A Methodology to Assess the Potential Impacts of Longwall Mining on Streams in the Appalachian Basin

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ABSTRACT
This paper presents a study of undermined streams, adjacent to longwall workings, which have been successfully mitigated after the panels were fully mined. The results of this case study are used to develop comparisons and guidelines for predicting the potential impacts of future mining development, under similar mining and geological conditions. The main parameters of the comparison include mining and geologic conditions, stream characteristics and potential ground movements calculated over existing and proposed longwall panels.

Results indicate that future longwall mining panels can be successfully designed to ensure that surface impacts on overlying streams can be successfully controlled and mitigated using standardized and well proven measures.

INTRODUCTION
Public and regulatory focus on the potential impacts of longwall mining on streams dictate that potential surface effects of undermining must be contained within acceptable levels and appropriate restoration and/or mitigation measures can be implemented during and after mining.

Ground movements due to underground mining may affect surface water bodies including rivers, streams, swamps, wetlands, lakes, farm dams or other water retaining structures. As discussed by Dawkins (2003), some of the more important potential environmental impacts on streams include reduced surface water supplies, reduced water quality, adverse ecosystem changes, diversion of stream flow lines and ponding. The author also suggested that groundwater resources may be impacted by dewatering or interconnection of aquifers, reduction in spring flow and/or stream base flow recharge, emergence of the groundwater table, flows into the mine, interference effects from adjoining mines and seam or overburden gas discharge to the atmosphere.

Overburden geologic structure and thickness, distance from the full extraction area, mine conditions and extent of surface movements all are key parameters in determining the degree of impacts on streams and the recovery cycle of the water resource due to lonwall or secondary extraction room and pillar sections (Agioutantis et al., 2013). At the same time undermined streams recover after a period of time with, or often without, the application of mitigation measures. In addition, the greater the overburden thickness, the less the extent of dewatering and the greater the potential for complete recovery of the water resource. The above apply to mining operations where the caving zone does not extent in the continuous deformation zone.

This paper presents a study of undermined streams in the Appalachian coal basin, which have been successfully mitigated after the respective longwall panels were fully mined. The results of this study are used to develop comparisons and guidelines that can be used for the prediction of potential impacts of future mining development, under similar mining and geological conditions. The comparison is based on mining and geologic conditions, stream characteristics, and the calculation of ground movements over existing and proposed longwall panels.

Ground movements due to underground mining and their prediction

The prediction of the ground response to underground mining and the potential impacts on streams and other water bodies requires a detailed analysis of a number of factors:

- Mining Factors: include panel geometry, mining thickness and the location in the three-dimensional space
- Stream Characteristics: include the watershed drainage area, the extent of undermining within the watershed, the location of each stream with respect to the mined panels, the angle of panel crossing, the valley hillside slopes along the stream beds, and the width of the valley bottom at each stream bed
- Geologic Factor: represent a complex, and often variable, set of conditions, including the general geology of the area, the stratigraphy between the extracted seam and the surface, the lithology and bed thickness of key formations, the location of key formations from the mining horizon and small- and large-scale tectonic features.

In subsidence engineering calculations, the overall response of the overburden to underground mining can be related to mine geometry, surface topography as well as overburden characteristics. A typical parameter representing overburden behavior is the percent hard rock in the overburden strata, i.e., the sum of the thickness of competent rocks (e.g., sandstone, limestone), having a minimum thickness of 5 feet, expressed as a percentage of the total overburden thickness (VPI&SU, 1987; Agioutantis and Karmis, 2015). In addition, caving characteristics and pre-existing fracture zones have an impact on the extent of fracturing and its propagation towards the surface.

The ground deformation indices that can be used for evaluating potential impacts to streams include the maximum subsidence (Smax), the maximum surface ground slope (±Tmax), the maximum tensile ground strain (+Emax), and the maximum compressive ground strain (-Emax), measured and/or predicted for the site in question. These ground deformation indices are defined in the available literature (Brauner, 1973; Peng, 1992; Karmis et al., 1990a, 1990b).

Different calculation models have been proposed to calculate vertical and horizontal displacements on the surface due to underground mining. Most of these models employ the influence function method, which can be easily calibrated to calculate surface movements for any mining geometry. Other indices, such as horizontal strain, can be calculated by differentiating the influence function at specific surface points assuming a horizontal terrain.

