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PERMEABILITY DETERMINATION FOR POTENTIAL INTERACTION BETWEEN SHALE GAS WELLS AND THE COAL MINE ENVIRONMENT DUE TO LONGWALL-INDUCED DEFORMATIONS

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ABSTRACT

This paper summarizes the changes in permeability at three boreholes located above an abutment pillar in a longwall coal mine in Southwestern Pennsylvania. The motivation of this study was to characterize the potential interaction between shale gas wells and the mine environment, through measurement of permeability changes for a comprehensive hazard assessment in the event of a well breach. Measuring permeability changes around boreholes subjected to longwall-induced deformations is one of the most effective ways to estimate fracture network characteristics and their capacity for gas flow from the borehole to the mine environment. In this study, permeability was measured through falling-head slug tests at different face distances to borehole locations during the mining of two longwall panels on either side of the pillar where the three test boreholes were located. The boreholes drilled to different depths above the active mining level had screened intervals to evaluate the response of different stratigraphic zones to mining-induced stresses. The results showed that the permeability around the slotted intervals of each borehole increased from their pre-mining values to their post-mining values and the permeability also increased from mining of the first longwall panel to mining of the second one, adjacent to the pillar.

INTRODUCTION

The recent shale gas revolution in the United States has led to the drilling of unconventional shale gas wells in the active and future coal reserves in traditional coal mining regions of Pennsylvania, West Virginia, and Ohio. Between 1,300 and 3,500 unconventional drilling permits have been issued each year since 2011 by the PA Department of Environmental Protection (PA DEP, 2018). In these regions, the wells drilled into the Marcellus or Utica Formations are expected to be mined through within the next five years. The shale gas wells have penetrated many coal seams, including some active longwall mines. For instance, in Southwestern Pennsylvania, shale gas wells may pass through the Sewickley, Pittsburgh, Upper Freeport, and Kittanning coal seams.

The existence of gas wells in the U.S. coal fields is not a new issue. However, the unconventional shale gas wells with very high gas pressure present new challenges as subsurface subsidence and abutment pressure can induce significant stresses and deformations to the casings of these gas wells. If the gas well casings are deformed or ruptured by excessive stresses, and the gas is released to the mine's gas emission zone (Karacan et al., 2011) through fracture networks above or within the pillars, explosive gas mixtures could reach active areas of the mine and seriously jeopardize underground miners' safety and health.

Current safety regulations allow for the drilling of unconventional shale gas wells in longwall chain pillars or barrier pillars ahead of mining if those pillars adhere to the requirements of 30 CFR 75.1700. The guidelines covering these shale gas wells are based on the 1957 Pennsylvania Gas Well Pillar Study (Commonwealth of Pennsylvania, 1957). The study provided guidelines for gas well pillars by considering their support area and overburden depth as well as the location of the gas wells within the pillars. However, the 1957 guidelines were developed for room-and-pillar mining under shallow cover and they are no longer applicable to modern longwall mining, particularly under deep cover. In December 2017, the Pennsylvania Department of Environmental Protection released the technical guidance, "Guidelines for Chain Pillar Development and Longwall Mining Adjacent to Unconventional Wells," in the Pennsylvania Bulletin (Pennsylvania Bulletin, 2017).

In 2012, the Pennsylvania Department of Environmental Protection (PADEP) initiated a call for research to update the Department's "Gas Well Pillar Regulations" (Commonwealth of Pennsylvania, 1957), which have been widely used by the Mine Safety and Health Administration (MSHA) and by other states over the last 60 years to address gas well pillar stability issues. To provide critical scientific data towards this effort, NIOSH initiated a research project in 2017 to evaluate the effects of strata deformations on the stability of shale gas casings and changes in permeability around the casings due to longwall mining under deep and shallow covers.

