Application of Subsidence Prediction Methodologies for Sizing Barrier Pillars for Stream Protection in Appalachia

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ABSTRACT

The prediction of ground movements due to underground mining is a mature methodology in subsidence engineering used to assess potential impacts to surface structures, facilities and water resources and to implement appropriate methods of control. Predictions of anticipated surface ground movements can be correlated to impact threshold levels for buildings, bodies of water, pipelines, railway and power lines, tailings dams, etc., to estimate the potential impact zone and the magnitude of damage, and to develop risk assessment plans. One methodology widely used for such predictions is the application of influence functions to calculate a number of deformation indices, including subsidence, slope, horizontal strain and surface curvature, at any point on the surface or at any elevation above the extracted seam. This methodology has been successfully implemented in the Surface Deformation Prediction System (SDPS) package.

One specific application of subsidence control is stream protection, particularly in shallow depths. While the stream must be protected, a very conservative approach may leave unnecessarily large blocks of unmined coal (i.e., barrier pillars or barrier pillar systems), without any particular benefit to the protection of surface waters. In this paper, typical barrier pillar sizing methodologies are compared and an approach is recommended for optimum pillar design that can provide stream protection from permanent dewatering. This approach is based on subsidence principles and sound empirical knowledge of ground movement characteristics, which have been developed for different mining, geological and topographic conditions in Appalachia.

INTRODUCTION

Mining Near-Surface Water Structures

A number of studies have been reported in the published literature discussing the factors influencing the extent and magnitude of subsidence impacts on surface water resources due to underground mining. The discussion below focuses mostly on research results related to the Appalachian coalfields in the eastern USA, where this particular issue is receiving considerable attention.

Several studies have addressed dewatering of stream resources in relation to the type of underground mining and overburden geology and thickness. The deformation of the overburden strata above the mine results in changes in hydraulic properties and may impact both the overlying underground and surface water bodies in addition to causing surface subsidence. Typically, impacts to water resources are greater above, and in close proximity to, the subsided area (Walker 1988; Rauch 1985; Hill and Price 1983). Considering the close association of the effects of underground mining on both the hydrologic regime and surface deformations, researchers traditionally have employed similar conceptual frameworks for describing and assessing their extent and magnitude. Such criteria may be defined on the basis of an angle or zone of influence (Tieman and Rauch, 1987). From a study of the effects of deep (500–600 ft, or 152–183 m) longwall mining on three nearby streams in northern West Virginia (Dixon and Rauch, 1988), the most significant stream flow change occurred before the longwall panel edge reaches the stream. However, it was reported that the streams recovered in a period of time ranging from eight months to five years. This study also showed that the greater the overburden thickness, the less the extent of dewatering and the greater the potential for complete recovery of the water resource.

In addition to overburden thickness, studies have also addressed the angle of hydrologic influence and the distance between the mine edge and the surface water body and how this parameter can influence form and function (i.e., discharge capacity, sediment transport, etc.), of the surface water resource. Angle of hydrologic influence is defined in a similar manner to the angle of draw, as the angle between the vertical and the line joining the edge of the mine panel to the limits delimiting the extent of hydrologic response. Several authors have reported values for angles of hydrologic influence, ranging from 24 to 45 degrees (Cifelli and Rauch, 1986; Dixon, 1988; Tieman and Rauch 1987; Walker, 1988; Dixon and Rauch, 1990; Tieman and Rauch, 1992). The extent of hydrologic effects of mining may also be defined in terms of the zone of influence as the buffer area above the mine panel that has been hydrologically affected. Typically these affects extend from about one to five hundred meters (Rauch, 1985; Booth, 1986; Walker et al., 1986; Tieman and Rauch, 1987; Dixon, 1988; Walker, 1988; Matetic and Trevits, 1990; Booth 2003). With regard to the horizontal distance of a water supply from the mine, Booth (1986) denotes that as the face of the panel approaches, the effects of dynamic strata movement increase, followed by a decrease of the hydraulic conductivities, due to the "traveling wave" extension and compression. This produces a drop and partial recovery of water levels with the highest impact above the centerline of the mine panel. In addition, a study that focused on the effects of deep mines on perennial streams in Greene County, Pennsylvania, concluded that, locally, the water levels of shallow aquifers dropped near the mine edge, but had no effect beyond a distance of 581–1,270 ft (~177–387 m) (Moebs and Barton, 1985).

In summary, studies show that longwall panels, or room-and-pillars sections with secondary pillar extraction, have the potential to affect surface water resources in the Appalachian coal basin. Overburden geologic structure and thickness, distance from the mine edge, mine conditions and extent of surface movements all are key drivers in determining the extent of impacts on streams and the recovery cycle of the water resource.

Guidelines for Mining Near-Surface Water Bodies

When considering the impacts of ground movements on surface bodies of water, the most comprehensive analyses of damage criteria and threshold values are derived from case studies from Britain, Australia and the USA. Different criteria have been proposed and can be divided into three broad categories: (a) mining geometry parameters, (b) surface deformation threshold values and (c) combinations of (a) and (b).

Table 1 summarizes different guidelines for mining under or near bodies of water. In many cases, mining under bodies of water depends on the depth between the mine and the surface water feature and/or the tensile strains that will develop on the surface, under the mass of the water or the water retaining structure. Where appropriate, the mining system is also given.

The guidelines presented in Table 1, can be summarized as follows:

- The British National Coal Board, as early as 1968, has recommended a maximum tensile strain value of 10 mm/m when mining under the ocean floor. Whittaker and Reddish (1989) have provided further discussion in support of this limit.

