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Examining Pull-Out Tests for Grouted Rib Bolts: A Comprehensive Analysis

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ABSTRACT

Resin-grouted bolts serve as a crucial means of stabilizing yielded coal ribs in underground coal mines. A comprehensive investigation into their efficacy was undertaken by a collaborative effort between the National Institute for Occupational Safety and Health (NIOSH) and Missouri University of Science and Technology (MST). This study involved pull-out tests in multiple locations, including six coal mines and the NIOSH research mine. A total of seventy-three (73) tests were conducted, of wide range of anchorage lengths, ranging from a short encapsulation length of 0.305 m to a fully grouted encapsulation length of 1.524 m.

The test findings indicate that when short encapsulation bolts are installed at high rotation speeds, their anchorage capacity is significantly reduced, leading to failure at the bolt-grout interface. Conversely, when these bolts are installed at lower rotation speeds, they exhibit greater capacity, with failure occurring at a higher anchorage load equivalent to the yield load of steel rebar. No matter what the rotational speeds were used during bolt installation in this study, the fully grouted bolts consistently experienced failure at the ultimate load of the steel rebar. Most of the tests carried out on partially grouted bolts with anchorage lengths of 0.610 - 0.914 m have shown behavior patterns like the fully grouted bolts, although exhibiting reduced stiffness. The outcomes of this research offer a profound insight into the ways in which resin-grouted bolts enhance the stability of coal mine ribs.

INTRODUCTION

Coal ribs, which are the walls of coal pillars, sometimes intentionally supported during mining operations to maintain their structural integrity. Due to the flexibility, effectiveness and relatively straightforward installation process, rib bolting systems have been widely used in underground coal mines. The installation of grouted bolts involves inserting resin cartridge and bolt into a drilled borehole and driving the bolt to break and mix the resin to form a mechanical interlock between the bolt and surrounding coal mass. When coal ribs start to deform and dilate, load is generated in the bolt to reinforce the ribs. However, the rib bolting system is complex because it involves various components, namely bolt, grout and the surrounding coal mass, and their interactions. The properties of these components and their interaction potentially affect the overall performance of the resin-grouted rib bolts. Due to the complexity, many different methods have been employed to investigate the bolting behaviors through laboratory and field testing, theoretical analysis, and numerical simulation.

The occurrence of rib falls presents severe safety risks, encompassing injuries, fatalities, and equipment damage.

1) Hydraulic Hand Pump
2) Pressure Transducer
3) Pressure gauge
4) Port Block
5) Quick Connects
6) Hydraulic Hose
7) Data Cable
8) MIDAS Data Logger
9) 25 mm Nut
10) Steel Washer
11) String POT and Mounting Plate
12) String POT (magnets attached for mounting)
13) Magnetic Eye Bolt (connect String POT for measuring the displacement of bolt head)
14) 20-ton Hydraulic Ram area = (0.12 m)
15) Pull Tube
16) 25 mm threaded bolt
17) Pull Claw
18) Bolt (Rebar)
19) Pull Collar
20) 6.35 mm Flat Plate
21) 222.4 kN Load Cell
22) 3.175 mm Flat Plate

