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EFFECT OF FULL-EXTRACTION UNDERGROUND MINING ON GROUND AND SURFACE WATERS A 25-YEAR RETROSPECTIVE

Francis S. Kendorski, Principal & Vice President
Agapito Associates, Inc.
Lombard, IL, USA

ABSTRACT

Over the past 25 years, the present author has written with several co-authors a series of papers beginning with the landmark paper in the 1st International Conference on Ground Control in Mining in 1981, in turn, based upon U. S. Bureau of Mines (USBM) funded contract research managed by the author with a final report issued in 1979, all concerning this paper's title subject, *Effect of Full-Extraction Underground Mining on Ground and Surface Waters.* Initially the work was a summary of British, Russian, and Hungarian experience tailored to United States strata conditions, but has evolved into a consistent and well-documented model of the behavior of strata influenced by full-extraction underground mining such as longwall coal mining. The several strata zones recognized in these works, Surface Fracture Zone, Constrained or Aquiclude Zone, Dilated Zone, Fractured Zone, and Caved Zone, have been observed by several workers in the field. The concepts presented initially 25 years ago have been adopted, rightly or wrongly, by state regulators, ground and surface water researchers, and mining practitioners. The development and utility of these concepts and recent findings will be summarized.

INTRODUCTION

Water inundations in underground mining, from either surface or underground sources, whether natural or impounded, have been a constant problem of mining and a great fear of miners. Most coal-mining districts around the world had very early developed guidelines for "protective" strata above mine workings, which are assumed to remain intact and serve as a barrier to water. The subject is one of great historical and practical interest, but is beyond the scope of this present paper.

The 1st Edition of Peele's *Mining Engineers' Handbook* published in 1918, has the following guidance based upon work by Douglas Bunting in the Northeastern Pennsylvania Anthracite District [1, p. 996] for 24-ft-wide mine openings:

$T = 1.5\ d^{0.5} + 5$ (strong measures, rock surface fully explored)
$T = 1.5\ d^{0.5} + 15$ (softer measures, liable to disintegration, rock surface fully explored)
$T = 1.5\ d^{0.5} + 40$ (strong measures, rock surface imperfectly explored)
$T = 1.5\ d^{0.5} + 50$ (softer measures, liable to disintegration, rock surface imperfectly explored)

where T = Thickness of Rock Cover (ft)
d = Depth of Surface Wash (ft)

The above is an exact quote and "surface" should be interpreted today as "strata;" while "wash" presumably is a local term for "unconsolidated materials." This exact same guidance persisted through the 3rd Edition of Peele's *Mining Engineers' Handbook* [2] published in 1941.

Some of the earliest concepts for describing strata behavior above longwall mining are contained in Orchard [3] in 1969, in which he described (from the bottom up) a caved zone, a "zone in which the permeability is sensibly unaffected," and a zone of increased permeability just below the surface. Shadbolt [4] described vertical areas within the strata that are characterized by (from the bottom up) caving, shearing and fracturing, bed separating, and surface cracking.

In 1973, the *SME Mining Engineering Handbook* replaced the out-of-date Peele's *Mining Engineers' Handbook*; however, guidance on the issue of "Mining under Bodies of Water" was afforded its own Subsection 26.7.6 [5], but with very limited guidance from Nova Scotia, the United Kingdom National Coal Board (NCB), and Newfoundland. For longwall full-extraction *undersea* mining, the NCB guidance was greater cover than 105 m (344 ft), and a tensile strain not to exceed 0.001 (10 mm per m), cumulatively.

In 1975, the former USBM (now a part of the National Institute for Occupational Safety and Health (NIOSH) of the Centers for Disease Control of the United States Department of Health and Human Services) initiated two contracts on the subject of mining near bodies of water [6]: one to Skelly and Loy of Harrisburg, Pennsylvania, [7] and one to K. Wardell and Partners, Newcastle, United Kingdom, [8] which issued their final reports in 1977. The USBM summarized the contract and other work in a publication in 1977 [6], which provided very general guidelines for full-extraction mining beneath a body of surface water of a minimum of 60 ft of "solid strata cover" for each foot of mined seam thickness. The report [6] also provided guidelines for "safety zones" around and under bodies of surface water of 200 ft horizontally from the high-water mark and vertically downward at a dip angle of 65° to a depth of 350 ft.