Table 1. Summary of different guidelines for mining under or near bodies of water (adapted from a report prepared for MSHA by D'Apollonia Engineering, 2009)

Criteria	Description	Underground Mining	Reference
Criteria based on mine geometry			
10t or 5s	Minimum solid overburden	Room and Pillar first mining	Babcock and Hooker (1977)
<10t or 5s provided competent bed is > 1.75s	Minimum solid overburden with competent bed	Room and Pillar first mining	Babcock and Hooker (1977)
max (3w or 270 ft)	Minimum solid overburden	Room and Pillar	Babcock and Hooker (1977)
w ≤ h/3	Maximum width of extracted panel	Room and Pillar	Babcock and Hooker (1977)
max (100 t or > 700 ft)	Minimum overburden	Total extraction	Skelly and Loy (1977)
60t	Minimum solid overburden	Total extraction	Babcock and Hooker (1977)
60t to 117t (worst case) 37t to 105t (limited potential)	Minimum overburden	Total extraction	Kendorski et al. (1979)
Criteria based on surface ground deformation			
< 0.010	Surface tensile strain	Total extraction	Skelly and Loy (1977)
≤ 0.010 (worst case) ≤ 0.015 (limited potential)	Surface tensile strain	Total extraction	Kendorski et al. (1979)
0.010	Surface tensile strain	Mining under the sea	NCB (1968)
0.010	Surface tensile strain	Mining under the sea	Whittaker and Reddish (1989)
Criteria based on mine geometry and surface ground deformation			
≤0.005; overburden ≥60t	Surface tensile strain and minimum overburden		Singh and Bhattacharya (1984)
≤0.005; suggested overburden ≥ 60t	Surface tensile strain and minimum overburden		Singh (1992)

where, h = overburden depth, w = maximum panel width, t = extraction thickness, s = entry width (all units in ft).

- Asimilar threshold value (8.75 mm/m) was also recommended by Babcock and Hooker (1977) in the Bureau of Mines Information Circular 8741, a document generally accepted as the "best practice" guide in the USA. The information in this circular was compiled based on the results of two research projects completed by Skelly and Loy and by Wardell and partners under contract to the USBM.
- Tensile strains on the surface should generally be less that 10 mm/m (0.010).
- A conservative maximum strain value between 5 mm/m and 7 mm/m (0.005–0.007) can be assumed for design purposes depending on the specific conditions.
- The minimum overburden for total extraction under a body of water is approximately 60 times the extraction thickness (60*t*).

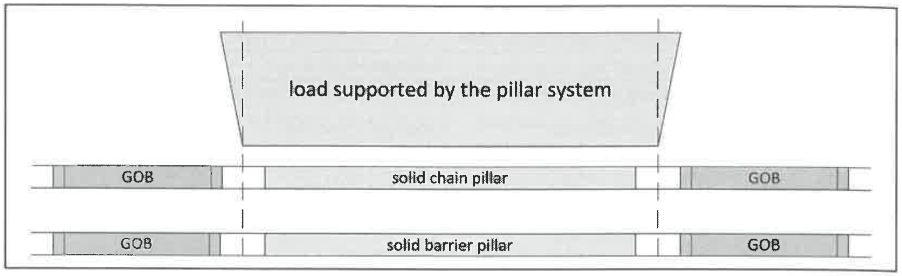

Figure 1. Conceptual diagram of supported load over solid barrier pillars using the ALPS methodology

DESIGN OF STABLE BARRIER PILLARS FOR STREAM PROTECTION

Barrier pillars for stream protection (or stream protection pillars) are designed based on the strength of the material compared to the expected loads from the overburden and the abutment pressures generated due to mining on one or both sides of the pillar. Such pillars are usually designed so that mine operations in adjacent panels are safe for the duration of mining. It should be noted, however, that stable pillars underground will not necessarily prevent ground deformations on the surface.

Analytical Methods

The width of barrier pillars can be calculated using analytical methods that account for the abutment angles due to the gob areas adjacent to the pillars. For the case of full extraction panels adjacent to solid barriers, the analytical methodology found in the Analysis of Longwall Pillar Stability (ALPS) can be utilized. The ALPS methodology was developed by NIOSH (Mark, 1992) and allows calculation of stability factors on chain pillars designed to support headgate and tailgate configurations during longwall extraction. In the case of fully extracted room-and-pillar section, the ARMPS methodology may be used (Mark and Chase, 1977; Mark et al. 2011).

For this application, ALPS was used to simulate the loads on a barrier pillar as follows: A very long chain pillar between two entries was created for a longwall panel width of 1,000 ft and an extraction thickness of 5 ft (Figure 1). The stability factor for isolated loading was calculated. The chain pillar was then assumed to be the barrier pillar between two full extraction panels.

Figure 2 shows a nomogram that was generated using the ALPS Classic formulation where the curves correspond to stability factors. Given the pillar width and the overburden depth, the corresponding stability factor for the solid pillar can be easily estimated for an extraction thickness of 5 ft. The ALPS Classic formulation calculates lower pillar stability factors than the ALPS Revised formulation and it is thus considered more conservative. The stability factors calculated in the following sections are based on the Classic formulation of ALPS.

Pillars between two full extraction panels may be partially mined ensuring, however, that the pillar system still remains stable. ALPS can be utilized to estimate stability factors for these pillar systems as well. Figure 4 shows a nomogram that was generated using the ALPS Classic formulation (using the isolated loading calculations) where the curves correspond to stability factors for pillar systems with a 50% extraction ratio and an extraction thickness of 5 ft. Pillar Stability Factor is defined under ALPS as the ratio of the pillar bearing capacity to the actual pillar load. When this ratio is greater than one then the pillar is considered stable (Figure 3).

For a given overburden depth, the stability factor of the pillar system remains constant as the pillar system width increases, as long as the extraction ratio remains the same.

Based on the ARMPS 2010 analysis (Mark et al. 2011), NIOSH recommends minimum stability factors for solid barrier pillars ranging from 1.5 to 2.0, depending on mine layout conditions and parameters. Table 2 lists the pillar widths calculated using the ALPS methodology for two different depths for solid pillars and pillar systems with 50% extraction.

