Minimizing impacts on streams
due to underground mining by predicting surface ground movements

by Zach Agioutantis, Christopher Newman, Gabriel Böde Jimenez Leon and Michael Karmis

When utilizing high recovery underground mining methods, such as longwall or high-extraction room-and-pillar mining, the movement and deformation of the overburden propagate toward the surface and may affect the integrity of overlying surface streams (Peng et al, 1996). Published studies cite three major mechanisms of subsidence as most likely to impact streams: displacement, slope and strain. While subsidence-induced vertical displacement cause little structural damage to the stream bed, it may create adverse drainage and stream flow issues as the subsidence trough allows for ponding (Dawkins, 2003). Subsidence-induced changes to the slope, or tilt, of a stream may have adverse effects on water flow. As the stream enters the subsidence trough, the gradient increases providing potential erosion control problems. When exiting the subsidence trough, a reduction of the gradient may inhibit stream flow, causing localized ponding (Peng, 2008). While vertical displacement and tilt both may have detrimental effects to surface streams, the resulting strains have been documented as being the most damaging to surface streams and structures causing distortion, fractures, or failure (Singh, 1992). When stream beds are subjected to high tensile strain, tensile cracks may form at the surface level allowing for the direct loss of stream flow through fissures. When stream beds are located in areas of high compressive strain, rock layers forming the stream bed can fail as the stream bed ruptures, upward, blocking stream flow or having the stream diverted into the fracture zone at the base (Iannacchione, et. al., 2010).

Recent investigations on the effects of underground mining on surface bodies of water suggest that to determine the degree of stream impact one must also consider the geologic structure and thicknesses, surface topography, watershed drainage areas, width of river bed and rate of mining. Due to the complex nature and number of parameters affecting surface streams, subsidence modeling tools and software packages should be implemented throughout all stages of subsidence planning, prediction and control. The Surface Deformation Prediction System (SDPS) utilizes the influence function for the calculation of final subsidence deformations with respect to the angle of influence, supercritical subsidence factor as a function of the percent hard rock, edge effect offset distance, and surface topography. Developed more than 25 years ago, SDPS has been continually updated with new analysis and prediction features, providing a reliable and versatile program for subsidence management methodologies. Most recently, the program has been updated to evaluate the effect of varying surface topography in the prediction of horizontal displacements, referred to as ground strain, allowing for the accurate three-dimensional representation of surface deformations in mountainous terrain (Agioutantis and Karmis, 2014). Ground strain has become one of the predominant deformation indices used in the evaluation of potential damage to surface structures (Karmis et al., 1995). Ongoing work with SDPS software seeks to investigate the calculation of ground strain in SDPS and its ability to accurately and realistically predict damage to surface streams due to underground mining operations.

Zach Agioutantis, Christopher Newman and **Gabriel Böde Jimenez Leon**, members SME, are Mining Engineering Foundation professor, graduate research assistant and graduate research assistant, respectively, at the University of Kentucky and **Michael Karmis**, member SME, is professor at Virginia Tech, email zach.agioutantis@uky.edu.

Calculating mining-induced strains

The prediction of surface strains due to underground mining utilizing the influence function method is a mature methodology widely used by researchers, industry engineers and regulatory agencies. Currently, regulatory agencies require a subsidence control plan documenting surface deformations within the mineral extraction area as a means of quantifying the effect of underground mining on surface bodies of water such as streams. Typically, mining-induced effects on streams are reported as horizontal strain magnitudes calculated in the x- and y-directions as simply the change in the horizontal length between two points divided by the original horizontal distance assuming the point lies on an infinitely horizontal plane. Unfortunately, surface bodies of water rarely lie along strictly vertical or horizontal planes. Therefore, directional, or axial, horizontal strain can be determined along a defined directional path such as a stream or river. As shown in Fig. 1, the directional horizontal

Over 40 Years of Experience

There are as many good reasons to build with The Reinforced Earth Company as there are applications for our solutions.

