SME Annual Meeting
Feb. 27 - Mar. 02, 2022, Salt Lake City, UT

Preprint 22-047

IDENTIFYING LONGWALL-INDUCED FRACTURE ZONE HEIGHT THROUGH CORE DRILLING

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) has been evaluating longwall mining-induced strata fractures and their impacts on casing stability of Marcellus shale gas wells located in longwall pillars. To understand the extent of overburden fractures after longwall mining, NIOSH researchers drilled a post-mining corehole into the fractured strata above the Pittsburgh coal seam longwall gob. Knowing the extent of the fracture zone height will help gas operators minimize the hazards of drilling into longwall gobs. The core was retrieved from the surface down to the top of the gob void. Various fractures were encountered varying from 35 to 64 degrees, depending on lithologic type and relative closeness to the gob. The longwall panel dimension was 457 m wide and 3657 m long, in which the total fracture zone height was found to be at 141 m and the hydraulic connected fracture zone at 87.7 m above the top of the Pittsburgh seam. In addition to core drilling through the gob, FLAC3D modeling was also used to simulate the formation of fracture zone and the orientations of longwall-induced fractures. This study provides much-needed evidence on the fracture zone of Pittsburgh seam longwall gobs to help gas operators avoid potential hazards associated with drilling through highly fractured zones.

INTRODUCTION

Researchers at the National Institute for Occupational Safety and Health (NIOSH) have been evaluating the interaction between coal longwall mining and the casing stability of gas wells of the Marcellus and Utica shales and other gas-producing formations within the Pittsburgh coal basin. Interest in the Marcellus and Utica shales began to increase due to new horizontal drilling techniques, the drilling of gas wells within the Marcellus and Utica shale basins now accounts for 85% of the increase of shale production growth in the United States between 2012 and 2015 (Krohn, J., Nülle, G. 2015). The first horizontal Marcellus well was drilled in 2004 with the majority of horizontal wells drilled after 2009. This drilling technique utilized a horizontal well that is angled deep underground and runs horizontally with in the Marcellus formation. At that time, there was little to no guidance regarding how close coal mines could mine to a horizontal gas well and where longwall fracture subsidence zones could be present for gas operations. Gas companies' typical practice was to drill in areas that had already been mined or drill ahead of the coal mines 10-year projections hoping that new guidance would be provided by then. Critical scientific data gathered by NIOSH over the past 5 years indicated that, depending on the depth of cover, mining distance, and overburden geology, a gas well's integrity may be adversely affected by longwall mining. Therefore, a safe option appears to be drilling into mined-out longwall chain pillars or longwall gobs. To help define the risk of operating a gas well into highly fractured longwall gobs, NIOSH researchers conducted pre-mining and post-mining core drilling into a 457-m-wide longwall gob. This paper will discuss the geology of the Pittsburgh seam overburden, results from the pre-mining and post-mining coreholes, and comparison with FLAC3D prediction of longwall-induced fracture zone height.

SETTING

The longwall mine in this study is located in Southwestern Pennsylvania and is mining the Pittsburgh seam. The longwall dimensions near the corehole are 457 m wide and 3657-m long, and the overburden thickness averages 198-335 m. The longwall panel was completely mined before the drilling of the corehole started. The corehole site was chosen over the longwall gob 280 m from the tailgate, 174 m from the headgate and 304.8 m from the longwall startup face (see Fig. 1). The surface elevation of the drill site was 427.6 m above sea level and cored to a depth of 283.4 m and a total drill depth of 292.6 m. The core was 5.08 cm in diameter (NQ), and the intention was to core within 30.48 m of the projected mine roof and observe any longwall induced fractures. An agreement was reached between the mine operator, the Mine Safety and Health Administration (MSHA), and NIOSH that drilling would cease if any major void was encountered, and drilling water circulation was lost. The drilling went well until an unnatural large void caused by mining was encountered at 294.4 m and the weight of all the drill steel and the bit became unsupported and caused the drill rig to violently jump. After that, drilling water stopped being circulated, and as per the drilling agreement the drilling operation ceased, and the coring was complete at approximately 42.6 m above the Pittsburgh seam.

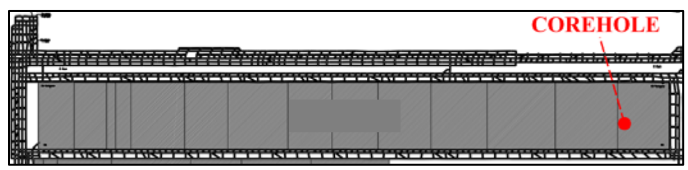

Figure 1. Location of the corehole drilled into a mined-out longwall panel.

GEOLOGIC SETTING

Despite the Marcellus shale and Pittsburgh coal seam being 1,219–2133 m apart in the strata and deposited almost 100 million years apart, they share much of the same areas within Pennsylvania and West Virginia, although the Marcellus shale extends further north into New York as seen in Fig. 2 and Fig. 3. The two maps highlight how natural gas and coal are both competing for much of the same areas, and the two industries are still seeking a solution on how to coexist without compromising safety and production.