There has been previous work that investigated permeability of gob and how it affects methane control in coal mines. For instance, Karacan (2009), investigated permeability changes around the slotted casings of gob gas vent holes (GGVs). Production of GGVs was monitored during mining of three adjacent longwall panels, were interpreted with significant factors and machine learning methods to be able to predict gas flow rates and concentration. Another study, which preformed slug tests to determine the factors affecting hydraulic conductivity around the GGVs, found that borehole location with respect to surface geology and mining advance rate were important for changes the hydraulic conductivity of the formations around the GGVs (Karacan & Goodman 2009). When GGV production was evaluated based on borehole location above the gob, it was shown that locating the borehole in the area under tension above the gob would yield higher gas production, mostly due to pen fractures under tensional stresses (Diamond et al. 1994; Schatzel et al., 2008).

This paper presents the recent results from a research study focusing on the longwall mining induced subsurface permeability changes around boreholes above an abutment pillar under shallow cover. Data had previously been collected on permeability changes at GGV locations, but no data had been collected on changes above abutment pillars, so it was unknown whether longwall-induced permeability changes extended to above the abutment pillars. The study included drilling bore holes at various depths and preforming slug tests to gather permeability data. Some additional results focusing on this research project have also been published previously by Schatzel et al. (2008), Su et al. (2018a, 2018b, 2019a and 2019b) and Zhang et al. (2019).

COMPLETION PROPERTIES OF THE BOREHOLES AND THE FIELD EXPERIMENT

The location of the four monitoring boreholes drilled for this study were in the overburden directly above an abutment pillar between two planned longwall panels. The boreholes were centered above a 38 m

(125 ft) by 84 m (275 ft) abutment pillar that was part of a three-entry gate road system (Figure 1) with 457 m (1,500 ft) wide longwall panels that had lengths of about 3,660 m (12,000 ft) on both sides. The distance from the center of a borehole collar to the edge of the pillar adjacent to an active panel varied between 12 m (40 ft) and 18 m (60 ft). Using the guidance from the 1957 PADEP study, this distance may be as small as 15 m (50 ft). The Pittsburgh seam, which was mined at this location, was at a depth of 147 m (482 ft) from the surface. Ventilation at the mine, which utilized bleeders was controlled by exhausting airflow and provided approximately 28.3 m^3/s (60,000 ft^3/min) of airflow to the active panel face at the headgate.

Three of the four monitoring boreholes were part of the slug test portion of this research and were labeled as FEB 1, 2 and 3 in Figure 1. The fourth borehole, shown as GCB in Figure 1, was to monitor ground movement in the horizontal direction. For the three boreholes specified for the slug tests, FEB 1 had a bottom hole depth of 127 m (417 ft), FEB 2 had a depth of 76 m (250 ft), and FEB 3 had a depth of 41 m (135 ft). The FEB boreholes were cased and cemented, except for the test intervals, which had screen lengths of 8 m (26 ft), 2.5 m (8 ft) and 2 m (7 ft) respectively. An isometric view of the three permeability monitoring boreholes is shown in Figure 2.

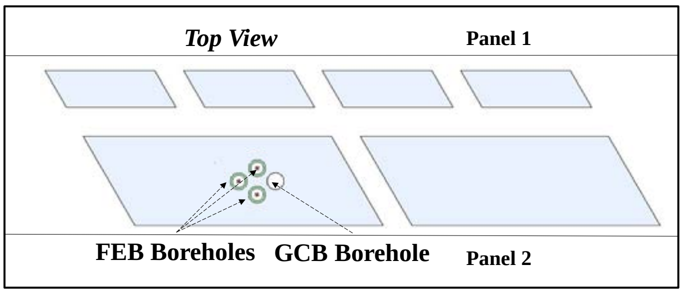

Figure 1. Three entry gate road layout.

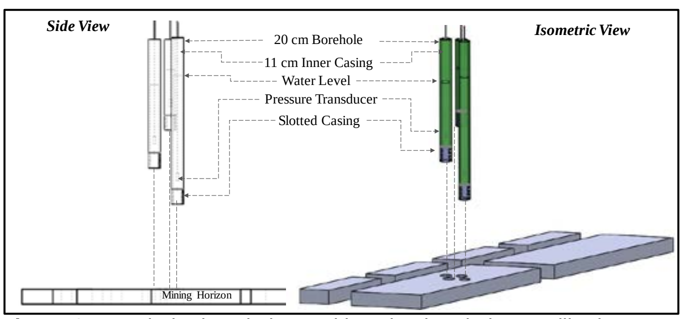

Figure 2. Borehole description and location in relation to pillar layout.