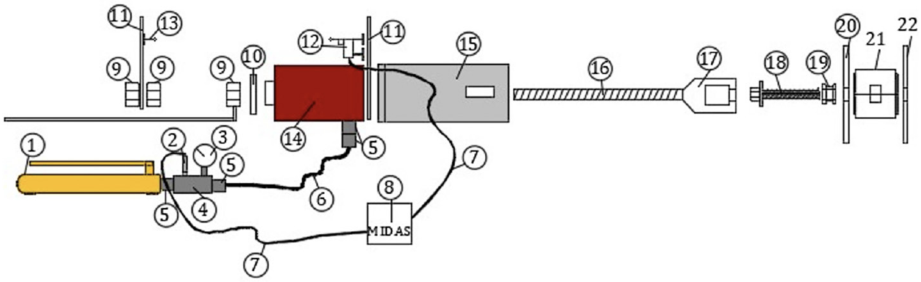


Figure 1. Pull-out test gear components

The effectiveness of the rib bolting systems mainly depends on the rib support design, which can be affected by the local geological condition, the type and size of coal ribs, and the load and stress on the ribs. Inadequate support design could result in insufficient reinforcement and subsequent rib instabilities. The rib bolting design in U.S. underground coal mines currently relies on a trial-and-error approach. Researchers from the National Institute for Occupational Safety and Health (NIOSH) have been working on the development of -an engineering-based approach for coal rib stability analysis and bolting design (Dolinar, et al., 1991, Mohamed, et al., 2019, Mohamed, et al., 2023). Pull-out test is a conventional method to investigate the load transfer mechanism and anchoring ability of bolts, providing crucial information for engineering-based rib support design. It involves the gradual application of axial load using a hydraulic jack to measure the force required for the bolt to be pulled out and provides valuable information about the anchorage capability of the bolts for bolting design. Pull-out tests can be conducted either in laboratory or on field. Figure 1 shows a schematic drawing of the components of the standard pull gear.

Laboratory tests are often favored over field tests due to their cost-effectiveness and ease of control (Blanco Martín et al., 2011; Ma et al., 2017; Ma et al., 2013; Bastami et al., 2017; Chen et al., 2018; Bartels and Pappas 1985). These laboratory experiments provide several advantages, enabling the examination of various factors affecting bolt performance. These factors encompass grout properties (Kilic et al., 2002); bolt surface configurations (Aziz et al., 2006 and Tao et al., 2017); bolt diameters (Rao Karanam and Dasyapu, 2005); host rock properties (Bartels and Pappas, 1985); and confining pressure (Moosavi et al., 2001).

It is important to recognize that the bond characteristics observed in laboratory tests may not accurately represent the conditions of bolts in the field. These- laboratory tests do- not account for various- factors, such as the presence of resin cartridge film, and machinery effects, all of which have the potential to impact bolt performance. In a comprehensive study conducted by Cincilla in 1986, over 1,000 pull-out tests were carried out on roof bolts across 11 underground coal mines throughout the United States. These tests encompassed various anchorage lengths of 0.305, 0.457, 0.610, and 1.219 m. The findings revealed a repeated trend: in most of the roof bolt tests, the behavior of the steel rebar became the dominant factor in the bolt's response to axial loading conditions imposed during the pull-out test, typically once the resin grout length exceeded approximately 0.610 m. To further investigate the anchorage failure of roof bolts, Mark et al. (2000) conducted Short Encapsulation Pull Tests (SEPT) in the roofs of underground coal mines. These tests grouted only the top 0.305 m of the bolt so that the bolts would not reach yielding during the tests. Subsequently, Chugh et al., 2016 carried out SEPTs to establish a comprehensive database for mine roofs in the Illinois coal basin. Their dataset comprised data from over 200 tests conducted in 20 mines across Illinois, Indiana, and Western Kentucky, encompassing a broad range of overburden depths, bolt lengths, and bolt diameters. The SEPTs conducted by Aziz et al. (2016) further confirmed that an encapsulation length of 0.305 m is appropriate for pull-out tests aimed at investigating roof bolt anchorage failure. Extending the encapsulation length beyond this point was found to potentially induce bolt yielding.

However, it is important to highlight that there is a significant lack of pull-out tests performed on the rib bolts, indicating the need for additional research in this specific area. This paper represents ongoing research, jointly undertaken by the National Institute for Occupational Safety and Health (NIOSH) and Missouri University of Science and Technology (MST). The objective of this study is to conduct a comprehensive investigation of the effectiveness of rib bolting in various coal seams within the Eastern mines of the United States. This will be accomplished by performing a series of pull-out tests in those mines in addition to the NIOSH Safety Research mine.