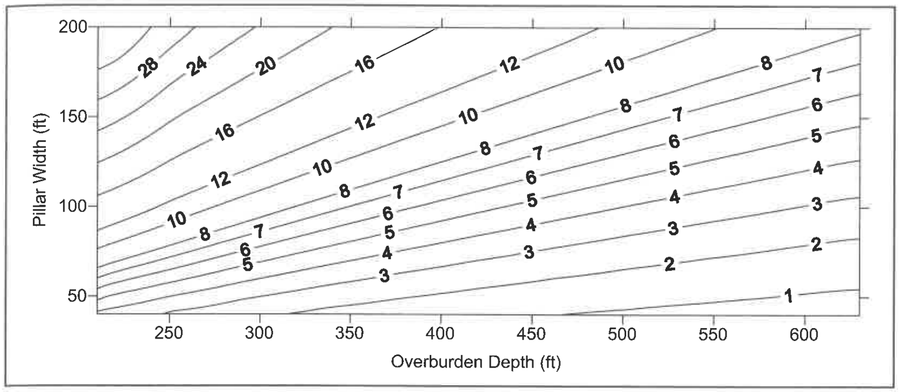

Figure 2. Nomogram for the calculation of solid barrier pillar stability factors based on pillar width and overburden depth using the ALPS Classic formulation (extraction thickness = 5 ft)

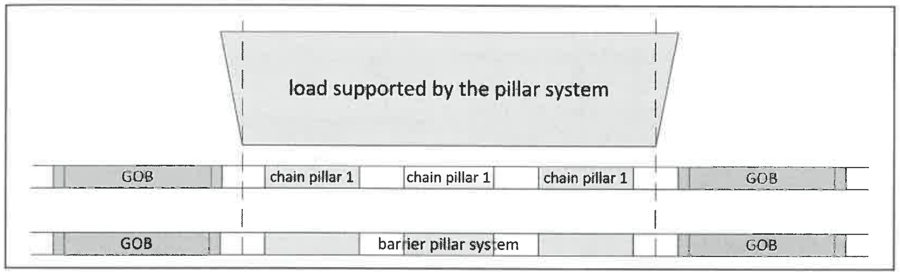

Figure 3. Conceptual diagram of supported load over barrier pillar systems using the ALPS methodology

Empirical Methods

A number of empirical design methods used to estimate the width of a solid barrier pillar are detailed in Kohler and Tadolini (1995). Kendorski and Bunnell (2007) published a study where these formulations are utilized for the design of an underground water barrier pillar. The methods referenced in these studies do not consider strains on the surface and are based on the mechanical loading of the pillar.

These formulations include:

- The Pennsylvania Mine Inspector's formula, where $W = 20 + 4t + 0.1h$
- The Pressure Arch method, where $W = 2.625*(h/20 + 20)$
- The British Coal Rule of Thumb, where $W = (h/10) + 45$
- The North American Method, where $W = (h*P)/(7{,}000 - h)$ and P is the adjacent panel width

Table 3 summarizes the estimated pillar widths for the above mentioned four methods for an overburden depth of 300 ft and 350 ft and an extraction thickness of 5 ft. In the case of the North American Method, an adjacent panel width of 2,000 ft was applied. Pillar widths range from 70 ft to 92 ft for a depth of 300 ft and from 75 ft to 105 ft for a depth of 350 ft. Also the

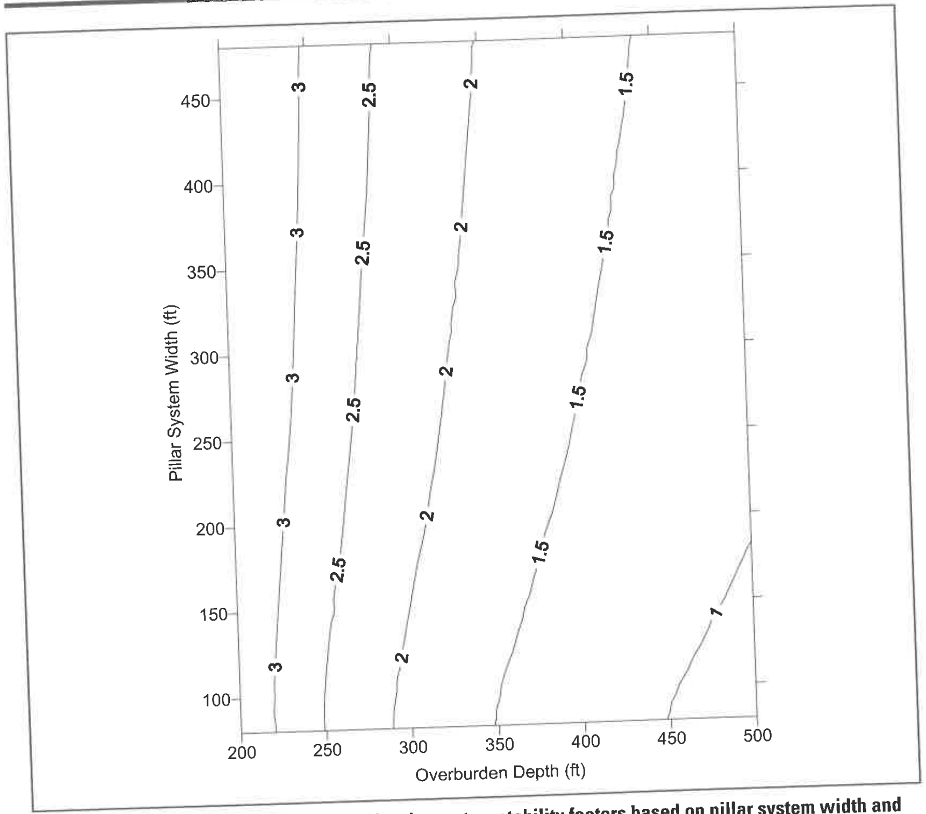

Figure 4. Nomogram for the calculation of barrier system stability factors based on pillar system width and overburden depth using the ALPS Classic formulation (extraction thickness = 5 ft, extraction ratio = 50%)

Table 2. Summary of stability factors for barrier pillars and barrier pillar systems using ALPS and extraction thickness = 5 ft

Depth (ft)	Barrier Pillar System Width (ft)	ALPS SF for Solid Barriers	ALPS SF for Barrier Systems at 50% Extraction
300	50	3.0	—
300	80	6.3	1.88
300	100	8.9	1.91
300	120	11.6	1.94
350	50	2.4	—
350	80	5.0	1.48
350	100	7.0	1.51
350	120	9.3	1.55

ALPS stability factor (Classic formulation) is given as calculated in the previous section.