The stratigraphic zones monitored for possible changes in hydraulic conductivity, or permeability, due to mining-induced deformation were the Sewickley coal bed, the Uniontown coal bed, whose thicknesses vary in this region (Figure 3). These coal beds often have lower compressive strength than the associated limestone, shale, and siltstone/sandstone units. Therefore, it was anticipated that the coal horizons would be the main zones of potential ground movement and where higher permeabilities would be present compared to the surrounding rock units.

The overburden depth of the Pittsburgh coal seam at this location was about 147 m (482 ft) to the top of the mined seam, which is commonly at 305 m (1,000ft) since shallower occurrences have often been previously mined and the area of the mine studied was located near a major stream valley. The Pittsburgh coal bed is longwall mined in this region due to its consistent quality and thickness. The coal zones in relation to the three boreholes in this study are displayed in Figure 3. The most commonly sought-after shale gas reserve in the region is the Marcellus shale which can be at a depth of about 2,100 m (7,000 ft) to 2,750 m (9,000ft). The Utica shale with variable overburden depths, typically at depths between 2,100 m (7,000 ft) and 3,660 m (12,000 ft) in the region, can also be a drilling target. Commonly, up to 30 wells can be positioned on a single drill pad to decrease drilling costs and to reduce the surface footprint of the wells.

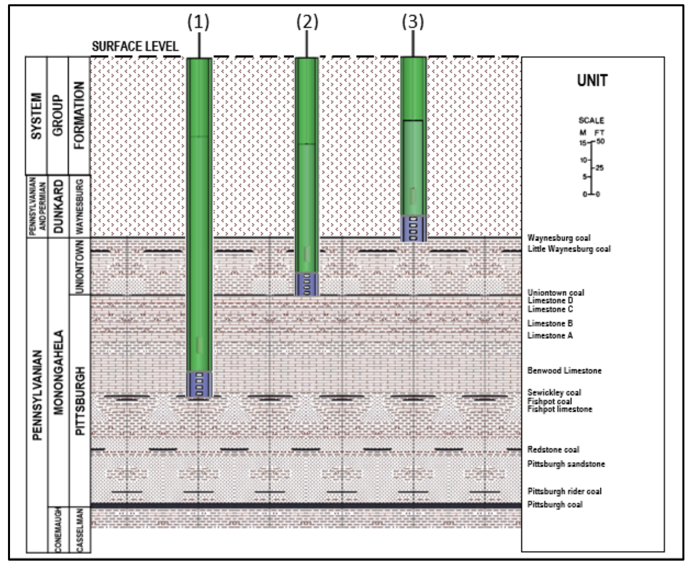

Figure 3. Geologic zone for each of the boreholes (modified from Edmunds et al., 2002).

Ground movement and subsidence are the primary factors creating the gas transport network associated with longwall gobs. From prior ground control studies (Su et al., 2019b), the primary component of movement that potentially deforms well casings in longwall pillars is subsidence (vertical movement) or horizontal movement. Both vertical and horizontal movement were monitored at the NIOSH study site with displacement arrays positioned in the GCB borehole, which was in close proximity to the FEB boreholes (Figure 1). The data showed that there was an insignificant amount of vertical movement in the borehole. However, horizontal movement measured by the monitoring array indicated significant horizontal displacement, as shown in Figure 4. This data shows that the primary zones of movement were the Uniontown and Sewickley coal seams. The Sewickley horizon measured over 16 cm of lateral movement in response to longwall mining passing the pillar.