IN-SITU PULL OUT TESTS FOR RESIN-GROUTED RIB

A total of 73 pull-out tests were carried out across six different coal mines and at the NIOSH Safety Research mine. The rib bolts were tested in five different coal seams: Pittsburgh seam, No 2 Gas seam, Kellioka seam, Jawbone seam, and Pocahontas No. 3 seam. No. 5 bolts, which has a diameter of 15.875 mm, were the dominantly tested bolts in this study although a limited number of No. 6 bolts with a diameter of 19.05 mm were also tested. All the tested bolts were grade 60 with a tensile strength of 414 MPa. The yield loads for No. 5 and No. 6 bolts are 82 kN and 118 kN, respectively. Most of the tested bolts were 1.219 m long, although some were 1.524 m in length. All the tested bolts were installed into holes with a 25.4 mm diameter, while the resin cartridge had a diameter of 23 mm.

Three different anchorage types of rib bolts were examined in this study: (1) Fifty-one (51) pull-out tests were conducted on Short Encapsulation (SEPT) bolts, each having an anchorage length of 0.305 m, (2) Fifteen (15) pull-out tests were conducted on fully grouted bolts (FGPT), and (3) Seven (7) pull-out tests were conducted on partially grouted bolts (PGPT), with anchorage lengths ranges from 0.610 m to 0.914 m.

All the rib bolts were installed within the coal seams. Most of the bolts were installed horizontally, although there were a few exceptions where the installation deviated from the horizontal orientation. Typically, we did not select the resin type for pull-out tests. Instead, we used the resin cartridge employed by the mine for rib bolting and follow their method of bolt installation. The spin time for all tested bolts was approximately 4–10 seconds, with a hold time of around 60 seconds. A minimum of 2 hours elapsed between bolt installation and testing. It is important to highlight that different roof bolters and operators participated in the installation of rib bolts in this study. The speed of bolt installation was generally unregulated, except when tests were performed in the NIOSH Research Mine. The tested bolts were subjected to a minimum axial displacement at the bolt head of 20 mm. In the process of conducting pullout tests on rib bolts, our primary goal was to prevent exceeding the fracture load of the steel rebar, except in few cases where the intention was to apply force until the bolt fractured, while adhering to all essential safety precautions.

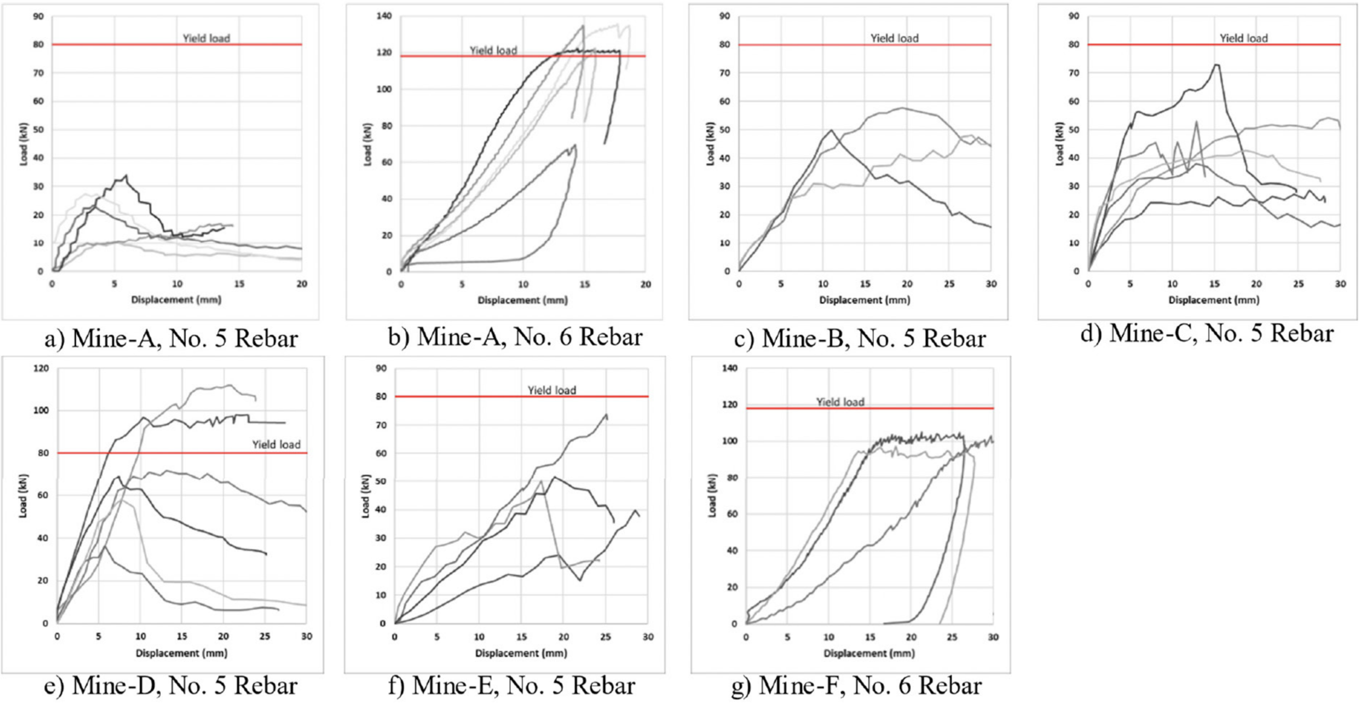
SHORT ENCAPSULATION PULL-OUT TESTS (SEPTS)

