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Permeability determination for potential interaction between shale gas wells and the coal mine environment due to longwall-induced deformations under deep cover

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ABSTRACT: This paper summarizes the changes in permeability for two boreholes located above an abutment pillar in a longwall coal mine to characterize potential interaction between shale gas wells and the coal mine operations under deep cover. To determine the safety of the mine environment in case of a potential well breach, fracture network characteristics are needed to conduct a comprehensive hazard assessment. Permeability was measured using a falling-head slug test and calculated in accordance with the Hvorslev model during the mine-by of a longwall panel on one side of the pillar. The two boreholes had screened lengths at different depths to evaluate stratigraphic zones of interest above the active mining seam. The permeability at each borehole increased from pre-mining to post-mining and was highest while the face was close to and during mine-by of the test site.

1 INTRODUCTION

Within the past 15 years, unconventional shale gas wells have been drilled through current and future coal reserves in Pennsylvania, West Virginia, and Ohio. Impacts on the mechanical integrity of these wells becomes a concern when mining occurs in and around these wells. The shale gas wells penetrate the coal seams and the coal seams are subsequently mined. The coal and shale gas industries need to know what the impacts of longwall mining are on the shale gas wells, what the potential deformation may be, and what stresses are imposed on the gas wells.

In 2012, the Pennsylvania Department of Environmental Protection (PADEP) recognized the 1957 Pennsylvania Gas Well Pillar Regulation (Commonwealth of Pennsylvania, 1957) was created without current data from modern day longwall mining and called for research to revise the outdated regulation. Also, the 1957 Pennsylvania Gas Well Pillar Regulation has been widely used by the Mine Safety and Health Administration (MSHA) along with CFR 75.1700 to manage gas well pillar stability issues. Therefore, given the posed questions and the need for further guidance given modern mining technologies and practices, the National Institute for Occupational Safety and Health (NIOSH) initiated research to address these issues.

One of the first steps in quantifying the interaction between the two processes is to determine the change in ground permeability at depths where longwall-induced deformations are of highest concern. If longwall-induced subsurface strata deformations and stresses should affect shale gas well casings and if a breach occurs, the changes in the ground permeability could potentially increase the rate of shale gas infiltration into an underground coal mine. Permeability field measurements have been conducted under various differing conditions. Boreholes placed in the barrier pillar and in the longwall gob areas under differing depths of cover have been monitored during completion of the longwall coal seam. Previously, three monitoring boreholes were monitored to experimentally measure borehole permeability and changing water head under shallower cover (deepest at

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127 m or 417 ft). Watkins et al. (2021) assessed permeability changes around boreholes above an abutment pillar under shallower cover. This paper will discuss a similar scenario except under deeper cover conditions (up to 238 m or 1,047 ft) and during the first longwall panel mine-by.

2 TEST METHOD

The study included drilling two boreholes to various depths to monitor the Sewickley and Uniontown horizons and performing field experiments to gather permeability data. Although Marcellus shale gas reservoirs are at much greater depths than the Pittsburgh coal bed longwall mines, the risk of a hypothetical casing failure is thought to be greatest where the maximum zone horizontal movement occurs in response to mining. This zone is typically shallower than the mined coalbed and within a few hundred meters of the unit. Additionally, the areas above abutment pillars are particularly important as shale gas wells are required to be drilled through them.

2.1 *Borehole and mine layout*

The most commonly sought-after shale gas reserve in the southwestern Pennsylvania region is the Marcellus Shale Reserve which can be located at a depth of about 2,100 m (7,000 ft) to 2,750 m (9,000 ft). Commonly, several wells can be positioned on a single drill pad to decrease drilling costs and reduce the surface footprint of the well.

The Pittsburgh seam, a relatively flat deposit, is longwall mined in this region due to its consistent quality and thickness. The stratigraphic zones monitored for possible changes in permeability due to mining-induced deformation were the Sewickley coal bed and the Uniontown coal bed, whose thicknesses vary in the region (Figure 1). These coal beds typically have lower compressive strengths than the adjacent limestone, shale, and siltstone/sandstone units (Rusnak & Mark, 2000; Mohan et al., 2001). A field study showed that horizontal fractures formed between layers with differing uniaxial compressive strengths and seam thicknesses (Palchik, 2005). This stratigraphy is found at the study site with the thick limestone units and thin coal beds (Figure 1). Consequently, zones of high ground movement would be associated with the coal horizons due to mining-induced deformation.

