SOME APPROACHES TO DETERMINE THE POTENTIAL INFLUENCE OF LONGWALL MINING ON GROUND WATER RESOURCES[1]

Derek Elsworth, Jishan Liu, and Zhihua Ouyang[2]

Abstract: An approach is developed to quantify the impact of longwall mining on the potential disruption of ground water resources. The underlying premise of the method is to assume that the primary mechanism causing dewatering is the development of new fractures, or the dilation of existing fractures, as a result of mining-induced displacements. Numerical simulation, using the finite-element method, is used both to determine the mining-induced distribution in strain and to complete hydrologic budget calculations with the revised permeability field. This approach is applied to mining geometries representative of the Appalachian Plateau to define the anticipated sensitivity of these systems to changes in overburden thickness, base level location, topography, and other relevant parameters. Results indicate that observed trends in dewatering behavior may be explained on the basis of zones of contiguous extensile strain, induced within the overburden as a result of mining. The systems are more sensitive to the sense of mining-induced strain (extensile versus compressional) than to the absolute magnitude. This is due to the extreme sensitivity of permeability to even relatively modest changes in extensile strain. Correspondingly, observational rules developed to predict the extent and location of potential aquifer dewatering are confirmed and may be extended to evaluate the potential long term influence of mining on the ground water system.

Additional Key Words: subsidence, aquifer dewatering, numerical modeling.

Introduction

Determination of the probable impact on ground water supplies is of key importance in the successful development of a longwall mine. The principal effect is that of dewatering, where disruption of the strata overlying the seam results in the development of hydraulic connections that had not existed prior to mining. The severity of failure, together with its spatial and volumetric extent, regulates the potential impact on ground water resources. The development of fracturing may result in the depressing of the existing ground water surface, which may remain depressed or may rebound with time. Where aquifers are used for potable or industrial water resources, this may result in the dewatering of wells, or in the degradation of water quality with the development of new hydraulic connections and the renewed mobility of oxygen within the subsurface. A considerable body of observational evidence has been compiled (eg. Leavitt and Gibbens 1992) to define the potential severity and extent of ground water influence in association with longwall mining. Analysis of this observational data set typically incorporates the indices of mining depth and the location of valleys to describe the possibility of dewatering and subsequent potential for recovery. Our approach, in the following, is to represent the phenomenological behavior of the system to reproduce these observed effects and enable extrapolation of the results both to nonstandard mining situations and in the evaluation of long-term effects.

Method of Analysis

Observational evidence indicates the form of potential dewatering above mined panels to be quite localized and limited to zones of induced extensional strain. Since the primary conduits for ground water flow in the sedimentary rocks of the Appalachian Plateau are the secondary fractures, hydraulic conductivities are strongly influenced by mining-induced extensional displacements. Our approach is to use numerical models to define the anticipated influence of mining on the ground water system through the following straightforward steps:

- The strain field that develops around a longwall panel as a result of mining is defined using a finite-element model that accommodates the influence of material failure and self-weight.

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- From this predicted strain field and from knowledge of the premining hydraulic properties of the overlying strata, the change in hydraulic conductivity that results from the strain field may be determined.
- With the modified conductivity field determined, the postmining hydrologic system may subsequently be defined through application of a ground water model. Again, this ground water model utilizes the finite-element method to determine the postmining hydrologic system where the position of the piezometric surface indicates changes in well or aquifer yields.

Determination of the Strain Field

The subsidence field that develops around a longwall panel may be determined directly from charts available in the Subsidence Engineers' Handbook (National Coal Board 1966). These charts relate the subsidence and surface strain profiles to parameters describing, mining depth, h, mining width, w, and seam thickness, t, alone, as illustrated in figure 1. The insensitivity of the resulting subsidence profile to the material properties of deformation modulus and strength results from the overriding influence of geometric controls on deformation. Following mining, the panel span is sufficiently large that closure between panel floor and roof is unavoidable. Consequently, the resulting strain field, $\varepsilon_x, \varepsilon_y$, is uniquely defined in terms of the parameters,

$$\varepsilon_x, \varepsilon_y = f\left[\frac{w}{t}, \frac{w}{h}\right] \tag{1}$$

where the influence of topography is also included in the term, w/h. Consequently, the strain field may be uniquely defined given that these geometric parameters are known, a priori, and the analysis is now completely decoupled from the material parameters describing the overlying strata. This lack of sensitivity has important considerations in reducing to a minimum the data required to complete an appraisal of the subsidence effect.