Recognizing a need for additional research into the issue of mining near surface waters and the potential hazards that existed for inundations of mines, in 1978, the USBM issued a new contract to Engineers International, Inc., of Downers Grove, Illinois [9]. The present author was project manager on that contract research. That contract research work resulted in the publishing in 1979 of the final report, *Criteria for Determining When a Body of Surface Water Constitutes a Hazard to Mining* [9], which was synopsized in a paper presented at the 1st International Conference on Ground Control in Mining in 1981 [10] by two of the authors of that final report, including the present author. The material in that publication [9] and presented at that conference [10] included the model developed for strata behavior in response to full-extraction mining and its effect of ground surface waters.

The final report [9] also addressed how to pre-plan an underground mine for a water inundation so as to allow safe escape, refuge, or direction of waters to sumps or mined-out evacuated areas. This portion of the report has since received renewed interest following the near-tragic Quecreek No. 1 Mine incident in Somerset County, Pennsylvania, in 2002. This author has been honored by being invited to address the Pennsylvania Governor's Special Commission on Abandoned Mine Voids and Mine Safety in Pottsville, Pennsylvania, in October 2002, and the Mine Safety and Health Research Advisory Commission in Washington, DC, in May 2003 on the subject of mine inundations.

1979 MODEL

The 1979 and 1981 publications [9, 10] drew heavily upon Australian [11, 12], Hungarian [13], Soviet [14], the United Kingdom [4, 5, 8], and United States [7, 15, 16, 17] experiences in full-extraction mining overlying strata behavior. The 1979 and 1981 publications used the original Figure 1, a cross section of the strata zones above a longwall full-extraction panel. Figure 1 is reproduced exactly as presented in the 1979 report, poor drafting, and all. The key findings presented in the 1979 and 1981 publications [9, 10] were the identification of the various zone of strata behavior above the full-extraction mining panel (from the bottom up):

Zone	Extent	Nature
Caved Zone	3t to 6t	Complete Disruption
Fractured Zone	30t to 58t	Continuous Open Fractures
Aquiclude Zone	Surface—50 ft to 30t Above Mine	Constrained with No Permeability Change
Surface Fracture Zone	To 50 ft Below Surface	Temporary Open Fractures

where t = mined seam thickness

While not the only publication of such concepts of strata behavior (see, for example, the excellent presentations in Coe and Stowe in 1984 [18], Peng and Chiang in 1984 [19], and Hasenfus, et al. in 1988 [20]), it was the first publication of a consistent, defensible, model for strata behavior and quantification overlying longwall full-extraction panels that could be used to predict the impact of the strata behavior on the mining water regime and inundation potential. Some of these concepts [19] included fewer strata behavior zones, such as Caved Zone (2 to 8t), Fractured Zone (28 to 42t), and Continuous Deformation Zone (extends to the surface).