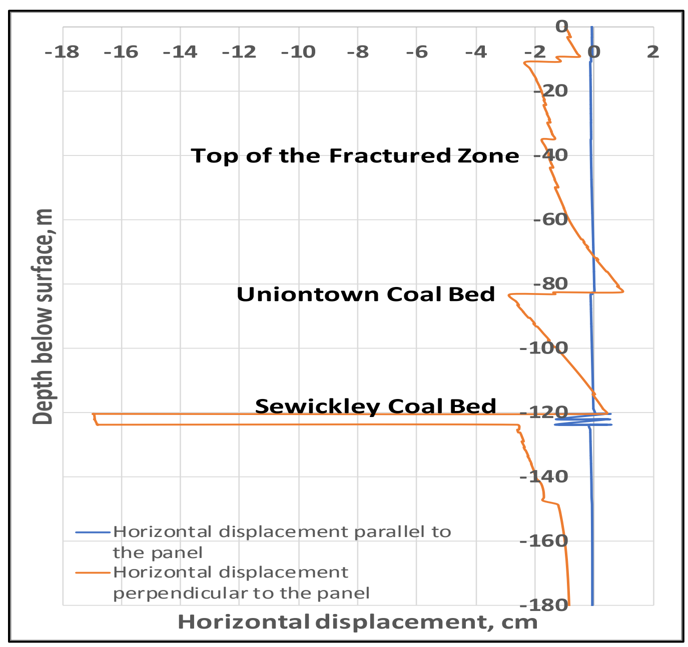

Figure 4. Horizontal displacement by depth (modified from Su et al., 2019b).

METHODOLOGY FOR SLUG TESTING

Falling-head slug tests were performed to measure the permeability of the selected stratigraphic zones throughout the mining of the longwall panels. These test zones were chosen to correspond to likely locations of high ground movement where increases in permeability were considered most likely. An INW PT2X (Seametrics) piezometer was utilized to track the long-term water table height and water slug height as pressure, which uploaded the data using the Aqua 4 software package with a field laptop. For the falling-head slug tests, a water slug height of up to 3 m (10 ft) was added to the boreholes. The fall of the water head was recorded at 5, 30 or 60 second intervals, depending on the expected drainage rate of the water. The piezometer readings, water slug height (H_w), and initial slug height (H_o) were converted to H_w/H_o values. Figure 5 shows examples of the water head changes over time at calculated permeability values as a result of different longwall face positions. In this figure, minus distance (-72 m) in the legend refers to an approaching longwall face, where a positive one (817 m) refers to moving away. Zero distance is where the longwall face was the same location as the borehole. In Figure 5, "mD" refers to the unit of permeability, millidarcy.

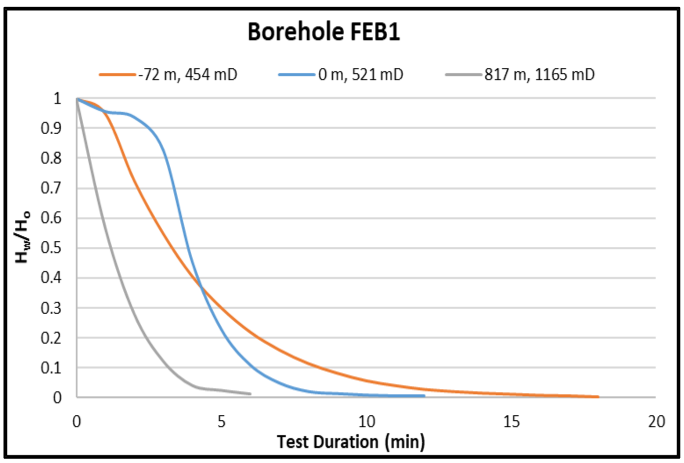

Figure 5. Water height curves from slug tests at different longwall positions

For the calculation of permeability from falling head slug tests, H_w/H_o values were plotted on a semi-log graph to determine the T_{37} time, which is the time, in minutes, in which the water slug drained to 37% of the initial water level (Dawson and Istok 1991). If the T_{37} value did not fall within the given data range, two points were chosen along the most linear section of the monitored data. The change in time divided by the change in the natural logarithm of H_w/H_o values can be used as a substitute for a T_{37} value. The T_{37} or its substitute value, was then used in the Horslev method for the calculation of hydraulic conductivity by applying Equation 1 (Dawson and Istok 1991):