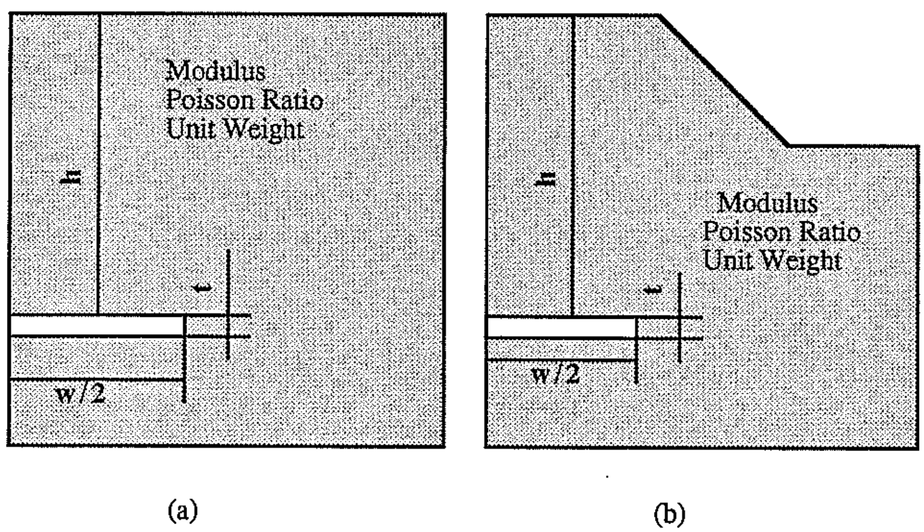


Figure 1. Idealized mining geometry relating seam thickness, t, and panel width, w, to the overburden thickness, h. Of importance is the location of the panel with respect to the topographic features for the (a) horizontal ground surface, and for (b) hillslope and valley base setting.

Determination of Conductivity Changes

With the strain distribution determined throughout the surrounding medium, changes to the permeability distribution may also be defined, provided an appropriate model is accommodated. A reasonable model is one that assumes the primary influence on hydraulic conductivity is provided by the secondary porosity, or fractures. The hydraulic conductivity, K, of a set of fractures of aperture b and spacing s may be defined as

$$K=\frac{gb^3}{12\nu s}, \tag{2}$$

where g is gravitational acceleration and ν is dynamic viscosity of the fluid. If it is assumed that a uniform strain field is applied to the fracture and matrix system, then the directional hydraulic conductivities are modified as

$$K_x=\frac{g}{12\nu s}[b+[s(1-R_m)+b]\varepsilon_y]^3 \tag{3a}$$

and

$$K_y=\frac{g}{12\nu s}[b+[s(1-R_m)+b]\varepsilon_x]^3, \tag{3b}$$

where the added factor, R_m, represents a modulus reduction ratio (mass modulus to intact modulus) that apportions the changes in strain between the fracture and matrix material. When R_m=1, the mass and intact material moduli are identical and the strain is uniformly distributed between fractures and matrix. This results in the smallest extensional change in conductivity. When R_m=0, the extensional strain is applied entirely to the fracture system and precipitates the largest possible change in conductivity. These values bound the behavior of the system. This representation of conductivities is extremely useful, since the modulus-reduction factor, R_m, may be readily evaluated from rock mass classifications (Ouyang and Elsworth 1993) defining structural behavior as a function of readily observable factors of rock structure. This avoids the difficulty, of defining conductivity enhancement in terms of the component moduli of fractures and matrix, parameters that are unlikely to be available in practice.

If the premining fracture spacing and conductivity distribution are known, or may be estimated, a priori, then an equivalent hydraulic aperture may be determined directly from equation 2. This initial aperture may be substituted directly into equations 3 to define the modified conductivities for use in the subsequent analysis.

The assumption necessary in this evaluation is that strains are uniformly distributed at the scale of a single element. These assumptions seem reasonable where strains are moderate, but may be questionable where significant strain localization occurs. The potential to represent this critical behavior is presently under evaluation.