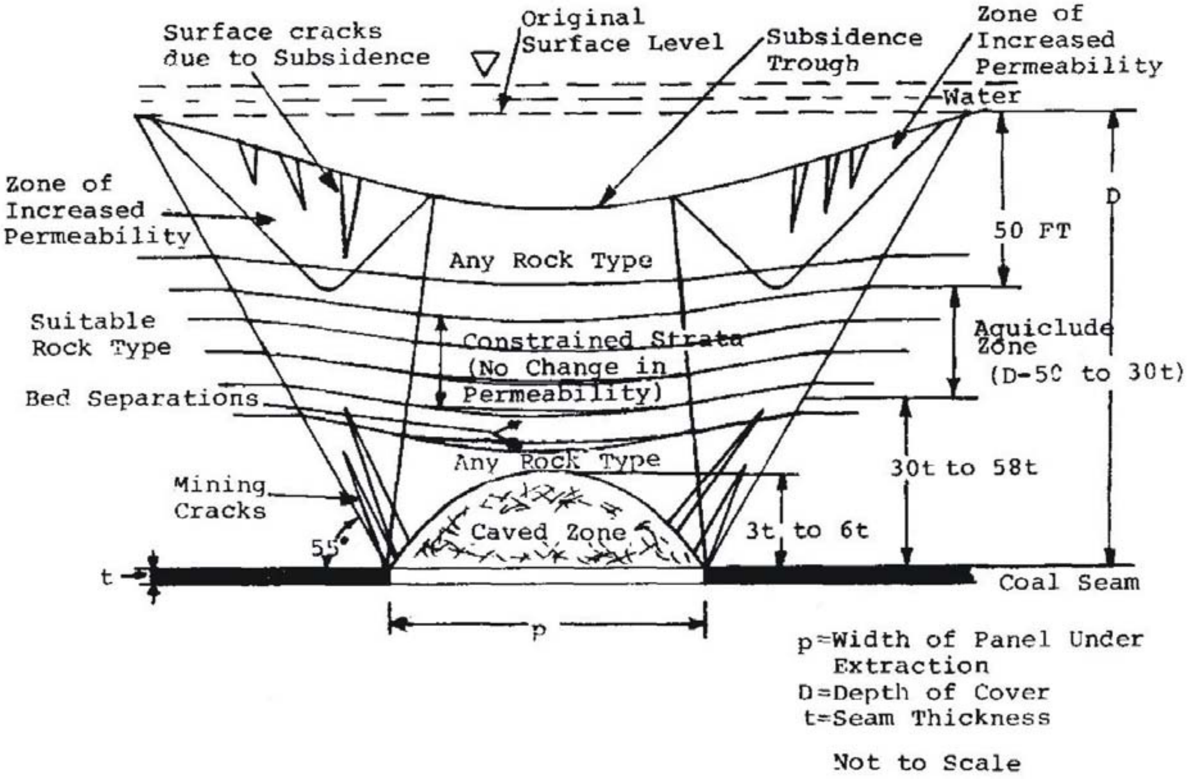

Figure 1. 1979 Model [9]

From 1972 through early 1977, Mazza and Mlinar [21] investigated the efficiency of vertical degasification holes above the Pittsburgh Coal Bed in northern West Virginia in both longwall and room-and-pillar mines, and found a rubblized zone extending approximately 100 ft (16*t*) above the mined seam and a zone of vertical strata movements and separations of as much as 350 ft (58*t*) above the mined coal seam. These zones today would correspond to the Caved Zone and Fracture Zone.

Liu [22] in 1981, cited in Peng and Chiang [19], developed the following relationships based on extensive Chinese experience for predicting the height of the fractured zone above longwall panels in SI System units:

Rock Type	**Height (m)**	**Std. Dev. (m)**
Hard and Strong Rock Compressive Strength > 39.23 MPa Good Water Conductivity	$100t/(1.2t + 2.0)$	8.9
Medium Hard Rock Compressive Strength >19.62 MPa < 39.23 MPa Worse Water Conductivity	$100t/(1.6t + 3.6)$	5.6
Soft and Weak Rock Compressive Strength >8.28 MPa < 19.62 MPa Bad Water Conductivity	$100t/(3.1t + 5.0)$	4.0
Weathered Soft and Weak Rock Compressive Strength >8.28 MPa <19.62 MPa Bad Water Conductivity	$100t/(5.0t + 8.0)$	3.0

1993 MODEL

In the 1980s and early 1990s, longwall mining became much more common in the United States, and both subsidence engineering and hydrogeology researchers began investigating the effect of longwall full-extraction mining on ground and surface waters, but from two different perspectives. The subsidence engineers were *looking up* into the strata to see what effect the deformations, fracturing, and water impacts would be on the mining activity below. The hydrogeologists were looking *down into* the strata to see what effect the deformations, fracturing, and water impacts would be on the ground and surface water resources above.

This dichotomy resulted in some confusion as to the extent and nature of the strata behavior and its respective impacts on the researchers' interests. With the now-expanding database in 1992 and 1993, we pulled together all available reference field and modeling case histories and tried to reconcile the differences in the observations. We realized that the *four* strata zone defined earlier, were actually composed of *five* zones: The Aquiclude Zone, in reality, consisted of two zones; a lower Dilated Zone of strata that have been affected by the subsidence and have dilated increasing their storativity potential and impacting well observations but with no direct or effective hydraulic connection to lower strata or the mine, and an upper Aquiclude Zone that is unaffected by the mining and subsidence deformations and has no change in permeability. Figure 2 shows these redefined zones. This concept was first published in 1993 at the 12th International Conference on Ground Control in Mining [23].