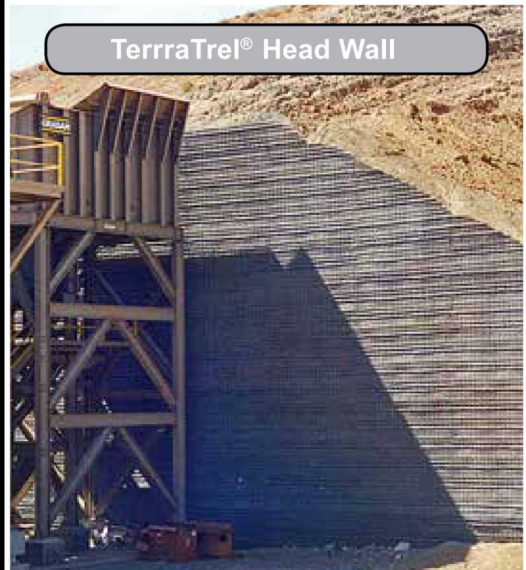
With over 45,000 completed structures across the USA isn't it time to put our experience to work for you?

Specify, Design and Build with confidence when you choose Reinforced Earth® products.

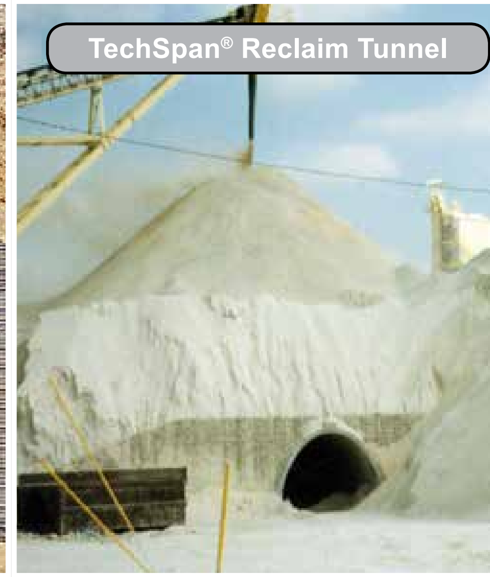
800.446.5700

www.reinforcedearth.com

ContactUs@reinforcedearth.com



TerrraTrel® Head Wall



TechSpan® Reclaim Tunnel

Reinforced Earth® Storage Hole

Reinforced Earth® Head Wall

Reinforced Earth® Storage Slot

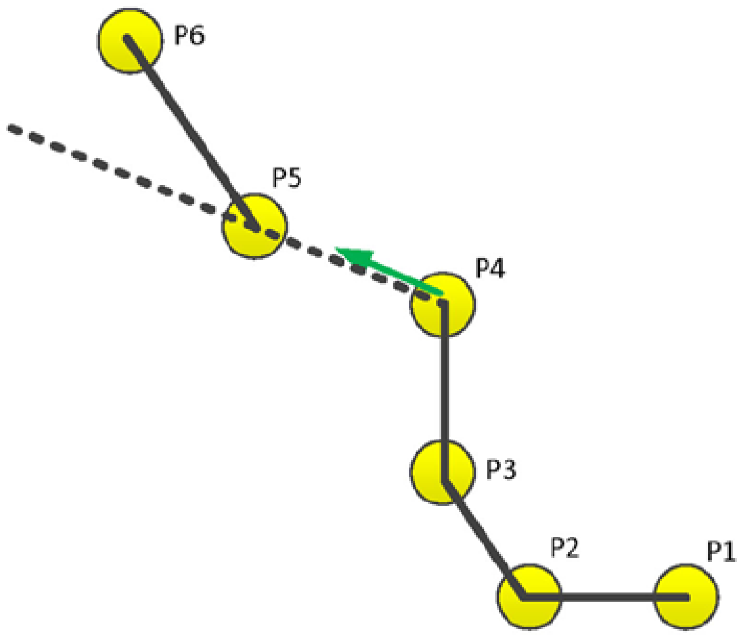
REINFORCED EARTH®

Crushing Transporting Conveying

Processing Storing Supporting

Figure 1

Directional (axial) horizontal strain.

