceed Actual Overburden Thickness?
2	25	**455.43**	yes	1552.33	yes
3	20	**255.88**	yes	760.64	yes
7	15	**33.38**	yes	117.78	yes
14	25	**73.29**	yes		
17	30	**48.34**	yes	179.21	yes
19	20	**467.03**	yes	1841.12	yes
21	17	**151.46**	yes	703.67	yes
23	17.5	**8.59**	no	12.34	no
25	20	**143.48**	yes	262.67	yes
26	17.5	**39.13**	yes		
29	17.5	**27.69**	yes		
30	30	**71.57**	yes		
31	15	**33.33**	yes	87.81	yes
36	15	**119.14**	yes		
39	22	**88.71**	yes		
41	30	**154.57**	yes	975.68	yes
42	12.5	**151.46**	yes	703.67	yes
43	20	**359.52**	yes		
44	20	**127.83**	yes	297.13	yes
45	10	**127.83**	yes	297.13	yes
48	6	**85.90**	yes	312.74	yes
49	20	**131.18**	yes	646.45	yes
50	40	**123.31**	yes	233.22	yes
55	25	**52.00**	yes		
57	50	**206.04**	yes	662.80	yes
58	20	**17.38**	no	54.28	yes
60	40	**104.32**	yes		
63	20	**31.77**	yes	206.25	yes
66	15	**33.33**	yes	87.81	yes
68	15	**7680.64**	yes	26267.50	yes
69	4	**2051.13**	yes	12794.73	yes
70	20	**128.25**	yes	2249.79	yes
71	20	**50.66**	yes	96.30	yes
76	30	**57.23**	yes		
78	30	**206.04**	yes	662.80	yes
79	20	**4340.21**	Yes	19016.07	yes
82	15	**94.17**	Yes	199.92	yes

* The blank entries denote sites where the Whittaker and Reddish equation could not accurately be used because the diameters of the chimneys were wider at the base than at the surface.

It may be seen from the table that the calculated height of the collapse-chimney equaled or exceeded the actual overburden thickness 95% of the time using the modified equation. In the cases that the equation misjudged the height of the collapse-chimney, it was only a slight underestimation, and one must keep in mind that many assumptions are made in using the equation (ie. room width, bulking factor, angle of repose, etc.). One should also note that the overburden thicknesses and seam thicknesses were taken from contour maps – not actually measured in the field. Therefore, there may be some inaccuracy in those numbers causing the calculated cave propagation height to be erroneous. It is also evident from the results displayed in the table that the Whittaker and Reddish original equation grossly overestimates the height of the collapse-chimney. Many of their predictions are 500 feet or more – higher than any recorded depth in a case of pit subsidence. This is mainly because the equation uses the room width, not the chimney diameter, to calculate the volume of available space to received caved rock within the mine room itself (referring to the Mw^2 portion of Equation 2.1.2). Therefore, in the cases where the diameter is less than the room width, the calculation of V_{space} is grossly overestimated.

The following figures are graphical representations of the effects of changing the values of variables in the calculation of the height of collapse-chimney from Equation 2.1.6, the modified equation.

It is easily seen from Figure 2.3 that the smaller the assumed diameter of the collapse-chimney, the higher the cave will propagate towards the surface of the earth.

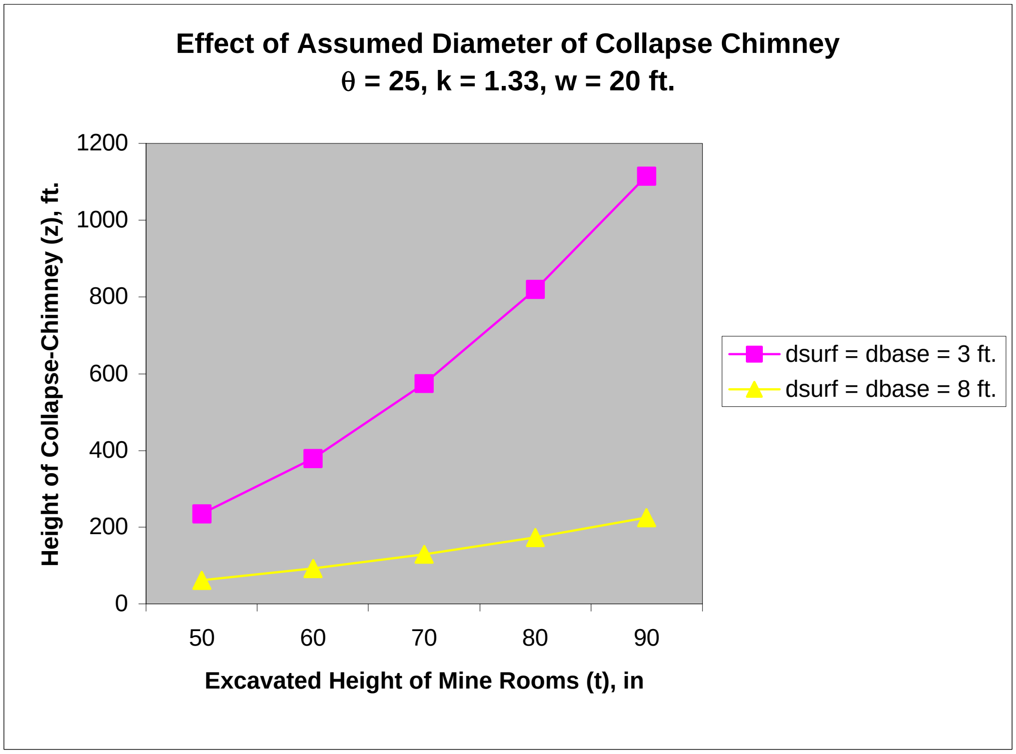


Figure 2.3 Effect of Assumed Diameter of Collapse-Chimney on Height of Collapse-Chimney

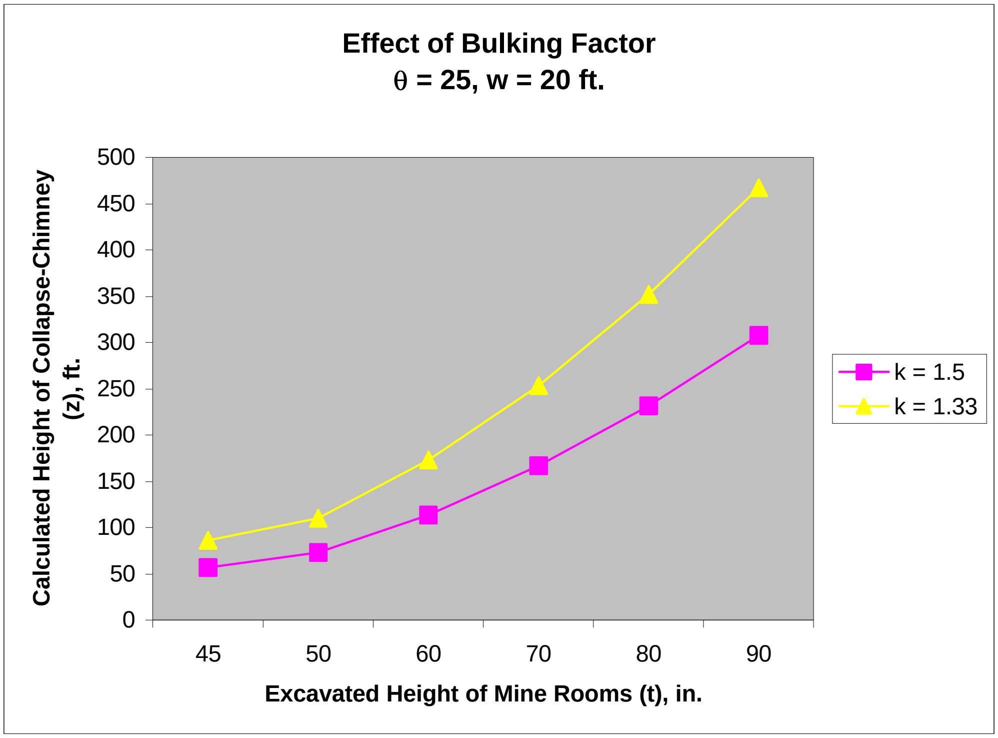


Figure 2.4 Effect of Bulking Factor on Height of Collapse-Chimney

It is obvious from Figure 2.4 that the larger the bulking factor of the caved material, the shorter the projected caving distance. This is due to the greater volume of swollen material filling in the available space, and eventually choking off the caving propagation process.

The following figure depicts the effect of varying the angle of repose of the caved rock within the underground rooms adjacent to the collapsed area.

Figure 2.5 shows, as expected, that the smaller the angle of repose, the higher the calculated caving height.

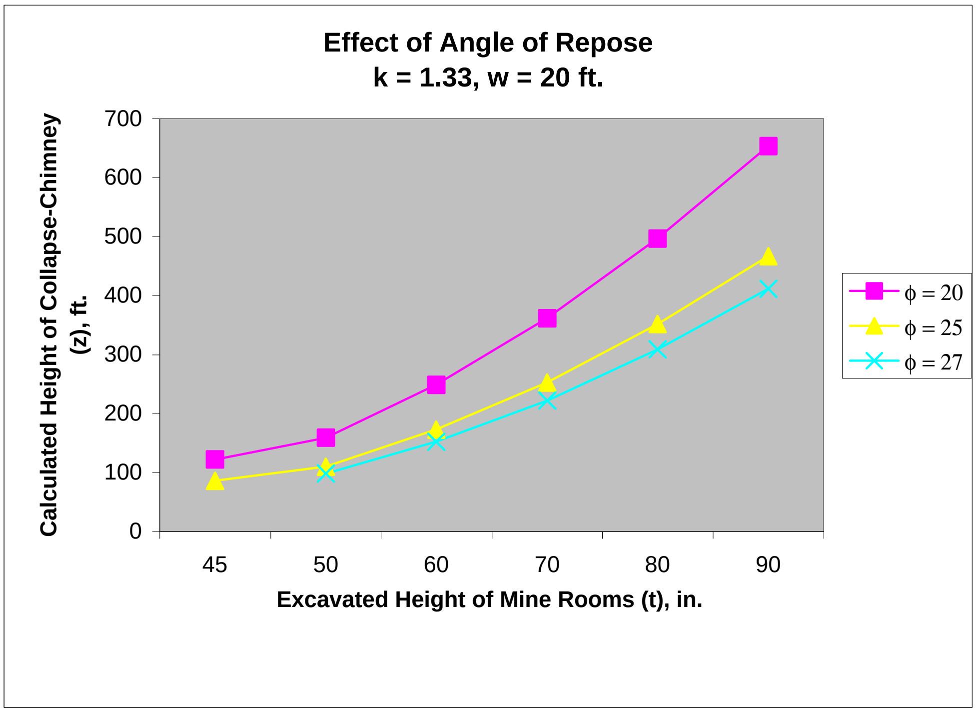


Figure 2.5 Effect of Angle of Repose on Height of Collapse-Chimney

Figure 2.6 displays the relationship between the height of the collapse-chimney and the underground room geometry. The plot indicates that as the width of the underground room increases, there is a decrease in the propagation of the chimney towards the surface.

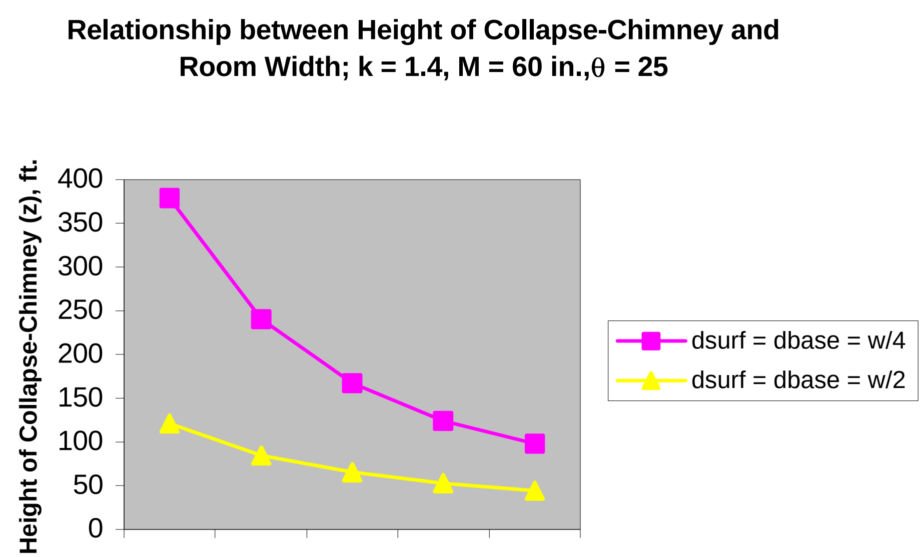


Figure 2.6 Relationship between Height of Collapse-Chimney and Room Width

Figure 2.6 Relationship between Height of Collapse-Chimney and Room Width

Many sinkholes that develop in southwestern Pennsylvania from the collapse of underground rooms are wider at their bases than on the ground surface. The following figure depicts the relationship between height of caving and excavated height of mine rooms for such a sinkhole. One may easily understand from the plot that a hole that widens at its base doesn't cave as high as a hole that maintains its diameter at its surface diameter all the way to its base, assuming that both of the holes surface diameters are the same. This plot also supports the idea that as the diameter of the collapse-chimney decreases, the height of caving increases.

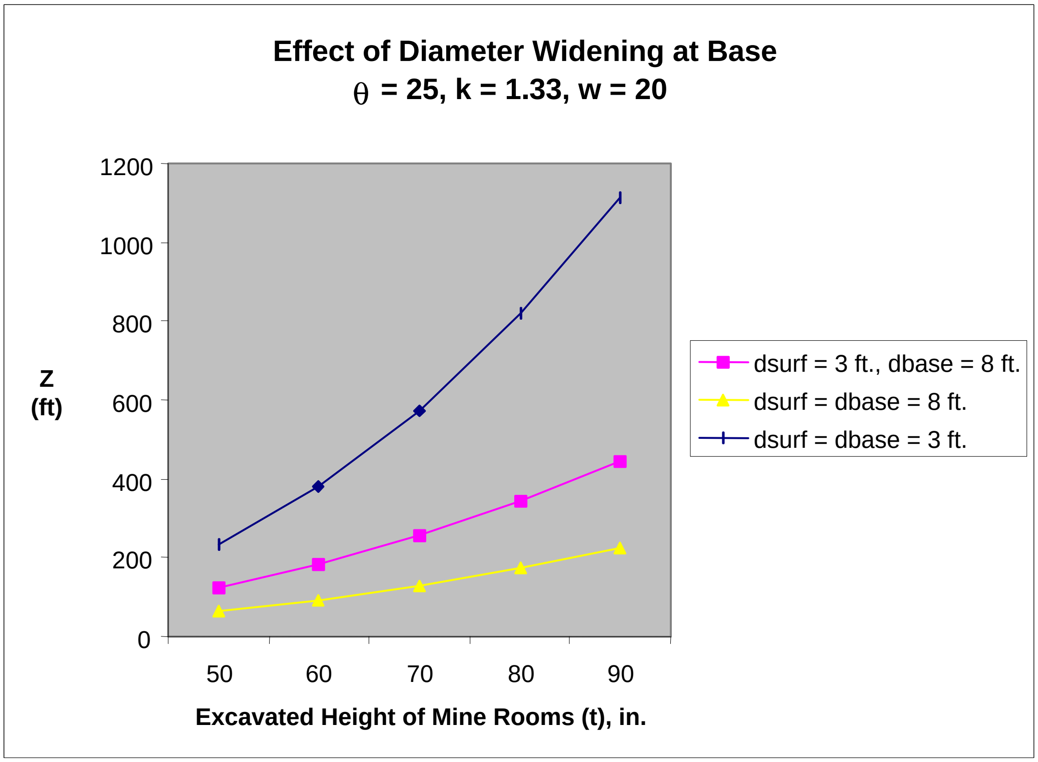


Figure 2.7 Effect of Chimney Diameter Widening at its Base on Height of Collapse-Chimney

2.3 Sand Model Experiments

A model was designed and constructed to demonstrate the formation of a chimney cave and possibly to validate Equation 2.1.6 utilizing sand as the caved material. Figures 2.8 and 2.9 are photographs of the apparatus made from plexiglass and wood. The model geometry is described in Figure 2.9.

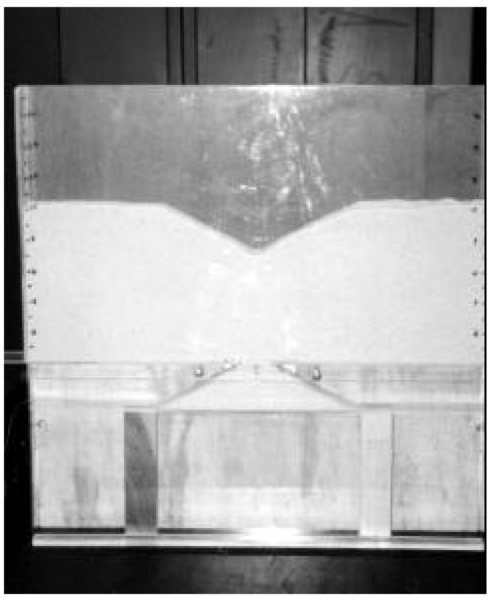


Figure 2.8 (a) Photograph of Sand Model Apparatus (front view)

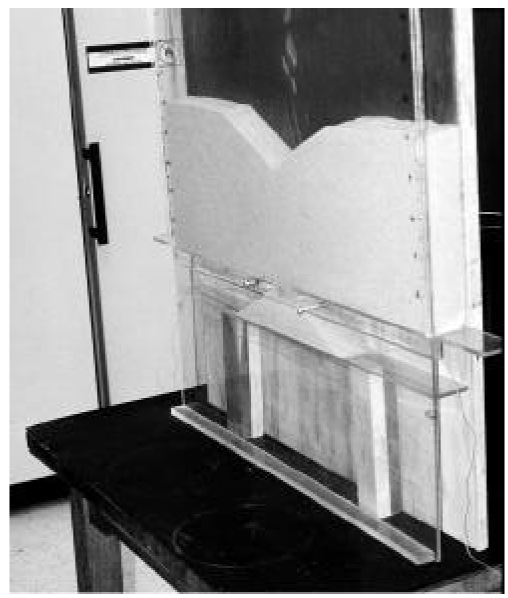


Figure 2.8 (b) Photograph of Sand Model Apparatus (isometric view)

The model was fabricated so that several operating parameters may modified. The height of the void representing the excavated height of the mine rooms may be adjusted by placing different size blocks underneath the lower plastic plate of the apparatus. The opening symbolizing the diameter of the caved roof (and normally the base diameter of the chimney cave) may be altered by pulling apart the two upper plastic plates to any desired distance. Finally, the thickness of overburden may be changed by adjusting the amount of sand placed in the model.