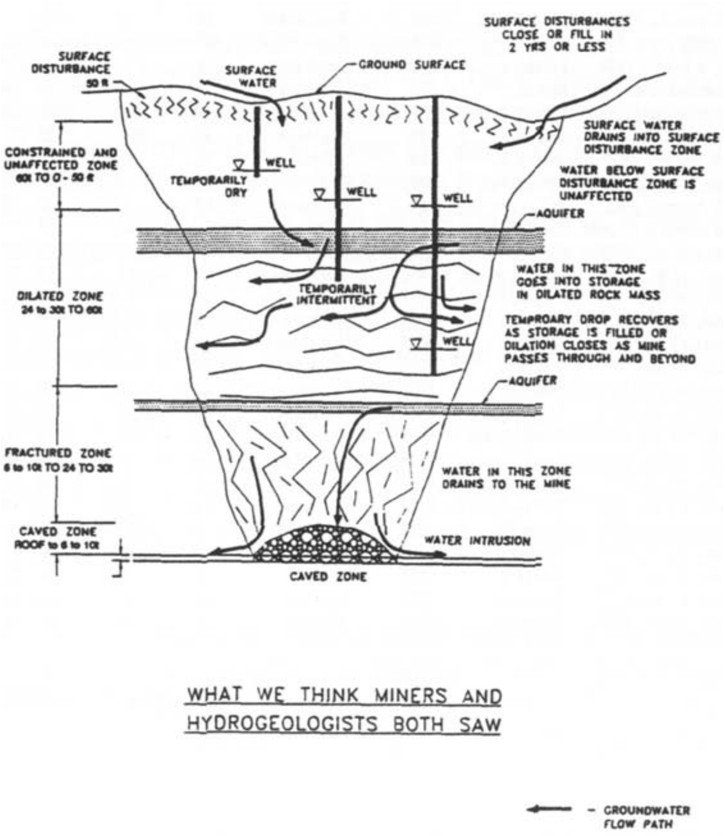

Figure 2. 1993 Model [23]

RECENT RESEARCH AND INVESTIGATIONS

Deep Aquifer Effects

In Pennsylvania, the Bituminous Mine Subsidence and Land Conservation Act of April 27, 1966, as amended in 1994, commonly called Act 54, was designed to regulate underground coal mining because underground coal mining affects the surface. Under the mandate of Act 54, the Pennsylvania Department of Environmental Protection must issue a report on the complex effects of underground mining during 5-year increments. In the 2003 Act 54 Report [24], written under contract by the Department of Earth Sciences of the California University of Pennsylvania, it is stated

> The response of the overburden can generally be divided into four zones. Zone 1 is a highly rubbleized, *caved zone* typically extending upward 6 to 10 times the coal seam thickness. Zone 2 is a *fractured zone* defined by massive block-type caving and vertical fracturing typically extending 24 to 30 times the coal seam height. Zone 3 is a zone of increased groundwater storage with dilated fractures (*dilated zone or continuous deformation zone*) and horizontal movements along weak-strong rock interfaces typically extending 30 to 60 times the seam thickness. Zone 4 is a *surface extension zone* where surface cracks typically open along the margins of the panel and above the working face of the panel. These surface cracks may open as the longwall face passes beneath the surface and close as the face moves away. Some researchers define an additional zone above zone 3 where the rock mass is constrained and there is no significant impact on groundwater movement or storage (develops where the mine is deeper than 60 times the seam thickness plus the depth of surface extension zone fracturing).

and further that

> …. the University's researchers can state that the majority of the ground-water recharge does not flow into the mines of Washington and Greene Counties. **If this is true, then ground-water recharge that does not report to the mines is still available within the system.** These results support the concept proposed by Singh and Kendorski [10]; Coe and Stowe [18]; and Hasenfus, et al. [20], that the hydraulic conductivity of the rock units located above the caved zone and below the shallow fracture zone remains largely unaffected by longwall mining. [Emphasis original]

Palchik [25] measured, using gas permeability, the growth of the fractured zone above the longwall panels of the Torezko-Snezhnyanskaya Area, in the Donets'k Basin, Ukraine, and found

> The maximum heights of the zone of interconnected fractures and separate horizontal fractures may reach 19–41 and 53–92 times the thickness of the coal seam respectively. It was found that the ratio between the maximum height of the zone of interconnected fractures and the thickness of the extracted coal seam increases with the increasing number of rock layer interfaces and decreases with the increasing stiffness of immediate roof. Observation shows that the formation of separate horizontal fractures began only 11–49.5 days after the height of the zone of interconnected fractures reached its maximum value.