For the scope of this paper, only the strata shared by the two industries will be discussed, which is between the surface and the Pittsburgh coal seam. The Pittsburgh coal seam is the first lithologic unit within the Monongahela group of the Pittsburgh formation, and the formation contains other major units such as the Sewickley coal and the Benwood limestone (see Fig. 4). The strata surrounding Pittsburgh coal seam consists of fairly regular intervals of claystone, coal, shale, sandstone, and limestone sequences known as cyclothems.

The post-mining core from the test site was easily retrieved and without any fracture anomalies for most of the run; however, at a depth of 196 m (141 m above the top of the Pittsburgh seam.) the first high-angle fracture in the core was observed. Subsequent fractures below the first fracture were observed on an average of 5.5 m between fractures until a depth of 249.3 m (see Fig. 5). The fractures fell into two different angle types, 60-64 and 36-40 degrees. Below 249.3 m, the fracture average increased to a fracture at every 1.37 m at which the fractures are assumed to be communicating due to the loss of drilling fluid. For the purposes of this paper, every fracture after 249.3 m (87.7 m above the Pittsburgh seam.) is within the hydraulic connected fracture zone since drilling operations had difficulty maintaining drilling fluid at this depth. As the overburden strata subsides, intermittent high-angle fractures are expected to be present in competent rock layers. Typically core from unmined strata around the Pittsburgh seam fractures near horizontal due to weaknesses in the bedding since lithology was deposited in a flat low-lying swamp environment.

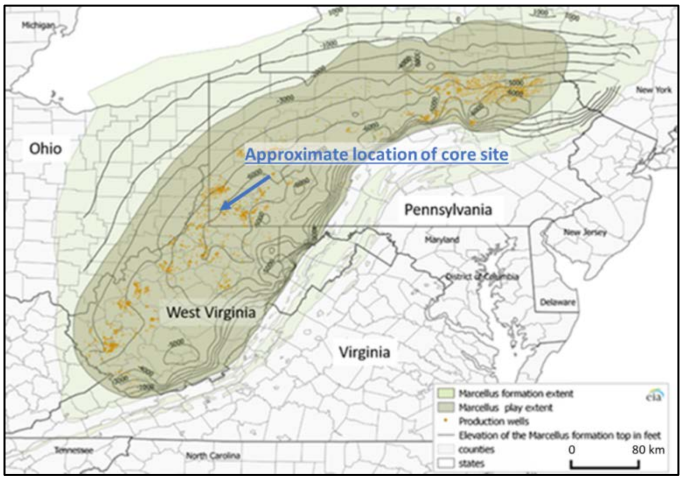

Figure 2. Extent of the Marcellus Shale Formation (Popova et al. 2015).

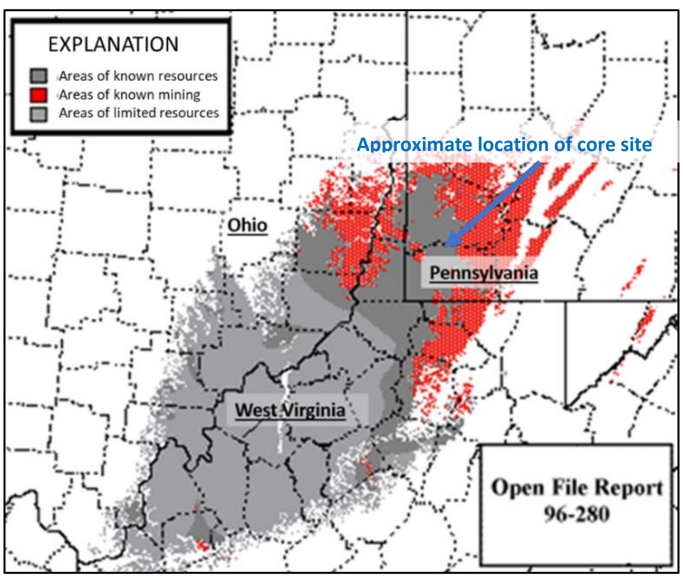

Figure 3. Extent of the Pittsburgh Coal (Ruppert et al. 1996).

High-angle 60 to 64-degree fractures started to appear at a depth of 196 m, or 141.1 m above the top of the Pittsburgh seam. The box with the highest frequency of high-angle fractures occurred between 270.3 to 273.4 m which contained six fractures (see Fig. 6).In total, there were 31 fractures between 196 to 282.7 m, and 12 of the fractures were between 60–64 degrees and all occurred in stronger rock units such as limestone, limey shale, or shaly limestone.

The lower angle fractures between 35–40 degrees occurred throughout the fracture zone, primarily in softer rock units (see Table 1). The corehole was drilled to a total depth of 294.4 m, but only 283.4 m of core was able to be recovered, and as described in the introduction, the rig hit multiple fracture gaps and drilling fluids being pumped into the corehole were unable to be recovered so drilling operations were halted based on the agreement with MSHA and the mine operator. The entire core log is too large to include in this paper, but the bottom section including depths from 251.4 to 294.4 m had the highest fracture density compared to the rest of the fracture zone (see Fig. 7).