2.3.1 Procedure

The following procedure was used during the experimentation process:

1. Adjust opening width to desired size.
2. Secure trap door in place.
3. Adjust height of void to choice size by positioning accommodating blocks underneath lower plastic plate.
4. Fill apparatus with desired amount of sand using side rulers to gauge proper height.
5. Release trap door allowing material to cave
6. Record Results
7. Remove all sand from apparatus using shop vac
8. Repeat test

Approximately 50 different experiments were conducted on the model, with each trial repeated 3 times to ensure accuracy, totaling 150 separate tests. The width of the opening was varied between 1 and 4 inches while the height of the void alternated between 3 and 4 inches. The height of the sand was set between 2 and 10 inches.

Soon after the experimentation process began it was evident that the model did not accurately simulate actual chimney caving. Due to the fact that sand has no swell factor, and very little cohesion, the results of the experiments could not validate the equation. In each case, the “collapse-chimney” propagated all the way to the sand surface, regardless of the overburden thickness. This is contrary to actual chimney cave formation because as discussed previously, they form from undersurface to ground level, and sometimes don’t ever reach the surface. It is possible to have a cavity form beneath the earth’s surface that remains undetected because it never propagates all the way to the top. This could not occur in sand. The shape of the sinkholes that developed on the surface of the sand were v-shaped, as evident in Figures 2.8 (a) and (b). They actually narrowed at their bases instead of widening. The holes were a mirror image of the caved material at the bottom of the model.

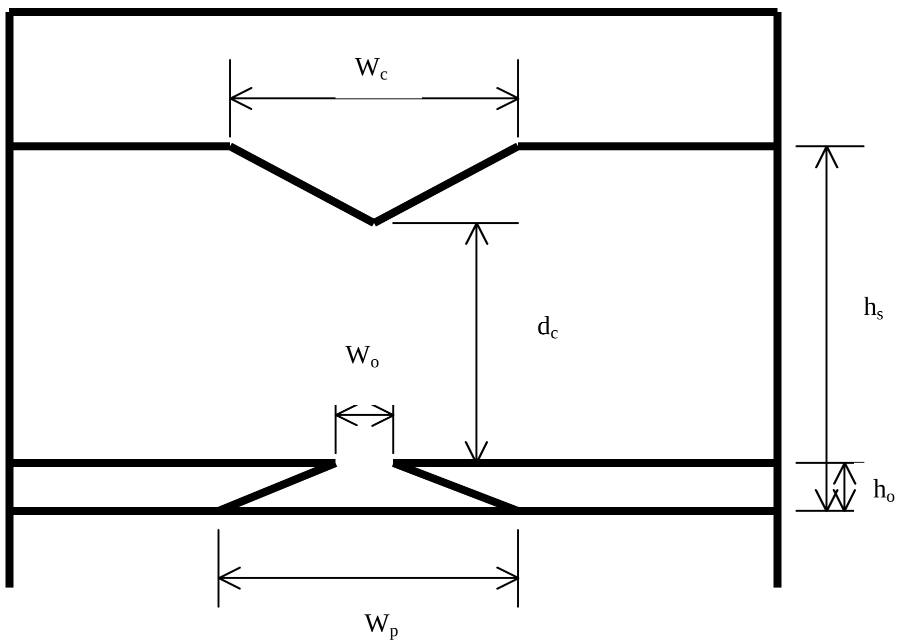


Figure 2.9 A Schematic of the Sand Model Apparatus

where W_o = width of the opening (represents diameter of caved roof, or d_{base} of sinkhole)

h_o = height of the void (represents excavated height of mine rooms)

h_s = height of sand placed in apparatus (represents thickness of overburden)

W_c = width of the caving, or sinkhole, on the sand surface

W_p = width of the caved pile of material

d_c = distance to bottom of sinkhole

* Please note that $h_s - d_c$ = depth of sinkhole

2.3.2 Experimental Results

The following graphs display the results of the experiments.

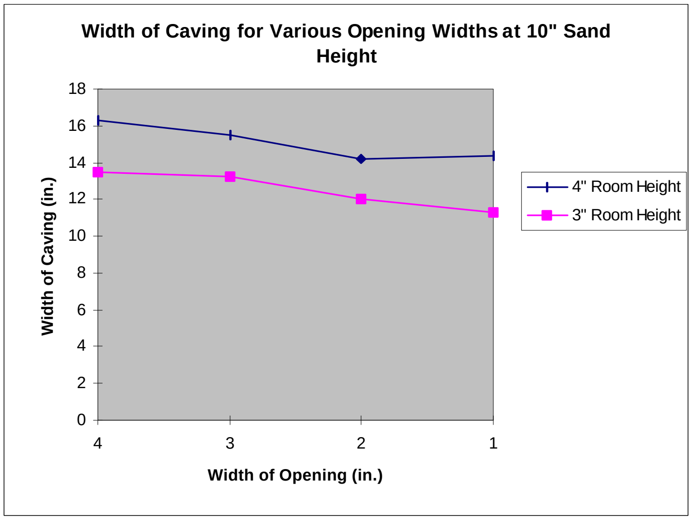


Figure 2.10 Width of Caving for Various Opening Widths at 10" Sand Height

Figures 2.10 through 2.15 clearly show that the width of the caving, or diameter of sinkhole, on the sand surface increased as the opening width increased, and also increased as the room height increased. However, as Figures 2.14 and 2.15 display, as the sand heights became increasingly smaller, the increase in caving width became harder to detect between the 4 and 3 inch room heights.

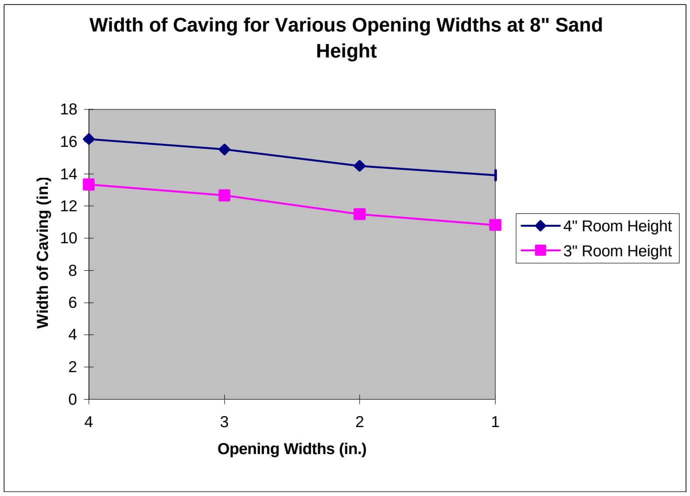


Figure 2.11 Width of Caving for Various Opening Widths at 8” Sand Height

As expected, Figures 2.11 and 2.12 both display the relationship that the larger the opening width, or portion of caved roof, the wider the sinkhole formed on the surface. These figures also clearly show the distinction that as the room height became taller, the sinkhole on the surface also widened.

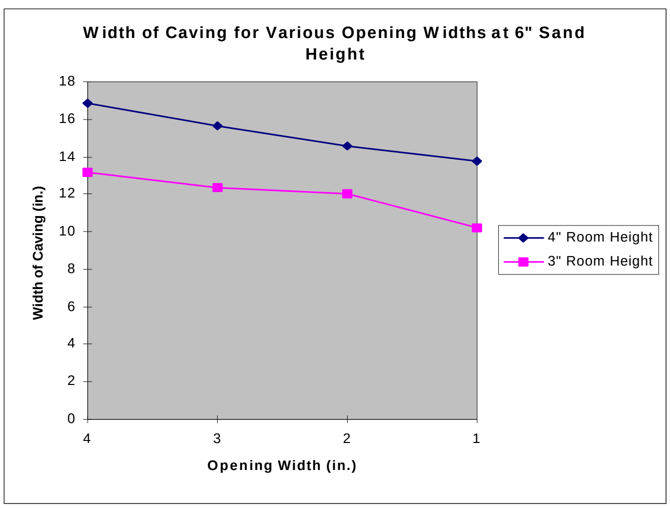


Figure 2.12 Width of Caving for Various Opening Widths at 6” Sand Height

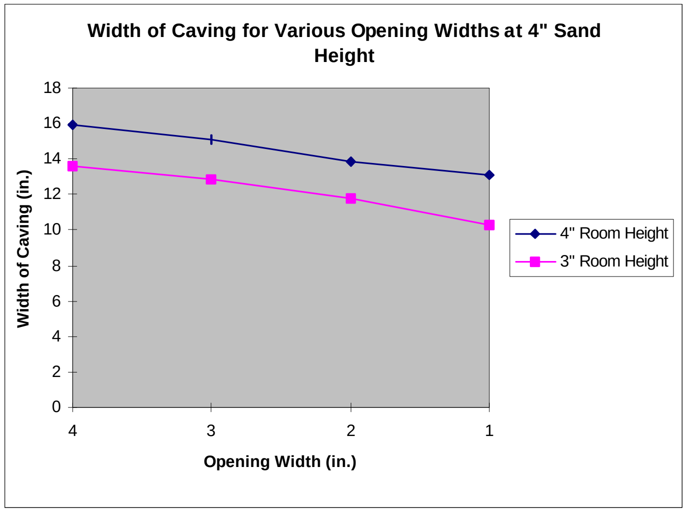


Figure 2.13 Width of Caving for Various Opening Widths at 4” Sand Height

Figures 2.14 and 2.15 clearly demonstrate that as the sand heights got smaller the distinction between widths of caving for the different room heights became harder to detect.

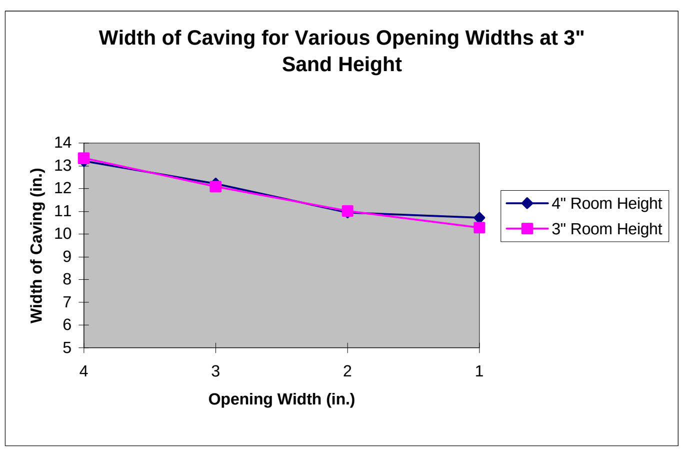


Figure 2.14 Width of Caving for Various Opening Widths at 3” Sand Height

In fact, several of the data points in Figures 2.14 and 2.15 overlap each other or show the experiments with 3 inch room heights caving wider than those with 4 inch room heights. This phenomenon is easily explained. Since the sand height (either 2 or 3 inches) is either equal to or less than the different room heights, the material should cave in an identical manner in either the 3 or 4 inch room heights due to the plethora of available space to receive the caved material. Therefore, theoretically, in Figures 2.14 and 2.15 all of the points should be overlapping.

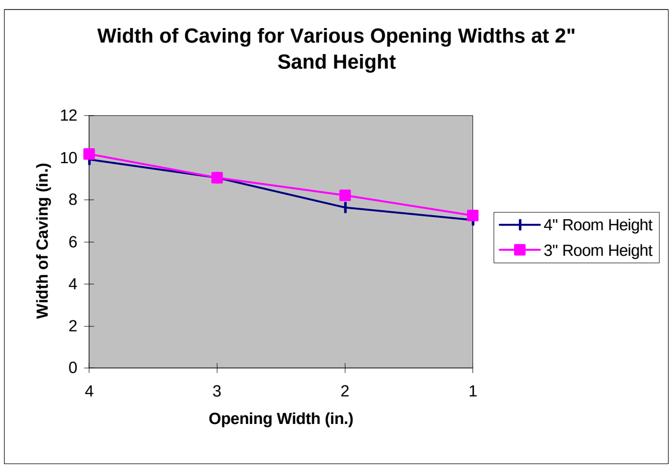


Figure 2.15 Width of Caving for Various Opening Widths at 2” Sand Height

The following graphs show the relationship between distance to caving and opening width for various room heights and sand heights.

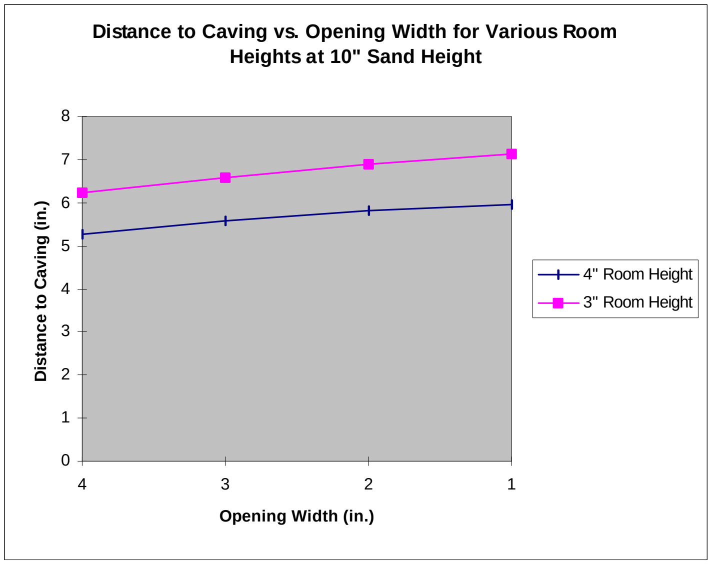


Figure 2.16 Distance to Caving vs. Opening Width for Various Room Heights at 10” Sand Height

It is displayed in Figures 2.16 through 2.19 that as the opening width increased, the distance to caving decreased. Referring to the note beneath Figure 2.9, that $h_s - d_c$ = depth of sinkhole, and realizing that for each plot the sand height remains constant, there is an inverse relationship between depth of sinkhole and distance to caving. In other words, as long as height of sand remains constant, as the distance to caving decreases, the depth of the sinkhole increases. Therefore, in these tests, as opening width increased, depth of sinkhole increased as well. Also, the plot demonstrates that as the excavated room height increased, the distance to caving decreased, or the depth of the sinkhole increased.

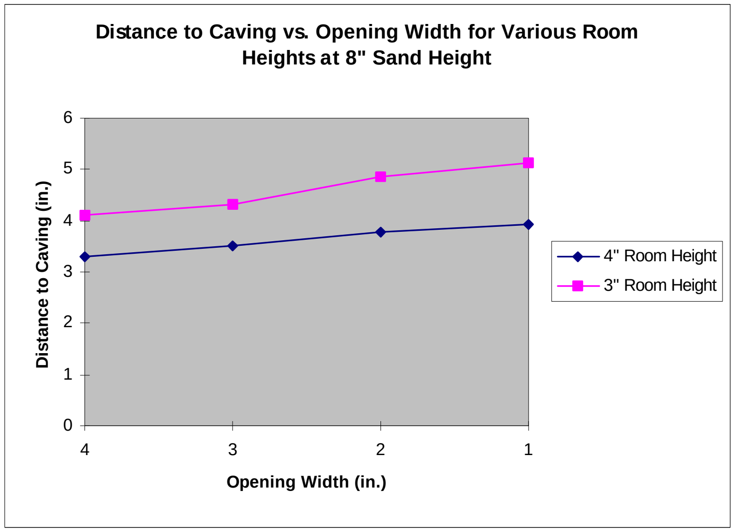


Figure 2.17 Distance to Caving vs. Opening Width for Various Room Heights at 8" Sand Height

Figures 2.17 and 2.18 support the above mentioned arguments with minimal variation.

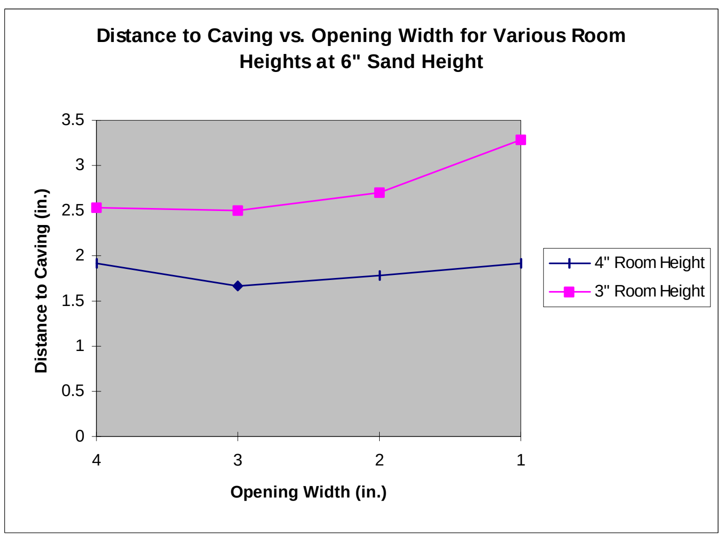


Figure 2.18 Distance to Caving vs. Opening Width for Various Room Heights at 6" Sand Height

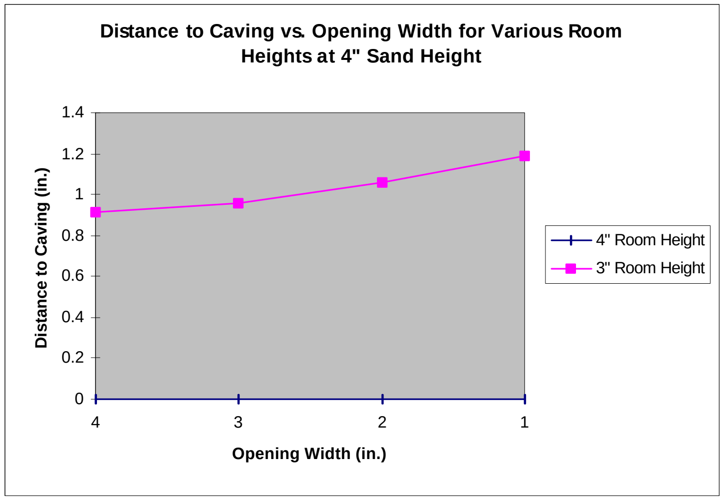


Figure 2.19 Distance to Caving vs. Opening Width for Various Room Heights at 4” Sand Height

Figure 2.19 shows that at a 4 inch room height and 4 inch sand height, there was no distance to the caving. The sinkholes simply bottomed out on the upper plastic plates of the apparatus. The same was true for a 3 inch sand height combined with a 3 or 4 inch room height and for a 2 inch sand height combined with a 3 or 4 inch room height. This is obviously due to the fact that the sand was thin enough to completely fall into the void.