Booth [26] collected groundwater monitoring data in two Illinois longwall mining sites from 1988 to 1995, and concluded

> Groundwater impacts are an environmental constraint of longwall mining, whether considered as a problem for residents of mined area or for companies in permit applications. Longwall mining affects overlying aquifers by several mechanisms, of which the most important are fracture dilation effects over the panel and drawdown effects transmitted outward through the aquifer from the primary potentiometric low. Groundwater levels may be lowered because of drainage to the mine, but normally this is retarded by an intermediate low-permeability zone, and a problem only for deeper wells that penetrate the lower fractured zone.

Near-Surface and Surface Effects

Stout [27], in examining the effects of longwall-generated surface effects on streams, reported

> Six longwall mined streams were compared to five reference streams that were unmined or had been room-and-pillar mined.
>
> Longwall mined streams were dry at 28% of sites, and all streams were impacted near their sources with stream width indicating remnant surface flow. Streams reemerged downstream, with most reappearing gradually along the downstream gradient. Stream width returned to reference conditions in four of six longwall mined streams in watersheds greater than 80 acres. Instantaneous stream temperatures were consistently 1-2°C cooler in longwall mined compared to reference streams, indicative of underground flow following stream subsidence.
>
> Longwall mined streams were similar in terms of pH and hardness, but significantly different in terms of alkalinity, conductivity, and dissolved oxygen when compared to reference streams. However, longwall mined streams were capable of supporting a diverse

> macroinvertebrate fauna at sites where water was present.
>
> Reference streams had diverse and ubiquitous aquatic macroinvertebrate communities across the region. Semivoltine taxa, those requiring perennial flow conditions for multiple years, were collected at 98% of reference stream sites. In contrast, longwall mined streams were dry at 28% of sites and had semivoltine taxa at only 48% of sites. Longwall mining results in a 50% reduction in the omnipresence of perennial aquatic biological communities in headwater streams in Marshall County.

Bartsch et al. [28] investigated the effects of longwall mining on near-surface and surface conditions, and found

> Date collection began several years prior to longwall mining and has continued for several years after mining. The data for the test site shows that although the shallow and deep groundwater levels were affected by longwall mining, the soil moisture, vigor rating, or the growth rate of trees did not decline significantly compared to the control site where there were no hydrologic impacts. The study shows that there are no known significant impacts to trees from longwall mining.

D'Appolonia Engineering Division of Ground Technology, Inc. [29], investigated the use of remote sensing imagery above longwall panels for tree canopy heath and concluded

> Throughout areas of predicted high tensile strain and ground disturbance (panel boundaries), no distinctive evidence of canopy distress was observed in the imagery, and the canopy was observed to be generally healthy in the field. The slight decline in tree health along the subsidence pools could not be distinguished in the remote sensing imagery, and the severe decline and mortality of the young ash stand was difficult to detect even with extensive scrutiny of the imagery.

Earth Sciences Consultants, Inc. [30] conducted a study to determine the effects of longwall mining subsidence on streams, wetlands, and riparian areas within a selected valley floor setting, and concluded

> Although this study has identified variation between the mined and unmined segments, the statistically limited database cannot be used with absolute certainty to conclude whether these changes are attributed solely to subsidence and/or are related to anthropogenic disturbances. These disturbances include increased erosion and/or runoff from crop and pasturelands, mowed areas, roads, and domestic activities. Therefore, approaches for mitigation and monitoring are not currently recommended.

While surface cracking and deformation has been reported numerous times and validated the concepts of the 1993 Model for near-surface strata behavior, recent studies are inconclusive as to any negative impacts of these effects.

CLOSURE

Recent investigations have consistently borne out the validity of the 1993 Model for strata behavior and characterization above full-extraction mining such as longwall mines first developed more than 25 years ago.

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