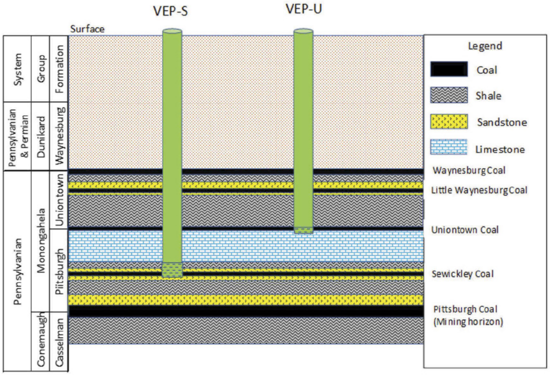

Figure 1. Generalized stratographic profile for the VEP boreholes (not to scale).

The primary factors creating the gas transport network associated with longwall gobs are ground movements related to subsidence. Previous ground control studies (Su et al., 2019) indicate the primary movement component that potentially deforms well casings in longwall pillars is subsidence or horizontal movement. FLAC3D™ modeling estimations show an insignificant amount of vertical movement for borehole locations above abutment pillars. However, higher magnitudes of displacement perpendicular to the panel are typical and are shown for this area in Figure 2. Although stratigraphic zones of maximum horizontal movement in the region can be variable, previous modeling shows that the Uniontown and Sewickley coal seams are among the likely locations (Su et al., 2019).

Most of the horizontal movement was estimated to be perpendicular to the longwall panel due to the ground subsidence pulling the strata above the pillar toward the caved gob zone, which is perpendicular to the panel direction. Figure 2 presents data for a nearby location and is representative for this monitoring site. Here, a horizontal displacement of about 0.7 cm (0.3 in) with a predicted casing diameter reduction of 0.15 cm (0.16 in) is predicted. A depth of approximately 155 m (509 ft) is when horizontal displacement increases to about 2.0 cm (0.8 in) and the predicted casing diameter reduction increases to 0.70 cm (0.3 in). These zones of maximum movement are also important locations for fluid transport as these are typically high permeability zones for the transport of gas from a hypothetical breach.

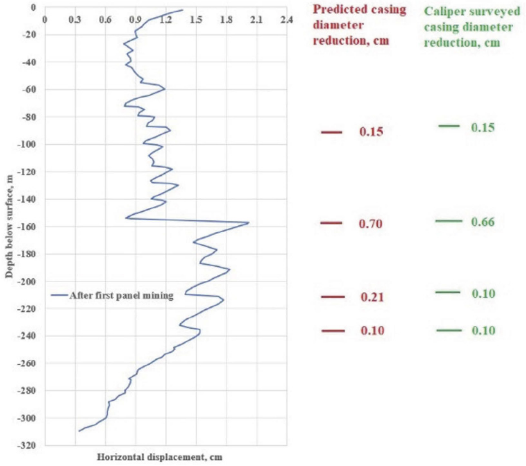

Figure 2. Shale gas well horizontal displacement by depth perpendicular to the panel from field measurements and FLAC3D™ modeling.

In southwestern Pennsylvania, monitoring boreholes used to examine longwall-induced permeability changes under deeper cover were drilled in the overburden directly above an abutment pillar between two planned longwall panels. The field test site is located on the top of a steep hill and has an overburden depth to the Pittsburgh seam of about 370 m (1,214 ft).

The monitoring boreholes are labeled as VEP-S and VEP-U to monitor the Sewickley and Uniontown formations respectively. VEP-S was drilled to a depth of 328 m (1,076 ft) ending at the Sewickley formation and VEP-U was drilled to a depth of 291 m (955 ft) ending at the Uniontown formation equivalent. According to Figure 2, at the depths of 291 m (955 ft) and 328 m (1,076 ft) the predicted horizontal displacement is expected to be 0.6 cm (0.2 in) and 0.3 cm (0.1 in), respectively.

The borehole pattern was 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 3) 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 was at most 18 m (60 ft). Using the guidance from the 1957 PADEP study, this distance may be as small as 15 m (50 ft). Measurements place the Pittsburgh seam to be at a depth of 370 m (1,214 ft) from the surface at this location.

The VEP-S and VEP-U boreholes were drilled and cased with a steel casing and grout baskets except for the test intervals, which had screen lengths of 3 m (10 ft) and 5 m (15 ft), respectively. Grout or bentonite were used to cement the borehole annulus outside of the casing.