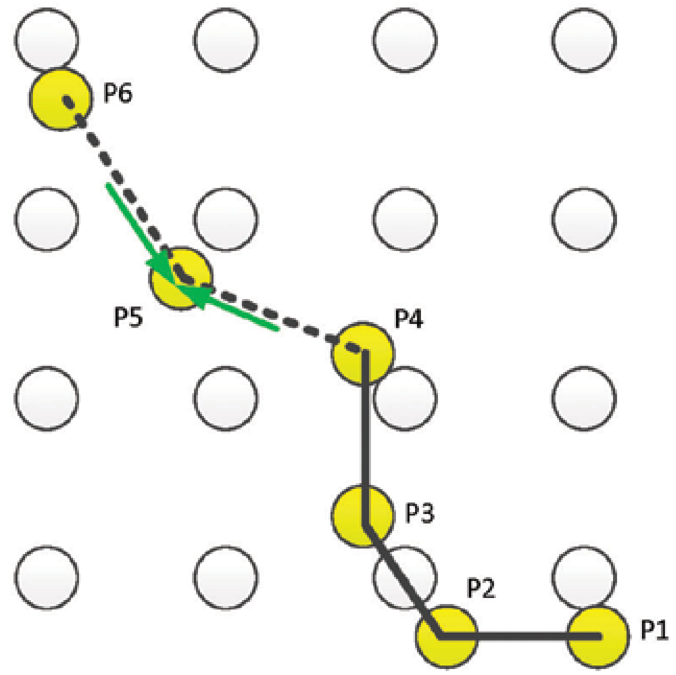


strain for a given point (P4) is determined with respect to the projected strain profile of the following point, or P5. Using the strain tensor at point P4, the normal and shear strain can be determined along the projected profile.

For a more accurate and realistic depiction of mining-induced impacts on surface streams, the ground strain calculation utilizes surface points surrounding the point of interest in order to determine the "overall relative movement" of the surface terrain. This is achieved by determining the ground strain at a given point as the difference between pre- and postmining total displacement from the previous and subsequent points over the premining displacements of these points. As seen in Fig. 2, if a stream has been defined along a directional path, the ground strain calculation at a given point (P5) is based on the three-dimensional displacements of the previous point (P4) and subsequent point (P6). However, as seen in Fig. 3, if a point of interest (P3) has been defined within a grid then the ground strain calculations at that point is based on the three-dimensional displacements of the four surrounding points.

Figure 2

Ground strain calculation along a directional path.

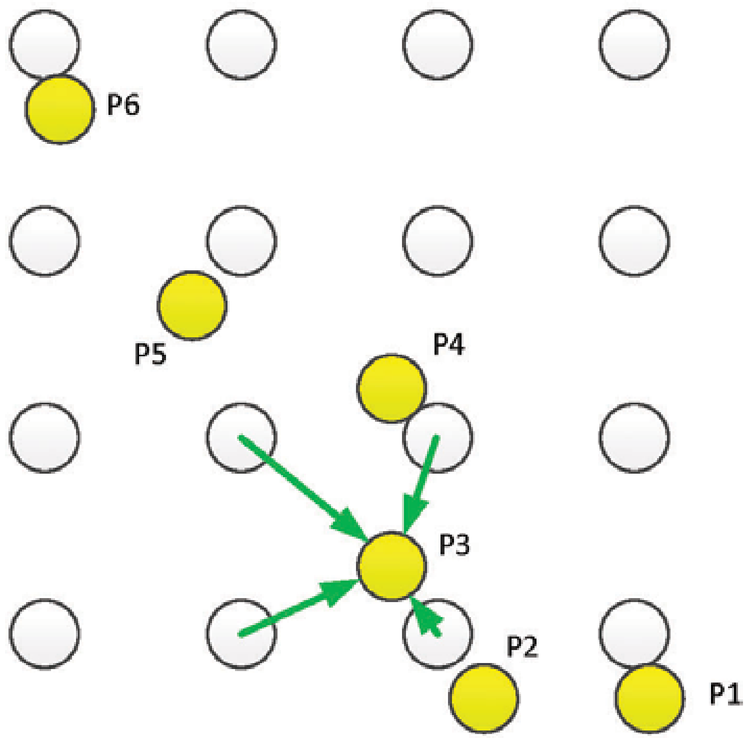


Case studies

Mineral extraction beneath bodies of water has been successfully practiced in the United States, England, Canada, Chile, Japan, Germany and Russia for more than a century (Kapp and Williams, 1972). However, the current public and regulatory focus on effects of underground mining on surface bodies of water has spurred more thorough investigations into the prediction of subsidence-induced damage and the monitoring of streams. Reference design guidelines developed by the National Coal Board (NCB) in the United Kingdom and the United States Bureau of Mines (USBM) complemented by England's experience in undermining the sea and research conducted by the NCB recommend that mining-induced tensile strains along the sea bed should not exceed 10 mm/m (Singh and Jakeman, 1999). These findings were also confirmed in research conducted by the USBM with a "best practice" threshold tensile strain value of 8.75 mm/m on the surface as well as a minimum overburden of 60 times the excavation height (60*t) (Babcock

Figure 3

Ground strain calculation using a grid of surface points.



and Hooker, 1977). The design criteria set forth by the NCB and USBM have been utilized around the world when undermining any body of water, whether on the surface or pooled underground.