3. FIELD DATA

3.1 Description of Study Area

3.1.1 Location

The area under investigation is located in southwestern Pennsylvania. The chimney subsidence incidents that were examined are located in 11 counties surrounding the Pittsburgh metropolitan area, with the majority located in Allegheny County (35%). They are as follows: Allegheny (28 occurrences), Armstrong (1 occurrence), Bedford (1 occurrence), Cambria (7 occurrences), Clearfield (15 occurrences), Fayette (11 occurrences), Greene (2 occurrences), Lawrence (3 occurrences), Somerset (1 occurrence), Washington (6 occurrences), and Westmoreland (4 occurrences). The sites are located on 33 separate USGS quadrangle maps, with up to seven incidents on a single map. Figure 3.1 is a map of Pennsylvania highlighting the study area.

Figure 3.1 A map of Pennsylvania highlighting area of interest

Table 3.1 shows the number of occurrences of chimney subsidence in each of the 34 quadrangle maps.

Table 3.1 Number of Chimney Subsidence Occurrences in each USGS Quadrangle

USGS Quadrange Map	No. of Occurrences
Murrysville	1
Braddock	7
Pittsburgh West	6
Glassport	5
Pittsburgh East	6
McKeesport	3
Nanty Glo	2
Houtzdale	6
Somerset	1
New Salem	2
Barnesboro	1
Wells Tannery	1
Connellsville	5
Philipsburgh	5
Wallaceton	1
Masontown	1
New Castle North	3
Hastings	2
Carrolltown	2
Mt. Pleasant	1
New Kensington, East	2
Bridgeville	1
Elderton	1
Smithfield	1
Ramey	1
Canonsburg	2
Dawson	1
Curwensville	1
California	1
Donora	2
Washington East	1
South Connellsville	1
Morgantown North	1

3.1.2 Topography

Much of the greater Pittsburgh area is characterized by steep hills and deep ravines. Pennsylvania is divided into several physiographic provinces (see Figure 3.2). Within each province are several sections. The sites under investigation fall into four sections within two provinces, with the majority of the sites occurring in the Pittsburgh Low Plateau Section – Appalachian Plateaus Province. This section includes all of Allegheny, Greene, Washington, and Armstrong Counties, most of Clearfield, Beaver, Butler, Clarion, Jefferson, Indiana and Westmoreland Counties, and parts of Lawrence, Cambria, Venango, Elk, and Fayette Counties. The Pittsburgh Low Plateau Section consists of a smooth, wavy, upland surface cut by numerous, narrow, relatively shallow valleys. Elevations in the area range from 660 to 1700 feet. The local relief on the uplands is generally less than 200 feet, but the relief between valley bottoms and upland surfaces may be as much as 600 feet. Valley sides are moderately steep except in the upper reaches of streams where the valley side slopes are quite gentle (PADCNR, 1997).

All of Somerset County, about half of Fayette and Cambria Counties, and parts of Westmoreland, Indiana, Blair, and Bedford Counties fall under the Allegheny Mountain Section – Appalachian Plateaus Province. Broad, rounded ridges separated by broad valleys are characteristic of this section. The ridges decrease in elevation from south to north, and occur on the crests of anticlines. Local relief on the broad, valley lowland is generally less than 500 feet, but relief between the ridge crests and the adjacent valley lowland can be greater than 1000 feet. The highest elevation in Pennsylvania is located in the Allegheny Mountain Section at Mt. Davis, 3210 feet. Elevations in the area range from 775 to 3210 feet (PADCNR, 1997).

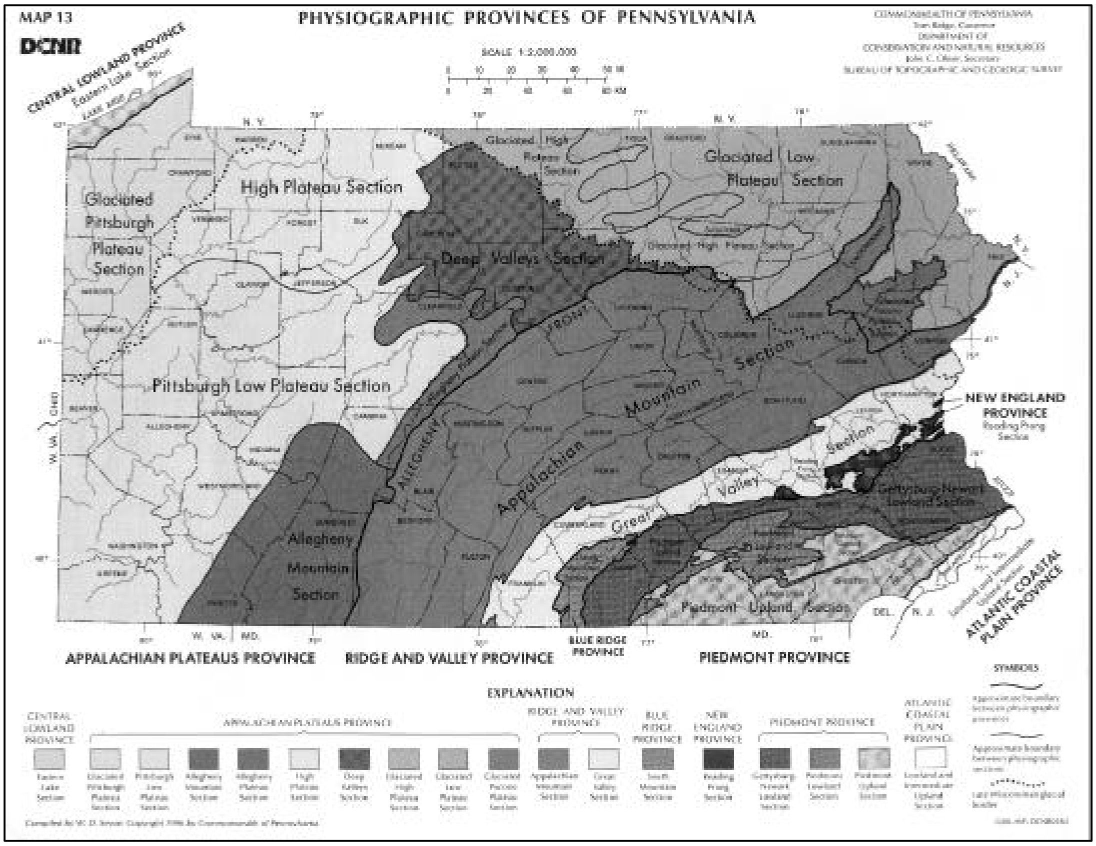


Figure 3.2 Physiographic Provinces of Pennsylvania (Commonwealth of Pennsylvania, DNR)

The Appalachian Mountain Section – Ridge and Valley Province – is made up of numerous, long and narrow parallel mountain ridges separated by narrow to wide valleys. The ridges are several hundred to more than a thousand feet higher than the adjacent valleys. The mountain ranges vary from 1300 to 1600 feet in elevation. Sandstones are present at the crests of the ridges, and relatively soft shales and siltstones occur in most of the valleys. Some of the valleys are underlain by limestone and dolomite. This section is located is central Pennsylvania, and contains parts of 22 counties from Bedford County in the southwest to Pike County in the northeast (PADCNR, 1997).

Finally, a few of the chimney subsidence case studies are located in the Glaciated Pittsburgh Plateau Section of the Appalachian Plateaus Province. This section contains all or most of Erie, Crawford, Mercer, and Lawrence Counties and parts of Warren, Venango, Butler, and Beaver Counties. This section consists mainly of broad, rounded uplands cut by long, linear valleys. The valley floors are flat, and are often wetlands. There is quite frequently a considerable depth of unconsolidated material beneath the valley floor. The lowlands are narrow to wide, and have steep slopes on one or both sides. Elevations in the area range from 900 to 2200 feet. Local relief between valley floors and top of adjacent ridges is between 100 and 600 feet (PADCNR, 1997).

3.1.3 Climate

The weather is affected in Pennsylvania by the varied physiographic features, and the commonwealth is divided into four distinct climatic areas: 1) The Southeastern Coastal Plain and Piedmont Plateau 2) The Ridge and Valley Province 3) The Allegheny Plateau and 4) The Lake Erie Plain. However, it is generally considered to have a humid continental type of climate. The temperature normally remains between 0° F and 100° F and averages about 47° F annually in the north-central mountains to 57° F in the extreme southeast. The average annual precipitation in western Pennsylvania is between 34 to 50 inches (Hickok, et al, 1971). Greatest amounts of rainfall usually occur in the spring and summer months, while February is the driest month. Precipitation in the east seems to be greater than in the west mainly due to coastal storms. (PA State Climatologist, 1997).

Gray et al., (1977) found some correlation between amount of rainfall per month and the number of subsidence occurrences during their extensive study of the area. They concluded that the 1971 – 1975 monthly data suggested that:

1. When precipitation in a certain month exceeds that of the preceding month, the number of subsidence incidents tends to be higher that same month or the month following.
2. Conversely, when precipitation decreases in a certain month, the number of subsidence incidents tends to be lower that same month or the month following.

Gray et al., (1977) also found that most subsidence incidents in the years 1971 – 1975 (36%) had taken place in spring, the three months March through May. Only 9% had taken place in late summer and autumn, the three months August through October. The applicability of this information will be discussed in section 3.2.4.

3.1.4 Geology

The Appalachian Plateau consists of nearly flat-lying beds of Pennsylvanian and Permian age sedimentary rocks (see Figure 3.3). These beds cycle between claystones, siltstones, sandstones, shales, limestones, and coal deposits (Thornbury, 1965).

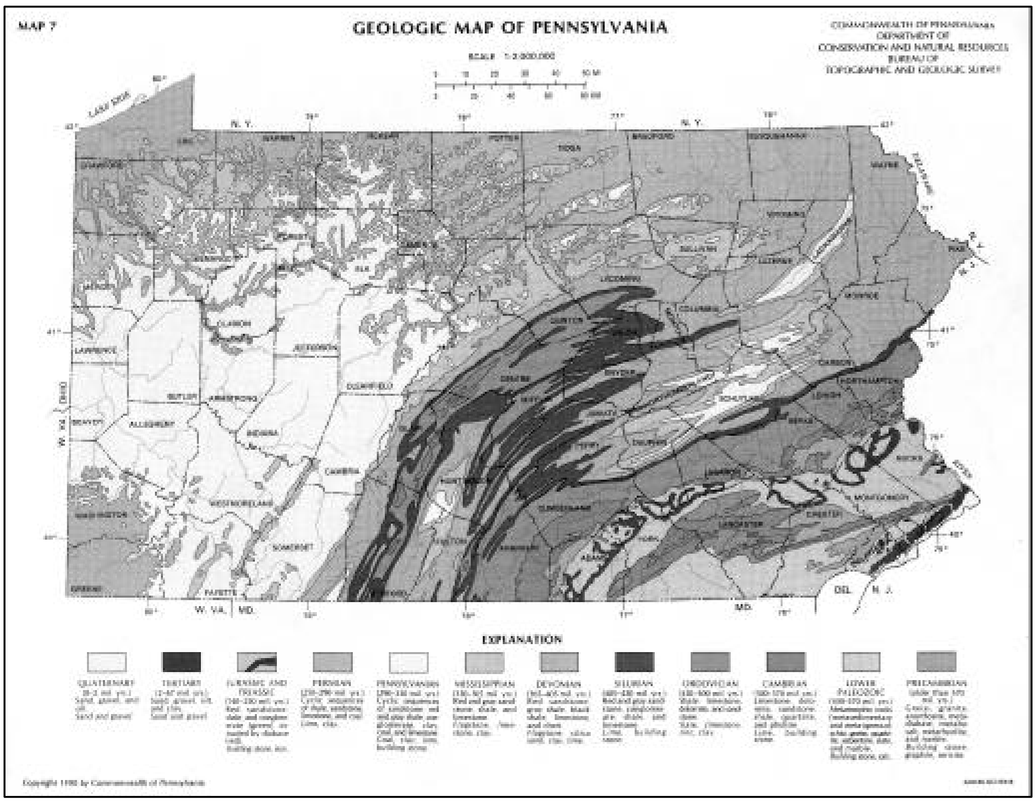


Figure 3.3 Geologic Map of Pennsylvania (Commonwealth of PA, DNR)

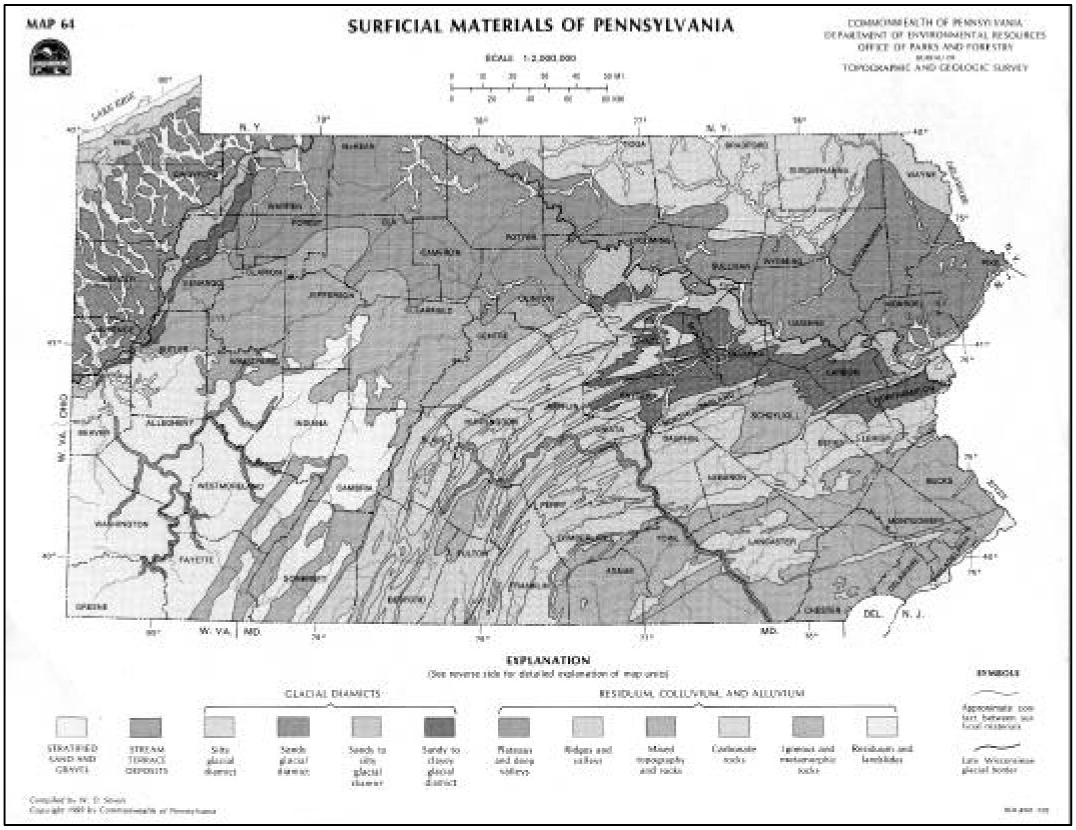


Figure 3.4 Surficial Materials of Pennsylvania (Commonwealth of PA, DNR)

Most of the surficial materials in the study area are classified as either: a) residuum and landslides or b) mixed topography and rocks (see Figure 3.4).

a) Residuum and Landslides

All of Greene, Allegheny, and Washington, and most or parts of Westmoreland, Fayette, Somerset, Cambria, Armstrong, Lawrence, and Clearfield fall into the residuum and landslides surficial materials category. This area consists of a mixed topography developed on mixed rock types which has moderately thick to thick residuum on the upland surfaces and moderately thick to thick colluvium on the hillsides. Residuum is a surface accumulation of unconsolidated rock debris developed in place by the processes of physical and chemical weathering operating on the underlying bedrock. Residuum varies in character from thin accumulations of angular rock fragments broken from the bedrock by the physical processes of freeze and thaw to thick accumulations of unfragmented bedrock that has been extensively altered by chemical weathering. Colluvium is defined as a hillside deposit of unconsolidated, generally matrix-supported, poorly sorted material that has been transported downslope by gravity-driven processes ranging in rate from slow (creep) to fast (debris flow). Up to 30 percent of the surface is underlain by landslide debris in this area, particularly in the southwestern five counties. This landslide debris is comprised of chaotic mixtures of residuum, colluvium, and bedrock. Alluvium (unconsolidated, well to poorly defined layers of clay, silt, sand, gravel, and some boulders) is thin to thick in the valley bottoms (Sevon, 1989).

b) Mixed Topography and Rocks

Parts of Fayette, Somerset, Cambria, Armstrong, and Clearfield fall into the mixed topography and rocks category. This is very similar to the residuum and landslides category as mentioned above. It consists of mixed topography developed on mixed rock types with moderately thick residuum on upland surfaces and thin to moderately thick colluvium on hillsides. The valley bottoms contain thin to moderately thick alluvium (Sevon, 1989).