As discussed in the following section, surface strain is probably the predominant criterion for evaluating potential impacts to water bodies, and, therefore, the difference between horizontal and ground strain should be further explained. Horizontal strain can be easily calculated using just the elevation of each surface point. However, in order to calculate ground strain, i.e. to account for the influence of the surface terrain around each surface point, the detailed surface topography around each individual surface point should be included in the calculations, as discussed by Agioutantis and Karmis (2013). Furthermore, in order to calculate strain values along a directional path, such as a stream bed

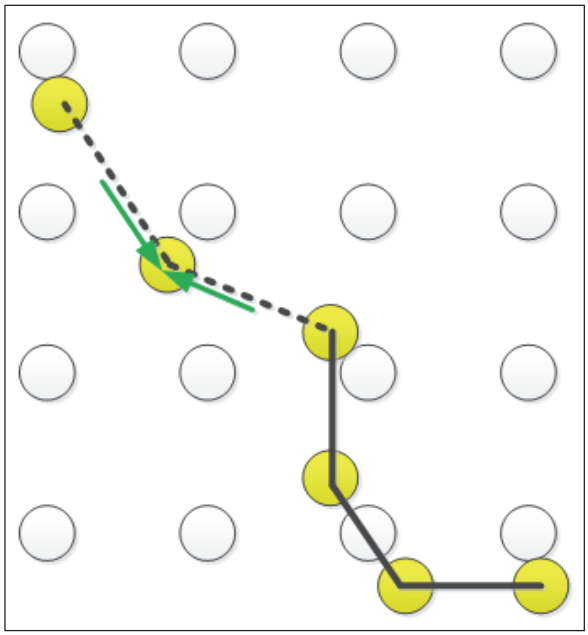

Figure 1: Surface elevation grid (empty circles), stream bed profile points (filed circles) and arrows showing neighboring surface points used for calculating directional strain.

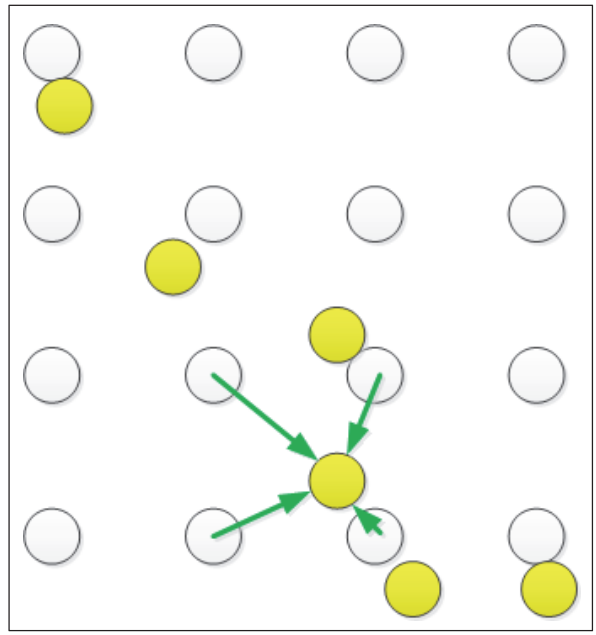

Figure 2: Surface elevation grid (empty circles), stream bed profile points (filed circles) and arrows showing neighboring surface points used for calculating ground strain.

path, directional or axial strain values can calculated along a specific profile. Figure 1 shows the calculation of directional strain, while Figure 2 depicts the calculation of ground surface strains at individual points.

Damage criteria for undermining bodies of water

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, based on a report prepared for MSHA by D'Apollonia Engineering (2009). There are cases where mining under bodies of water depends on the depth between the mine and the surface water feature, which can be calculated as a function of extraction thickness, and/or the tensile strains that will develop on the surface, under that mass of water or under the water retaining structure. The conditions given in Table 1 relate to mining systems pertaining to full (i.e., longwall) or high extraction (room-and-pillar with secondary recovery) mining.

With respect to strains on the surface due to underground mining, the guidelines presented in Table 1, can be summarized as follows (see also discussion by Agioutantis et al, 2013):

- Tensile strains on the surface should generally be less than 0.010 ft/ft (10 mm/m) (Skelly and Loy 1977; Kendorski, 1979);
- The threshold value of 0.0875 ft/ft (8.75 mm/m) which is traditionally used was originally recommended by the U.S. Bureau of Mines (Babcock and Hooker, 1977).