The effect of underground longwall mining on surface streams has long been investigated in the Appalachian coal field. In the United States, it is common practice to design mining operations so that there is a minimum overburden (i.e., 60*t as previously discussed) between the coal seam and surface body as recommended by the USBM. In accordance with regulations set forth by regulatory agencies, the mine company must demonstrate that the stream is not damaged through pre- and post-mining stream monitoring commonly achieved through stream flow measurements. Although these measurements do not directly correlate to the prediction of stream damage from mining-induced subsidence, there are a series of commonalities between the study sites which should not be ignored.

In 1986, impact studies were conducted for streams A-H with respect to a mine located in northern West Virginia. The mine overburden ranged between 213 and 400 m (700 and 1,300 ft) with surface topographic relief between 91 and 152 m (300 and 500 ft). To investigate the effects of mining on the streams, flow measurements were taken at 22 monitoring stations located over mined out and subsided areas. Large reductions in stream flow (about 50 percent) were observed at monitoring station G5 along stream G and monitoring stations H1-H3 along stream H. It is suggested that, in all four instances, stream flow was rerouted to underground aquifers through tensile cracking in the stream bed due to mining-induced subsidence. In the case of stream G, monitoring stations downstream of monitoring station G5 had abnormally high flow rates, suggesting that the loss of water above station G5 was being discharged by the aquifer into stream G between stations G5 and G3. This same concept of stream flow rebound was suggested for stream H. However, this was not tested because monitoring stations were not established downstream of station H1 (Tieman and Raunch, 1992).

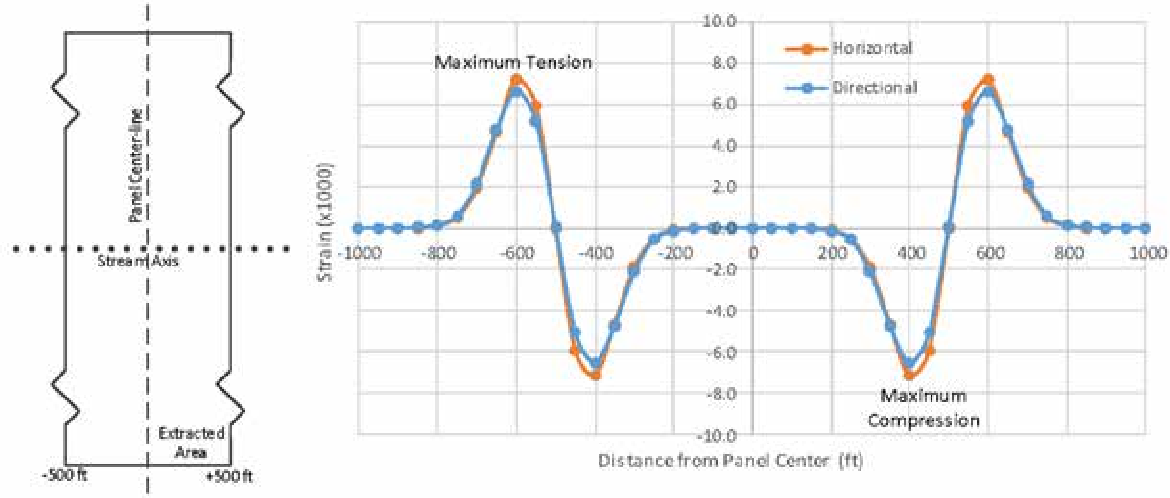
Similar results were obtained in a 1997 stream impact study conducted for four different streams (Stream A-D) overlying four different longwall mines (Site A-D) with an average depth of 170 m (550 ft) operating in the Pittsburgh coal seam. At Site A, post-mining monitoring observed an average flow loss of 15 percent between stations A2 and A3. The author indicates that the flow loss between stations A2 and A3 was most likely due to high surface strains located over the gate roads. At Site B, during mining, measurements indicated an average 30 percent reduction in stream flow between monitoring stations B1 and B2. Stream flow reductions continued after mining ceased with an average loss of 16 percent. This sustained reduction in flow between stations B1 and B2 were attributed to the outcropping of bedrock as well as high tensile strains along the panel's edge. At Site C, post-mining measurements indicated reductions in stream flow over the gate roads of panels three and four. These flow reductions were again attributed to high surface strains (Johnson, 1991).