Finally, Lawrence county consists of stratified sand and gravel and sandy glacial diamict. Stratified sand and gravel includes flat-surfaced deposits in valley bottoms and hummocky deposits along valley sides. The valley-bottom deposits comprise clay, silt, sand, and gravel arranged in layers, approximately parallel to the surface. The deposits along the valley sides consist mainly of sand and gravel layers that are steeply inclined. The sandy glacial diamict has moderate to abundant silt and sand and minimal clay (Commonwealth of PA, DER, Map 64).

3.1.5 Pennsylvania Coal

Pennsylvania contains both bituminous and anthracite coal fields (see Figure 3.5). The coal in the area of interest is contained in the main bituminous field, which consists of high-volatile bituminous coal in beds that are nearly horizontal (see Figure 3.6). This field lies in approximately 20 counties extending in a northeast-southwest direction. Most of this coal was deposited during the Pennsylvanian period of the earth's time scale (Edmunds et al., 1968). The bituminous coals of Pennsylvania are associated with shale, sandstone, clay, and limestone, as mentioned previously. The rocks of these fields are folded into many anticlines and synclines extending in a general northeast direction across western PA (Sisler et al., 1928).

The following table is a list of the coal beds that were mined out beneath the 79 incidents of chimney subsidence under investigation.

Table 3.2 List of Coal Seams in Study Area

Pittsburgh
Lower Kittanning
Upper Kittanning
Lower Freeport
Upper Freeport
Brookville
Redstone
Moshannon (actually Lower Freeport – known as "Moshannon locally in Clearfield County)

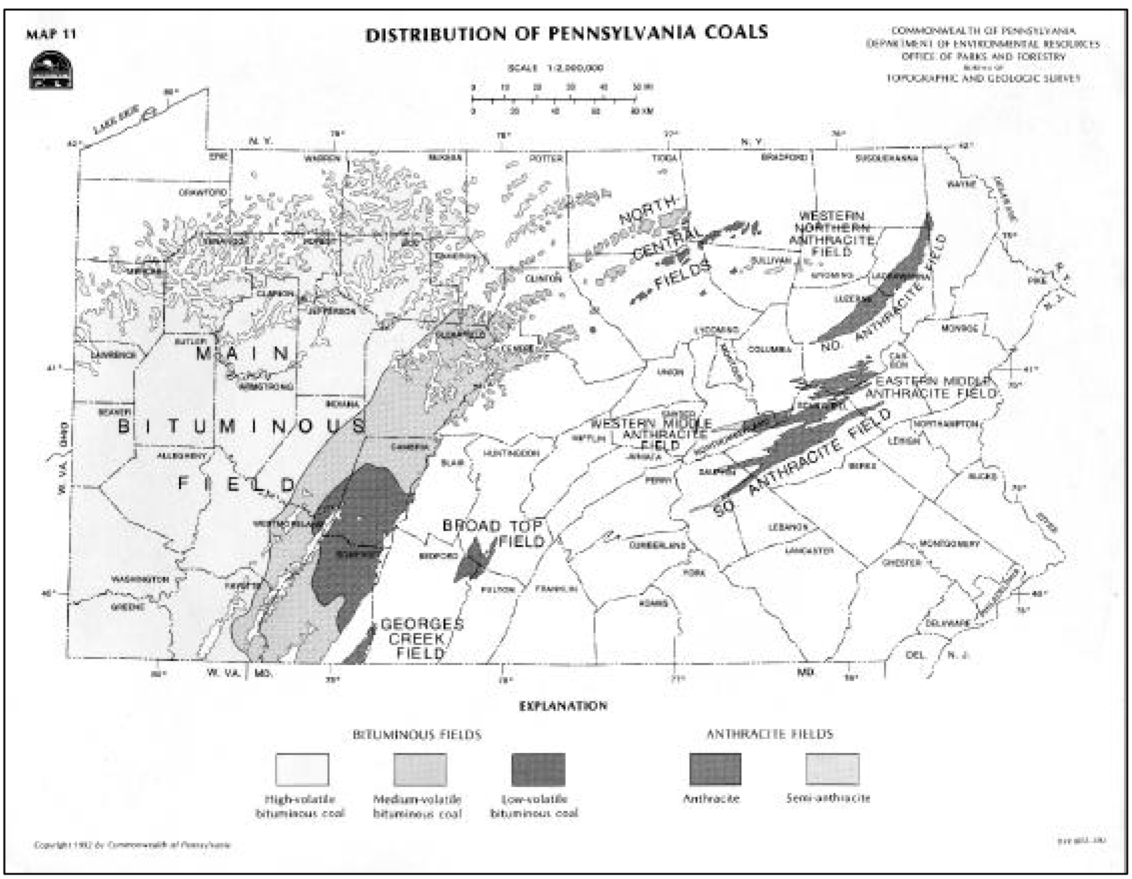


Figure 3.5 Distribution of Pennsylvania Coal Fields (Commonwealth of PA, DNR)

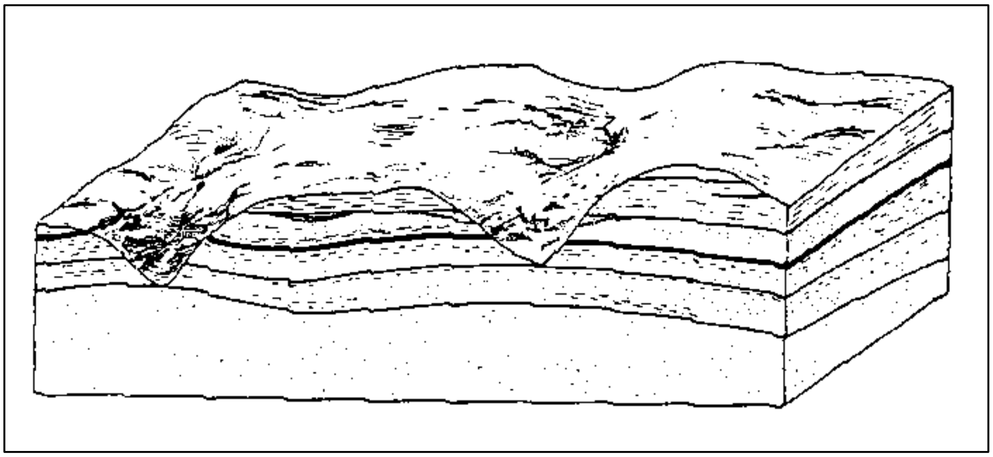


Figure 3.6 Schematic Block Diagram of western Pennsylvania showing nearly horizontal coal strata (Edmunds and Koppe, 1968)

According to Sisler (1928), of the former U.S. Bureau of Mines, the coal beds of Pennsylvania are confined to two systems: Permian and Pennsylvanian. The Pennsylvanian system is divided into an upper, or Pittsburgh, series and a lower, or Pottsville series. The Pittsburgh series is represented by the Monongahela, Conemaugh, and Allegheny groups. The Pottsville series contains almost no large workable coal beds. The Permian system is also divided into and upper and lower series, but only outcrops in Greene and Washington counties, and has almost no commercial importance (Sisler et al., 1928).

a. Monongahela Group

This group ranges from 200 to 375 feet in thickness and includes the strata between the top of the Waynesburg coal and the base of the Pittsburgh. It includes the Waynesburg, Sewickley, Redstone, and Pittsburgh coals, with the Pittsburgh coal being the most valuable and well known in southwestern Pennsylvania. The seam is known for being uniform in thickness and regularity (Johnson, 1929). It ranges from 4 to 16 feet in thickness, averaging about 7 feet (Sisler et al., 1928). The bed is divided characteristically into a roof and main division, with the roof division rarely mined due to numerous bone, clay, and shale partings. The majority of the chimney subsidence incidents under investigation occurred over mined out Pittsburgh coal (Sisler et al., 1928).

b. Conemaugh Group

The Conemaugh group is characterized by the presence of thick beds of red shale. The coal beds in this group are generally less than a foot thick, and are only locally mineable with no important economic value (Sisler et al., 1928).

c. Allegheny Group

More mineable coals are present in the Allegheny group than in any other group in Pennsylvania. The main outcrop is in Westmoreland, Somerset, Cambria, Clearfield, Jefferson, Indiana, Clarion, Armstrong, Lawrence, and Beaver counties. The mineable coals are Upper and Lower Freeport, Upper, Middle, and Lower Kittanning, Brookville, and Clarion. Many of the sites under investigation occurred above mined out coal from these seams. The Upper Freeport ranges from a few feet to 9 feet thick, and is very valuable. The Lower Freeport seam ranges from a few inches to 16 feet thick, and has been mined for its value as a smokeless steam coal. The Upper Kittaning coal ranges from a few inches to 7 feet thick, and its greatest thickness and highest quality are in Cambria and Somerset counties. The Lower Kittaning coal ranges from 15 inches to 7 feet thick, and is probably the most persistent bed in the Allegheny group. Finally, Brookville coal is characterized as being dirty, and ranges from a few inches to 8 feet thick, but does have local importance in several counties (Sisler et al., 1928).

3.2 Documentation of Case Studies

3.2.1 Origin of Case Studies

In order to gather actual field data relating to the subject matter, 79 specific incidents of chimney subsidence were researched and collected. These case studies were obtained from files located at the Department of the Interior, Office of Surface Mining Reclamation and Enforcement (OSM) in Pittsburgh, Pennsylvania. All of the events were cases that had been reclaimed through OSM in the Pittsburgh metropolitan area, and had occurred since 1992. The cases chosen were a random sample of example occurrences taken from several hundred documented cases on file at OSM.

3.2.2 Data Collected

Inside each of the 79 case folders was a detailed recounting of the event that had transpired. Each file was comprised of information regarding the exact location of the incident (latitude and longitude), the approximate date of occurrence, the name of the reporting party (usually the homeowner), the name of the investigating party (OSM staff member), and the circumstances under which the chimney cave was discovered. Many of the folders contained information on the name of the mine and mining company that had undermined the area, the name of the coal seam that had been extracted, and the date that the mine had been abandoned. The majority of the files also contained a detailed description of the pit that had developed (diameter and depth of hole), the thickness of the overburden at that location (inferred from a contour map), and pictures of the hole before and after reclamation. Other data included in the files were method and cost of reclamation, and any additional observations that the investigator may have noted while conducting a site evaluation. Information regarding the thickness of the coal seams that had been mined out was not included in the files. This data was obtained for the holes in the database using the USGS Coal Quality Database (1997). This USGS database contains seam thickness information for various locations where drill samples have been taken.

3.2.3 Database

Following the collection of the files, a large database was compiled containing each piece of information contained in the folders (see Appendix B). The original database contained 83 incidents; however, upon further examination it was determined that 4 of the holes had developed under circumstances not due to chimney subsidence. Therefore, a total of 79 cases were documented.

3.3 Analysis of Data Collected

3.3.1 Dimensions

As mentioned previously, most chimney caves are shaped conically in profile; tending to have wider diameters at their bases, and getting narrower towards the surface. This typical shape somewhat resembles a bottle with the cap off. If the hole has a chance to erode before reclamation, the diameter at the surface may widen creating an hourglass shape. If there was no mention in the file of two different diameters, it was assumed that the hole was cylindrical in shape having the same diameter at top and bottom. Of the 79 occurrences in this database, the mean surface diameter was 4.66 feet and the mean base diameter was 6.31 feet, with a minimum and maximum for both of 0.75 feet and 18 feet, respectively. The mean depth of the 79 holes was 10.53 feet, with a minimum of 3 feet and maximum of 27.5 feet. Figure 3.7 shows the distribution of the depths of the holes.

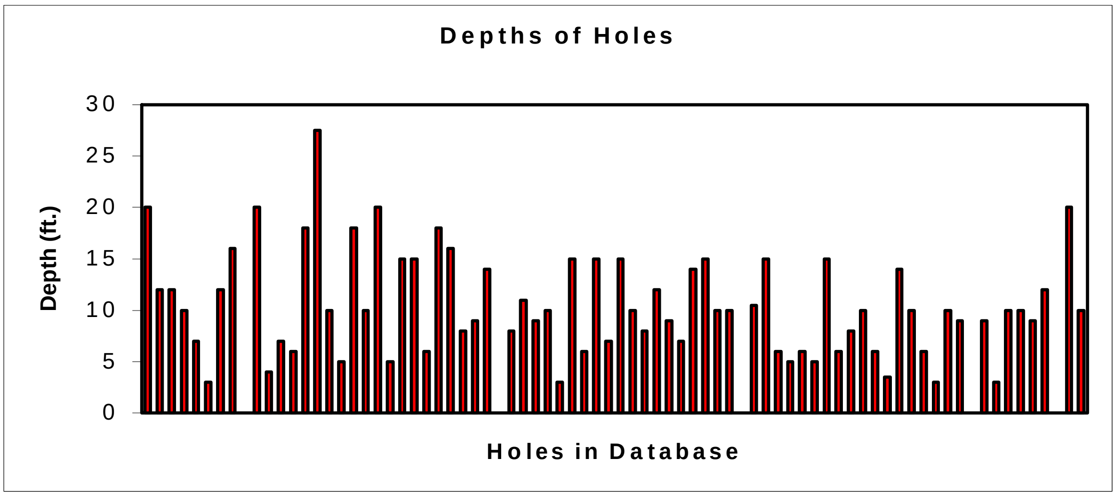


Figure 3.7 Depths of Holes in Database

The mean depth to the underlying coal seam from ground surface (overburden thickness) at these locations was 20.82 feet, with a range of 4 to 50 feet. In each case the thickness of the coal seam was assumed to reflect the mining height, or height of the underground room. The mean thickness of the seams was 54.6 inches, with a minimum of 23 inches, and a maximum of 93 inches. Figures 3.8 and 3.9 show these distributions.

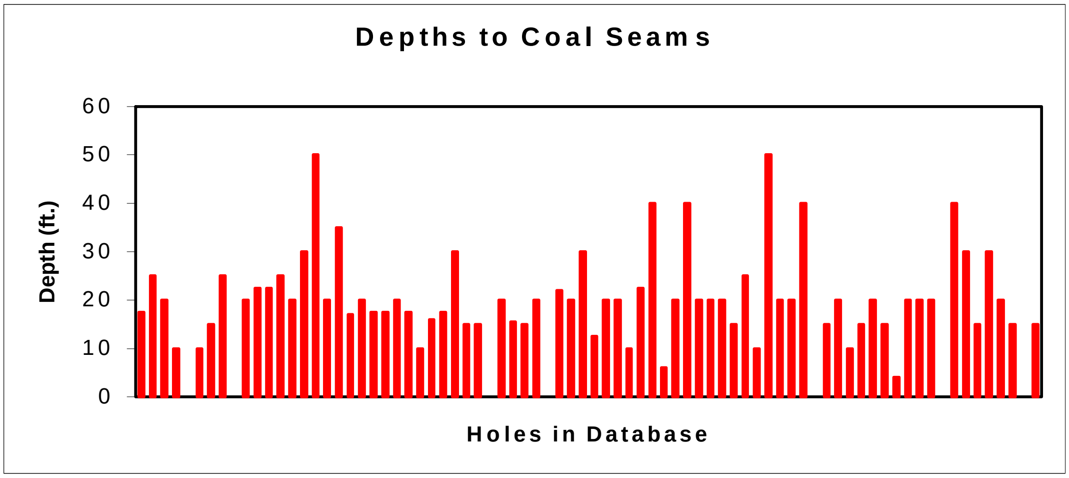


Figure 3.8 Overburden Thickness of Holes in Database

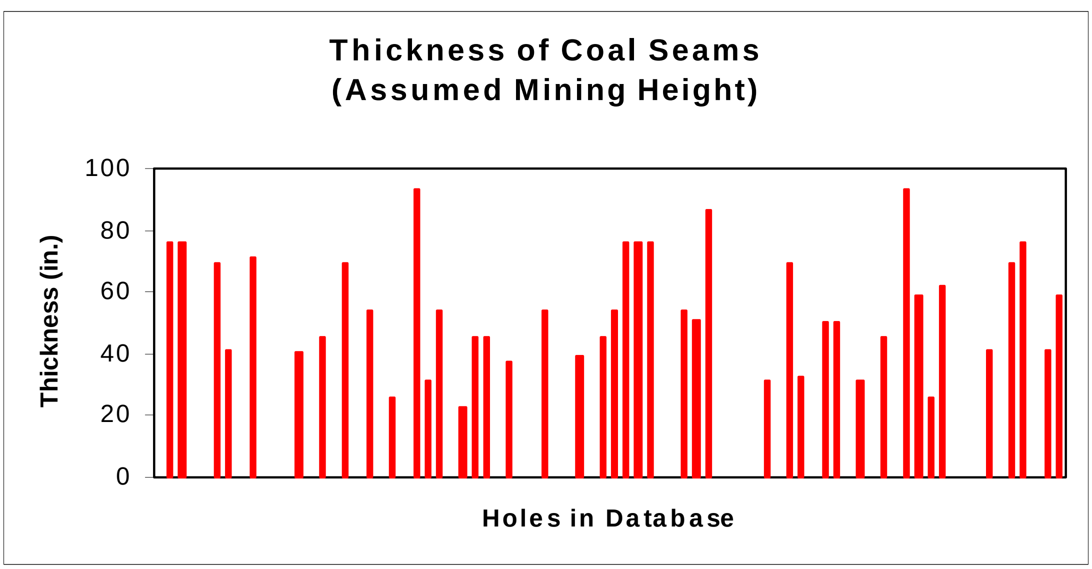


Figure 3.9 Thickness of Coal Seams below Holes in Database

A truncated cone or cylinder was used to estimate each hole's volume. The average volume of the holes in the database was 360.8 cubic feet.