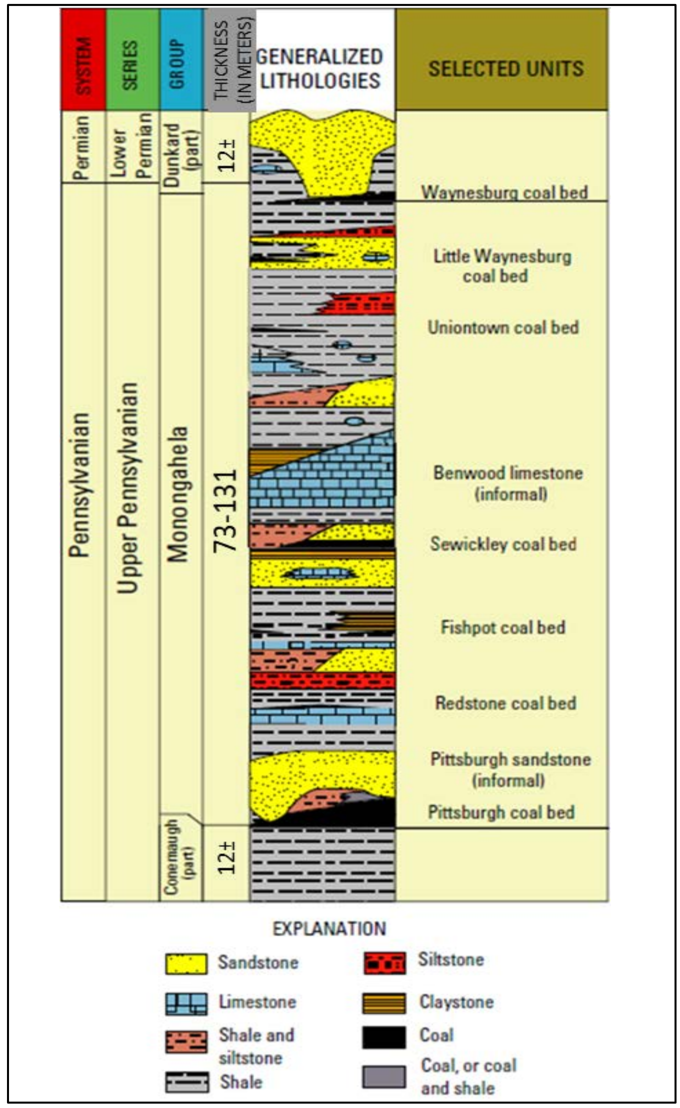

Figure 4. General stratigraphic column of the Monongahela group including the Pittsburgh seam (Tewalt et al. 2000).

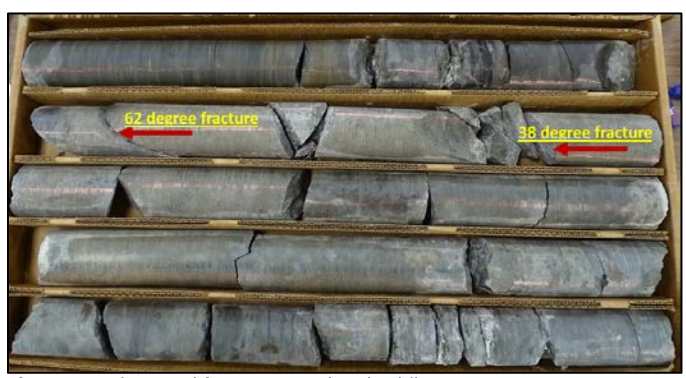

Figure 5. Abnormal fractures against bedding.

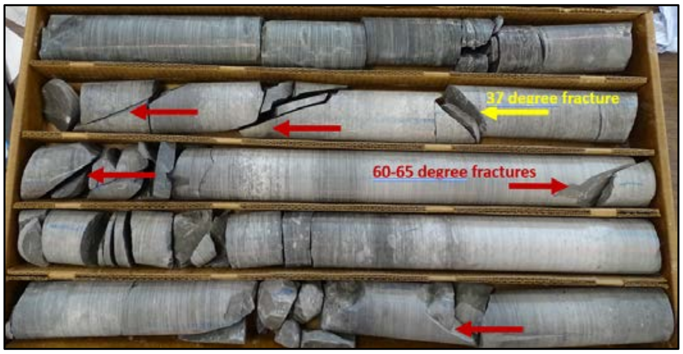

Figure 6. High-angle fractures (in red) and low-angle fractures (in yellow) at a depth of 270.3 to 273.4 m.

Table 1. Depth, fracture angle, and lithology type of subsidence-induced fractures.