DESIGN OF BARRIER SYSTEMS FOR STREAM PROTECTION

Mine planning engineers and regulators have often applied empirical rules for the protection of surface structures. For example, the Pennsylvania Bituminous Mine Subsidence Act of 1966, provided protection for certain surface structures by using an offset from the structure and a protection angle assumed to be 15°. Although this specific formulation is not used for stream protection, it is of interest as in a similar manner, a protection angle and offset distance are also used to develop an empirical stream protection barrier method.

Other "rules of thumb" are applied to determine the size of barrier pillars or barrier systems for stream protection and the distance required between the edge of the mine panel or mined area and the surface stream above, to ensure that potential impacts on the surface water structure are minimized. Such formulae are usually empirical, conservative, inflexible and limiting, as they ignore a number of parameters affecting the propagation of movement from the mine level to the surface water structures. A commonly utilized empirical rule that has been accepted in the Appalachian region (Mullins 2012) is depicted in Figure 5.

Table 3. Solid barrier pillar widths estimated using pillar design formulations based on mechanical loading for an extraction thickness of 5 ft and two different overburden depths

Formulation	Solid Pillar Width (ft) for $h = 300$ ft	ALPS SF
Pennsylvania Mine Inspector's formula	70	5.2
Pressure Arch method	92	7.8
British Coal Rule of Thumb	75	5.7
The North American Method	90	7.6
	Solid Pillar Width (ft) for $h = 350$ ft	
Pennsylvania Mine Inspector's formula	75	4.5
Pressure Arch method	98	6.8
British Coal Rule of Thumb	80	5.0
The North American Method	105	7.6

This rule assumes both a horizontal and a vertical buffer zone, and uses mining and subsidence empirical parameters, i.e., overburden thickness, coal seam height, and an upper limit value for the angle of draw. The boundaries of the horizontal buffer area are defined from the horizontal distance ($W/2$) between the panel rib and the centerline of the stream (as in Figure 5). This horizontal distance is a function of the angle of draw (γ), the overburden depth (h) and a constant offset ($B/2$) (from Figure 5). The empirical rule assumes a minimum offset distance ($B/2$) of 50 ft (~17 m) from the stream centerline, an acceptable limit for most Appalachian headwater streams. However, for very wide streams this width can increase accordingly, to better protect the stream bed, bank and adjacent alluvial floodplain. For the Appalachian region, the angle γ is taken as the upper limit of the angle of draw for the region, which assumes a value of $\gamma = 28$ degrees (Karmis et al., 1983). Thus, the rule of thumb equation is given below:

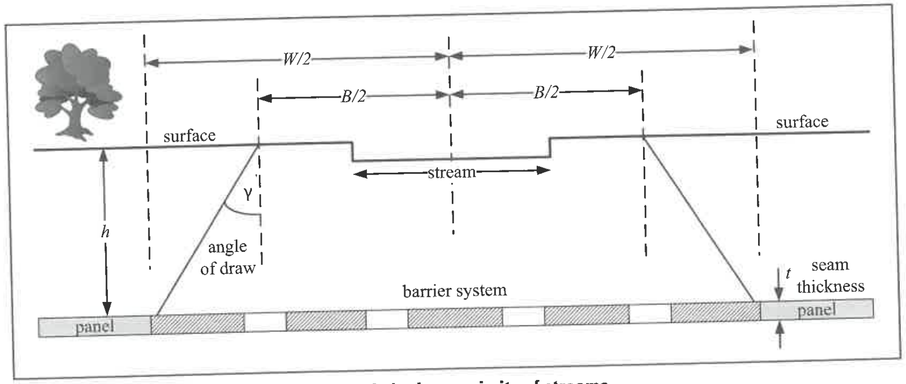

Figure 5. Buffer zone for full extraction panels in the proximity of streams

$$\frac{W}{2} = \frac{B}{2} + h * \tan(\gamma) \leq > W \\ = B + 2h * \tan(\gamma) \tag{1}$$

The vertical buffer zone is used to ensure that the stream is at a safe distance from the fracture zone (FZ) that develops around the caved area of the mine panel (Peng 1992). The vertically applied buffer zone determines whether complete, or partial, extraction of the coal seam below a water structure is allowed. Figure 6 shows a conceptual diagram of the different zones that develop over a fully extracted area. The caving zone that develops immediately above the panel has a height ranging from $5t$ to $10t$, where t is the extraction thickness. This is followed by the FZ, which may extend from $30t$ to $50t$ (Peng and Chiang 1984). From the top of the FZ to the surface is the continuous deformation zone (CDZ) which often includes (particularly on valley bottoms) cracks, fractures, etc., because of tectonic stresses and structural features. It is assumed that water can be drained in this zone to a distance of about 100 ft (~31 m).