In order to determine if there were correlations between any of these variables, several graphs were made plotting various items. Figure 3.10 displays the relationship between the depth of each hole and it's diameter at the ground surface.

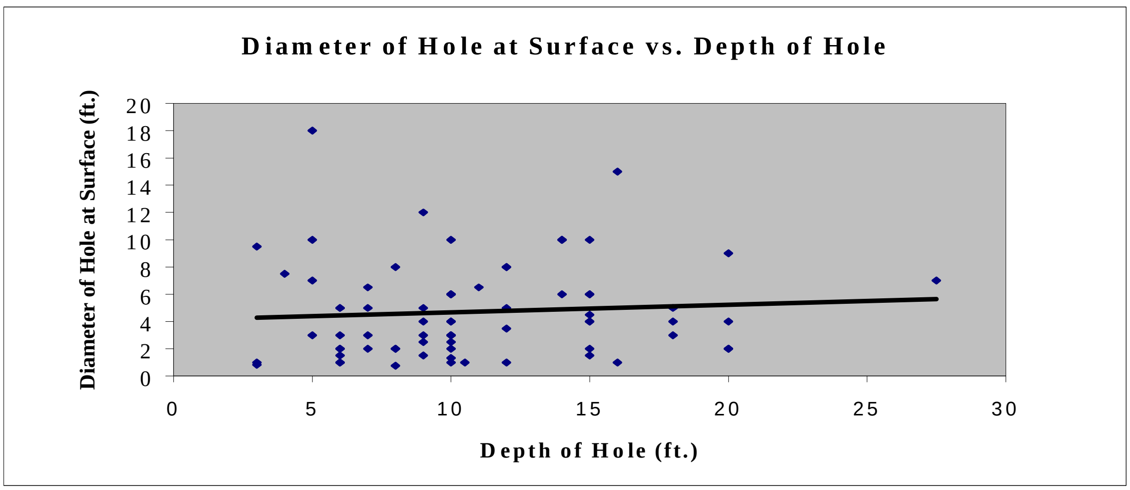


Figure 3.10 Diameter of Hole at Ground Surface vs. Depth of Hole

It is easily seen that there is virtually no correlation between depth of hole and its surface diameter. For example, a 5 ft. deep hole may have a 3 ft. or a 17 ft. surface diameter. The same is true for depth of each hole versus diameter of each hole at its base (see Figure 3.11).

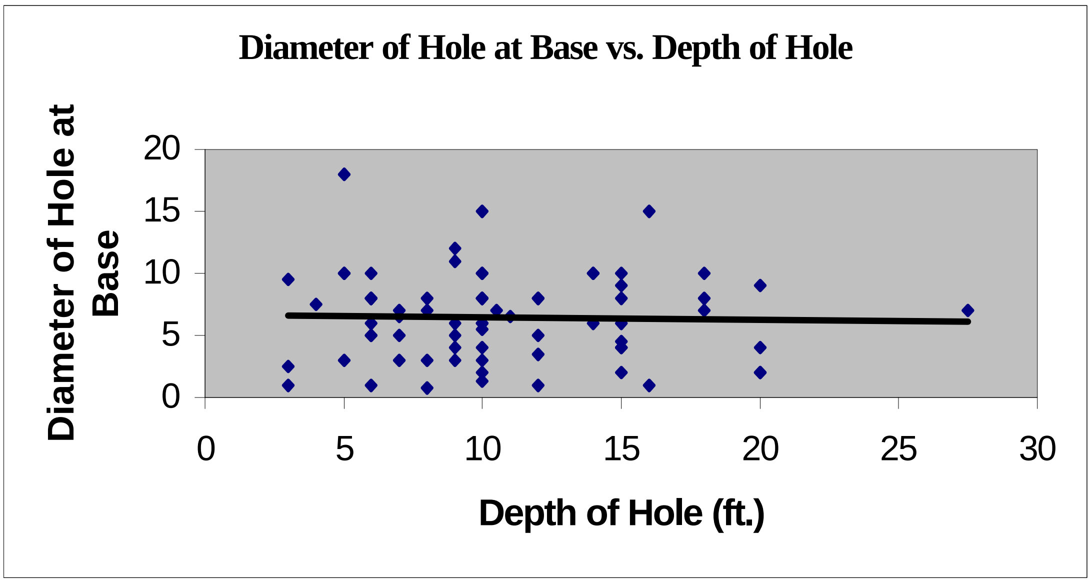


Figure 3.11 Diameter of Hole at Base vs. Depth of Hole

It was believed that the size of each hole should increase with increased seam thickness, or mining height. This is simply due to more space for the material to cave into. A slight correlation was found between seam thickness and volume of hole for the sinkholes in this database. The sand model experiments also verified this idea, in predicting an increased sinkhole diameter and depth for an increase in room height. Figure 3.12 displays this relationship.

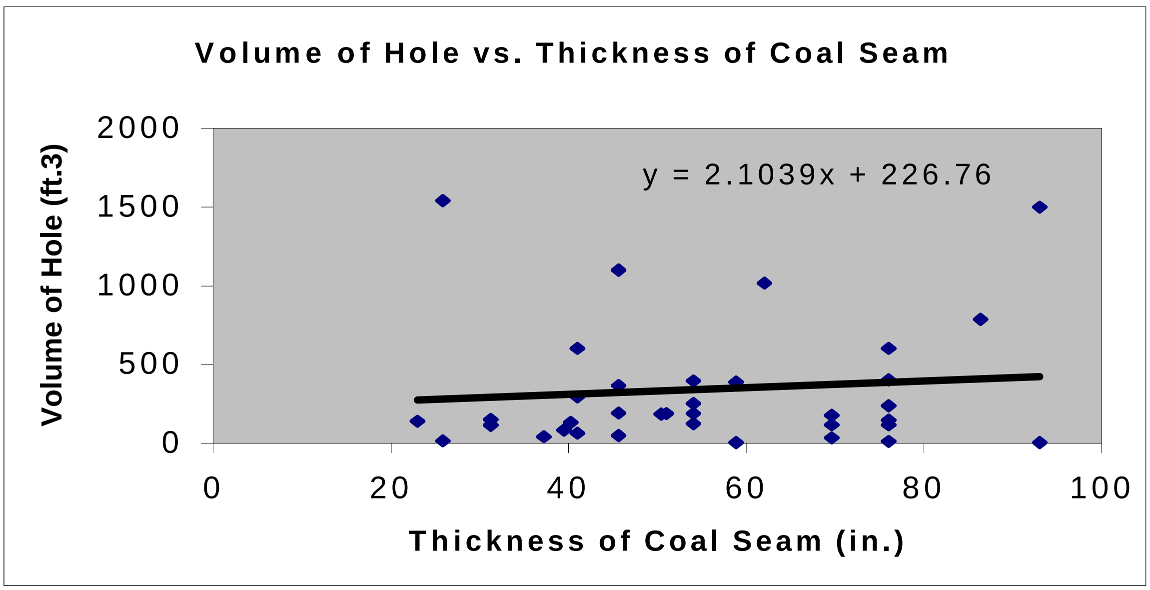


Figure 3.12 Volume of Hole vs. Seam Thickness

3.3.2 Cost and Method of Reclamation

As discussed in Chapter 1.2.5, the chimney caves contained in the database were reclaimed one of two ways: backfilled with concrete, or excavated and backfilled with stone. The preferred choice of reclamation is stone since it is cheaper and easier; however, if access to the site is limited, then the method of choice is concrete. The concrete is pumped into the hole through a hose attached to a nearby truck. The two methods of reclamation were used almost equally for the holes in this database. About 29 holes were backfilled with stone, and 24 with concrete. Many of the files did not include this information. Figure 3.13 displays the distribution of methods.

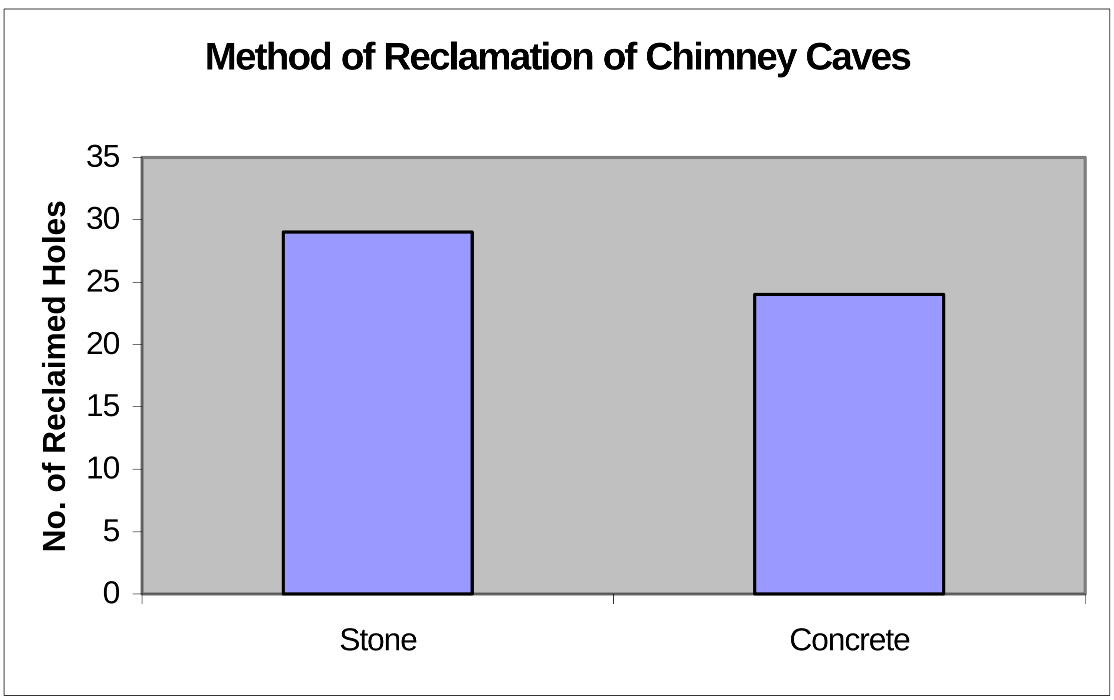


Figure 3.13 Method of Reclamation of Chimney Caves in Database

The cost to reclaim a chimney cave seemed to average out at around $2500 (slightly higher for concrete, slightly lower for stone) per pit, regardless of it's apparent size. This is because often times there are small holes or cracks at the base of the pit that allow the backfilled material to leak into the mine's adjacent entries. Material may also move laterally through cracks or fractures within the pit itself. Therefore, it is difficult to estimate the amount of material needed to reclaim such a subsidence.   The following graph shows the cost of reclamation for each hole in the database for both stone and concrete reclamation methods.

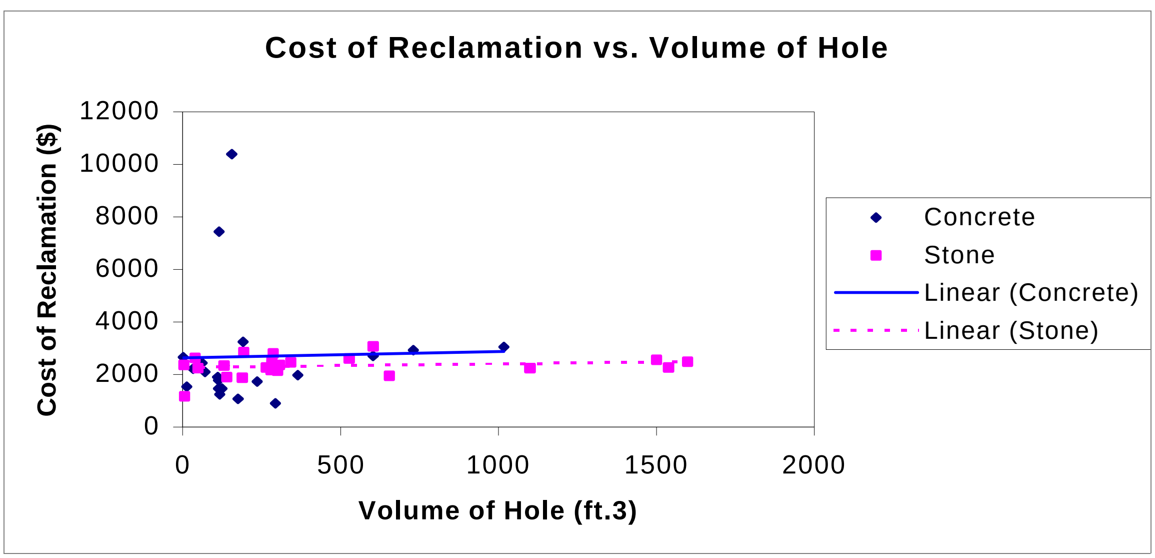


Figure 3.14 Cost of Reclamation vs. Hole Volume

3.3.3 Time

Chimney caving is a phenomenon that usually does not occur for many years after mining operations have ceased and mines have long been abandoned. On average, the incubation period, or elapsed time between mine abandonment and propagation of chimney cave to ground surface, of chimney caves that developed in this database is approximately 60 years. All of the pits developed at least 20 years after mining operations had ceased, and about 71 % of them occurred 60 or more years later (see Figures 3.15 and 3.16).

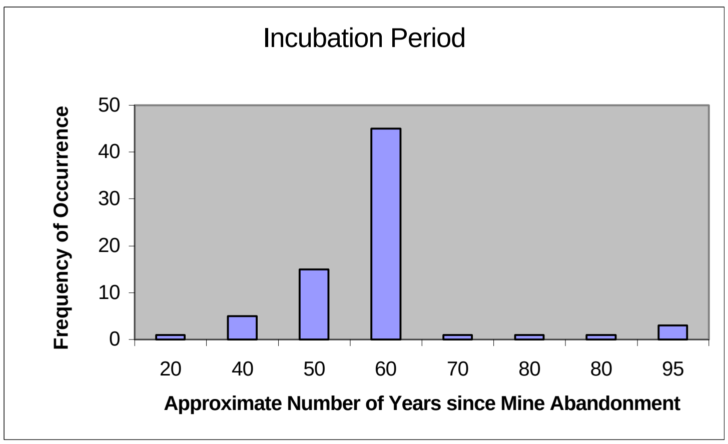


Figure 3.15 Incubation Period for Occurrences in Database

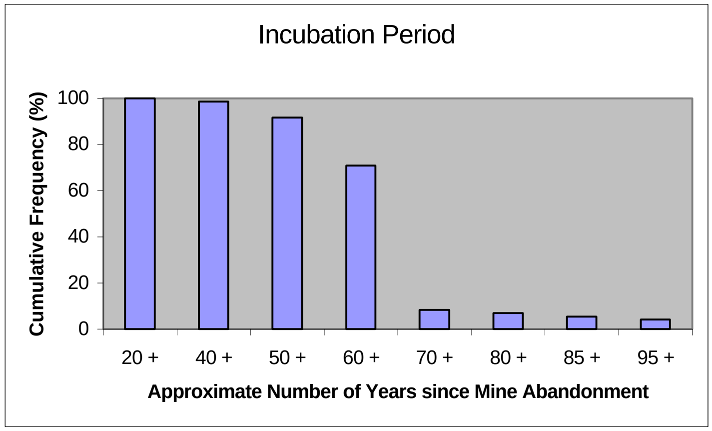
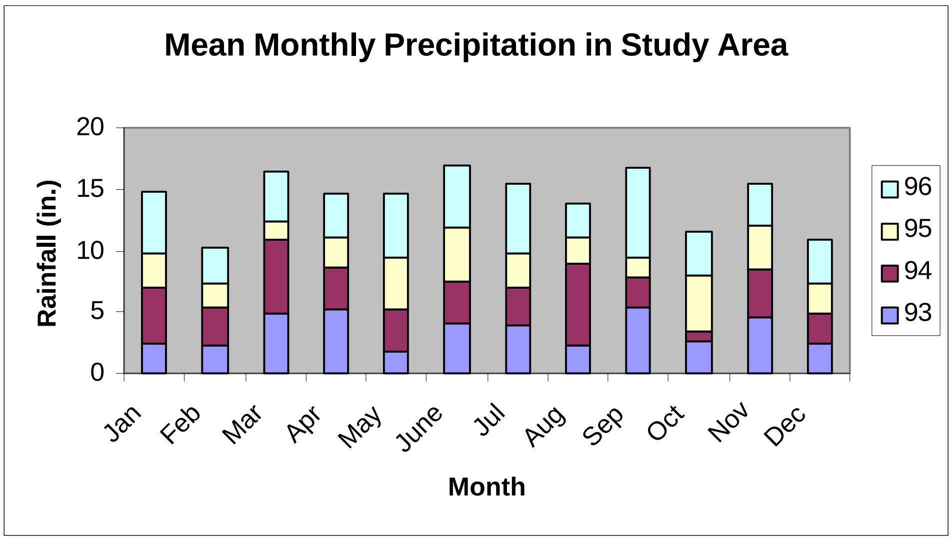


Figure 3.16 Cumulative Frequency of Occurrences since Mine Abandonment

3.3.4 Rainfall

As discussed in section 1.3.3, Gray et al., (1977) found a correlation between subsidence incidents and monthly rainfall for the years 1971 – 1975. In order to verify their findings, monthly rainfall data for the study area was obtained from the Pennsylvania Department of Agriculture, State-Federal Agricultural Statistics Service, Middle Atlantic River Forecast Center for the dates from January 1993 through December 1996. These data were compared to the total number of subsidence incidents reported to the United States Department of Interior's Office of Surface Mining (OSM) in Pittsburgh during that time period. The following figures show both the rainfall and the number of incidents reported. The data obtained validates the statement by Gray et al., (1977) that most subsidence incidents take place in the spring, the three months March through May. Approximately 42% of the incidents that occurred during these years happened during these months. Gray et al., (1977) reported that only 9 % of the incidents occurred during the three months August through October. About 19.5% of the incidents occurred during these months for the data presented here. The least number of occurrences developed in



December (5%).