Depth (m)	Fracture Angle	Lithology Type
196	37	Shale
217.6	62	Limestone
217.7	38	Limestone
218.2	39	Limestone
226.4	64	Limey Shale
231.5	63	Limey Shale
235.1	35	Shale
249.3	38	Shale
249.9	39	Shale
251.4	39	Limey Shale
251.6	38	Limey Shale
251.7	38	Limey Shale
251.9	36	Limey Shale
252.3	60	Limy Shale
252.6	37	Shale
261.2	40	Sandy Shale
262.4	35	Shale
270.3	60	Limy Shale
271.2	60	Limy Shale
271.4	60	Limy Shale
271.5	39	Limestone
272.4	61	Limestone
272.7	63	Limestone
273.1	63	Limestone
273.7	40	Limestone
274.1	63	Limestone
276.1	36	Limy Shale
276.4	38	Limestone
279.8	38	Limestone
281	38	Shaly Limestone
282.7	60	Limy Shale

The entire length of the core run measured to be 283.4 m in depth, which is estimated to be 53.6 m above the top of the Pittsburgh seam and a total drill depth of 294.4 m which is estimated to be 42.6 m above the Pittsburgh seam. The lithology from 283.4 m to 294.4 m was determined by the drill cuttings.

FLAC3D MODEL

Numerical modeling techniques have been developed by NIOSH to calculate longwall-induced stresses and deformations (Esterhuizen et al., 2010; Tulu et al., 2017; Zhang, et al., 2020). In this study, a FLAC3D model was set up to simulate the formation of longwall-induced fractures in the overburden and to estimate the fracture zone height based on the mining and geological conditions of the longwall panel in which the post-mining corehole was drilled. Fig. 8 shows the cross-sectional view of the FLAC3D model. To simulate longwall-induced stresses and deformations along the center of the panel, a slice of the overburden at the panel center parallel to the long axis of the panel was modeled. The overburden geology in the model was based on the lithology of the post-mining corehole. Table 2 shows the rock properties used in the model. Bedding planes between different rock types were modeled as interfaces with friction and cohesion. The Mohr-Coulomb failure criterion was used for the coal pillar, overburden, and floor. The gob was modeled by strain-hardening hyper-elastic material implemented by the 'FISH' scripting language available in FLAC3D. The overburden depth in the model was 342 m, and the dimension of the gob was 396.2 m from the setup entry to the longwall face. Horizontal stress was initialized in the model with three times the vertical stress parallel to the panel and two times the vertical stress perpendicular to the panel (ITASCA. 2017). The longwall retreating was simulated by multiple steps. A 350.5 m long gob was introduced at the first step, and the face then advanced three steps with 15.2 m per step to reach a 396.2 m long gob over which surface subsidence was fully developed.

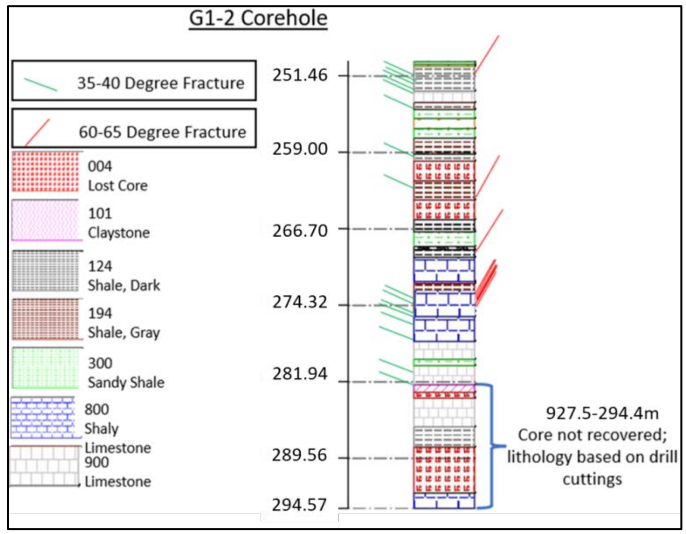

Figure 7. Log of the corehole from 251.4–294.57 m.

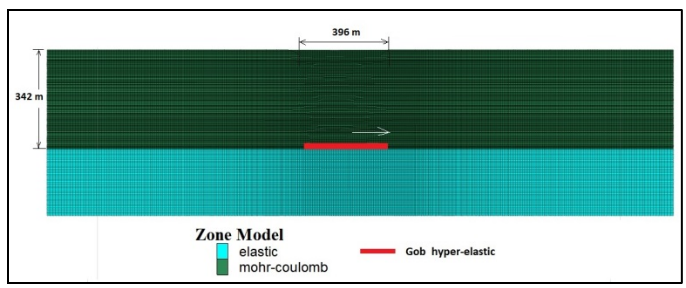

Figure 8. Cross-sectional view of the FLAC3D model.

Table 2. Rock properties used in the model.