$$K = \frac{r^2 Ln(L/R)}{120 L T_{37}} \tag{1}$$

where K is the hydraulic conductivity in m/sec, r is the radius of the well casing, in m, R is the radius of the well screen in m, L is the length of the well screen in m and T_{37} is the time in minutes for 37% of slug height to drain. For this study, the radius of the well casing and well screen was 0.0508 m for both variables. The hydraulic conductivity value, K, was then used to calculate the absolute permeability of the screened section as described by Equation 2:

$$k = \frac{K\mu}{\rho g} \tag{2}$$

where k is the absolute permeability in m^2, μ is the dynamic viscosity of the fluid in kg/ms, ρ is the density of the fluid in kg/m^3, and g is the gravitational acceleration in m/s^2.

Multiple assumptions about the slug test and ground aquifer are applied when conducting the Hvorslev method to calculate permeability. This method assumed that the water slug is added instantaneously, the groundwater flow is described by Darcy's Law, and the volume of water that flows into the aquifer is equivalent to the change in water volume within the well casing. The aquifer is assumed to be incompressible, homogeneous, isotropic, and vertically confined by aquicludes. The injection well is assumed to have a negligible radius in relation to the size of aquifer, the well has a screen with a negligible head loss, and the water slug flow travels horizontally away from the well in all directions (Dawson and Istok 1991).

Falling-head slug tests were conducted on each of the three boreholes three times a week when the longwall face was in close proximity to the boreholes. When the active longwall face passed the borehole locations and was further away, the sampling rate for falling-head slug tests was approximately once a week. Long term continuous water pressure readings were also recorded between slug tests at a 15-minute sampling interval. The long-term data provided insight into the trends of equilibrium water level height inside the boreholes.

DISCUSSION OF RESULTS

Slug testing on the FEB boreholes began when the longwall face was 72.5 m (238 ft) away for the first panel and when the face was 290 m (950 ft) away for the second longwall panel. Slug testing continued on both longwall panels until the development of those panels reached completion. Figures 6 through 11 display the slug test permeability figures for FEB boreholes 1, 2, and 3 respectively. The data labels for the Figures 6 through 11 correspond to the distances of the longwall face to the boreholes. Data labels in black are for distances before the longwall face reached boreholes and labels in red represent the face distances past the borehole locations. The final face distance to borehole measurement was unknown for panel 2 and was estimated at 915 m (3000 ft) based on average face advance rates. A summary of the minimum and maximum permeability values calculated are available in Table 1 for comparison of values.

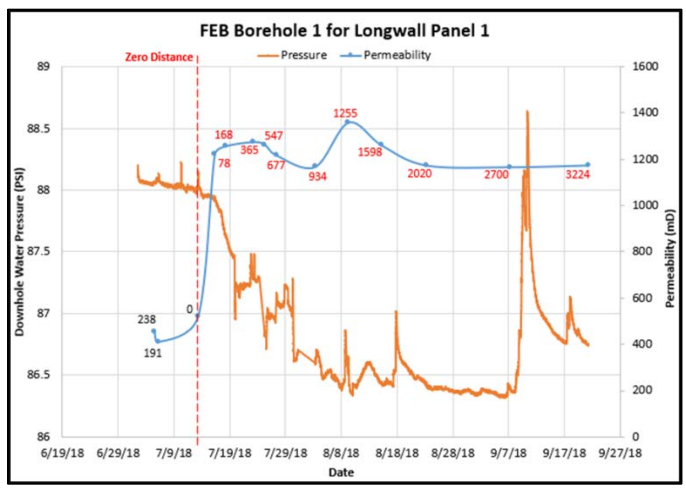

Figure 6. Permeability and long-term downhole water pressure for FEB 1 during longwall panel 1 development.

Table 1. Measured Permeability Values for FEB Boreholes in milliDarcy (mD).