If the overburden depth of the seam under a stream is less than $50t$ + 100 ft (where t is in ft) then a protection pillar should be left in place as defined in Figure 1. First mining can occur in this pillar up to 50% extraction, or to an extraction ratio that will avoid surface movements. For depths greater than $50t$ + 100 ft, the stream can be fully undermined, since an intermediate zone (Figure 6) is present and the drainage zone does not communicate with the FZ to allow dewatering towards the mine level. The above logic is given mathematically below.

$$H_c = 50t + 100\,ft \begin{cases} \text{if } h > H_c \text{ then full} \\ \text{undermining is possible} \\ \\ \text{if } h \leq H_c \text{ then only} \\ \text{first mining is allowed} \end{cases} \tag{2}$$

According to the rule of thumb for a 5-foot extraction, the CDZ is in contact with the FZ when $H_c + 50t + 100 \Rightarrow H_c\ 50*5 + 100 = 350$ ft, i.e., the maximum depth for which a protection pillar may be required under the stream. In this particular layout, for mining depths over 350 ft, full extraction under the stream is allowed, while for less depth, only partial extraction is allowed. As a result, the overburden depths for the two case scenarios are set to 300 ft (~91 m) and 350 ft (~107 m), respectively, as in Figure 3. The two depth values selected also satisfy the $60t$ rule, i.e., $60t = 60 \times 5 = 300$ ft, as given in Table 1.

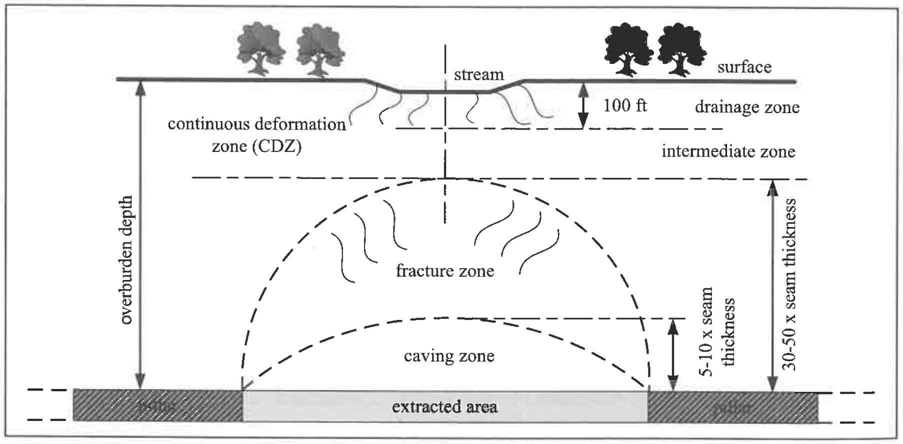

Figure 6. Caving zone, fracture zone and continuous deformation zone (adapted from Pengand Chiang 1984)

Table 4. Barrier pillar widths estimated using pillar design formulations based on rule of thumb formulations for water body protection for an extraction thickness of 5 ft and different overburden depths

Depth (ft)	Pillar System Width	ALPS SF for 50% Extraction Along the Whole Pillar System
300	420	2.35
350	472	1.98

The minimum (W_{min}) values for the barrier pillar half-widths using the empirical protection rule are determined using Equation 1 as follows:

$$\frac{W_{\min}}{2} = \frac{B}{2} + h * \tan(28^\circ) \\ => \frac{W_{\min}}{2} \\ = \begin{cases} \text{for } h = 300 \text{ ft} \rightarrow \dfrac{W_{\min}}{2} \\ \quad = 210 \text{ ft} => W_{\min} = 420 \text{ ft} \\ \\ \text{for } h = 350 \text{ ft} \rightarrow \dfrac{W_{\min}}{2} \\ \quad = 236 \text{ ft} => W_{\min} = 472 \text{ ft} \end{cases} \tag{3}$$

The above results are summarized in Table 4. Also the ALPS stability factor (Classic formulation) is presented to allow comparison between the different designs.

DESIGN OF PILLARS AND BARRIERS FOR STREAM PROTECTION USING A SURFACE MOVEMENT APPROACH

Prediction of Ground Deformations Due to Underground Mining

The development of rigorous and well-accepted ground deformation prediction methodologies for assessing mining impacts on surface structures, facilities and water resources is important for subsidence control. This task can be extremely complex because of the number and nature of the parameters affecting ground deformation induced by underground mining, including surface morphology, mine plan, coal structure elevation and characteristics, rate of mining, overburden lithology, and the type of surface facility or water resource to be protected.

A number of subsidence prediction methodologies have evolved and have reached considerable maturity and acceptance in recent years. This can be attributed to both a need for more accurate estimation of potential impacts and damages, as well as the ability to execute more sophisticated calculations. In addition, subsidence impacts and protection of surface and underground water resources have received considerable attention by the mining industry and the regulatory and permitting agencies.

The Surface Deformation Prediction Software (SDPS) is a suite of software modules that can address both surface deformations due to underground mining and mine stability issues. This package was originally developed by Virginia Tech in the 1980s, but since then has been constantly updated and expanded. Prediction of ground deformations is mainly accomplished using the influence function method (Karmiset al. 1990). Several static or dynamic (i.e., dependent on the rate of mining) surface deformation indices can be calculated at any location, given a digitized mine plan, digitized surface topography and knowledge of appropriate subsidence parameters. Calculations are based on several empirical relationships, developed through the statistical analysis of data from a number of case studies (VPI&SU1987; Karmiset al. 1992). Calculated deformation indices include horizontal and ground strain (i.e., strain on a horizontal plane at a given surface point, or strain that accounts for the aspect and slope of the surface in the vicinity of the point), principal strains and maximum strains, either compressive or tensile.