Figure 3.17 Mean Monthly Precipitation in Study Area

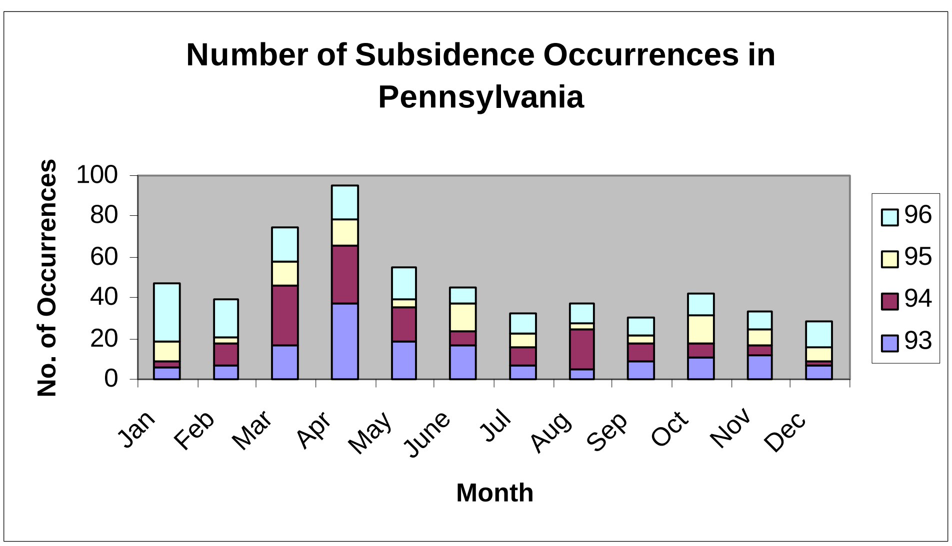


Figure 3.18 Number of Subsidence Occurrences in Pennsylvania

4. DISCUSSION OF RESULTS

4.1 Theoretical

The expression (Equation 2.1.3) developed by Whittaker and Reddish (1989) does provide a starting point for predicting the development of a sinkhole even though several assumptions are made in the calculation such as constant bulking, no lateral movement of the rubble, and perfect geometries. Whittaker and Reddish consider the diameter of the chimney to be in the range of $D = w$ and $D = w\sqrt{2}$, because that is what they have observed the pit diameters to be in their experience. The equation also assumes the shape of the collapse-chimney to be a right cylinder. The applicability of this equation in southwestern Pennsylvania is somewhat limited, however. In this vicinity, the diameters of chimney caves are often a small fraction of the width of the mine rooms. Also, although some of the sinkholes in the region may be cylindrical in shape, many of the sinkholes widen at the base of the hole, creating a truncated cone shape. The Whittaker and Reddish equation grossly overestimates the height of the collapse-chimney for cases where the chimney diameters are smaller than the room widths since the calculation for available space to receive caved rock (V_{space}) does not accurately accommodate chimney diameters (D) less than the room widths (w). Their equation only takes into account those cases where the entire section of roof over the junction has collapsed to produce a chimney subsidence expression on the surface. In addition, the equation does not accurately calculate the volume of available space to receive caved rock (V_{space}) even for those holes where D does equal or exceed w. It assumes that the material caving into the abandoned mine room falls in a truncated square pyramid shape rather than in the shape of a truncated cone. Therefore, a new equation (Equation 2.1.6) has been developed that serves chimney diameters of all sizes, accommodates the possibility of sinkholes with a wider base, and also considers the shape of the fallen material to be that of a truncated cone rather than a truncated square pyramid.

Many conclusions were drawn from changing the values of the variables in the equation. It was determined that the smaller the assumed diameter of the collapse-chimney, the higher the cave will propagate towards the surface of the earth. The larger the bulking factor of the caved material, the shorter the projected caving distance. The smaller the angle of repose, the higher the calculated caving height. Finally, as the width of the underground room increases, there is a decrease in the propagation of the chimney towards the surface.

Unfortunately, the modified equation could not be verified using the results of the sand model experiments. Due to the fact that sand has no bulking factor, and very little cohesion, the shape of the sinkholes that developed in the tests did not accurately reflect true chimney subsidence surface expressions. In each case, the “collapse-chimney” propagated all the way to the sand surface, regardless of the overburden thickness. The shape of the sinkholes that developed on the surface of the sand were v-shaped. However, the sand model tests did indicate that as the room height increased, both the diameter and depth of the sinkholes increased. This was validated by the database analysis in the conclusion that as the seam thickness (room height) increases, the volume of the sinkhole increases.

4.2 Experimental

Equation 2.1.6, used to calculate the height of the collapse-chimney, was verified using the results obtained from the chimney caves contained in the database. In order to determine whether or not there is a possibility of developing a sinkhole on the surface, one would compare the thickness of the overburden in the area of interest to the calculated height of the collapse-chimney. If the thickness of the overburden were to exceed the height of the collapse-chimney, the hole would not propagate all the way to the earth's surface. Since all of the documented collapse-chimneys in the database propagated through to the surface, the height of the collapse-chimney calculated from this modified equation should equal or exceed the actual thickness of the overburden. There are 79 documented case studies in this database; however, because many of the files are missing one or more pieces of pertinent information, only about half of the cases could be used to verify the equation. The calculated height of the collapse-chimney equaled or exceeded the actual overburden thickness 95% of the time using the modified equation. In the cases that the equation misjudged the height of the collapse-chimney, it was only a slight underestimation, and one must keep in mind that many assumptions are made in using the equation (ie. room width, bulking factor, angle of repose, etc.). One should also note that the overburden thicknesses as well as seam thicknesses were taken from contour maps – not actually measured in the field. Therefore, there may be some inaccuracy in those numbers causing the calculated cave propagation height to be erroneous. It is also evident from the results of the attempted verification of Equation 2.1.3 that the Whittaker and Reddish equation grossly overestimates the height of the collapse-chimney. Many of their predictions are 500 feet or more – higher than any recorded depth in a case of pit subsidence. This is mainly because the equation uses the room width, not the chimney diameter, to calculate the volume of available space to received caved rock within the mine room itself (referring to the Mw^2 portion of Equation 2.1.2). Therefore, in the cases where the diameter is less than the room width, the calculation of V_{space} is grossly overestimated.

In southwestern Pennsylvania, Equation 2.1.6 seems to predict the height of a potential collapse-chimney quite accurately. In order to safely determine whether a site has potential to develop a chimney subsidence, one should acquire as much information regarding the underground conditions as possible. If certain conditions can not be obtained, one should assume worst case conditions (small bulking factor, small angle of repose, etc.) in order to obtain the highest projected caving distance. If the thickness of overburden at that location exceeds this projected caving distance, chances are that no chimney cave will propagate through to the surface.

5. SUMMARY AND CONCLUSIONS

The conclusions derived from this study of the occurrence and prediction of chimney subsidence in southwestern Pennsylvania are summarized as follows:

It was theoretically proven that:

1. The smaller the assumed diameter of the collapse-chimney, the higher the cave will propagate towards the surface of the earth.
2. The larger the bulking factor of the caved material, the shorter the projected caving distance.
3. The smaller the angle of repose, the higher the calculated caving height.
4. As the width of the underground room increases, there is a decrease in the propagation of the chimney towards the surface.
5. A hole that widens at its base doesn't cave as high as a hole that maintains its diameter at its surface diameter all the way to its base, assuming that both of the holes surface diameters are the same.

Conclusions drawn from the sand model experiments:

6. The sand model experiments did not accurately simulate actual chimney caving. Due to the fact that sand has no swell factor, and very little cohesion, the results of the experiments could not validate the equation. In each case, the "collapse-chimney" propagated all the way to the sand surface, regardless of the overburden thickness. The shape of the sinkholes that developed on the surface of the sand were v-shaped, as evident in Figures 2.8 and 2.9. They actually narrowed at their bases instead of widening.

7. The width of the caving, or diameter of sinkhole, on the sand surface increased as the opening width increased, and also increased as the room height increased.
8. As the opening width of the sand model apparatus increases, the distance to caving decreases, or the depth of the sinkhole increases. Also, as the excavated room height increases, the distance to caving decreases, or the depth of the sinkhole increases.

It was evident from the analysis of the case studies contained in the database that:

9. Of the 79 occurrences in the database, the mean surface diameter was 4.66 feet and the mean base diameter was 6.31 feet, with a minimum and maximum for both of 0.75 feet and 18 feet, respectively. The mean depth of the 79 holes was 10.53 feet, with a minimum of 3 feet and maximum of 27.5 feet.
10. The mean depth to the underlying coal seam from ground surface (overburden thickness) at these locations was 20.82 feet, with a range of 4 to 50 feet. In each case the thickness of the coal seam was assumed to reflect the mining height, or height of the underground room. The mean thickness of the seams was 54.6 inches, with a minimum of 23 inches, and a maximum of 93 inches.
11. A truncated cone or cylinder was used to estimate each hole's volume. The average volume of the holes in the database was 360.8 cubic feet.
12. There is virtually no correlation between depth of hole and its surface diameter or depth of hole and its base diameter.
13. The size of each hole should increase with increased seam thickness, or mining height. This is simply due to more space for the material to cave into. A slight

correlation was found between seam thickness and volume of hole for the sinkholes in this database. This also validates the results of the sand model experiment in that as the room height increases, both the depth and diameter of the sinkhole increase.

14. About 29 holes were backfilled with stone, and 24 were backfilled with concrete.

15. The cost to reclaim a chimney cave seemed to average out at around $2500 (slightly higher for concrete, slightly lower for stone) per pit, regardless of it's apparent size. This is because often times there are small holes or cracks at the base of the pit that allow the backfilled material to leak into the mine's adjacent entries. Material may also move laterally through cracks or fractures within the pit itself. Therefore, it is difficult to estimate the amount of material needed to reclaim such a subsidence.

16. On average, the incubation period, or time lapse between mine abandonment and occurrence of subsidence incident, of chimney caves that developed in this database is approximately 60 years. All of the pits developed at least 20 years after mining operations had ceased, and about 71 % of them occurred 60 or more years later.

17. The data obtained validates the statement by Gray et al., (1977) that most subsidence incidents take place in the spring, the three months March through May. Approximately 42% of the incidents that occurred during these years happened during these months. About 19.5% of the incidents occurred during

these months for the data presented here. The least number of occurrences developed in December (5%).

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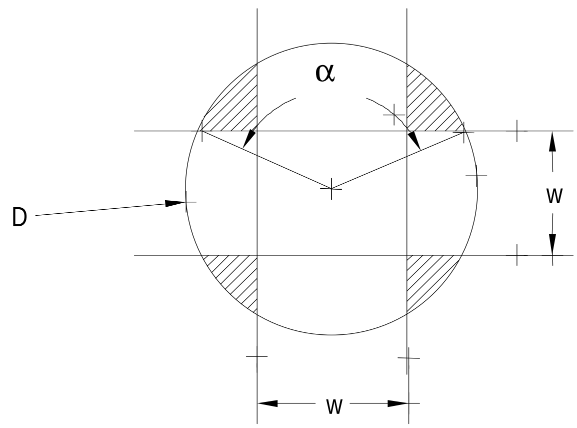
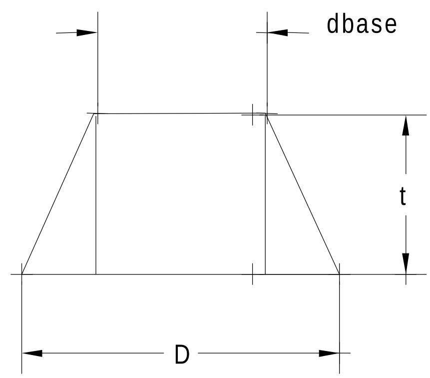
APPENDIX A

Derivation of Modified Equation (Equation 2.1.6)

Consider the following figures in the derivation of Equation 2.1.6.





$D_{base} = d + 2t \cot \theta$

The shaded areas on the figure indicate the locations of the coal pillars. The volume of available space to receive caved rock equals the entire volume of the sinkhole after swell (in shape of a frustrum) plus the available space underground (also in the shape of a frustrum) minus the volume of the coal pillars in the region .

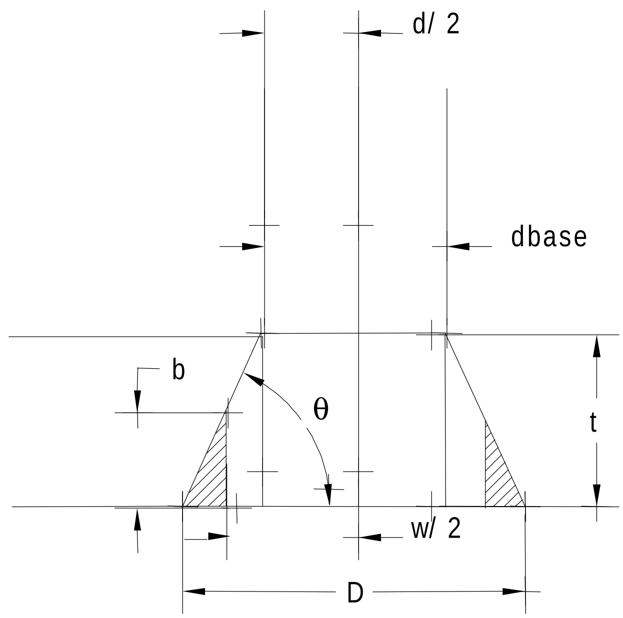
$$A_{shaded} = 4 \left[(D/2)^2/2 \, (\alpha - \sin\alpha)\right] - \left[\pi \, (D/2)^2 - w^2\right]$$

$$= D^2/2 \, (\alpha - \sin\alpha) - \pi D^2/4 + w^2$$

$$\cos(\alpha/2) = (w/2)/(D/2) = w/D \quad \therefore \quad \alpha = 2 \arccos(w/D)$$

$\therefore\ A_{shaded} = D^2/2\ (2 \text{ arcos } (w/D) – \sin(2 \text{ arcos } (w/D)) - \pi D^2/4 + w^2$

$= D^2 \text{ arcos } (w/D) - D^2/2 \sin(2 \text{ arcos } (w/D) - \pi D^2/4 + w^2$



$\tan\theta = b / (D/2 – w/2) = 2b/(D - w)\ \therefore\ b = (D – w)/2 \tan\theta$

$V_{shaded} = 1/3\ A_{shaded}\ b$

$\therefore\ V_{shaded} = 1/3\ [D^2 \text{ arcos } (w/D) - D^2/2 \sin(2 \text{ arcos } (w/D) - \pi D^2/4 + w^2]\ (D – w)/2 \tan\theta$

$= (D – w)/6 \tan\theta\ [D^2 \text{ arcos } (w/D) - D^2/2 \sin(2 \text{ arcos } (w/D) - \pi D^2/4 + w^2]$

The volume of the sinkhole (considered to be in the shape of a truncated cone, or frustrum) is shown below.

$V_{sinkhole} = \pi/12\ z\ (d_{base}{}^2 + d_{surf}{}^2 + d_{base}d_{surf})$

where z = the height of the collapse chimney

The volume of the underground frustrum equals:

$V_{frustrum} = \pi/12\ t\ (d_{base}{}^2 + D^2 + Dd_{base})$

Therefore, the volume of available space to receive caved rock is equal to:

$V_{frustrum} + V_{sinkhole} - V_{shaded}$

$$V_{space} = \pi/12\ t\ (d_{base}^2 + D^2 + Dd_{base}) + \pi/12\ z\ (d_{base}^2 + d_{surf}^2 + d_{base}d_{surf}) - \tag{2.1.5}$$

$$(D - w)/6 \tan\theta\ [D^2 \operatorname{arcos}(w/D) - D^2/2 \sin(2 \operatorname{arcos}(w/D) - \pi D^2/4 + w^2]$$

The volume of caved material, after swell, equals the volume of the sinkhole times the swell factor, k

$$V_{caved} = \pi/12\ z\ (d_{base}^2 + d_{surf}^2 + d_{base}d_{surf})\ k \tag{2.1.4}$$

Equating (2.1.4) and (2.1.5), z is equal to:

$$z = 12/(\pi\ (k\text{-}1)\ (d_{base}^2 + d_{surf}^2 + d_{base}d_{surf}))\ (\pi/12\ t\ (d_{base}^2 + D^2 + Dd_{base}) - \tag{2.1.6}$$

$$((D - w)/6 \tan\theta)\ (D^2 \operatorname{arcos}(w/D) - D^2/2 \sin(2\operatorname{arcos}(w/D)) - \pi D^2/4 + w^2))$$

where,

D	$= d_{base} + 2t \cot\theta$
V_{caved}	= volume of caved rock from collapse-chimney
V_{space}	= volume of available space to receive caved roof rock
k	= bulking factor (1.33 to 1.5)
z	= height of collapse-chimney
d_{base}	= diameter of collapse-chimney at base
d_{surf}	= diameter of collapse-chimney at earth's surface
w	= width of mine rooms
t	= excavated height of mine rooms
θ	= angle of repose of caved rock within mine rooms adjoining collapse area