Borehole ID	Panel 1		Panel 2	
	Min	Max	Min	Max
FEB 1	411	1360	1100	5080
FEB 2	21.9	245	11.5	386
FEB 3	2730	32900	38500	13200

FEB Borehole 1 (FEB 1) data for mining of the first and second panel, which was monitored the deepest interval of the three wells is displayed in Figures 6 and 7 respectively. Permeability values displayed in milliDarcies (mD) in FEB 1 reached a peak value of 1,360 mD during mining of the first panel and 5,080 mD for the second panel. For this borehole, an increase in permeability correlated to a drop in water height inside the borehole for the mining of the first panel and a majority of the second panel. FEB 1 is at the greatest depth of the three boreholes and could see more effects of compression from the fractured rock mass above than the other boreholes. Reduced permeability from compression alongside increased permeability effects from formation of a fractured network could explain how the permeability from formation of a fractured network could explain the long-term permeability trends for FEB 1.

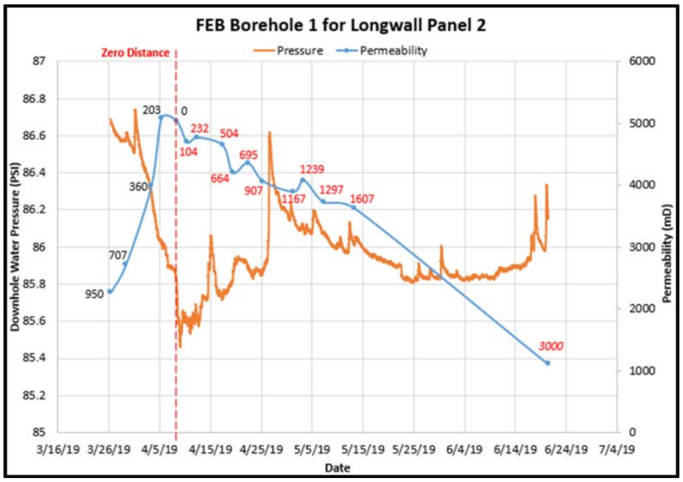

Figure 7. Permeability and long-term downhole water pressure for FEB 1 during longwall panel 2 development.

In general, permeability values can be considered as steady after the initial increase when the face passed the borehole location by approximately 51 m (168 ft) during the mining of the first panel. The other issue that needs to be taken account is the proximity of the extracted panel to the borehole locations. As depicted in Figure 1, first panel is further away from the boreholes due to the mine layout, which protects the boreholes and the attenuates the influence of the effects of the subsidence on the strata. Therefore, it is possible that after the initial effects of the deformation at that interval, which manifest as permeability increase, it stays almost constant for completion of panel 1. On the other hand, the edge of the second panel is closer to the borehole locations where the effects of dynamic subsidence at this monitoring interval could be more pronounced, as observed as the continued change in permeability values even after the longwall face moved further away.

FEB Borehole 2 (FEB 2) data, which monitored the Uniontown coal interval, is displayed in Figures 8 and 9. FEB 2 had maximum permeability values of 245 mD and 386 mD for the two panels. These values corroborate with less horizontal displacement at that interval, as shown in Figure 4. FEB 2 had minimum permeability values recorded post-mining for both panels, with the lowest permeability calculated at 11.5 mD during mining of panel 2. FEB 2 also displayed higher peak permeability values for the second panel compared to the first longwall panel but had a final permeability value similar to the data first recorded when the first longwall was 73 m (238 ft) from the borehole. Unlike FEB 1, a drop in long-term water height in borehole FEB 2 coincided with a drop in calculated permeability values across development of both longwall panels. The difference in the water height correlation between the two boreholes could be caused by the differing vertical location within the gob fracture network. The proximity of the edge of the panels to borehole location had less effect at FEB 2 as opposed to FEB 1, which is proven by comparable average permeability values, the effects of subsidence is less and is felt along a longer interval as opposed to a very localized zone (Figure 4).