To assess the anchorage capacity of grout while avoiding the yielding of steel rebar, the anchorage length for all SEPTs was set to 0.305 m, as established in previous research studies (Mark et al., 2000; Chugh et al., 2016;

Aziz et al., 2016). Figure 2 displays the load-displacement curves obtained from the SEPTs conducted in six different mines. The y-axis represents the recorded load in kN, while the x-axis represents the measured head displacement in mm. The red line indicates the yield load of the examined bolts in kN. It's worth mentioning that the SEPTs for rib bolts No. 5 and No. 6 in Mine-A, were installed on different days by different operators. Additionally, the tests in MineE intentionally terminated before reaching bolt yielding, because of inadequate safety precautions in the event of bolt failures.

It is apparent from Figure 2 that there is no unique load-displacement pattern that can be extracted from the conducted SEPTs. These tests exhibited a range of behaviors, with some SEPTs demonstrating softening characteristics, while others exhibited a consistent plastic behavior. Table 1 provides a summary of the key features extracted from Figure 2 for all the SEPTs. Notably, Table 1 shows a significant variation in the measured average peak loads for No. 5 Bolts, ranging from 26% to 88% of the yield load of steel rebar. Conversely, No. 6 bolts exhibit consistent average peak loads, ranging between 83% and 74% of the yield load of steel rebar.

Prior to carrying out the SEPTs, there was no expectation that any of the tested bolts would yield, and that failure would happen at the grout/bolt interface. However, the tests revealed that in many of the performed SEPTs, bolt failure was the result of steel yielding. Figure 2b shows



a) Mine-A, No. 5 Rebar
b) Mine-A, No. 6 Rebar
c) Mine-B, No. 5 Rebar
d) Mine-C, No. 5 Rebar
e) Mine-D, No. 5 Rebar
f) Mine-E, No. 5 Rebar
g) Mine-F, No. 6 Rebar

Figure 2. Load-displacement curves for SEPTs

Table 1. Summary of the key features of all SEPTs

Mine	Coal seam	Number of Tests	Rebar Diameter (mm)	Bolt Length (m)	Average Peak Load (kN)	Load Range (kN)	Average Peak Displacement (mm)	Rotation Speed (rpm)
A	No 2 Gas	5	19.05	1.219	115	69–134	15	n/a
		5	15.875	1.219	22	10–34	6	n/a
B	Pittsburgh	3	15.875	1.219	52	48–58	19	n/a
C	Pittsburgh	6	15.875	1.219	47	24–72	17	n/a
D	Kellioka	7	15.875	1.219	72	36–111	9	n/a
E	Pocahontas No. 3	2	15.875	1.219	45	40–50	23	n/a
		2	15.875	1.524	63	52–73	22	n/a
F	Jawbone	3	19.05	1.524	98	93–101	20	n/a
NIOSH Safety Research Mine	Pittsburgh	3	19.05	1.219	107	98–112	19	170
		6	19.05	1.219	79	17–61	25	780
		3	15.875	1.219	103	90–109	18	170
		6	15.875	1.219	46	17–61	9	780