Ground deformation prediction can also be applied in the case of surface water resources. Maximum allowable tensile strains on the surface is considered one of the best indicators for controlling the development of new cracks or extending existing cracks on the surface. Using SDPS, surface deformations including tensile strains as well as final surface profiles can be calculated at any surface point, e.g., the bottom of a stream. It should be noted that strain on the surface

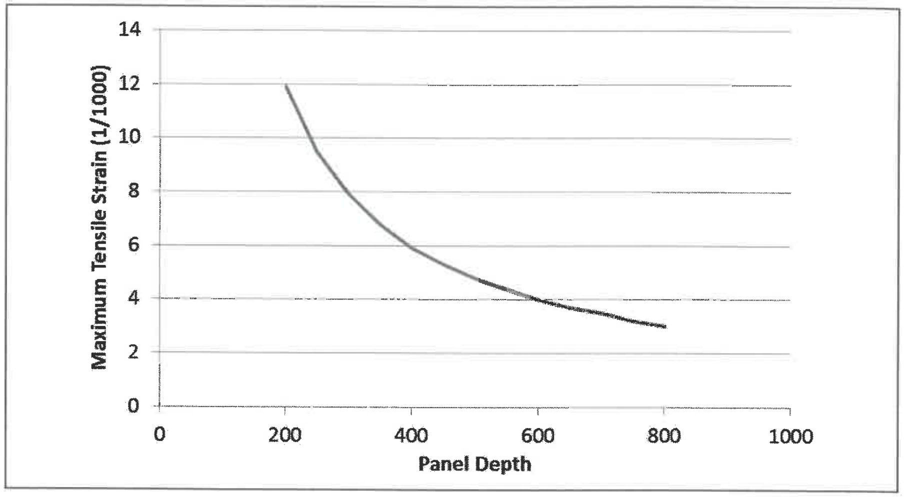

Figure 7. Maximum tensile strain with depth for extraction thickness = 5 ft

decreases with the increasing depth of cover to the extracted seam. Figure 7 presents the decrease of the maximum tensile strain on the surface for different overburden depths in the case of a supercritical fully extracted area and an extraction thickness of 5 ft. The calculations were performed using default subsidence parameters for the Appalachian region (Agioutantis and Karmis 2012).

In the next section tensile strains are calculated for a range of stream protection barrier pillar sizes and an approach is recommended for optimum pillar design given Appalachian underground mining conditions. All calculations given below refer to final subsidence effects after all mining has ceased. Movements while mining is in progress (dynamic movements) are expected to be much less than final movements (Karmis et al. 2008).

Pillar System Design Based on Surface Deformations

Pillar design methodologies based on loading and stability do not account for surface deformations. As already mentioned, pillars or pillar systems may be stable, but deformations may occur on the surface above the pillar. In this section, ground movements on the surface due to underground mining are related to barrier pillar geometries.

An example is presented below to illustrate this concept using the following assumptions:

- Calculations are completed using one mine geometry for two different overburden depths. In each case the maximum ground strain is calculated for different barrier pillar widths under the protected surface body.
- The overlying surface is horizontal. A set of surface points in a dense grid is set to correspond to a stream bed. The location of the edges of two high extraction panels (i.e., longwall panels) located on either side of the stream are varied with respect to the stream centerline.
- The rectangular longwall mine panels are assumed to have the same geometrical characteristics, i.e., width = 1,000 ft (~300 m), length = 1,800 ft (~550 m) and extraction thickness of t = 5 ft (~1.5 m). The dimensions of the panels are selected such that they will be supercritical, i.e., width-to-depth > 1.2.

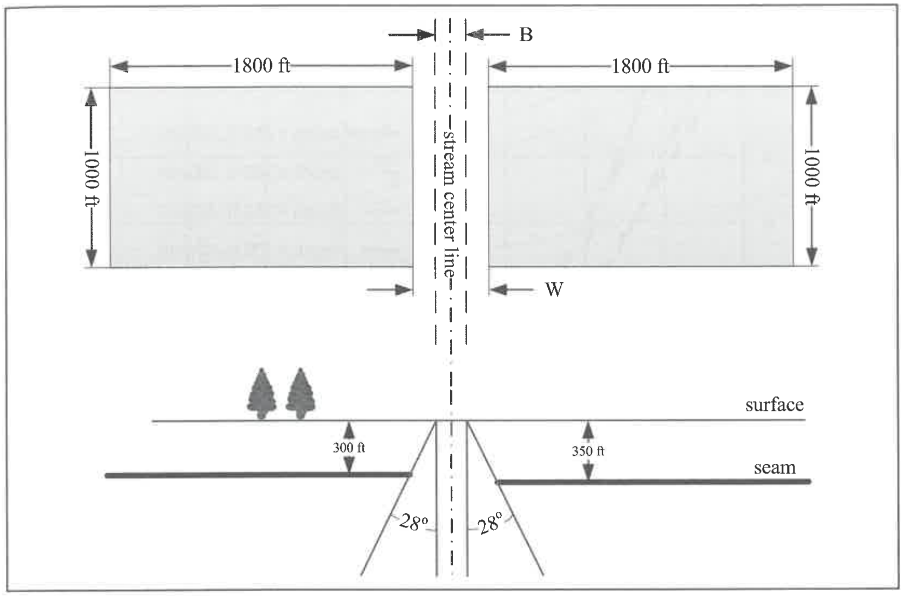

Figure 8. Plan view and section of two mine panels in the proximity of a stream (distances in ft). Protection/buffer zones are calculated using the "rule of thumb" for $\gamma = 28°$ and for depths of 300 ft (~100 m) and 350 ft (~117 m).

- The overburden geology is assumed to be represented by 50% hard rock. The supercritical subsidence factor for these conditions is about 40%.
- The influence angle used in this analysis is the default value for the eastern Appalachian coalfields (i.e., $\tan\beta=2.31$ or $\beta\approx67°$).
- The strain coefficient used in this analysis is the default value for the eastern Appalachian coalfields (i.e., Bs=0.35 ft).
- It is assumed that the stream section of interest has a width of 20 ft (~6 m), an initial depth of 0.5 ft (~0.15 m) and vertical banks.

The parametric analysis was run by varying the width of the barrier pillar (W), as in Figure 8. The analysis was completed using the influence function method available in the latest version of the SDPS software (Agioutantis and Karmis 2012), which can easily be applied to any mining geometry, in order to calculate the ground strain at the stream centerline for different *stable* barrier pillar system widths (W).