Rock Type	Young's Modulus, psi (Mpa)	Poisson's Ratio	Cohesion, psi (Mpa)	Internal Friction Angle, degrees	Tensional Strength, psi (Mpa)
Coal	3×10^5 (2,070)	0.30	270 (1.9)	28	40 (0.3)
Claystone	4.2×10^5 (2,900)	0.3	270 (1.9)	28	40 (0.3)
Shale	1.68×10^6 (11,600)	0.25	1,700 (11.7)	35	650 (4.5)
Sandy shale	1.68×10^6 (11,600)	0.25	1,700 (11.7)	35	650 (4.5)
Sandstone	1.68×10^6 (11,600)	0.25	2,600 (17.9)	35	1,000 (6.9)
Limestone	2.5×10^6 (17,400)	0.22	2,300 (15.9)	35	880 (6.1)
Shaley limestone	2.5×10^6 (17,400)	0.22	2,100 (14.5)	38	850 (5.9)
Shaley sandstone	2.2×10^6 (15,000)	0.22	1,700 (11.7)	38	700 (4.8)
Silty shale	1.68×10^6 (11,600)	0.25	1,700 (11.7)	32	600 (4.2)

The model was verified with measurements of surface subsidence and front abutment pressure in similar conditions. Fig. 9 shows the surface subsidence developed along the center of the panel when the face is 396.2 m from the setup entry. A maximum subsidence of 1.6 m is reached at about 182.8 m inby the longwall face, which is typical of

Pittsburgh seam longwall subsidence under similar overburden depth. Fig. 10 shows the predicted vertical stress distribution in the overburden over the longwall face. The predicted peak front abutment pressure is 28.9 Mpa, about 3.4 times the overburden pressure, and the predicted vertical stress relief zone in the gob is within about 152.4 m inby the face. Both the predicted abutment pressure and gob pressure agree reasonably with the measurements of longwall-induced stresses in the Pittsburgh seam.

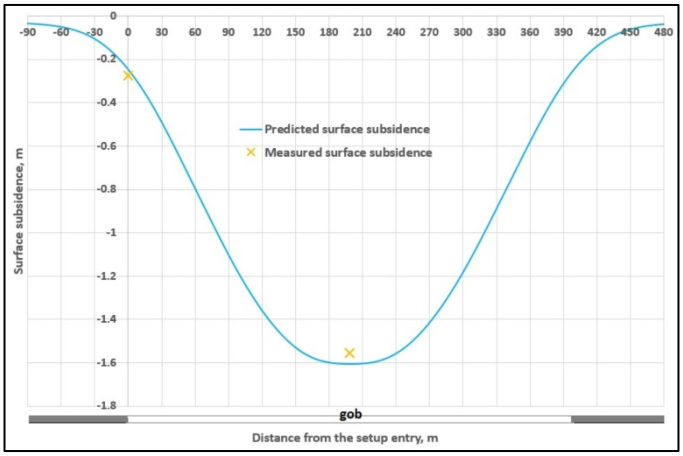

Figure 9. Predicted surface subsidence along the longwall panel.

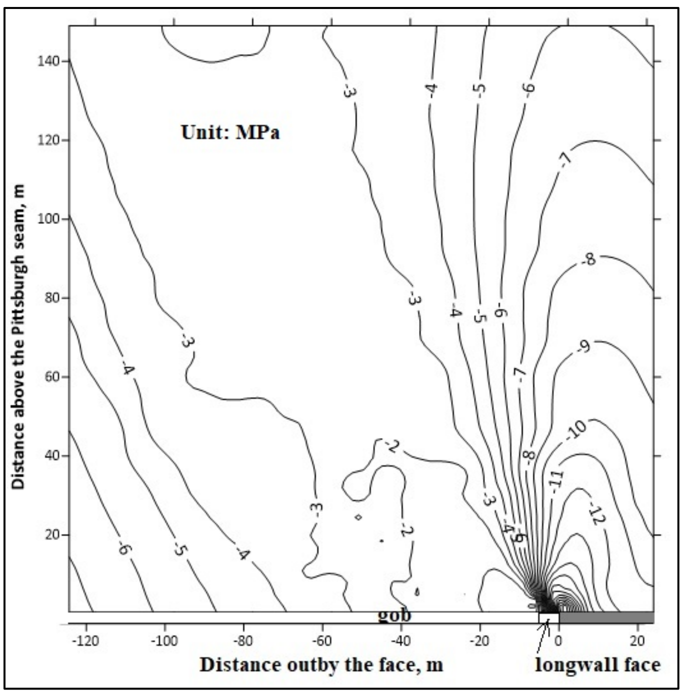

Figure 10. Vertical stress distribution in the overburden over the longwall face.

LONGWALL-INDUCED STRESS CHANGES AND FRACTURE ZONE FORMATION

Many researchers reported that there are three distinct zones, the caved zone, fracture zone, and continuous deformation zone, in the overburden rock mass above longwall coal mines (Whittaker and Reddish, 1989; Bai and Elsworth, 1990; Peng, 1992). The caved zone is highly broken material and develops upwards three to six times the underlying coal seam thickness (Peng, 1992). The fracture zone is developed above the caved zone. It can be divided into three parts that are rock blocks, through-going vertical fractures, and horizontal fractures due to the detachment of bedding planes (Palchik, 2003). Peng (1992) also reported that the thickness of fractured zone varies from 28 to 42 times the mining height.