that in Mine-A, the steel rebar yielded in all the SEPTs for No. 6 bolts, except for one test. Also, Figure 2e shows that some of SEPTs encountered yielding of steel rebars and many of the tests achieved loads of 75% of the yield load. Figure 2f illustrates that in Mine-F, the peak loads of the SEPTs reached 83% of the yield load, with one of the tests intentionally terminated before reaching the point of bolt yielding.

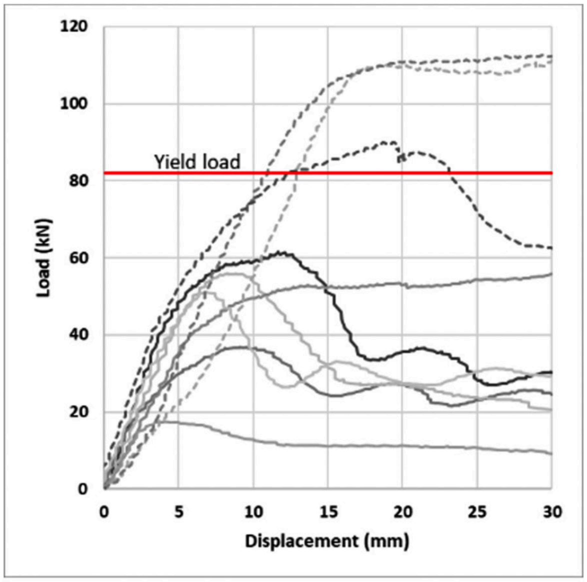
Could the larger bolt diameter tested in Mine-A be a contributing factor behind achieving the yield load in SEPTs, as illustrated in Figure 2b? Could the rotational speed employed during bolt installation have an impact on achieving the yield load in some of the SEPTs? To address the preceding questions, more controllable SEPTs were carried out in the NIOSH Safety Research Mine. These experiments included the evaluation of two bolt sizes, No. 5 and No. 6. Additionally, two different levels of rotation speeds were used for bolt installation: 170 rpm and 780 rpm. Figure 3 displays images illustrating the process of creating a horizontal hole in an almost vertical coal pillar rib, along with a photo of the bolts successfully installed within the coal seam.

Figure 4 presents load-displacement curves resulting from all SEPTs conducted at the NIOSH Safety Research mine. The solid lines represent the load-displacement curves of bolts installed at a high rotational speed of 780 rpm, while the dashed lines show the load-displacement curves

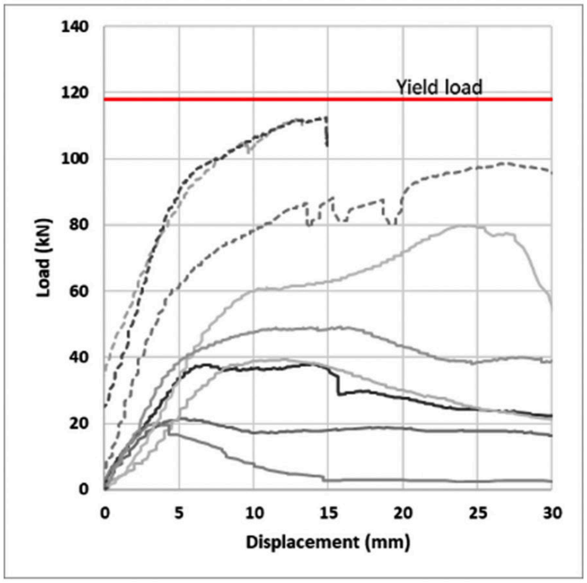
a) Drilling horizontal hole for bolt installation