Determination of Postmining Ground Water Regime

With the modified conductivity distribution determined from an evaluation of the strain field, and equations 3, the influence on the postmining ground water regime may be evaluated. A forward finite element model is applied that accounts for the influence of a continuously distributed conductivity field, defined as a result of the previous analysis. With boundary conditions applied to represent ground water and surface recharge, the change in elevation of the phreatic surface may be defined for the postmining regime. This enables the influence of mining on well yields, aquifer yields, and flow patterns to be identified.

Some examples of application of this form of analysis are outlined in the following paragraphs.

Ground Water Flux Charts

The basic dimensionless variables that identify geometry and material parameters may be used to describe the behavior of the system using a minimum set of nondimensional variables. Using the hierarchy that deformation controls flow through the distribution of body strains, it is possible to define flow rates, Q, in terms of the functional relations

$$\frac{Q\nu\gamma}{gs^2E_m}\left(\frac{s}{b}\right)^3 = f\left[\frac{b}{s};R_m;\frac{w}{t};\frac{E_m}{\gamma h}\right], \tag{4}$$

where γ is the unit weight of rock, E_m is the mass modulus, and all other parameters are as previously defined. To further simplify the analysis, the ratio b/s may be sensibly linked to the modulus reduction ratio, R_m, enabling a single chart to describe behavior, as illustrated in figure 2. These may be used to define flux volumes into excavations that result from mining.

Topographic Controls on Behavior

Observational evidence within the Appalachian coalfields supports the contention that topography exerts a significant influence on the potential for dewatering (Leavitt and Gibbens 1992, Donohue 1993). This dewatering may be short lived, or it may be longterm. Water supplies located in valley bases are less susceptible to interruption than those located at hilltop, and shallow wells are less likely to be influenced than deeper wells. These observations may be explained relative to the prevalent mechanisms of conductivity enhancement that develop within the overburden strata in response to mining-induced displacements. This treatment is pursued in the following paragraphs.

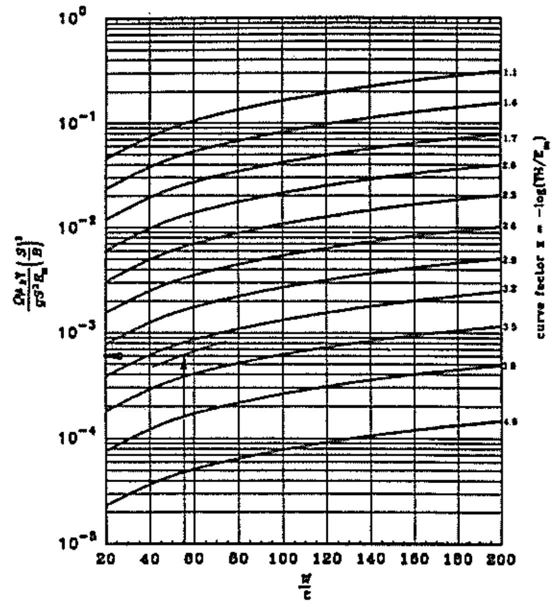


Figure 2. Design chart representing the variation in dimensionless flow rate, Q_d, as a function of mining width to seam thickness ratio, W/t. Parameters describing the system are unit weight of rock, γ, fracture spacing, s, initial fracture aperture, b, and rock mass modulus, E.

Model Assumptions

The mining-induced strain field is evaluated through use of a nonlinear finite element model developed to represent large displacements in strain softening strata. The nonlinearity is realized through changing the elastic constants for overburden elements subject to extension and in-panel elements subject to full compression and closure. These behavioral models are based on stress and strain criteria, respectively. The model has been carefully validated against subsidence profiles for Appalachian coalfields (Liu 1993), and in a more generic sense against empirical models for subsidence [National Coal Board 1966].

Because the processes representing the failure and subsequent deformation of the overburden are accurately represented, the resulting subsidence profiles are relatively insensitive to the material parameters of strength and deformation modulus. Instead, the constraints on subsidence, as applied through the maximum convergence between roof and floor, result in a small range of feasible displacement fields. Under this constraint, the induced strain field may be evaluated without need for complex material parameters and still represent a reliable depiction of the true situation. The model has been extensively tested and calibrated against a variety of available data (Liu 1993).