As identified in the retrieved cores, two types of fractures can be induced by longwall mining: horizontal fractures and angled fractures. The horizontal fractures are induced by bedding plane slips and separations caused by overburden movements along horizontal and vertical directions. When overburden subsides, the strata in layers bend down towards the mining horizon inducing shear stress along bedding planes. If the shear stress is greater than the strength of the bedding plane, a slip or a horizontal fracture occurs. The bedding plane separations could occur when different layers of strata with different stiffnesses bend down. Fig. 11 shows the predicted bedding plane slips over the longwall gob. It shows that bedding plane slips occur over the gob at bedding plane locations from the mining horizon to the surface, which is evidenced by the horizontal breakings in the retrieved cores. The angled fractures are associated with overburden yielding and movements caused by longwall-induced stress changes resulting from roof caving. Three stress components are obtained from the model to analyze the principal stress changes for strata yielding. Longwall mining causes vertical stress in the overburden to redistribute as a result of roof caving with abutment pressure created outby the face and vertical stress relief inby the face. The longwall-induced vertical stress change ranges within certain distances from the face. As shown in Fig. 10, the vertical stress relief zone ranges within about 121.9 m inby the face along the gob and within about 121.9 m from the coal seam to the surface. The vertical stress relief near the face is one factor that contributes to development of fractures in the overburden.

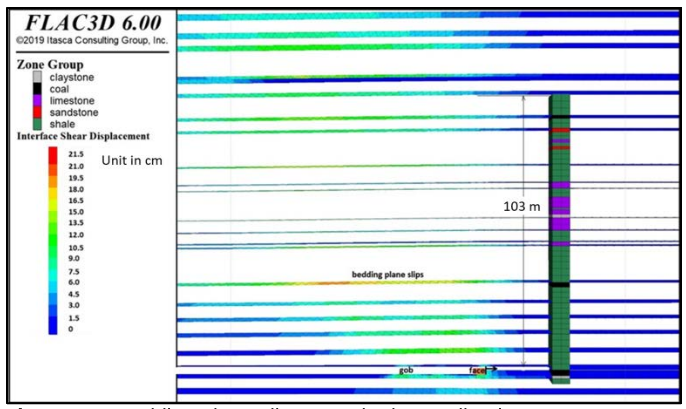

Figure 11. Bedding plane slips over the longwall gob.

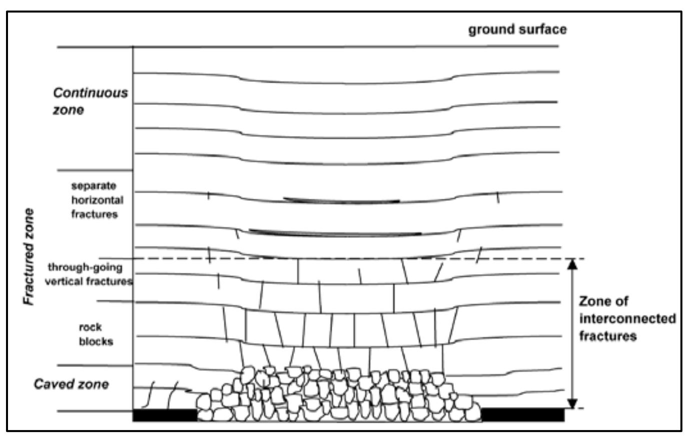

Figure 12. Overburden zone movement due to longwall mining (Palchik, 2003).

Fig. 13 shows the shear stress distribution in the overburden over the longwall face. Shear stress is induced by the overburden overhanging behind the face and is distributed right inby and above the face. The shear stress concentration zone is within about 30.4 m inby the face and within about 121.9 m above the coal seam, with the high shear stress concentrating near the coal seam and reducing rapidly above the coal seam. Longwall-induced shear stress is another factor in generating fractures in the overburden.

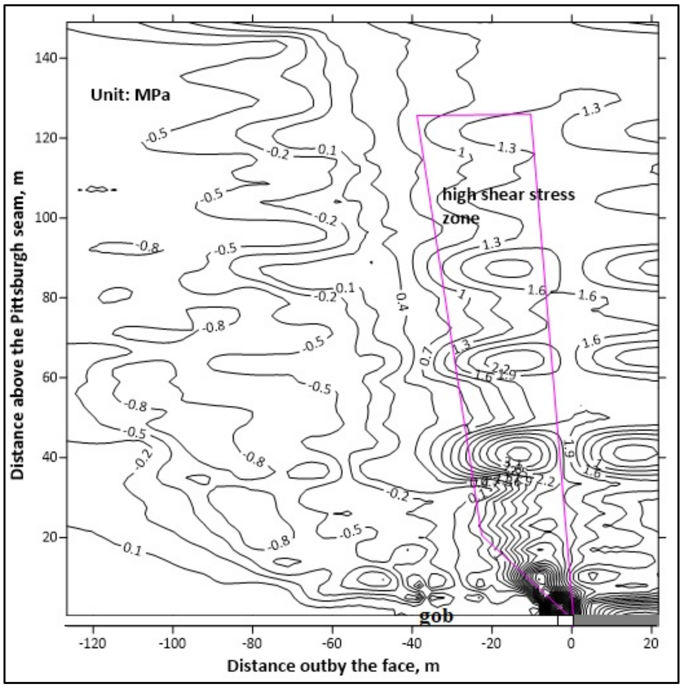

Figure 13. Shear stress (Sxz) distribution in the overburden over the longwall face.