2.2 *Falling-head slug tests*

Throughout the mining of the first longwall panel, researchers conducted falling-head slug tests to measure the permeability of the slotted casing lengths. VEP borehole slug testing began when the longwall face was 273 m (897 ft) away for the first panel and will continue until the completion of mining for both panels. To date, only the first longwall panel has been

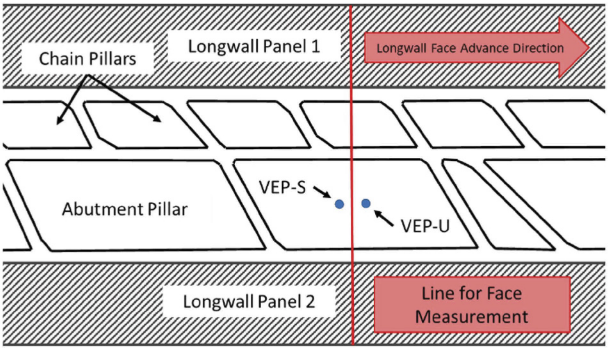

Figure 3. Top view of a three-entry longwall layout. Test boreholes and mining direction are shown.

completed. These test zones were chosen to correspond to probable locations of high ground movement where increases in permeability were considered most likely. An INW PT2X (Seametrics™) piezometer tracked the long-term equilibrium water height and water slug height (Figure 4). For the falling-head slug tests, a water slug height of up to 3 m (10 ft) was added to the boreholes. The previous study (Watkins et al., 2021) recorded the fall of water head at 5, 30, or 60 s intervals, depending on the expected drainage rate of the water. However, during the current study the rate of loss was at a much slower rate and, therefore, the data was recorded every minute, and the falling rate was later determined from the downloaded data.

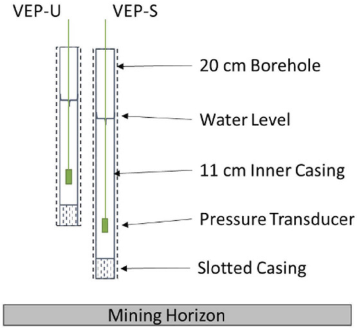

Figure 4. The sideview of the VEP-S and VEP-U monitoring boreholes (not to scale).

When the longwall face was 364 m (1193 ft) away from the monitoring site, the slug tests were conducted on each of the boreholes twice a week. The frequency increased to three times per week when the longwall face was within 100 m (328 ft) of the boreholes. When the active longwall face passed the borehole locations and was further away, the sampling rate for slug tests was approximately once per week. Once the longwall panel was completely mined, long-term continuous water pressure readings were recorded every eight hours. The piezometer readings, water slug height (H_w), and initial slug height (H_o) were converted to H_w/H_o values.

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 slug height (Dawson & Istok, 1991; Watkins et al., 2021). For a 10-ft water slug, the T_{37} time would be calculated as the time it took for the slug to drain to 3.7 ft. If the T_{37} value did not fall within the given data range, two points were chosen along the most linear section of the semi-log plot of the slug test, and the slope of those two points estimated the T_{37} time. Watkins et al. (2021) details the application of T_{37} in the Hvorslev method to determine the hydraulic conductivity. The hydraulic conductivity is dependent upon the well casing radius, the well screen radius, and the length of the well screen. For both VEP boreholes, the well casing radius is 0.052 m (2 in), and the well screen radius is 0.104 m (4 in). The well screen length is 4.6 m (15 ft) for VEP-U and is 3.0 m (10 ft) for VEP-S.

As with the previous study, 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 (Watkins et al., 2021). The aquifer is assumed to be incompressible, lithologically 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.

3 RESULTS AND DISCUSSION

3.1 *VEP-U*

Figure 5 displays the changes in water head from experimental data in VEP-U. The data was collected when the longwall panel was at varying distances from the monitoring boreholes. In this figure, the negative distance (– 54 m or -177 ft) in the legend refers to an approaching longwall face and the positive distance (+61 m or +200 ft) refers to the longwall face moving away. Zero distance is where the longwall face passed the center of the test abutment pillar and is the basis for position measurements. As seen in Figure 5, the permeability was 3.19 x 10^{-15} m^2 (3.2 mD) when the longwall was 54 m (177 ft) from mining by the monitoring holes. The permeability de-creased slightly to 2.51 x 10^{-15} m^2 (2.51 mD) during the mine-by before rising to 5.33 x 10^{-15} m^2 (5.33 mD) when approximately 61 m (200 ft) beyond the monitoring boreholes.