The form of the mining-modified conductivity field is determined through the unique relationship linking induced strains and hydraulic conductivities, as represented by equations 3. It is important to note that this modified conductivity field may develop both extreme heterogeneity and anisotropy, as conditioned by the induced strain field. This modified conductivity field may then be used to define the potential for strata dewatering as conditioned by the topographic setting. This behavior is evaluated in the following paragraphs.

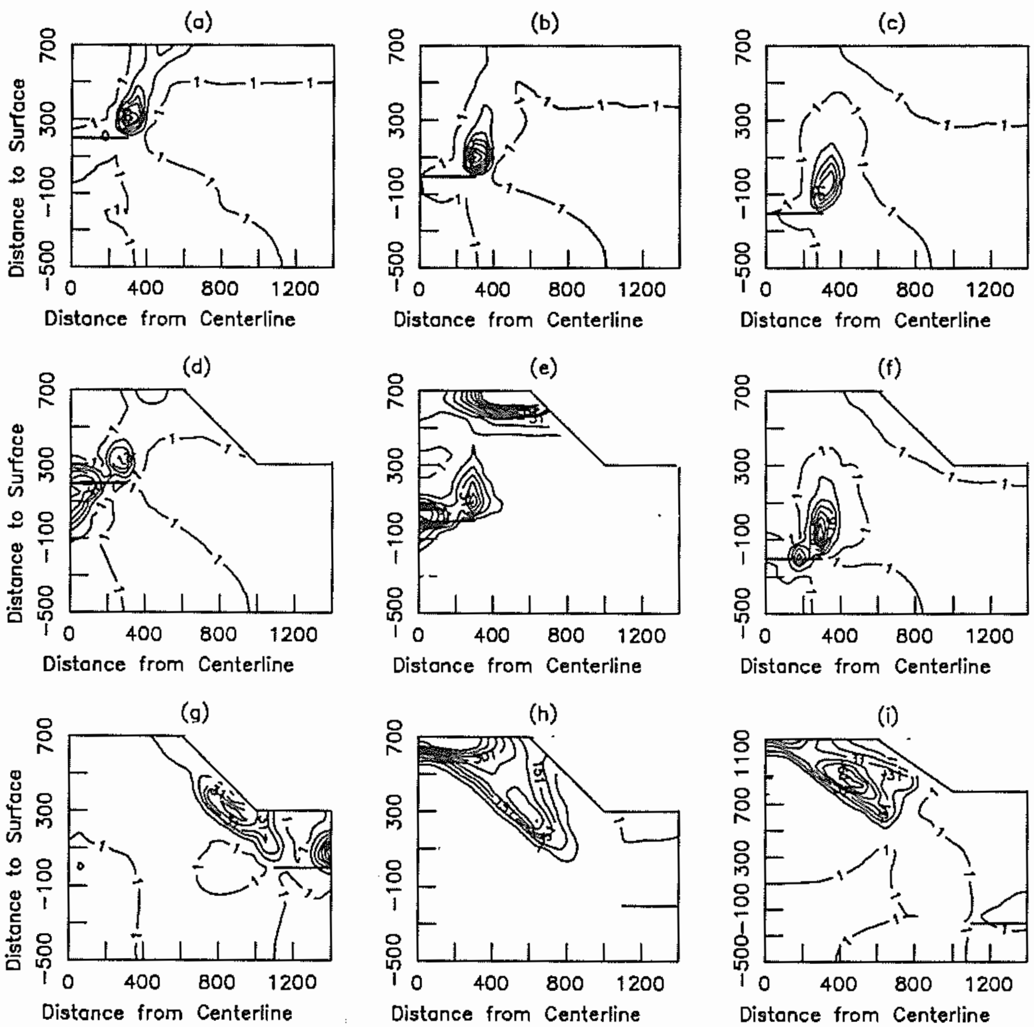


Figure 3. Transverse vertical sections showing contours of the ratio of postmining vertical hydraulic conductivity to premining hydraulic conductivity for mining at depths of 500 to 900 ft in topographic environments representing plateau (top), subhilltop (center), and subvalley (base). The null influence contour (representing zero strain) is represented by a ratio of unity. Ratios greater than unity represent mining-induced conductivity enhancement. Horizontal and vertical axes are marked in ft.