Fig. 14 shows the horizontal stress distribution in the overburden over the longwall face. With roof caving and overburden subsiding, the in-situ horizontal stress in the overburden over the gob is redistributed within rock layers that bend downward. As shown in Fig. 14, the horizontal stress increases at the lower portion of the rock beds but reduces at the upper portions. Significant horizontal stress changes occur in the overburden right above the longwall face. The horizontal stress reduction at the upper portion of the rock layers induces tensile strain, which may contribute to formation of high-angle fractures over the longwall face. The combination of the stress changes of the three stress components described above would result in changes in principal stresses. Fig. 15 shows the longwall-induced principal stress vectors in the overburden over the longwall face.

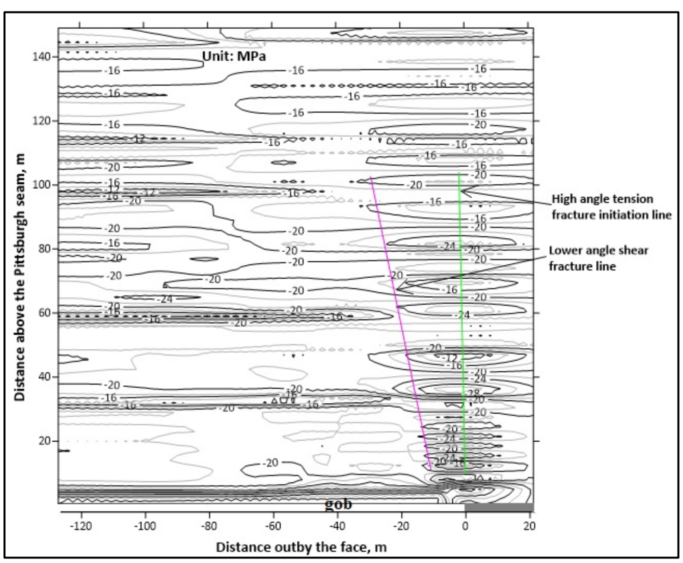

Figure 14. Horizontal stress distribution in the overburden over the longwall face.

Longwall mining causes principal stresses to change in both orientation and magnitude over the gob, and the principal stresses tend to rotate clockwise with the maximum principal stress increasing and minimum principal stress decreasing. The change of principal stress magnitude leads to large differential principal stress between the maximum and the minimum, or the maximum shear stress. For a given type of rock, its failure is highly associated with the maximum shear stress applied to it. Shear fractures are formed when shear failure occurs in the overburden inby the face, depending on the stress level and rock strength. Based on the orientation of the minimum principal stress and rock internal friction angle, the orientations of longwall-induced shear fractures are predicted as shown in Figure 15 based on the Mohr-Coulomb failure criterion. The longwall-induced shear fractures are low-angle fractures about 40 degrees to the horizontal.

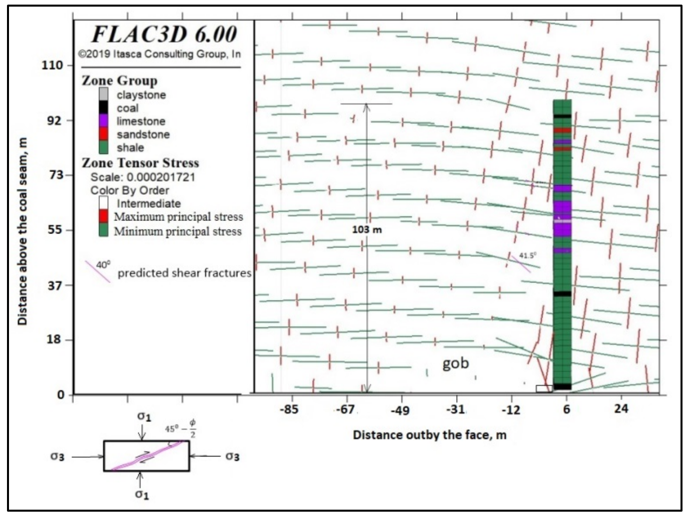

Figure 15. Longwall-induced principal stress vectors in the overburden over the longwall face.

Using the Mohr-Coulomb failure criterion, the yield zone above the face can be predicted by the model. As rock fractures are generated during the process of overburden yielding, the yield zone above the face can represent the longwall-induced fracture zone. Fig. 16 shows the fracture zone height predicted by the model. The hydraulic connected fracture zone reaches approximately 103 m above the coal seam.