While case studies from the Appalachian coal field observed damages to stream beds, stream flow measurements do not provide quantifiable data sets from which to base design criteria and parameters with respect to stream protection. Often, stream flow data are highly sensitive to seasonal changes, climate fluctuations (Owsiany and Waite, 2001) and ground run off (Dixon and Raunch, 1990). However, each of these five cases document the presences of increased tensile strains attributing to the detailed investigations into surface strain development due to underground mining provides a more qualitative approach in evaluating damage to surface bodies of water. While all regulatory agencies require pre- and post-mining stream flow monitoring, Australian mining companies correlate their stream data to the initial prediction and development of surface strains.

In the 1980s, five longwall panels were developed beneath the Pacific Ocean. Four panels (LW1, LW4, LW5 and LW7) were located in the Borehole seam with an average depth of 228 m (750 ft), excavation height of 2.25 m (7.4 ft) and panel width of 116 m (381 ft). The overlying panel (LW3) in the Victoria Tunnel seam had an average depth of 165 m (541 ft) (> 60 t) and a panel width of 138 m (453 ft). LW3 was positioned directly above LW4 and therefore was mined first. The calculated strains,

Figure 4

Case 1 - Transverse profile, flat-lying stream.



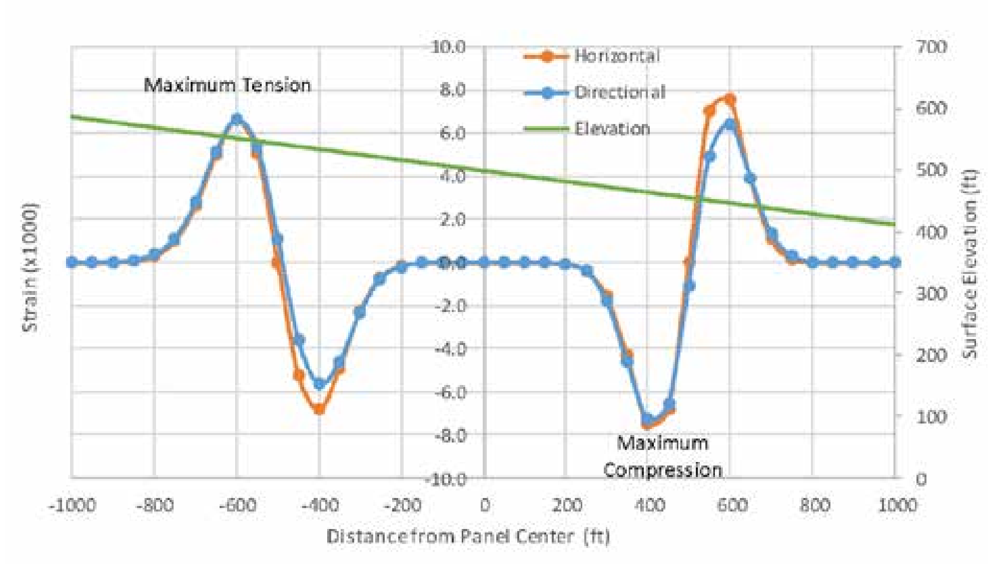
with respect to the methodology outlined by the NCB, due to the extraction of LW3 was 3.5 mm/m. The cumulative strain after the extraction of panel LW4 was 6 mm/m. Although both strain and minimum overburden parameters fell into the guidelines of both the NCB and USBM, during the mining of panel LW3 six major water inflow events occurred at the mine resulting in 2.5 times the normal water inflow rate (Holla, 1991).

The Bellambi West Colliery, located in the southern coalfields of New South Wales (NSW), began longwall operations in the Bulli Seam beneath the Cataract Reservoir in 1991 with an average depth of 375 m (1,230 ft) and a mining height of 2.5 m (8.2 ft). Mining began with 110 m (361 ft) wide panels and 66 m (217 ft) wide interpanel pillars. Data obtained from surface monitoring stations above the first two panels (501 and 502) observed a maximum subsidence of 173 mm (0.57 ft) with a maximum tensile strain of less than 0.5 mm/m and maximum compressive strain of 0.3 mm/m (Singh and Jakeman, 2001). Later, from 1998 to 2001, five panels with widths of about 150 m (490 ft) were mined, resulting in a maximum surface subsidence of 240 mm and tensile strains of 0.5 mm/m (McNally and Evans, 2007).