APPENDIX B

Site No.	Site Name	City	Latitude	Longitude	County	Project Number	Contact Person	Diameter of Hole ft.	Depth of Hole ft.	Depth to Coal Seam	Mining Company	Name of Mine	Name of Seam	Date of Collapse	Date that Mining Ceased
1	Chicken Stree	Penn Township	40.3806	79.6722	Westmoreland	PA-97-009	Dan	8 x 10	20	15 to 20	Pittsburgh Coal Co.	Lynn Run Mine	Pittsburgh	10/20/96	1936
2	Renz	Churchill	40.4408	79.8442	Allegheny	PA-97-016	George	3.5	12	25 ?????	Pittsburgh Coal Co.	Hampton Mine	Pittsburgh	early 8/96	prior WWII (1936)
3	Seminora	Penn Hills	40.4906	79.8186	Allegheny	PA-97-040	Rick	5	12	20	Pittsburgh Coal Co.	Snyder No. 3 Mine	Pittsburgh	03/23/97	.940's or prior to 193
4	Augusta Stree	Pittsburgh	40.4322	80.0236	Allegheny	PA-96-035	Jeff	3 on surface 15 at 10 ft. depth	10	10????	unknown or Pitt. Coal Co.		Pittsburgh	03/08/96	prior to 1936
5	Hindman	Library	40.2861	80.9806	Allegheny	PA-96-015	Dan	2 on surface 5 at 7 ft. depth	7		Consumers Fuel Co. or Snowden Coke Co.	Snowden Mine		12/22/95	1930's
6	Everitt	Munhall	40.3883	79.9250	Allegheny	PA-97-032	George		3	10 ??		Schotting No. 3 Mine	Pittsburgh	late 1/97	prior to 1936
7	Dale Road	Jefferson Borough	40.2794	79.8881	Allegheny	PA-96-021	Rick	8	12	10 to 20	Pittsburgh Coal Co.	Walton 2nd Pool Mine	Pittsburgh	01/31/96	prior to 1940's
8	Bill Fix	North Huntingdon	40.3417	79.7575	Westmoreland		Rick	15	16	25	Reed Coal Co.		Pittsburgh	Fall, 96	prior to 1950's
9	Hiquet	North Versailles	40.3603	79.8136	Allegheny	PA-97-052	Dan	4 x 5	lepth to top of rock = 9			McHaffey Mine	Pittsburgh	late 3/97	prior to 1950's
10	Swahn	Penn Hills	40.4589	79.8125	Allegheny	PA-96-045	Rolland	2 3	20 3	20 20	Pittsburgh Coal Co.	Sandy Creek Mine		04/04/96	prior to 1936
11	Sowalla	Nanty Glo	40.4661	78.2556	Cambria	PA-95-007	Dan	7.5	4	20 to 25	Webster Coal & Coke Co.	Nanty Glo No. 14 Mine	Lower Kittanning	11/29/94	.950's or prior to 193
12	Sowalla II	Nanty Glo	40.4661	78.2556	Cambria	PA-96-041	Dan	8 x 5	7	20 to 25	Webster Coal & Coke Co.	Nanty Glo No. 14 Mine	Lower Kittanning	03/26/96	.950's or prior to 193
13	Christine Yarger										Jones & Hensel Coal Mining Co.				1940
14	Croft	Somerset	40.0031	79.0678	Somerset	PA-96-066	Dan	2 at surf. 6x10 at 6 ft. depth	6	20 to 30	unknown or Neva Mine ??		Upper Freeport	06/27/96	prior to 1940
15	Churner						George				Jones & Hensel Mining Co.				
16	County Home	South Union Township			Fayette	PA-97-026	George	4 at surf. 8' at least at base	18	20	unknown	Snyder No.2	Pittsburgh	12/16/96	prior to WWII
17	Formeck	Barnesboro	40.6603	78.7894	Cambria	PA-97-022	George	7	25 to 30			Country Bank Mine	Lower Freeport	12/03/96	prior to WWII
18	Dodson	Broad Top Township	40.1192	78.2300	Bedford	PA-97-003	Jeff	2x3 at surf. 10 at 10 ft. depth	10	50	Keystone Coal Co.		Barnett-Lower Kittanning	09/29/96	prior to 1950
19	Bohlin	White Oak	40.3097	79.8089	Allegheny	PA-97-023	Rick	3	5	20	Boston Coal Co.	Yough No.2	Pittsburgh	12/10/96	late 1930's or early 40's
20	Cummings All	Connellsville	40.0247	79.5942	Fayette	PA-97-017	Jeff	3 at surf. 10 at depth of 18 ft.	18	35	B&O Railroad	B&O mine??	Pittsburgh	11/17/96	prior to 1940
21	Helen Davis	Carnegie	40.3972	80.1131	Allegheny	PA-97-021	George	4	10	approx 17 ft.			Pittsburgh	11/30/96	
22	Gaal	Everson	40.0917	79.5847	Fayette	PA-96-036	Rolland	4	20	20	Staufeer & Wiley Coal Co.	Home Mine	Pittsburgh	02/26/96	mid 1930's

Site No.	Site Name	City	Latitude	Longitude	County	Project Number	Contact Person	Diameter of Hole ft.	Depth of Hole ft.	Depth to Coal Seam	Mining Company	Name of Mine	Name of Seam	Date of Collapse	Date that Mining Ceased
23	Gormont	Philipsburg	40.8925	78.2375	Clearfield	PA-97-034	Dan	14 x 22	5	15 o 20			Upper Kittanning	02/21/97	1940's
24	Husted	West Decatur	40.9206	78.3061	Clearfield	PA-96-043	Dan	5x4	15	15 to 20			Moshannon	03/25/96	prior to 1940's
25	Garrison	Dunkard Township	39.7528	79.9583	Greene	PA-97-005	Rolland	10x10	15	20	Kelleys Creek Colliery	Maiden Mine	Pittsburgh	10/03/96	prior to 1971??? or 1936
26	Giordano	New Castle	41.0639	80.3467	Lawrence	PA-97-011	Bill	3 at surf. 8' at base	6	15 to 20			Brookville	10/26/96	1901
27	Mildred Snyde	Robinson Township	40.4719	80.1250	Allegheny	PA-97-058	Rick	5 at surf. 7 below grade	16 to 20	10		Moon Run Mine	Pittsburgh	05/20/97	prior to 1950's
28	Maple Street	Everson	40.0917	79.5847	Fayette	PA-96-065	Jeff	1	16	16	Staufeer & Wiley Co.	Home Mine	Pittsburgh	06/21/96	prior to 1936
29	Centennial St	Houtzdale	40.8236	78.3472	Clearfield	PA-96-029	Dan	2 at surf. 7 below grass line	8	15 to 20		Country Bank Deep Mine	Brookville	02/25/96	1950's
30	Cence	Hastings	40.6633	78.7161	Cambria	PA-97-002	Dan	2.5 at surf. 10x12 below surf.	9	30	Oak Coal Co.		Lower Freeport	09/28/96	Prior to 1950's
31	Burley	Patton	40.6247	78.6936	Cambria	PA-96-018	Jeff	10	14	15	PA Coal & Coke Co.	Ashcroft No. 55	Lower Freeport	01/19/96	prior to 1940's
32	Bungard	Mt. Pleasant Township	40.2078	79.5389	Westmoreland	PA-96-061	Rolland	see remarks		15	Mt. Pleasant Coke Co.		Pittsburgh	05/23/96	prior to 1936
33	Carr	Houtzdale	40.8286	78.3431	Clearfield	PA-96-078	George	2 at surf. 3 at base	8				Upper Kittaning	09/07/96	prior to WWII
34	Renton Road	Renton	40.5083	79.7189	Allegheny	PA-96-046	Dan	5x8	11	20	Union Collieries Company	Renton No.4	Pittsburgh	04/12/96	1920's
35	Ruyechan	West Mifflin	40.3883	79.8792	Allegheny	PA-96-026	Rick	1.5' at surf. 6' just below grass, nar-rows to 2' at depth of 9'	9	15.5	Park Coal Co.	Park Mine	Pittsburgh	02/21/96	1940's
36	Scalise	Carnegie	40.4017	80.1122	Allegheny	PA-96-076	George	3' at surf. 8' at base	10	10 or 20	Pittsburgh Coal Co.	Fort Pitt Mine	Pittsburgh	09/01/96	prior to WWII
37	Schneider	West Mifflin	40.3961	79.8708	Allegheny	PA-96-048	Dan	10 in. at surf 2.5' at base	3'	20	Pittsburgh Coal Co.		Pittsburgh	03/17/96	prior to1936
38	Williams	West Mifflin	40.3556	79.9558	Allegheny	PA-96-049	George	6	15	<29	Pittsburgh Coal Co.	First Pool No. 1 Mine	Pittsburgh	04/19/96	Prior to WWII
39	Walker	Elderton	40.6822	79.3297	Armstrong	PA-96-082	Bill	2' at surf. 6' just bel. surf.	6' ?	30 or 15-20			Upper Free-port	09/07/96	1950's
40	Zelahy	Penn Hills	40.4869	79.8172	Allegheny	PA-96-039	Rolland	6' at surf. 8-10' bel. grade	15'	20		Snyder #3	Pittsburgh	03/28/96	prior to 1936
41	Elder Townsh	Hastings	40.6558	78.7044	Cambria	PA-97-042	Rolland	3	7			Binder Brothers Mine	Lower Freeport	04/02/97	1930's
42	Greenleaf III	PIttsburgh	40.4372	80.0319	Allegheny	PA-97-046		4	15	10 to 15			Pittsburgh	03/28/97	1940's
43	Lougeay Roa	Penn Hills	40.4486	79.8167	Allegheny	PA-96-016	Dan	3' at surf 5.5 below surf.	10		Rochez Bros.	Boch Mine	Pittsburgh	1/17/96	prior to 1936
44	Maurizi	North Versailles	40.3783	79.8044	Allegheny	PA-97-033	Jeff	8	8	70 ?	Taylor Bros. Coal Co.	Mine # 1	Pittsburgh	01/14/97	prior to 1936
45	McCarrick	Penn Hills	40.3417	79.8250	Allegheny	PA-96-004	Rolland	8	12	10 ?		Snyder # 3	Pittsburgh	10/26/95	1940's
46	Prepelka	Whitaker	40.3975	79.8889	Allegheny	PA-97-014	Rick	4	9	20 to 25	Pittsburgh Coal co.	Holly No. 1 & Holly No. 2 mines	Pittsburgh	11/09/96	early 1940's
47	North High Sc	West Mifflin	40.3808	79.8758	Allegheny	PA-96-052	George	5 at surf. 7 at base	7	40	Pittsburgh Coal co.	Risher Mine	Pittsburgh	04/27/96	prior to 1936

Site No.	Site Name	City	Latitude	Longitude	County	Project Number	Contact Person	Diameter of Hole ft.	Depth of Hole ft.	Depth to Coal Seam	Mining Company	Name of Mine	Name of Seam	Date of Collapse	Date that Mining Ceased
48	Pennsbury IV	Pennsbury	40.4292	80.1042	Allegheny	PA-97-007	George	6	14	6	Pittsburgh Coal Co.	Moon Run Mine	Pittsburgh	10/03/96	prior to 1977?
49	German Town Road	German Town-ship	39.8625	79.9542	Fayette	PA-97-036	Rolland	4	15	20	Frick Coke Co.	Leckrone-Ronco Mine	Pittsburgh	03/03/97	1930's
50	Delucia	Ramey Borough	39.8625	79.9542	Clearfield	PA-96-072	Jeff	10	10	40	Ramey Coal Co.		Lower Kittanning	07/25/96	prior to 1940
51	Evelyn Miller	Houston	40.2528	80.2097	Washington	PA-96-014	Rolland	6	10	20	Pittsburgh Coal Co.	Binder Brothers Mine		12/22/95	1930's
52	Evelyn Miller	Houston	40.2528	80.2097	Washington	PA-97-047	Rolland	4	4 or 15 ??	20	Pittsburgh Coal Co.	Binder Brothers Mine		04/09/97	1930's
53	Nelson	Vanderbilt	40.0356	79.6553	Fayette	PA-96-009	Dan	1 at surf. 9x5 bel. surf.	10.5	20	H.C. Frick Coal Co. or W.J. Rainey Co.	Fort Hill Mine	Pittsburgh	11/25/95	1930's
54	McDonald	Hawk Run	40.9250	78.2042	Clearfield	PA-97-006	Jeff	1x2 at surf 8 at base	15	15	unknown		Freeport	09/01/96	prior to 1940
55	Leighty	Neshannock	41.0383	80.3406	Lawrence	PA-96-071	Rick	1' at surf. 8' at base	6	25	New Castle Railroad & Mining Co.		Brookville	07/30/96	prior to 1940
56	Patkalitsky	Houtzdale	40.8111	78.3519	Clearfield	-97-015+E206		6x8 10' at base	5	10	unknown		Freeport CRDP	11/11/96	prior to 1900
57	William Lewis	Gastonville	40.2581	79.9931	Washington	PA-97-031	Rick	5	6	50	unknown	Gastonville No. 1 Mine	Pittsburgh	01/29/97	prior to 1940's
58	Wink	Curwensville	40.9917	78.5417	Clearfield	PA-96-074	Rolland	10x10 or 6	5	20			Lower Freeport	08/13/96	
59	Yankovich	South Union	39.9089	79.7647	Fayette	PA-97-013		2	15		South Union Coal Co.		Pittsburgh	10/26/96	prior to 1936
60	Ray Street	Decatur	40.8842	78.2328	Clearfield	PA-96-063	George	1x2 on surf. 10' just bel. surf.	6	40		Cuba No. 2 Mine	Lower Free-port	06/18/96	prior to 1914
61	Ryen	Morris	40.9703	78.1983	Clearfield	PA-96-055	George	8 to 10 in. at surf.	> 8		Lane Mining Co.	Lane #5 Mine	Lower Free-port	05/21/96	1910
62	Sirakos	Houston	40.2417	80.2125	Washington	PA-96-020	Rolland	6	10	15?	Houston Coal Co. or Pitts. Coal Co.		Redstone	01/25/96	1930's or 1940's
63	Smulick	New Castle	41.0506	80.3436	Lawrence	PA-94-101	Dan	5 4 2 holes	6 6	20	New Castle Railroad & Mining Co.		Brookville	08/12/94	1930's
64	***Sutton***	***Hawk Run***	***40.9289***	***78.2136***	***Clearfield***	***PA-96-055***	***Rick***						***Moshannon***		***prior to 1950's***
65	Travis	Brisbin			Clearfield	PA-97-027	Jeff	1x8	3 to 4	10	Jones & Hensel Coal Mining Co.		Upper Freeport	01/02/97	prior to 1940
66	Burley	Patton	40.6247	78.6936	Cambria	PA-96-018	Jeff	10	14	15	Pennsylvania Coal & Coke Corporation	Ashcroft No. 55	Lower Freeport	01/19/96	prior to 1940
67	Helms	South Connellsvile	39.9903	79.5881	Fayette	PA-97-018	Jeff	1 at surf. 3 at base	10	20			Pittsburgh	11/08/96	prior to 1940
68	Hager II	Dilliner	39.7331	79.9514	Greene	PA-96-037	Jeff	1	6	15	Maple-Sterling Coal Co.		Pittsburgh	03/15/96	prior to 1950
69	Good Street I	Houtzdale	40.8208	78.3542	Clearfield	PA-96-079	George	1	3	4 ?	Berr & White	Franklin No. 10	Lower Freeport	09/11/96	prior to WWII
70	Godissart	Chester Hill	40.8908	78.2308	Clearfield	PA-97-048	Rick	1' 4" at surf.	10 +	20			Upper Kittanning	03/29/97	1950's
71	Allen	Robinson	40.3900	80.2661	Washington	PA-97-001	Rick	12' at surf.	9	2 or 20 ?	Pittsburgh Coal Co.	Montour No. 9	Pittsburgh	09/30/96	1940's
72	*Carr*	*VOIDED*	*VOIDED*	*REPEAT*											
73	Beal	Upper Tyrone	40.1031	79.5544	Fayette	PA-96-024	Jeff	1	unknown	20	Scottdale Diamond Mining Co.		Pittsburgh	01/29/96	prior to 1940

Site No.	Site Name	City	Latitude	Longitude	County	Project Number	Contact Person	Diameter of Hole ft.	Depth of Hole ft.	Depth to Coal Seam	Mining Company	Name of Mine	Name of Seam	Date of Collapse	Date that Mining Ceased
74	Torrey	Library	40.2864	80.0183	Allegheny	PA-95-047	George	3	9		Pittsburgh Coal Co.	Montour No. 10		06/23/95	1940's
75	Stablein	Speers	41.4528	79.8803	Washington	PA-94-021	Dan	8x11	3	40	H.C. Frick Coal Co.	Little Squaw Mine	Pittsburgh	12/01/93	early 1940's
76	Sichi	Belle Vernon	40.1292	79.8622	Fayette	PA-97-004	Rick	4' at surf. 8' at base	10	20 to 40	Pittsburgh Coal Co.	Somers No. 1 Mine	Pittsburgh	10/02/96	1940's
77	Bennett	Mt. Pleasant	40.1044	79.5536	Fayette	PA-97-038	Jeff	2	10	15	H.C. Frick Coal & Coke Co.		Pittsburgh	01/15/97	prior to 190
78	Bickerton	Floreffe	40.2564	79.9247	Allegheny	PA-93-067	Dan	5	9		Pittsburgh Coal Co.	Hilldale Mine	Pittsburgh	early 3/93	1940's
79	Handis	Wilkinsburg	40.4417	79.8708	Allegheny	PA-97-069	Rolland	1	12	20	Pittsburgh Coal Co.	Sandy Creek Mine	Pittsburgh	07/03/97	
80	Sarver	Renton	40.5097	79.7172	Allegheny	PA-95-014	Rolland	see notes. & files for exact sizes		15	Union Collieries Co.	Renton No. 4	Pittsburgh	01/11/95	1930's
81	Scaglione	North Belle Vernon	40.1264	79.8722	Westmoreland	PA-96-032	Rolland	2	20		Pittsburgh Coal Co.	Somers Mine No. 1	Pittsburgh	03/04/96	1930's
82	Sefchick	Morann	40.8125	78.3583	Clearfield	PA-94-008	Steve	6' at surf. 8' at base	10	15			Lower Freeport	10/01/93	
83	***Seifert***	***Wilkins***	***40.4181***	***79.8333***	***Allegheny***	***PA-92-046***	***Rolland***	***2' at surf. 6' at base***	***6***		***Pittsburgh Coal Co.***		***Pittsburgh***	***08/20/92***	