FEB Borehole 3 (FEB 3) data, which monitored the highest interval, is displayed in Figures 10 and 11. FEB 3 had the highest overall permeability values calculated, with the peak values being 32,900 mD and 127,000 mD for longwall panels 1 and 2. All permeability data recordings for FEB 3 were higher for the second longwall pass compared to the first pass, with the final permeability value being approximately 3 times higher than the final value for the first longwall pass. FEB 3 displayed loose correlation between permeability and water level height in the hole, but that could be from surface water reaching the borehole which would violate the assumptions needed to apply the Hvorslev methodology for permeability calculation. Nevertheless, given the data from GCB borehole and the location of the test being in a major stream valley, one of the plausible explanations can be that the monitoring interval was in pre-existing close-to-surface fractures due to the valley (Karacan and Goodman, 2009). These existing fractures had both higher initial permeabilities, as shown in the calculated data, and also generated much higher permeabilities even with smaller disturbances presented in Figure 4. In fact, even in GGV production monitoring experiments (Karacan and Goodman, 2009), it was shown that the GGVs located at valleys produced at higher rates exactly due to the same reason. However, the likelihood of a shale gas well casing being ruptured at this interval seems low.

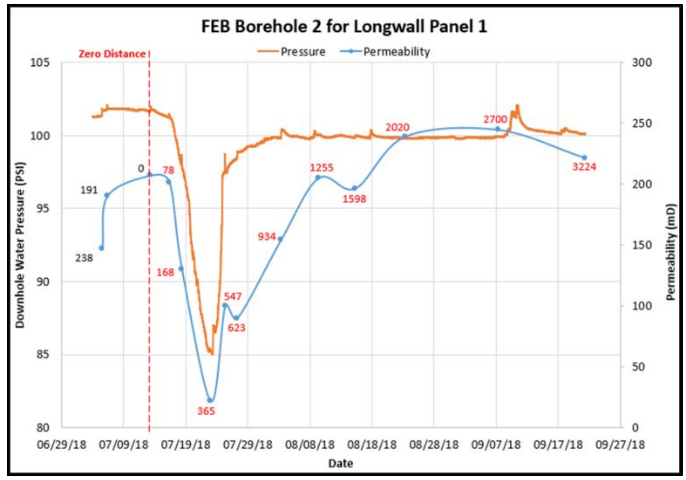

Figure 8. Permeability and long-term downhole water pressure for FEB 2 during longwall panel 1 development.

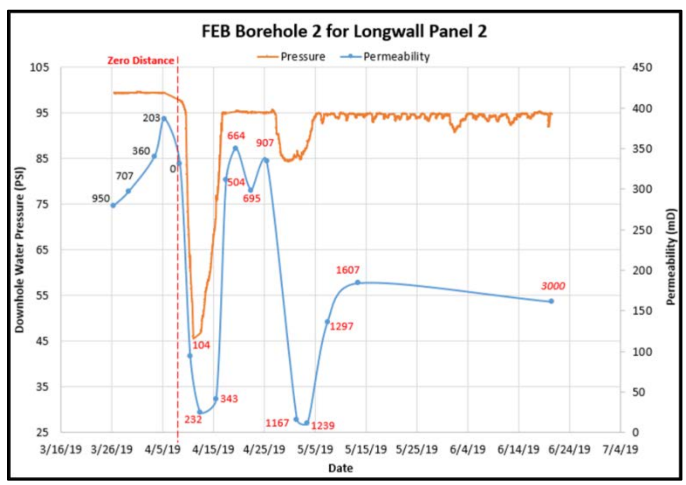

Figure 9. Permeability and long-term downhole water pressure for FEB 2 during longwall panel 2 development.

The permeability of the Sewickley coal seam (FEB 1), as described by Figures 6 and 7, had its highest values directly before or after the longwall face had reached the location of the boreholes. The high risk of gas inflow from the Uniontown coal seam (FEB 2) into active mining works was right before the advance of the longwall face passed the location of the boreholes. For mining of both panels, the permeability within the FEB 2 borehole reached relative minimums directly after undermining of the boreholes location, which would lower the potential flow rate of shale gas into the mine. FEB 3 had the highest permeability by two orders of magnitude, but the depth of the FEB 3 borehole is the furthest from the actively mined Pittsburgh seam and the influence from surface water networks on the assumptions needed for the slug test calculations was unknown. Influence from surface water systems could have also caused a high initial permeability that was further increased by longwall-induced deformations. The permeability values for the FEB boreholes were similar to those calculated from a similar study where the boreholes were located above the longwall gob for which that maximum permeability values range from 1,600 mD to 65,000 mD (Schatzel et al. 2008).