Parametric Results

To investigate the impacts of topography on domestic water supplies, the influence of mining in three topographic settings, namely, plateau, subhilltop, and subvalley settings, is evaluated using three different mining depths for each of the idealized geometries. The plateau setting comprises a horizontal ground surface, with the subhilltop and subvalley settings exhibiting the topography of figure 1. The changes in hydraulic conductivities generated by subsidence of the overburden are evaluated. Since change in water supply will be most influenced where conductivities are increased, the most obvious index to define zones of potential dewatering is the ratio of postmining to premining hydraulic conductivity. These ratios are reported for vertical and horizontal conductivities in the nine distinct mining geometries in figures 3 and 4, respectively. The following conclusions may be drawn from these results.

According to figure 3, the enhancement in vertical hydraulic conductivityis limited to a narrow region around the panel for the plateau mining settings. This zone appears coincident with the area of high lateral extensional stresses that develop at the abutment and slope upwards at approximately the angle of draw. Where mining is shallow, the zone may extend to, or close to, the surface. As the mining depth increases, the region of vertical conductivity enhancement becomes encapsulated in a zone of reduced conductivity. Where topographic influences are included, this zone may spread into the near-surface regions of the surface layer for the subhilltop mining settings, or into upslope areas for the subvalley mining settings. The zone of vertical hydraulic conductivity enhancement may extend up to 400 ft above the mined coal seam for both plateau and subhilltop mining settings.

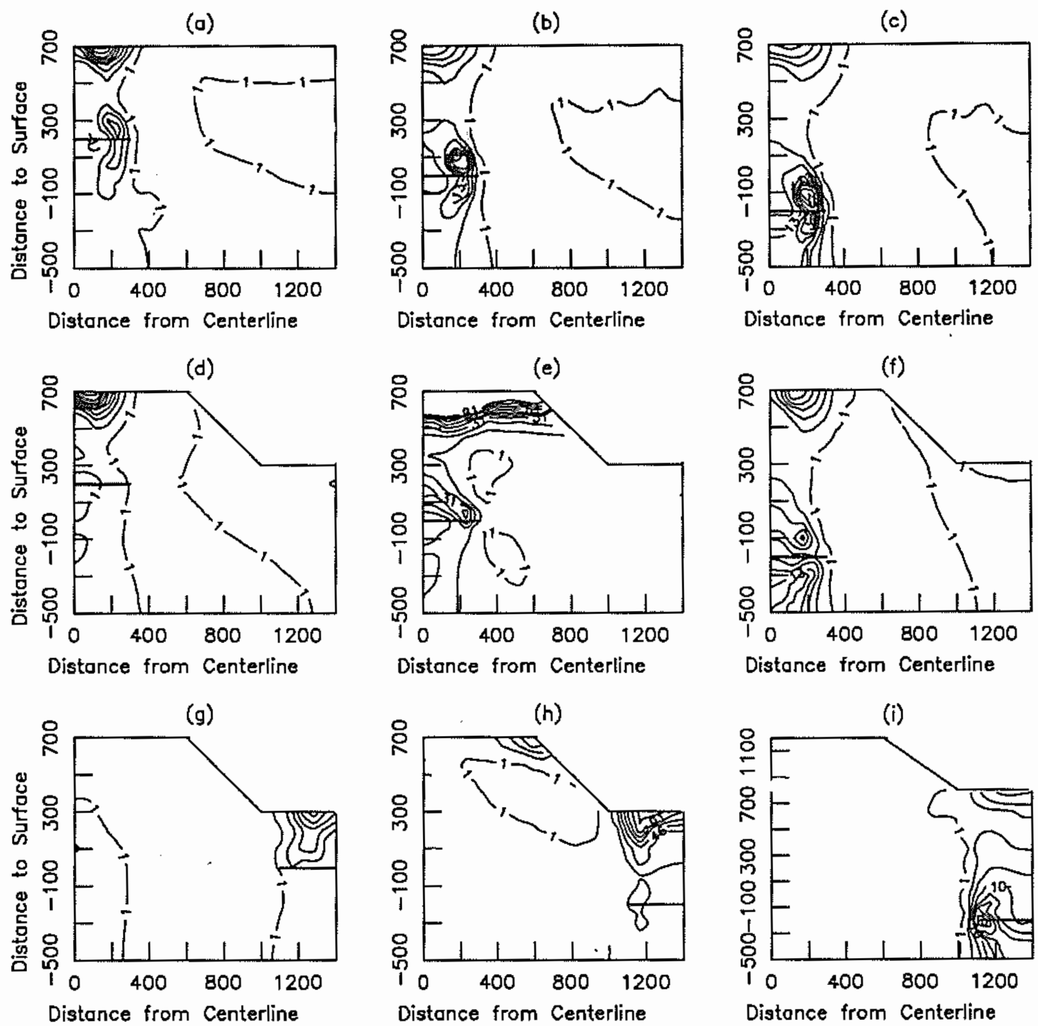
For subhilltop mining settings, a zone of vertical hydraulic conductivity enhancement may develop within the surface layer in addition to that around the panel. The zone of vertical hydraulic conductivity enhancement shifts into upslope areas for the subvalley settings. The influence of topography diminishes for subhilltop settings as the depth of the overburden increases. This critical depth may be about 900 ft. However, topographic influence still plays a dominant role for the subvalley mining settings even as the depth of overburden exceeds 1,000 ft below the valley surface.