Similarly in 1991, longwall operations in the Dudley seam of the New Castle coalfield sought to undermine Lake Macquarie. In developing a seven-panel longwall district beneath the lake, a very conservative overburden thickness of 110 times the excavation thickness and surface tensile strains of 7.5 mm/m were maintained. With an average depth of 248 m (814 ft), seam thickness of 2.2 m (7.2 ft), and panel width of about 137 m (450 ft), 2 mm/m surface strains were calculated with respect to the methodology documented by the NCB. All seven longwall panels were deemed successful, as no water inundation was

Figure 5

Case 2 - Transverse profile, surface sloped at 5°.



reported by the mine (Holla, 1991).

From 1988 to 1994, the Tower Colliery began longwall operations in the Bulli seam 430 m (1,411 ft) beneath the Cataract River Gorge. The first five panels with panel widths of 110 m (360 ft) and 10 to 48 m (33 to 157 ft) wide barrier pillars were successfully mined with a maximum subsidence of 325 mm and surface strains less than 1 mm/m. The subsequent five panels were widened to 155 m (508 ft) panels resulting in a maximum subsidence of 475 mm (1.56 ft) and noticeable cracking in the river bed. Strain damage to the bed rock drained the Cataract River till flow ceased in 1994 (McNally and Evans, 2007).

The design guidelines set forth by the NCB and USBM have limited application in terms of undermining streams because they both assumed large bodies of water (reservoirs, lakes, oceans) and nonvarying topography. In addition, these investigations were more focused on mine inundations and not specifically surface damage. With a strict focus on damage to the stream bed and the loss of water into the upper register of the overburden, the 10 mm/m recommendation should be defined as an upper threshold with design parameters more likely falling within the 5-7 mm/m range. As seen in the Australian case studies, monitoring or calculating the strain developed by undermining surface bodies of water allows for a better depiction of the damage caused by underground mining operations. In developing more accurate methods for determining strain values at the surface, mining engineers will be able to better model the damages to surface streams. Utilizing these enhanced models allows for the establishment of optimum extraction sequencing as well as more effective mitigation practices to be implemented.

Figure 6

Angled profile, flat lying stream.

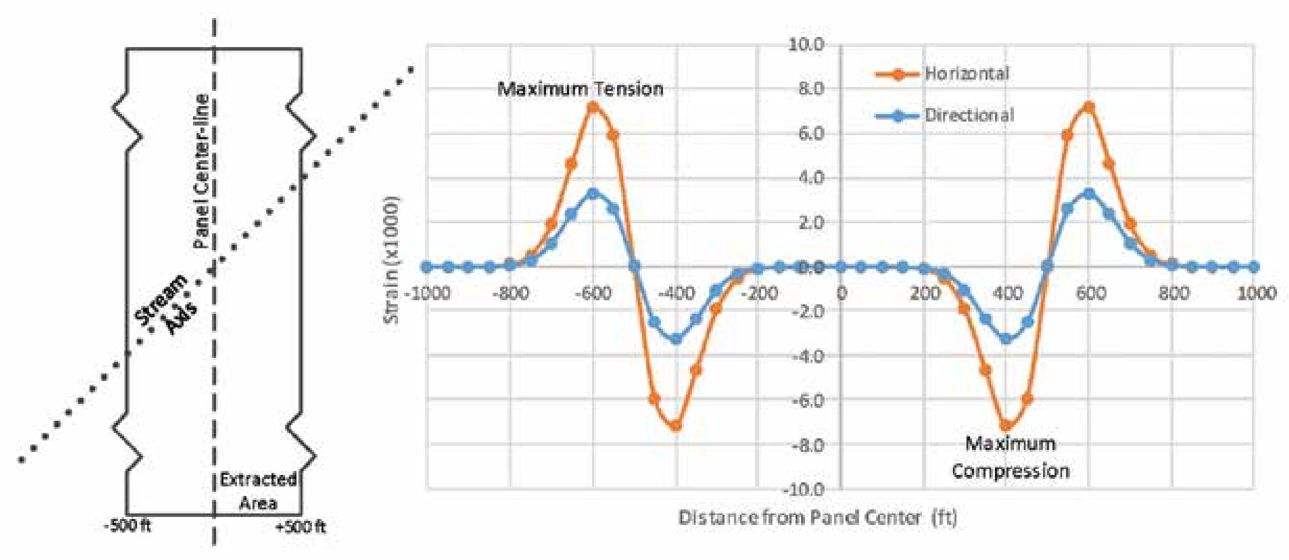
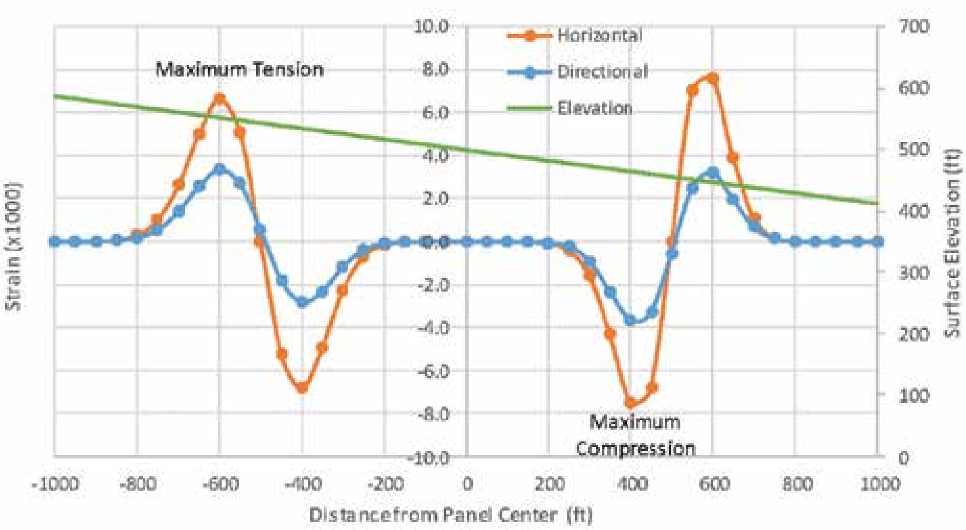