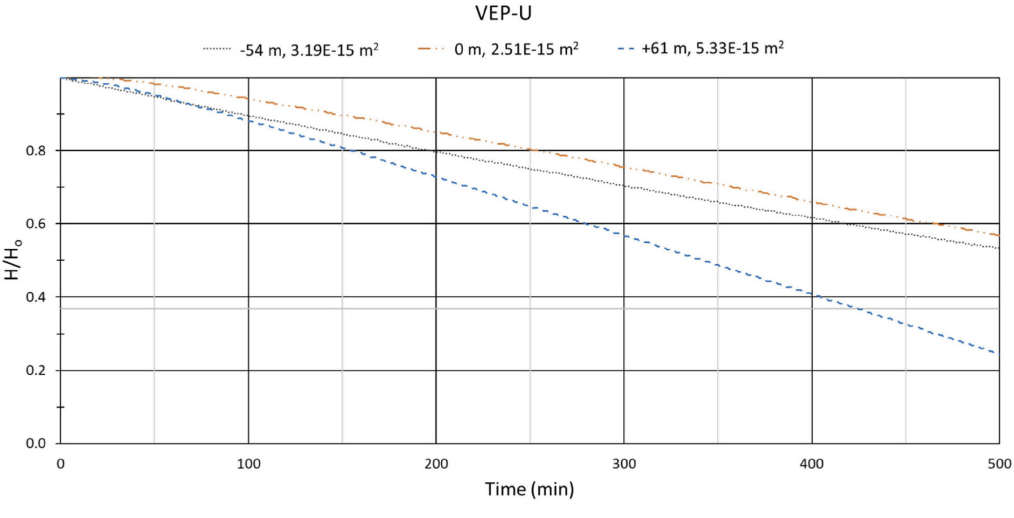

Figure 5. VEP-U water height curves for slug tests at various longwall positions. The negative value refers to the approaching longwall face and the positive value refers to the face moving away from the test location.

Figure 6 shows the permeability, m^2, and pressure measurements, kPa, at the Uniontown horizon from VEP-U. The numbers above the bars are the distances (m) of the longwall panel from the monitoring boreholes. The black negative numbers above the bars indicate the longwall panel approaching the monitoring location and the red positive numbers above the bars indicate the distance as the longwall panel passes the monitoring location. Prior to mining, the permeability in VEP-U was 0.19 x 10^{-15} m^2 (0.19 mD). The borehole water level steadily rose prior to 08/23/2021. This is seen in the rise in associated pressure measurements (orange plots) on Figure 6. The longwall panel was mined by the abutment pillar on 08/25/2021 when the permeability was 2.51 x 10^{-15} m^2

(2.54 mD). The water levels and pressures were also the highest at this time with pressures just over 910 kPa (132 psi). When the longwall panel passes the monitoring point, the permeability increases and reaches a maximum of 5.33 x 10^{-15} m^2 (5.4 mD) and the pressure in the hole drops to 585 kPa (85 psi). After this maximum, the permeability drops to a low of 8.78 x 10^{-16} m^2 (0.89 mD) before slightly rising. The downhole pressure is relatively steady during the first half of September and hovers around 500 kPa (73 psi) before dropping at the end of September.

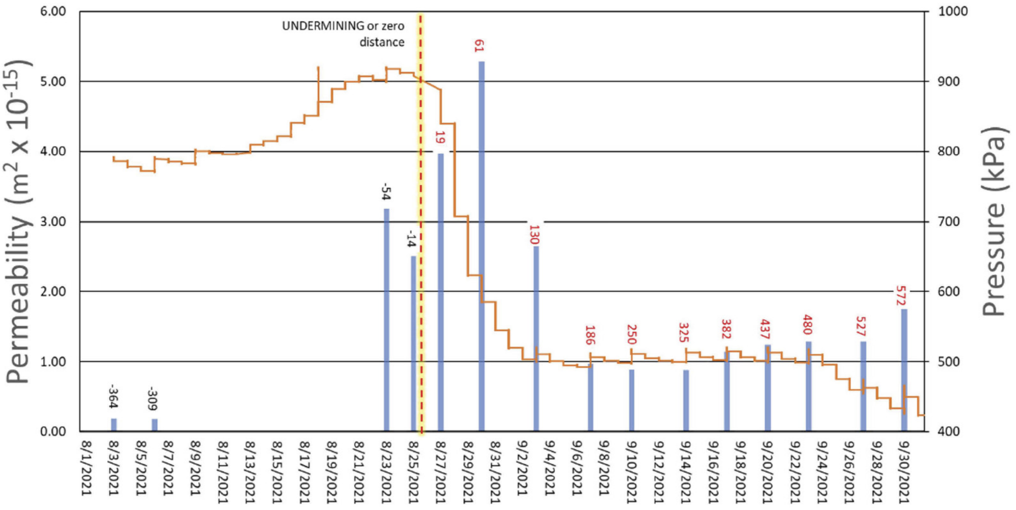

Figure 6. Permeability values and pressure measurements from VEP-U at the Uniontown horizon. Black numbers on the graph indicate the distance (m) of the longwall face advancing toward the monitoring point, and red numbers indicate the distance (m) of the longwall.