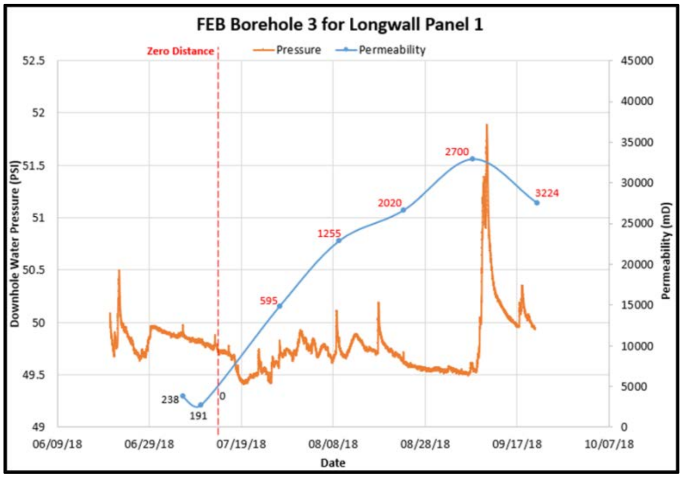

Figure 10. Permeability and long-term downhole water pressure for FEB 3 during longwall panel 1 development.

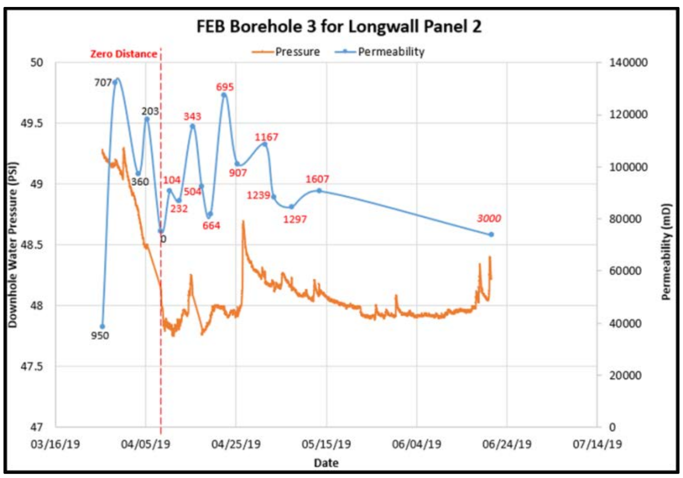

Figure 11. Permeability and long-term downhole water pressure for FEB 3 during longwall panel 2 development.

SUMMARY

NIOSH conducts work to eliminate mining fatalities, injuries, and illnesses through relevant research and impactful solutions. This study fulfills part of that plan by reducing the risk of mine disasters through preventing or limiting an influx of shale gas into active mine workings. Flow characteristics of that potential shale gas influx were studied by performing slug tests on three boreholes above a longwall coal mine pillar; these tests were utilized to track permeability changes adjacent to the gob fractured zone caused by the advance of two longwall panels on either side of the pillar. The permeability data from the slug tests and long-term water height values can be used to characterize potential gas flow interactions between shale gas wells and the longwall coal mine environment. A determination of the fractured zone properties is required for an assessment of the risks surrounding shale gas well drilling through coal mine pillars.

The three boreholes monitored in this study (FEB 1, 2, and 3) showed calculated maximum permeability values of 5,030 mD, 386 mD and 127,000 mD, respectively. All the boreholes displayed an increase in permeability during the first longwall pass, and an increase in maximum permeability between the first and the second longwall passes. The values calculated represent changes rock in permeabilities along the length of the slotted sections on the casings with the horizontal extents of the zone of permeability change unknown. The data gathered from this research will be utilized in future studies that will produce more detailed information on the gas well/coal mine interaction that will benefit coal mines, natural gas companies and the regulatory agencies.

DISCLAIMER

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. Mention of any company or product does not constitute endorsement by NIOSH.

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