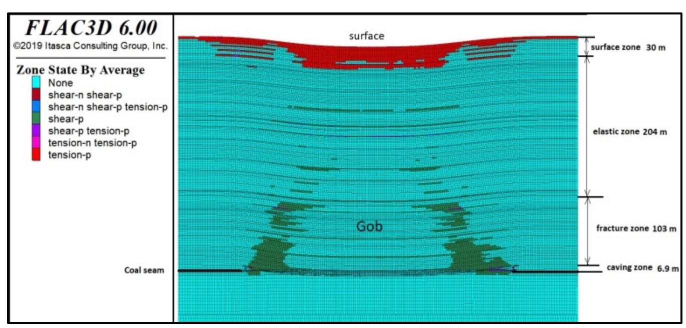

Figure 16. Fracture zone height predicted by the model.

The model also shows four zones formed after longwall mining in the overburden: caving zone, fracture zone, elastic zone, and surface zone. The caving zone is about three times of the mining height for Pittsburgh seam supercritical longwalls. The elastic zone, or continuous deformation zone, in which rock strata mainly bend without breaking, is formed above the fracture zone and below the surface zone. The rock in the surface zone is naturally fractured, and longwall subsidence could open the existing fractures.

CONCLUSIONS

The following conclusions are made based on the fractures identified from the cores drilled through a Pittsburgh seam longwall gob and FLAC3D modeling of longwall-induced fractures in the overburden:

- The total height of the longwall-induced fractures extended 141.1 m above the Pittsburgh coal seam.
- The high-angle fractures frequency of occurrence intensifies and become more prevalent at 87.7 m above the Pittsburgh coal seam which is deemed the hydraulically connected fracture zone.
- Strength and thickness of the rock has a strong correlation to the angle of fracture.
- Stronger and thicker rock types tend to produce higher 60-64 degree fractures.
- Weaker or thinner units tend to produce shallower 35-40degree fractures.
- Fractures in the longwall gob are induced by longwall-induced stress changes and tensile strain. The low angle fractures are longwall-induced shear fractures about 40 degrees to the horizontal.
- FLAC3D predicted a hydraulic connected fracture zone height of about 103 m above the Pittsburgh coal seam, which compares reasonably well with the 87.7 m intensified fracture zone determined from core drilling through longwall gob.

DISCLAIMERS

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH.

On behalf of all authors, the corresponding author states that there is no conflict of interest.

REFERENCES

1. Krohn, J., Nülle, G. (2015, July 28). “Marcellus, Utica provide 85% of U.S. shale gas production growth since start of 2012.” www.eia.gov/todayinenergy/detail.php?id=22252

2. Popova, O., Frye, E., and Panarelli, E. (2015, April 1). “Updated geologic maps provide greater detail for Marcellus formation.” www.eia.gov/todayinenergy/detail.php?id=20612

3. Ruppert, L., Tewalt, S., and Bragg, L. 1996. “Map Showing Areal Extent of the Pittsburgh Coal Bed and Horizon and Mined Areas of the Pittsburgh Coal Bed in Pennsylvania, Ohio, West Virginia, and Maryland”. U.S. Geological Survey Open-File Report 96-280.

4. Tewalt, S.J., Ruppert L.F., Bragg, L.J., Carlton, R.W., Brezinski, D.K., Wallack, R.N., and Butler, D.T. (2000). “A Digital Resource Model of the Upper Pennsylvanian Pittsburgh Coal Bed, Monongahela Group, North Appalachian Basin Coal Region”, Professional Paper 1625-C, U.S. Geological Survey.

5. Esterhuizen, G.S., C. Mark, and M.M. Murphy. 2010. Numerical model calibration for simulating coal pillars, gob and overburden response. In the Proceedings of the 29th International Conference on Ground Control in Mining, pp. 1–12.

6. Tulu, I.B., G.S. Esterhuizen, K.M. Mohamed, and T.M. Klemetti. 2017. Verification of a calibrated longwall model with field measurements, In Proceedings of the 51st US Rock Mechanics/Geomechanics Symposium, 25–28 June 2017. San Francisco.

7. Zhang, P., H. Dougherty, D. Su, J. Trackemas, and B. Tulu, 2020. “Influence of Longwall Mining on the Stability of Gas Wells in Chain Pillars.” International Journal of Mining Science and Technology. Volume 30, Issue 1, January 2020, Pages 3-9.

8. ITASCA. 2017. FLAC-3D, Version 6.0, User’s Guide.

9. Whittaker, B.N. and Reddish, D.J. 1989. Subsidence: Occurrence, prediction, and control. Elsevier Science Pub. Co.

10. Bai, M. and Elsworth, D. 1990. Some aspects of mining under aquifers in China. Mining Sci Technol 10(1), pp.81–91

11. Peng, S.S. 1992. Surface subsidence engineering. Society for Mining, Metallurgy and Exploration.

12. Palchik, V. 2003. Formation of fractured zones in overburden due to longwall mining, Environmental Geology 44, pp.28–38.

13. Jeremic, M.L. 1985. Strata mechanics in coal mining, A.A Balkema, Rotterdam.