Figure 7

Angled profile, surface sloped at 5°.



Hypothetical cases and discussion

In order to highlight the differences between the horizontal and ground strain calculations, the following four hypothetical models have been developed in SDPS investigating the magnitudes of both horizontal and ground strains with respect to stream location. In each model, a stream has been defined as a series of equally spaced congruent points along the surface. Each stream has been defined over a long wall panel at a depth of about 152 m (500 ft), extraction thickness of 1.82 m (6 ft), supercritical subsidence factor of 50 percent, and an edge effect of 0 m. Default parameters have been assigned by the program defining ground responses.

In Case 1, horizontal and ground strains have been calculated along a transverse line or stream which bisects the longwall across the full extent of the subsidence trough without any subsidence influence from either end of the panel. In Fig. 4 the prediction points have been defined along a horizon. From the results, one finds the horizontal strain (Em) and ground strain (EGA) magnitudes are similar in profile with the ground strain providing slightly lower magnitudes for the peak compressive and peak tensile strains. These differences in the ground strain calculation are attributed to the incorporation of total surface displacements from pre- and post-mining.

In Case 2 (Fig. 5) the stream has been redefined such that it dips at a 5° angle from east to west. With a sloping terrain there is an overall strain increase on the downhill side of the stream and an overall strain decrease on the uphill side. Again, one finds that the incorporation of the pre- and post-mining surface elevations in the ground strain calculation provides lower strains in the tensile downhill region and compressive uphill regions of the subsidence trough in comparison to the horizontal strain calculation.

Cases 3 and 4 investigate a scenario in which a stream crosses the full extent of the subsidence trough at a given angle. In Case 3, (Fig. 6) equally spaced prediction points have been defined along a flat-lying stream. In determining model results, the maximum horizontal strain is determined as the larger of the horizontal strain values calculated in the x- and y-directions. However, in providing a more accurate depiction of the strain development along the defined stream bed, ground strain results have been calculated with respect to the change in pre- and post-mining surface elevations as well as directional strain vectors connecting each pair of consecutive points along the stream path.

In Case 4, the surface (stream) has been redefined such that it dips at a 5° angle from east to west across the subsidence trough at a given angle. Here, again, the ground strain calculation (Fig. 7) provides a more realistic evaluation of strain developments along the stream through its incorporation of both changes in topography and directional strain vectors.

Summary and conclusion

This paper examines the implementation of the ground strain calculations into the SDP Software for analyzing the impact of underground mining on surface streams. Several cases were examined using SDPS comparing horizontal strain and ground strain results. These exercises suggest that the ground strain calculation will provide more accurate and realistic evaluation of the structural integrity of the stream bed while horizontal strain calculations can overpredict the strain regime. In providing a more accurate approximation of ground movements, mining engineers will be able to establish optimum extraction sequences mitigating the effects of underground mining on surface streams.