Table 1. Summary of different guidelines for high extraction mining under or near bodies of water (adapted from Agioutantis et al, 2013 and a report prepared for MSHA by D'Apollonia Engineering, 2009)

Criteria	Description	Underground mining	Reference
Criteria based on Mine Geometry			
max (100*t* or > 700 ft)	Minimum overburden	Total extraction	Skelly and Loy (1977)
60*t*	Minimum solid overburden	Total extraction	Babcock and Hooker (1977)
60*t* to 117*t* (worst case) 37*t* to 105*t* (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)
0.00875	Surface tensile strain		Babcock and Hooker (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 >= 60*t*	Surface tensile strain and minimum overburden		Singh and Bhattacharya (1984)
<= 0.005; suggested overburden >= 60*t*	Surface tensile strain and minimum overburden		Singh (1992)
where, *t* = extraction thickness			

As a result, a conservative maximum tensile strain value between 0.005 ft/ft (5 mm/m) and 0.007 ft/ft (7 mm/m) can be assumed for design purposes depending on the specific conditions. The analysis presented below considers the above thresholds for ground strain as discussed previously.

Methodology

A number of streams that were initially undermined and subsequently restored were evaluated as the first step in this study. These streams are located in a major coal mining district in eastern USA. To accomplish this, data pertaining to mining parameters, overburden properties and ground deformation measurements in the vicinity of these streams, and over the undermined areas (e.g. subsidence and strain), were collected. Chain or gateroad pillars between fully extracted longwall panels were evaluated for stability, since this has a direct bearing on the value for the edge effect offset distance for each panel and thus on the subsidence profile. Subsequently, the ground deformation prediction model was calibrated using measured data, in order to determine the site specific values for the subsidence engineering parameters, i.e. influence angle, edge effect offset, supercritical subsidence factor, and strain coefficient. Note that in cases where actual field calibration data are not available, regional parameters (as published in the literature) can be used in the prediction models.

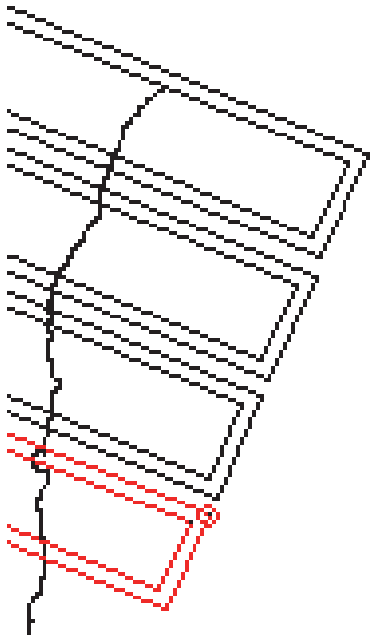

Figure 3. Partial mine plan of the model used for calculating surface deformations at surface points along undermined stream.

Multiple streams were examined in the same area. Finally, a reference database was developed where different comparison factors were listed, i.e.: depth to the coal seam, panel width, chain pillar design, width of valley bottom, maximum tensile and compressive strains, maximum ground slope, size of mined and unmined watershed upstream of longwall mining, percent hardrock in the overburden. Also, the state of the stream after restoration was recorded in the same data set.

Figure 3 shows the simplified mine plan for the study area and the surface points corresponding to a single stream crossing all panels. Panel widths were in the order of 1000 ft. Panel depths ranged from about 400 to 600 ft. Subsidence measurements were used to determine the local subsidence and strain parameters to be used with the ground deformation calculation models. For each panel the edge effect offset distance is also shown (offset line inside the panel boundary). Figure 4 shows the subsidence profile and the pre- and post-mining surface elevations along the stream, while Figure 5 shows the ground strain profile and the pre- and post-mining surface elevations along the stream. The maximum calculated vertical movements (subsidence) were about 4.2 ft, and the calculated peak tensile strains were in the order of 0.012 ft/ft (12mm/m). The maximum change in surface slope was in the order of 2% (Figure 6).

It is also evident that for this analysis where chain pillars are stable, water pooling may occur between successive subsidence troughs (Figure 4). Also, the sloping terrain may alleviate high tensile or compressive strains (Figure 5).

STREAM MITIGATION PROCEDURES AND PRACTICES

Even when streams may be impacted due to high tensile or compressive strains that can lead to diminution in flow, water will not be lost to the mine, and flow diminution can be successfully mitigated by healing the cracks that were created in the upper strata horizons, or by installing liners in the stream