Figure 9 presents the calculated values of maximum strain plotted for the different depths of 300 ft and 350 ft (~100 m and ~117 m). Under those conditions, the recommended pillar width assuming a tensile strain threshold value of 5 mm/m is approximately 80 ft. It should be noted that the parametric analysis was conducted assuming that the barrier pillar underneath the stream is stable (i.e., not yielding). When stable pillar systems are developed next to full extraction areas, then an edge effect develops for that extraction area, which shifts the inflection point of the resulting subsidence profile towards the gob. This edge effect accounts for the cantilevering of the overburden strata above the gob. The edge effect was automatically estimated using the SDPS package as a function of the overburden (Agioutantis and Karmis 2012). It is immediately

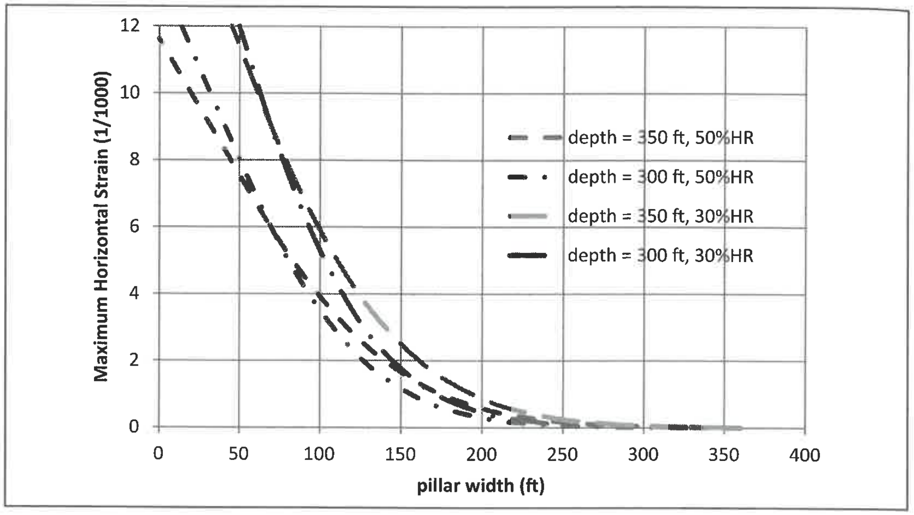

Figure 9. Maximum strains at the stream centerline as a function of barrier pillar width for a 5 ft extraction thickness under 300 ft and 350 ft of overburden for 50% and 30% hardrock

evident that pillar system widths greater than 300 ft (~100 m) result in zero surface strains in the area under examination.

Using the SDPS capabilities, alternative assumptions and scenarios can be calculated and compared. For example, Figure 9 also shows the calculated tensile strain on the surface for the same selected depths, assuming a different geology, i.e., 30% hardrock. In this case, due to the softer overburden, higher strains will be encountered and, therefore, assuming a horizontal strain threshold value of 5 mm/m, the recommended barrier pillar width is in the order of 110 ft.

Figure 10 presents a nomogram where barrier pillar width (*W*) can be calculated as a function of depth (*h*) for different maximum values for tensile strains on the surface. Figure 11 presents a similar nomogram relating pillar width and overburden depth for different subsidence values on the surface for an extraction thickness of 5 ft. The subsidence values are given here in inches.

DISCUSSION

Barrier pillar widths for the protection of surface water resources were calculated using an analytical approach as given by the ALPS formulation. Nomograms were generated for solid barriers as well for barrier pillar systems with 50% extraction. In addition solid barrier pillar dimensions using several empirical formulas were also calculated. Pillar system widths were estimated using a rule of thumb for water body protection, applied in the Appalachian region. Crossing such pillar systems via mains, or other low extraction works, will not compromise the overall stability of the barrier system. All of the above calculations were mainly performed for typical mine plan geometries, i.e., extraction thickness of 5 ft and depths ranging from 300 ft to 350 ft.

Due to the rationale behind these formulations, none of these approaches can estimate the potential surface tensile strains that may lead to drainage of a surface water resource. The application of a well-accept ground deformation prediction methodology allows the calculation of barrier system pillar widths, for given maximum allowable surface tensile strains. To facilitate this task, nomographs were generated relating barrier system pillar width and overburden depth to surface tensile strains, as well as surface subsidence. Thus, pillars can be designed by minimizing the potential surface effects. In all cases these pillars

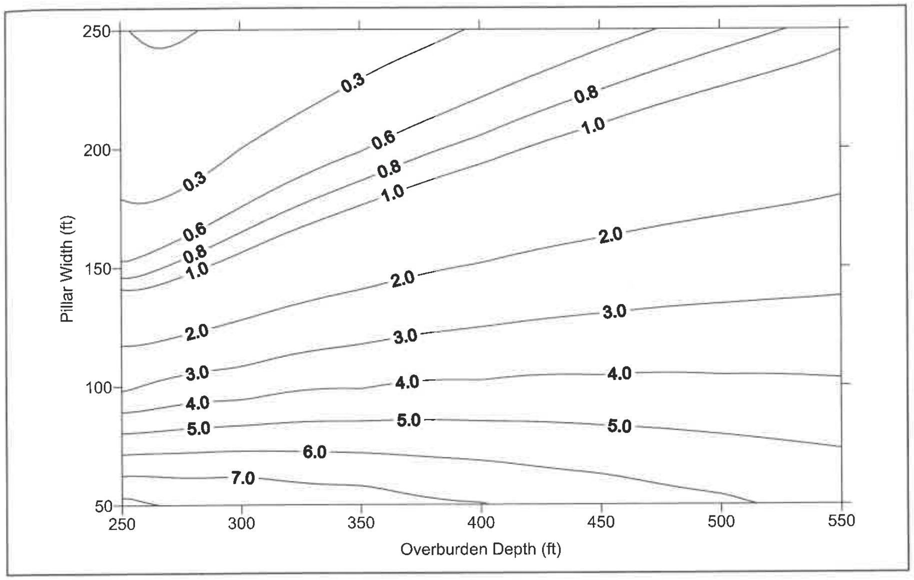

Figure 10. Nomogram relating pillar width and overburden depth for different maximum strains on the surface (1/1000) for an extraction thickness of 5 ft