3.2 *VEP-S*

Figure 7 displays the water changes before, during, and after the longwall panel mine-by of VEP-S. When the longwall face was approaching the monitoring site (54 m or 177 ft away), the permeability was 1.41 x 10^{-15} m^2 (1.43 mD). The permeability then increased to 2.70 x 10^{-15} m^2 (2.74 mD) during the longwall panel mine-by before increasing again to 1.27 x 10^{-14} m^2 (12.8 mD).

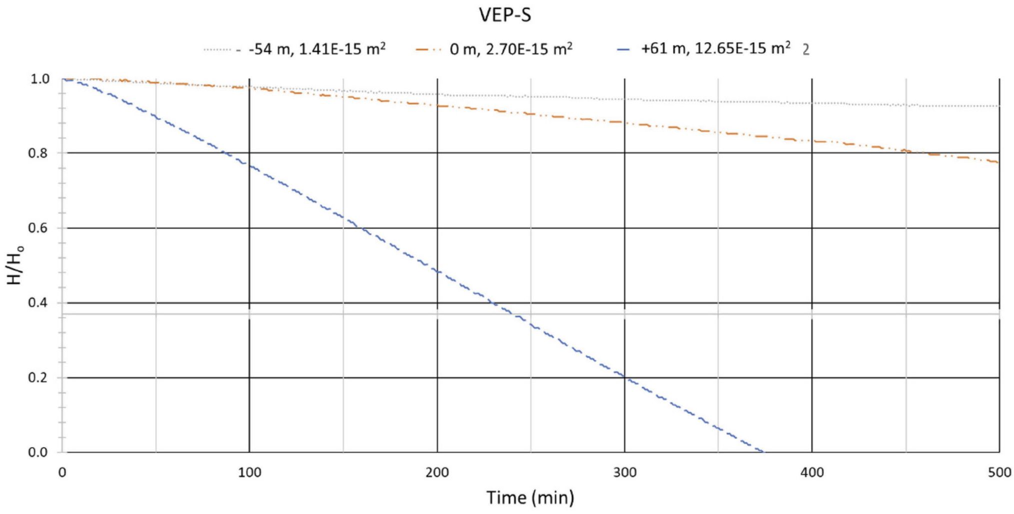

Figure 7. VEP-S water height curves for slug tests at various longwall positions. The negative value refers to the approaching longwall face and the positive value refers to the face moving away from the test location.

Figure 8 shows the pressure measurements and the corresponding permeability values. The highest permeability, 1.755 x 10^{-14} m^2 (17.8 mD), occurred two days after the mine-by when the panel was 19 m (62 ft) past the monitoring point (Figure 8). The associated water pressure at this point was 885 kPa (128 psi). After the longwall panel mine-by, the pressure decreased and held steady at around 500 kPa (73 psi), while the permeability values varied in the range of 0.97 x 10^{-15} m^2 – 1.93 x 10^{-15} m^2 (0.98 mD – 1.96 mD). Towards the end of September, the pressure started decreasing again as the permeabilities slightly increased.