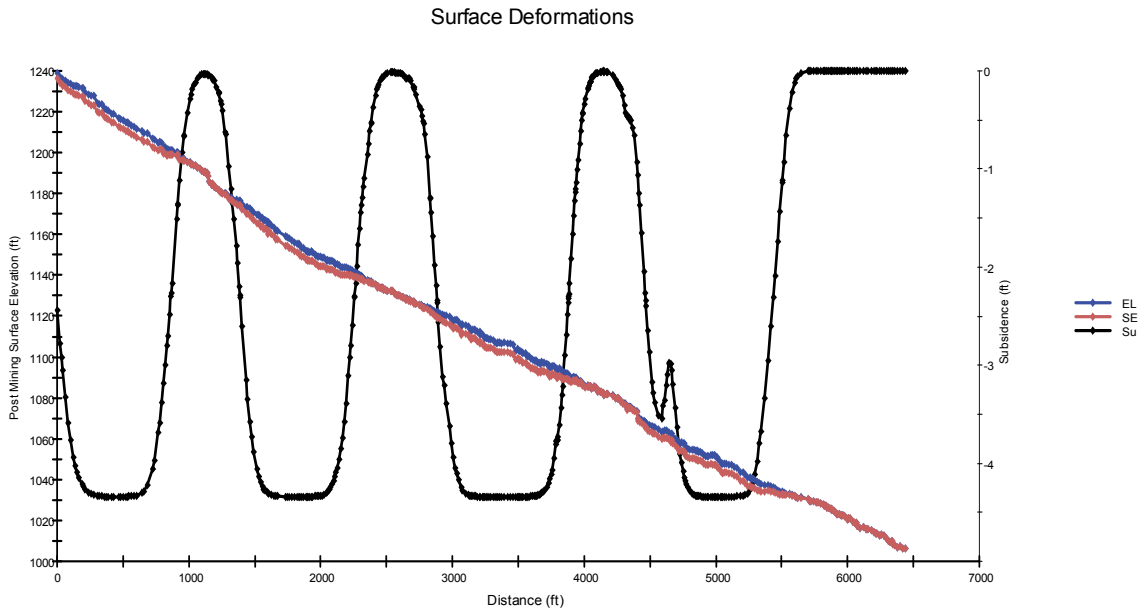

Figure 4: Subsidence profiles and pre/post surface elevations along stream bed.

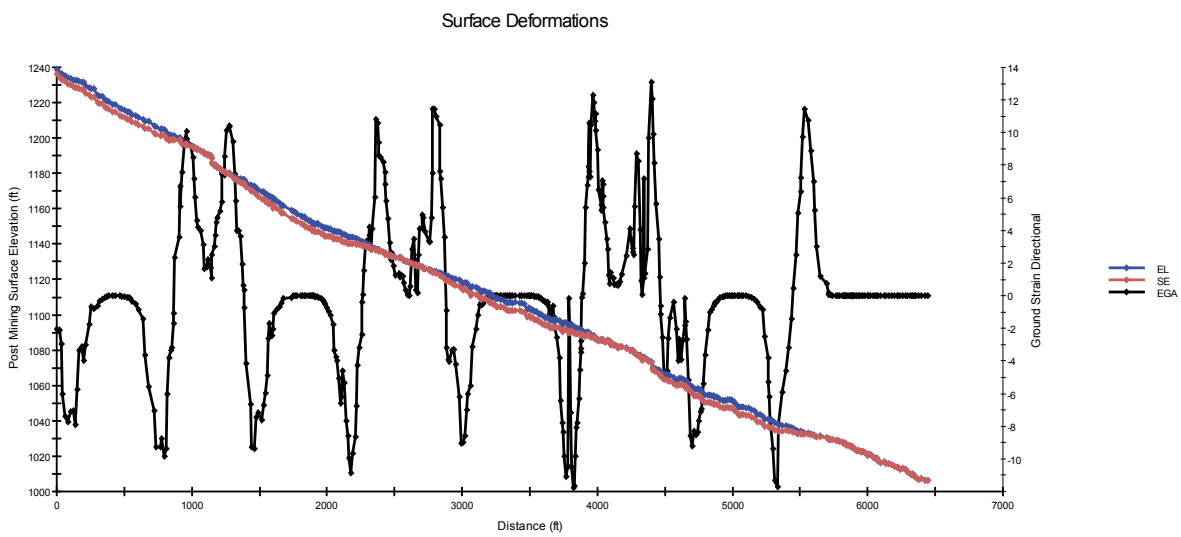

Figure 5: Ground strain and pre/post mining elevations along stream bed

beds. Clearly, mitigation measures should be planned in advanced of mining and prudent engineering practice should involve the following:

- Establish baseline flow and water quality measurements, at a predetermined interval (i.e. 100 ft) along the stream flow path, in order to document and identify potential flow loss
- Conduct flow and water quality measurements at the same reference points in order to identify changes from baseline parameters
- Develop a staged approach for achieving stream mitigation. In general, less invasive mitigation