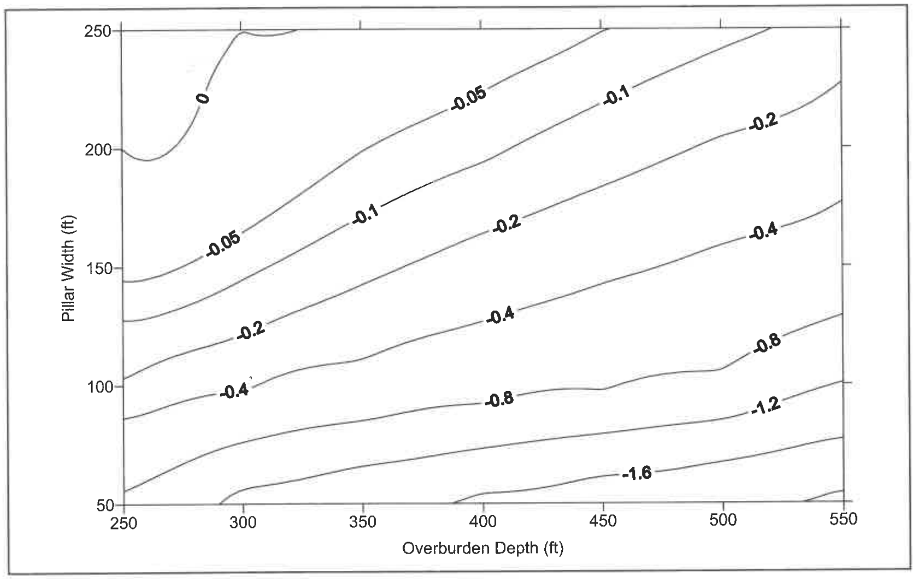

Figure 11. Nomogram relating pillar width and overburden depth for different subsidence values on the surface (in inches) for an extraction thickness of 5 ft

Table 5. Summary of barrier pillar design formulations that can be considered for water body protection. Data refer to extraction thickness = 5 ft, 50% hardrock and overburden depth ranging between 300–350 ft.

Pillar Design Approach	Depth (ft)	Solid Barrier Pillar Width (ft)	Barrier System Width (ft)	Strain on the Surface	Subsidence (in)	Comments
Empirical methods for water body protection	300		420	—		An overall extraction of 50%, ALPS SF = 2.35
	350		472	—		An overall extraction of 50%, ALPS SF = 1.98
Empirical methods based on mechanical loading	300	70–92		—		ALPS SF = 5.2–7.8
	350	75–105		—		ALPS SF = 4.5 – 7.6
Analytical (ALPS)	300	50–120	80–120	—		ALPS SF (solid)= 3.0 – 11.6 ALPS SF (50%)= 1.88–1.94
	350	50–120	80–120	—		ALPS SF (solid)= 2.4 – 9.3 ALPS SF (50%)= 1.48–1.55
Ground deformation calculations	300	~60		0.007	1.1 in	ALPS SF = 4.1
		~80		0.005	0.4 in	ALPS SF = 6.3
	350	~60		0.007	1.3 in	ALPS SF = 3.2
		~80		0.005	0.6 in	ALPS SF = 5.0

should also demonstrate an acceptable stability factor.

Table 5 summarizes the findings for all approaches. Results indicate that the width of barrier pillar systems calculated using rules of thumb significantly overestimate the protection zone and thus may sterilize coal reserves. Using ground strain as the driving criterion, coupled with analytical calculations of stability factors for barrier pillar systems, may result in an optimum design of such barriers pillars left underground for the protection of surface water bodies.

Most empirical approaches for stream protection operate on the assumption that a stream will be protected from dewatering if the fractures extending down from the continuous deformation zone will not meet with the fractures propagating up due to the caving/disturbed gob zone. This approach, although simplistic, provides the basis for all empirical formulations for the protection of streams or other surface water bodies. This methodology has allowed estimates of protection pillars to be made and does not in any way replace a full hydrologic investigation for the area of interest. In this paper, the same rationale was used, but in this case, the barrier pillar for stream protection was calculated using surface tensile strains.

Finally, the SDPS model has the ability to provide tensile strain calculations that can be used for stream protection for a range of depths, topographic conditions and lithologic environments.

CONCLUSIONS

Potential impacts on surface water bodies may be avoided when tensile strains on the surface are kept to low values. It is well documented in the literature that surface cracks and water impacts can be contained if the surface tensile strains, due to underground mining, are kept below 10 mm/m (0.010 in/in). In this study, even more conservative values were utilized which ranged from 5 to 7 mm/m.

The methodology presented was developed for the design of barrier pillars and barrier pillar systems for stream protection based on a different approach than the traditional barrier pillar stability. In this case the maximum expected tensile strain on the surface (under static or dynamic conditions) is used to estimate the width of the barrier system as a function of depth. The nomogram generated in this paper corresponds to a specific extraction thickness, but similar nomograms can be generated for different extraction thicknesses using the SDPS package. Thus, mine planners and regulators can use these nomograms to design barrier systems based on a specific maximum tensile strain criterion. Subsidence and stability factor nomograms can also be utilized for a comprehensive analysis of each case. It is also possible to cross such pillar systems via mains or other low extraction configurations which are not expected to compromise the overall stability of the barrier system.

Results indicate that the width of barrier pillar or barrier pillar systems calculated using rules of thumb overestimate the protection zone and thus may sterilize significant coal reserves without offering additional protection benefits. Using ground strain as the design criterion, coupled with analytical calculations of barrier pillar stability factors, may result to a barrier pillar system that optimizes extraction and also provides protection to surface water bodies.

This approach presents a novel method for estimating barrier pillars for stream protection. The examination and analysis of additional case studies will be important to further establish, validate and utilize this methodology in practice.

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