The lateral extent of the zone of vertical hydraulic conductivity enhancement is relatively limited and is typically confined within 200 ft of the panel edge. This is true for the plateau and subhilltop mining settings alike. The other zone of vertical conductivity enhancement may extend up to 400 ft within the surface layer from the edge of the coal seam for subhilltop mining settings. For subvalley mining settings, the lateral extent of the zone of vertical conductivity enhancement extends farthest from the mine panel edge. The zone extends along the surface layer, especially in the upslope direction. This feature appears to develop as a result of, and is controlled by, the topography.

The zones of mining-induced horizontal conductivity enhancement are illustrated in figure 4. Conductivity enhancement develops both around the panel and within the surface layer for the plateau mining settings. For subhilltop mining settings, this zone forms only within the surface layer when the overburden depth is less than 900 ft, with deep conductivity enhancement developing immediately above the panel. An auxiliary zone forms within the surface layer when the overburden depth is greater than 900 ft. For subvalley mining settings, these zones are formed only (1) around the panel when the overburden depth is greater than 500 ft or (2) within the surface layer when the overburden depth is less than 500 ft. The vertical extent of horizontal conductivity enhancement may be less than 200 ft for all the mining settings.

Conclusions

According to these model results, the distributions of the hydraulic conductivity enhancement zones are quite different for the three mining settings. These differences appear to be controlled by the combination of both mining geometry and topography. Two parameters may be recognized as the most important, namely, the elevation difference between the well base and the mine panel, and the overburden depth, for both the plateau and subhilltop mining settings. For subvalley mining settings, one parameter may be recognized as the most important, namely, the depth of the overburden. These three parameters can be used to evaluate the potential for strata dewatering. Each parameter exhibits a critical value which can be used in evaluating the potential for strata dewatering. For subhilltop mining situations, the critical overburden depth is about 900 ft. For depths of overburden greater than 900 ft, the influence of topography on the potential for dewatering diminishes, as would be anticipated. The critical value of mine-to-well elevation separation is about 500 ft for both plateau and subhilltop settings. As defined previously, if the value is more than 500 ft the well is defined as a shallow well, and otherwise as a deep well. These two situations exhibit different responses to longwall mining. For the subvalley mining settings, the critical value for the overburden depth is about 500 ft. If the depth of overburden is greater than 500 ft, wells completed within the valley may be recharged by ground water discharge from upslope areas; otherwise, it may possibly be dewatered due to longwall mining.



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These results appear in general agreement with observations and analyses reported for the Appalachian coalfields (Ciffeli and Rausch 1986, Hasenfus et al. 1990, Leavitt and Gibbens 1992, Matetic and Trevits 1992, Donohue 1993).

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