Site No.	Time Lapse yrs(approx)	Method of Reclam.	Cost of Reclam. dollars	USGS Quadrangle Map	Remarks
1	60	stone	2486	Murrysville	File states that project manager could look into the hole and see that the main entry paralleled the road w/ a side entry going under road. A hole had been filled about 10 yrs. ago about 100 ft. away. File states that hole was caused by a collapse of mine entry.
2	60	concrete mix	7431.57	Braddock	Hole located at rear wall of house. House foundation walls and possible support pillars are visible in lower half of hole. Base is dry and open into mine workings which appear to lead away from hole in several directions including under the house.
3	60	concrete mix	1720	Braddock	Coal seam visible at base of hole. Void progresses through sandy, weathered, friable bedrock on an angle into mine workings. Hillside contained numerous other depressions that appeared to be past subsidence events. Inconsistencies on mining company.
4	60	concrete mix	2920	Pittsburgh West	6 years prior a subsidence void, of unknown size and depth, was backfilled by City of Pittsburgh. It was located 100 ft. from current void.
5	60	concrete mix	2100	Glassport	A smaller hole exists at the base of the hole which extends down to an undetermined depth. No warm air or steam emanating from hole, so not believed that bottom of hole is into mine workings. Number of sinkholes observed w/i 200 ft. radius of hole.
6	60		14248	Pittsburgh East	Hole occurred in stone wall. Two smaller projects carried out in same yard in 1990 and 1995. Pothole leads into dry, open workings, at least 25 ft. long and 6 ft. wide. During last phase of concrete pumping, a 4 ft. deep by 3 ft. dia. hole opened in the backyard beneath contractor.
7	60	limestone aggregate	3084.12	Glassport	3 additional holes discovered on nearby hillside w/ at least 1 connecting to mine workings and venting a mine atomosphere. Highly carbonaceous shale roof material could be observed at the lowest depth of the void, indicating that the mine roof and/or coal seam was present w/i 10 - 20 ft. of the ground surface. A strong mine atmosphere could be smelled, but no reading for any common mine gases existed.
8	50		6780	McKeesport	Surface void apparently connects to a mine entry, which appears to be at least 10 ft. wide. No water observed from ground surface, but youth who entered mine reportedly saw water flowing deeper w/i mine.
9	50		2245	McKeesport	Subsidence located near a gas line Total depth of subsidence is estimated at 21 - 24 feet to the base of the Pittsburgh coal seam.
10	60	concrete No. 1 stone	3387	Braddock	Note: 2 holes
11	50		4942.74	Nanty Glo	Landowner said that the area where the hole is located subsided on 2 other occasions in 1976 and 1985. Discrepancy in file: could be PA Coal and Coke Co. and 15 - 20 feet below surface (not 20-25) A new hole opened up while excavating of 3 x 3 by 20 ft. deep. Mine timb-ers could be seen in bottom of new hole. After filling holes, 2nd hole set-tled. The hole was 6' in dia. and 4-5 ' deep.
12	6	stone	2166.9	Nanty Glo	Hole has a cone-shaped hole at the bottom which extends down to an undetermined depth. Hole developed after a car backed over the area. It's in a sidewalk area. Area is subsiding due to the water level being drawn down w/i the mine as a result off the mine drain that was placed by OSM in 1993.
13	57		1950	Houtzdale	Underground mine blowout hole
14	60	concrete mix	2348	Somerset	A smaller hole is at the bottom that continues to an undetermined depth. It appears that the subsidence developed over an entry.
15			1810	Houtzdale	due to u/g mine blowout
16	60		2615	New Sale?? left of union-town	Base of hole is dry and appears to lead into open mine workings.
17	60	concrete mix	3236.8	Barnesboro	Base of hole is dry and appears to lead into open mine workings. Hole branches out into at least 2 horizontal openings at mine level.
18	50	stone	2454.18	Wells Tannery	
19	60	soil	450	McKeesport	the sidewalls of the depression are comprised entirely of clayey soils, w/ no bedrock being observed. No visible connection to the mine level.
20	60	stone	1950.6	Connellsville	
21		concrete mix	1460	Pittsburgh West	small opening at base which leads into open mine workings. Pothole is cone shaped. Hole slopes toward house at steep ange. An elliptical-shaped area of depressed ground extends outward from the surface opening and appears to be migrating toward neighboring property. WPA map indicates no evidence of mining, but neighbors recall presence of abandoned headings in the area. Mining could have been conducted here prior to WWII at Fort Pitt Mine by Pitt. coal co. Alterna-tively, the workings may be the result of an old, abandoned house coal operation.
22	60		9990	Connellsville	Hole opened at left corner of driveway and street. Discrepancy in file: Could be Scottdale Iron & Steel Co. Upon excavation sinkhole, an entry running diagonally benath Maple St. was exposed. Overburden at this depth was about 6'. Because of the direction of the entry beneath the street, further excavation would have intersected numerous utilities. The excavation was backfilled w/ stone and street repaved. Mine void

Site No.	Time Lapse yrs(approx)	Method of Reclam.	Cost of Reclam. dollars	USGS Quadrangle Map	Remarks
					beneath st. is 10' high and 12' wide.
23	50	crushed ss rock	2275	Philipsburg	In addition to the hole, an area behind the trailer is beginning to settle. Tension cracks have developed w/i a 14' circular area around depression. A previous AML project was conducted across the street several years back. According to property owner, the hole has grown in size by 5' since it first occurred. Originally the hole was 10' deep, but gradual caving of the sides of the hole filled it so it's depth was only 5'. They excavated the depression, too, but no void was found.
24	60	stone	2150	Wallaceton	Hole opens up to an undetermined width at the base. Some water was present at bottom of hole. Hole is near a wooded area. Within woods numerous sinkholes were seen, but none w/ an open hole. Surface water may have drained into hole by presence of ditch next to hole. Upon excavating the hole, an entry could be seen going parallel to rd. Could be Country Bank Mine.
25		stone	2559.5	Masontown	
26	95		1975.7	New Castle	Pothole had grown since first noticed.
27	40		don't avg.	Pittsburgh West	Hole connects to a mine passageway at a depth of about 15-20 ft.
28	60		1982	Connellsville	
29	40	stone	1910	Houtzdale	hole quickly bells out below grass line. A vein of coal can be seen near bottom of hole. Upon excavation, a partially collapsed entry could be seen.
30	40	concrete mix	1964	Hastings	No cool air or any other observable connection to the mine was seen w/i the hole. Hole located next to the foundation. It extended down under the footer and basement floor. About 5 feet of the footer was exposed and unsupported due to the collapse.
31	60	stone	2240	Carrolltown	Significant snowmelt and rainfall most likely contributed to soils & other unconsolidated materials to enter an abandoned underground mine. Exposed horizontal tunnels at the base of the void. From the large size of the void and the lack of depositional material at the bottom, it's evident that surface drainage affected the formation of the void.
32	60	stone, rip rap	3888.5	Mt. Pleasant	2 holes. One is 2 ft. in dia. and 10 ft. deep. 2nd hole is 30 ft. long, 20 ft. wide and 15 ft. deep. The subsidence is in a low spot and drains surface water in the underground mine.
33	60	stone	2636	Houtzdale, PA	Hole's base has been sealed w/ collapsed earth and the hole is not open into mine workings. The day it happened the weather was clear and dry. Hole is also dry. No info. was uncovered regarding history of coal mining at site.
34	70	stone, asphalt	3859.88	New Kensington, East	At time of occurrence, hole was only 18" dia. Then hole widened to current size. A mine entry can be seen at the base going in a SE direction. The area where the hole developed had been settling since 11/95. The township kept placing asphalt over the sunken area to bring it up level.
35	50	concrete	1893.71	Pittsburgh East	Overburden consists of clayey soils w/ some signs of bedded shale at the very deepest part of subsided area. 15.5 is depth to floor of mine
36	60		3758	Pittsburgh West	There was also a second pothole, much smaller, located at the base of a shallow depression about 20' from 1st hole. Overburden extends to a depth of about 10', which is the level of mine roof. Open mine workings and the exposed coal seam are visible on the sw side of the hole. Hole is dry. Air from mine workings vents at the surface of the hole. Maps show 20' diff. in elev. of surf. and coal seam
37	60	stone	1171	Pittsburgh East	Hole in an area where subsidence problems have occurred in the past.
38	60		2318	Glassport	hole had been present for 2 yrs prior, but just became much larger in early April, 96. Hole is steep sided hole is open into mine workings w/ a coal seam visible at base. Maps suggest a 29 feet o/b thickness, but actual observations suggest thinner.
39	40		2225	Elderton	The hole is filled w/ collapsed debris forming an inverted cone to about 30" from the ground surface. Water is at 24 " from surface & is near the shallow ground water level depicted by the spring fed pond about 10' east of the pothole.
40	60		2296.4	Pittsburgh East	surface opening appears to lead into an abandoned mine heading; dark shale/roof coal is visible near bottom of opening and apparent horizontal void extends beyond sight distance.
41	60	stone	2247	Hastings	hole is steep walled and appears to lead into open mine workings.
42	50		1999	Pittsburgh West	Coal and an open entry can be seen at the bottom of the hole. 2 previous holes have occurred near it.
43	60	concrete & stone	6178	Braddock	an entry was observed leading from base of hole toward nearby yard. An entry which previously extended under road has collapsed. It appears this area was an intersection of 2 u/g haulageways.
44	60		2110.2	Braddock	hole started smaller, but continued to slough and enlarge until 2/14 when complaint was called in.
45	50	concrete	2702.21	Braddock	
46	50	concrete mix	1475	Pittsburgh East	a small depression developed in the yard on Nov. 9 and by the 11th it was the dia. of 4' and 8' deep. Sidewalls of hole were comprised entirely of clayey soils w/ no bedrock visible. Earthen materials that had subsided into the mine workings had completely filled any connection to the mine interval. Depth to seam is suggested by maps to be 10 ft, but could not see
47	60		1296	Pittsburgh East	walls of hole are vertical, esposing 2-3 feet of soil underlain by some 4' of shale bedrock. Hole not open to mine workings.

Site No.	Time Lapse yrs(approx)	Method of Reclam.	Cost of Reclam. dollars	USGS Quadrangle Map	Remarks
48	20		2651	Pittsburgh West	opening of hole at surf. is crossed by a mat of tree roots. Base of hole dry and may open into mine workings. Maps of area indicate site surf. elev. is 1025' and Pitt. coal seam 1019'. Another hole was filled in 95 less than 200' from site.
49	60	stone	1885	Smithfield	
50	60		2350	Ramey	
51	60	stone	2490	Cannonsburg	
52	60	stone	1860	Cannonsburg	
53	60	concrete	10398	Dawson	warm air was emanating from the hole, indicating connection to abandoned coal mine workings. Four entries can be seen leading from the hole. It appears the area was an intersection (junction). Initial reports indicated that excessive heat was coming from the hole when it first appeared on the 25th. A state AML project, Dunbar Mine Fire, was completed nearby in 1993. That abatement work involved placing a cut-off trench w/i the same mine complex to stop the spread of the fire. Any signs of fire in this area would mean the fire had gotten around the trench. Gas readings and a temp. were taken and no signs of fire were recorded.
54	60	stone	2360	Philipsburg	
55	60	concrete mix	1785	New Castle North	a small earthern depression was reported by Mr. Leighty in 1995. The problem was investigated and evaluated as not mining related. Then in mid-June 96, this hole opened up in same location. Sidewalls of the depression consist of clay w/ no bedrock visible. Also, significant root growth was present w/i the soil/ subsoil zone.
56	95	stone	2808		u/g mine maps do not show mining directly beneath the residence Resident heard a loud noise and discovered the pothole the next morning.
57	60	concrete	1250	Glassport	According to Mr. Lewis it was a country bank mine called "Concinnati Mine" No open connection to the mine workings below. The overburden consists of a thin soil layer underlain by shaley sandstone, which is very friable and weathered. The hillside appears to contain numerous other depressions that appear to be past subsidence events. Mr. Lewis said that several of his neigh-bors have backfilled voids that suddenly appeared in the past.
58		soil	2385	Curwensville	
59	60		2092.71	New Salem	
60	80		8591.71	Philipsburg	the hole is likely connected to open workings as a draft is occasionally noticeable at the surf. O/b consists of 2 - 3 feet of soil and rock immediately beneath the road; below this is a 3-4 ft. high open mine void. Two prior osm projects were done in this area. Drilling investigations indicate that the top of the U. Freeport seam is at an elev. of 1500 ft. Ray St. site is a 1540 ft.
61	85		2706.5	Philipsburg	Mr. Ryen uncovered a passageway into abandoned mine workings while digging postholes. Opening extends steeply downward for at least 8' which is the limit of visibility. The opening likely reaches the abandoned workings as a draft is noticeable. ******Regionally the L. Freeport seam averages 5-6 feet thick but locally may range up to 14 ft. thick.
62	60	stone	2387.72	Washington East or Cannon-sburg	
63	60	stone	2855.27	New Castle North	excavation of each hole was stopped when a solid layer of clay was encountered.
64				***Philipsburg***	***the excavation of the subsided area revealed that the void was being created by a falling mine air shaft.*** The shaft was about 5x5x18 ft. deep. It was excavated and backfilled w/ 31.8 tons of riprap.
65	60		1583	Houtzdale	several previous OSM emergency projects were located w/i 1-2 blocks of the house including Yarger & Persian Ave. Blowout. Also - Mr. Travis said that he had another subsidence hole develop in the early 80's about 100 ft. from his house/
66	60	stone	2240	Carrolltown	Significant snowmelt and rainfall most likely contributed to soils and other unconsolidated o/b to enter abandoned area.
67	60	concrete	2215	South Connellsville	
68	50	stone	2369.08	Morgantown North WV-PA	void located at edge of depression which measured 5' in dia. and 1' deep. A previously abated AML project has also redeveloped creating 1-2' wide cracks, 3-4' deep in a different part of the yard.
69	60	concrete mix	2670	Houtzdale	The steep-walled hole is 1' dia. at surf., widening downward. The base is dry, but appears to lead in one direction into open mine workings. A prior OSM project (Good Street) was completed 20' from this site in March, 1985
70	40	concrete mix	1542	Philipsburg	void connects to mine passageway of 12' long, 4' wide, and 3-5' high (see map)
71	50	concrete mix	3050	Clinton	A large, con-shaped, mass of material remains lodged w/i the depression. the void beneath the cone shaped mass can be viewed thru the tension cracks surrounding the subsided area.????
72					
73	60	stone	1334.22	Connellsville	This subsidence hole in the driveway had occurred for the third time in 2 weeks. Mr. Beal filled the hole himself the first 2 times w/ gravel and soil, but problem reoccurred. Area located 3/4 mile from ongoing Prittstown mine fire project area.

Site No.	Time Lapse yrs(approx)	Method of Reclam.	Cost of Reclam. dollars	USGS Quadrangle Map	Remarks
74	50	grout	2413		It appears that soil and rock are being piped away by subsurface waters of a nearby mine drain. Hole opens to a greater dia. at depth and slopes gently down driveway. Walls of the hole reveal a thin veneer of soil overlying a 4-foot section of thinly-bedded shale containing coal stringers. Base of hole is dry and covered w/ collapse matrial and pieces of ceramic pipe and logs. 12' east of driveway is a 2' dia. mine drain pipe exposed in the ditch along road. Video -camera exam. of pipe reveals an open pipe ending at a mine entry w/ drainage flowing around one of support posts near hole. Upon further examination of site, cause of problem was determined to be collapse of mine roof; not piping by subsurface waters. Hole bells out to 15' long by 7' wide at base.
75	50	stone	2258	California	Another area of slightly depressed nature can be seen at edge of hole, indicating that additional settlement may occur. Mr. Stablein indicated that he had a small subsidence hole develop in his driveway last spring which he filled himself. He also said a hole developed on his neighbor's property and a nearby street about 10 yrs. ago. He indicated that they appear to be in direct line w/ each other. A roof drain was found adjacent to hole which could have been leaking which could have contributed. Final resoration could not be accomplished due to frozen and wet ground. HEAVY RAINS HAD OCCURRED PREVIOUS WEEKEND!!
76	50	concrete mix	900	Donora	
77	95		800	Connellsville	An underground mine fire which has been burning for many years is the source of the void. The Bureau of Mines conducted a project in this area in the 1960's. Project abatement work was not designed to extinguish the mine fire but instead to contain it. Although Mr. Bennett's house is in no danger due to the spreading mine fire, occasionally the fire results in subsidence voids like this. Problem area is located w/i 300' of Beal Subsidence. Several other OSM emergencies w/i general vicinity that have been completed w/i past few years. Sag area present around vertical opening of about 30' dia. w/ tension cracking visible at points along sag perimeter.
78	50	concrete	1085	Glassport	Portion of garage foundation damaged as a result of the hole. Depression present in adjacent alley
79		concrete??	1800	Braddock	Base of hole is dry w/ a mond of collapsed earth at its center. Base of hole slopes to nOrth.
80	60	stone	6023.25	New Kensington	the problem was located in a wwoded area adjacent to several homes. 3 holes and 2 depressions. 3 holes ranged from 8-12 ft. long and 4-6 ft. wide. holes averaged 10 ft. in depth. All extended down to top of mine entry which was about 5 ft. below observed bottom of holes. Depressions have existed for a long time based on amt. of garbage in them. All holes w/i 100 ft. of eachother. Property owner complained of mine water draining into his basement. The back wall of the basement has been damp to a height of about 5 ft. Wall is bowed inward from lateral earth pressure. Water at some time has flowed across the garage floor and stained the door sill. At time of investigation, wall was damp along seam w/ the garage floor. A month after reclaiming, two holes had settled and one had collapsed into mine entry again.
81	60	concrete	2450	Donora	hole beneath the down spout of the porch. Roof coal and shales above Pitts. coal can be seen in sides of subs. hole.
82			975	Houtzdale	
83			***1760***	***Braddock***	***it became apparent while excavating the hole that it did not develop as a result of mine subsidence. A large amt. of fill is located in the area and settlement of*** this fill caused the problem. The hole was dug down to 10 ft. and then backfilled w/ stone.

VITA

The author was born in San Francisco, California on November 1, 1974 where she lived until the age of four, until moving with her family to northern Virginia in 1979. Ms. Dyne resided there until she graduated from Oakton High School in June of 1992. She enrolled at Virginia Tech in the fall of 1992 and graduated with a B.S. degree in Mining Engineering in the spring of 1996.

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