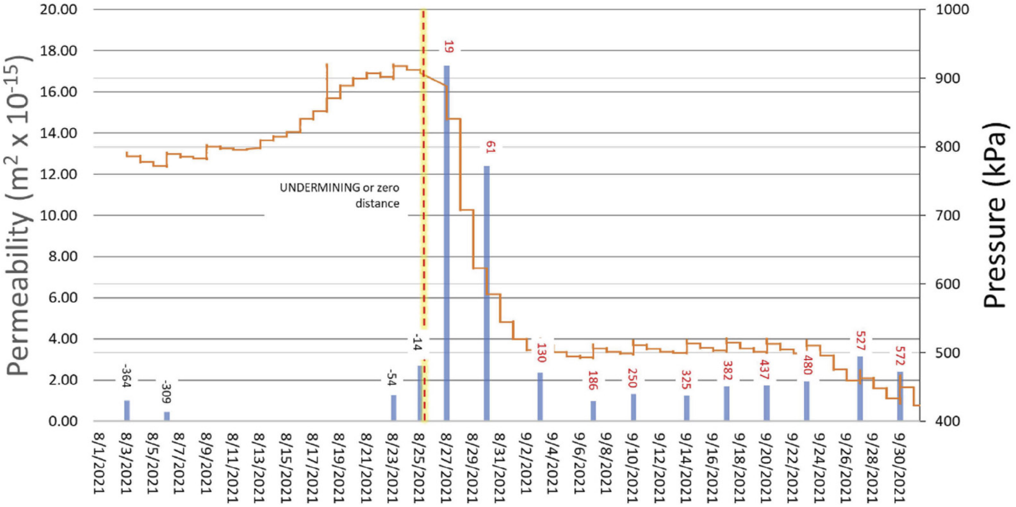

Figure 8. Permeability values and pressure measurements from VEP-S at the Sewickley horizon. Black numbers on the graph indicate the distance (m) of the longwall face advancing toward the monitoring point and red numbers indicate the distance (m) of the longwall.

3.3 *Comparison*

Table 1 lists the minimum and maximum measured permeability values after the first longwall panel mine-by as well as the predicted horizontal displacements. As with the previous study, the deeper Sewickley horizon saw higher permeability values since it is closer to the mining horizon and would be most impacted by the compression of the fractured rock. The maximum permeabilities under deeper cover are smaller than for shallower cover by an order of magnitude of two for both horizons. As seen in Table 1, the maximum permeability for the Sewickley horizon under deeper cover was 1.75 x 10^{-14} m^2 (17.8 mD) and 1.34 x 10^{-12} m^2 (1358 mD) under shallower cover. For the Uniontown horizon, the maximum permeability under deeper cover was 5.33 x 10^{-15} m^2 (5.4 mD) and 2.42 x 10^{-13} m^2 (245 mD) under shallower cover.

Table 1. Minimum and maximum permeability values for VEP-S and VEP-U resulting from this study and for corresponding FEB-1 and FEB-2 (Watkins et al., 2021).

			Longwall Panel 1 Measured Permeabilities		Predictions
Borehole ID	Horizon of Interest	Overburden Depth m (ft)	Minimum m^2 (mD)	Maximum m^2 (mD)	Horizontal Displacement cm (in)
VEP-S	Sewickley	328 (1,076)	4.64E-16 (0.47)	1.75E-14 (17.8)	0.6 (0.2)
VEP-U	Uniontown	291 (955)	1.84E-16 (0.19)	5.33E-15 (5.4)	0.3 (0.1)
FEB-1	Sewickley	127 (417)	4.06E-13 (411)	1.34E-12 (1358)	17 (6.7)
FEB-2	Uniontown	76 (249)	2.16E-14 (22)	2.42E-13 (245)	4 (1.6)

The previously stated trend also correlates with the predicted horizontal displacements. The predicted displacements for both shallower and deeper covers are larger for the deeper Sewickley horizons than for the Uniontown. The horizontal displacement prediction was 0.6 cm (0.2 in) for the deeper cover and 17 cm (6.7 in) for the shallower cover and, for the Uniontown seam, it was 0.3 cm (0.1 in) and 4 cm (1.6 in) for the deeper and shallower covers, respectively. The predicted horizontal displacements are also 1-2 orders of magnitude in difference with the shallower cover having higher values than that of the deeper cover.

4 CONCLUSIONS

At a mine site in southwestern Pennsylvania, permeability measurements were conducted over a 2-month period on two boreholes monitoring the Uniontown and Sewickley coal horizons under deeper cover for these seams. The permeability values were higher for the Sewickley horizon (maximum 1.75×10^{-14} m^2) than for the Uniontown horizon (maximum 5.33×10^{-15} m^2). This also corresponds with the predicted horizontal displacement values for each.

When comparing the previous work by Watkins et al. (2021) that was conducted under shallower cover, the Sewickley unit also exhibited higher permeability compared to the Uniontown horizon. However, there is a significant difference in that the maximum deeper cover values are 2 orders of magnitude smaller than the maximum measured for previous shallower cover.

Future work will include monitoring permeabilities at this deeper cover site during an idle mining period between panels and during a second panel mine-by. The future monitoring efforts will be compared with the previous shallower cover data, contributing to the current knowledge and database.

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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