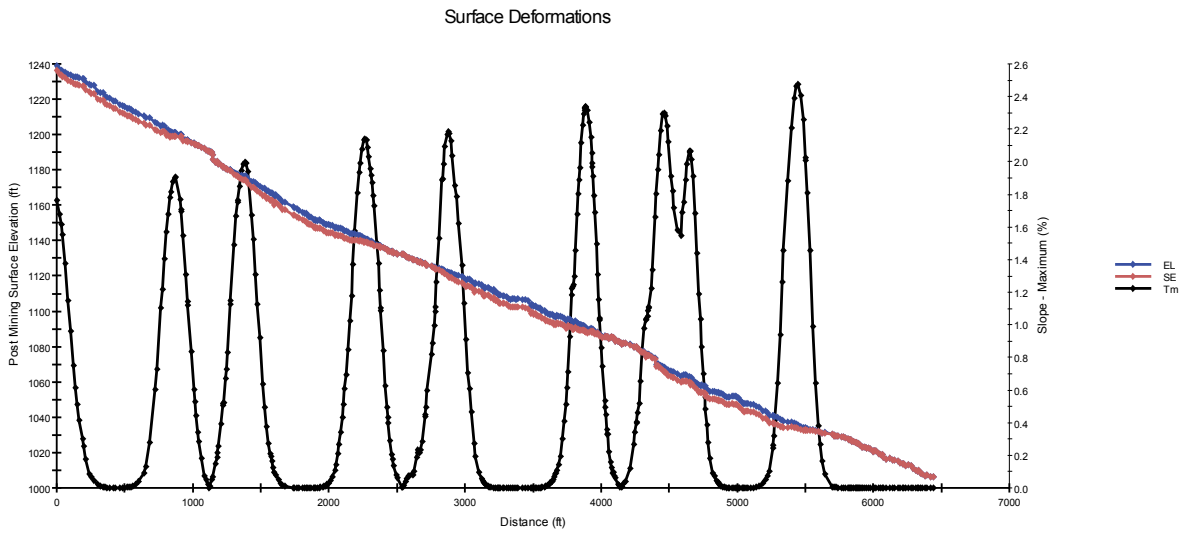

Figure 6: Surface slope changes and pre/post mining elevations along stream bed

measures such as stream bed lining should be used first. This can be followed by grouting, on a primary grid, to a shallow depth of a few feet. More aggressive mitigation measures can be implemented, if abnormally high flow loss and severe bedrock abnormalities are observed. The later may be applied through a secondary inject grid for medium depth grouting of several feet.

Furthermore, the following should be incorporated in the mitigation strategy.

- The primary and secondary borehole grid should be established as a function of flow loss and severity of impact.
- The spacing of the primary and/or secondary borehole grouting grids should be specified in terms of feet (i.e., 5 ft, 10 ft, 20 ft, etc.).
- Borehole drilling and grout injection should continue until grout injection rates decrease, i.e., bedrock closure is achieved.
- Stream flow testing should be conducted, as mitigation progresses downstream, and compared to the baseline flow in order to determine whether flow conveyance has improved.

Planning for new longwall panels in the same area

A number of streams were examined during this study, which have been restored using the above mentioned procedures. Stream restoration was considered successful as water flow and water quality was restored to pre-mining levels. A dataset was developed with successful stream restoration cases which was subsequently utilized for the planning of new panels in the same region.

More specifically, a number of indices was extracted pertaining to the successful mitigation cases, such as width to depth ratios and the maximum values for a number of ground deformation parameters. More or less favorable conditions were established for each of these comparison indices. For example, obtaining lower ground strain values constitutes a favorable condition compared to higher values.

When planning for a new set of panels, panel geometry, overburden characteristics and surface conditions can be entered in the database and compared against those in the reference dataset using

the aforementioned comparison indices and, therefore, changes can be introduced at planning level to allow for better stream mitigation potential in case of stream undermining.

CONCLUSIONS

A reference database was developed that includes a number of factors that can be used to compare mining conditions as they pertain to potential impacts to surface streams due to underground mining. These factors include, but are not limited to, the following factors: depth to the coal seam, width of valley bottom, tensile and compressive strains, maximum change in ground slope, size of mined and unmined watershed upstream of longwall mining, and stream mitigation status.

The related ground movements ground movements can be reliably calculated using well accepted technology. Pre- and post- mining elevation profiles along the stream flow lines can be used to determine potential water pooling areas as well as potential high tensile and high compressive strain areas which may lead to bed rock fracture.

Furthermore, the stream status after mitigation was included in the dataset. More specifically, data collected pertaining to stream undermining in the Appalachian basin showed that although strains exceeded the maximum values suggested in the literature, the streams were restored to their original condition using guidelines and protocols established by the mining company.

The developed dataset provided the operator with guidance during the planning stage of future longwall panels in the vicinity of the study area thus incorporating stream impact mitigation procedures and protocols for mitigating impacts due to mining-induced subsidence and ground strain.

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