While these results are promising, more thorough SDPS evaluations need to be conducted validating the application of ground strain to current underground mining methods and techniques. Currently work is underway in collecting and analyzing case studies from both the Appalachian and Illinois coal fields of the United States to further validate the ground strain calculation. From the collection of case studies, statistical analyses can be conducted for the development of design criteria for stream impacts due to underground mining with respect to ground strain concentrations along the stream bed. ■

Acknowledgements

This study is sponsored by the Appalachian Research Initiative for Environmental Science (ARIES). The views, opinions, and recommendations expressed in this paper are solely those of the authors and do not imply any endorsement by ARIES employees or other ARIES affiliated researchers.

References

Agioutantis, Z., Karmis, M., et al., 2014, Development of an enhanced methodology for ground movement predictions due to longwall mining in the Illinois basin. 33rd International Conference on Ground Control in Mining: 312-319.

Babcock, C.O. and Hooker, V.E., 1977, Results of research to develop guidelines for mining near surface and underground bodies of water (No. BM-RI-8741). Bureau of Mines, Denver, CO. Denver Mining Research Center.

Booth, C.J., 2006, Groundwater as an environmental constraint of longwall coal mining. *Environmental Geology,* 49(6): 796-803.

Dawkins, A., 2003, Potential management and rehabilitation requirements of environmental effects from longwall subsidence on streams, lakes and groundwater systems. 2003 Coal Operators' Conference: 117-124.

Dixon, D.Y. and Rauch, H.W., 1990, The impact of three longwall coal mines on streamflow in the Appalachian coalfield. 9th International Conference on Ground Control in Mining: 169-182.

Holla, L., 1991, Some aspects of strata movements relating to mining under water bodies in New South Wales, Australia. 4th International Mine Water Congress: 233-244.

Iannacchione, A., Tonsor, S., Witkowski, M., Benner, J., Hale, A. and Shendge, M., 2010, The effects of subsidence resulting from underground bituminous coal mining on surface structures and features and on water resources: 3rd ACT 54 five-year report. University of Pittsburgh.

Johnson, K.L., 1991, Effects of longwall mining on streamflow in the Pittsburgh seam basin. 16th International Conference on Ground Control in Mining: 25-32.

Kapp, W.A and Williams, R.C., 1972, Extraction of coal in the Sydney basin from beneath large bodies of water. Conference of the Australian Institution of Mining and Metallurgy: 77-87.

Karmis, M. and Agioutantis, Z., 2015, A methodology to assess the potential impacts of longwall mining on streams in the Appalachian basin. 2nd Environmental Considerations in Energy Production Conference: 90-98.

Karmis, M., Mastoris, J. and Agioutantis, Z., 1995, Potential of the "damage angle" concept for assessing impacts of underground mining. *SME Transactions*, 296: 1883-1886.

McNally, G. and Evans, R., 2007, Impacts of longwall mining on surface water and ground water, southern coalfield NSW. NSW Department of Environment and Climate Change. eWater Cooperative Research Center.

Owsiany, J.A. and Waite, B.A., 2001, The response of a high order stream to shallow cover longwall mining in the northern Appalachian coalfield. 20th International Conference on Ground Control in Mining: 149-156.

Peng, F.F., Sun, V.Z., and Peng, S.S., 1996, Modeling the effects of stream ponding associated with longwall mining. *Mining Engineering*, 48: 59-64.

Peng, S.S., 2008, Coal mine ground control, 3rd Ed., West Virginia University, Morgantown, WV, pp. 750.

Singh, M.M., 1992, Mine Subsidence, Section 10.6, SME *Mining Engineering Handbook, 2nd Ed*., SME, Littleton, CO, pp. 967-971.

Singh, R.N. and Jakeman, M., 1999, Longwall mining under the Cataract reservoir. *Journal of Mines, Metals, and Fuels*, 47(11):282-288.

Singh, R.N. and Jakeman, M., 2001, Strata monitoring investigations around longwall panels beneath the Cataract reservoir. Mine Water and the Environment, 20(2): 55-64.

Tieman, G. and Rauch, H., 1992, Study of dewatering effects at a longwall mine in northern West Virginia. 3rd Workshop on Surface Subsidence due to Underground Mining: 214-221.