b) Installed rib bolts

Figure 3. SEPTs preparation carried out at the NIOSH Safety Research Mine

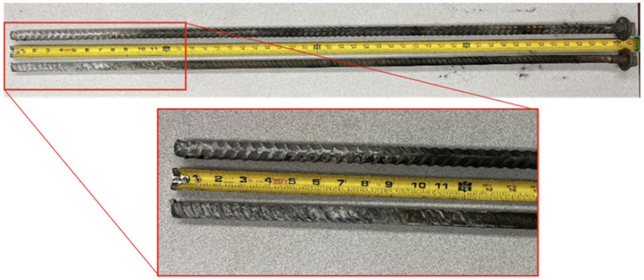


b) No. 5 bolt

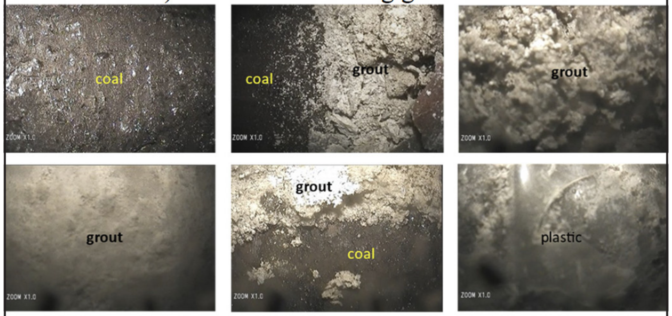


a) No. 6 bolt

Figure 4. Load-displacement curves for SEPTs conducted in NIOSH Safety Research Mine – Solid curves represent bolts installed at high rotation speed of 780 rpm and Dotted curves represent bolts installed at low rotation speed of 170 rpm



a) Tested bolt showing grout residues



b) Snapshots taken at various positions within the borehole

Figure 5. Post-testing photographs showing No. 5 tested bolt installed at a rotational speed of 780 rpm, along with snapshots captured within the drilled borehole

for bolts installed at a low rotational speed of 170 rpm. Table 1 provides a summary of the key features of all SEPTs extracted from Figure 4.

Figure 4 clearly demonstrates the profound influence of the rotation speed utilized during bolt installation on the measured anchorage capacity of SEPTs. Employing a high rotational speed during bolt installation results in diminished anchorage capacities. A comparable trend was previously observed by Mishra in 2015, who conducted laboratory-based SEPTs to investigate the impact of spin time and rotational speed on bolt performance. These findings emphasize the significance of both spin time and rotational speed in determining bolt capacity.

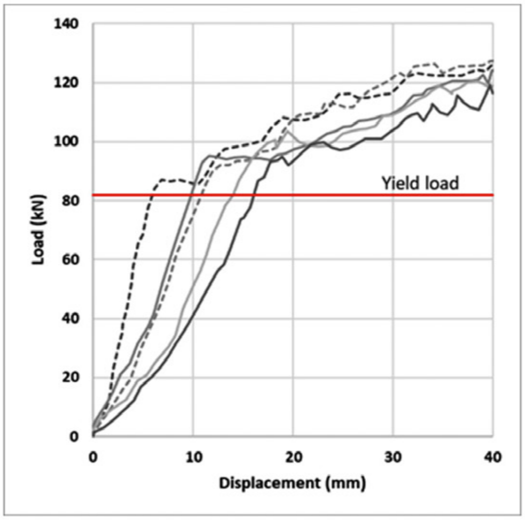
a) No. 6 bolt

Figure 5 shows post-testing images of a tested bolt that was installed at a high rotational speed, along with snapshots taken inside the drilled borehole. These images reveal that the bolt/grout interface of the No. 5 tested bolt exhibits signs of damage, while the grout appears to be firmly bonded to the borehole boundaries.

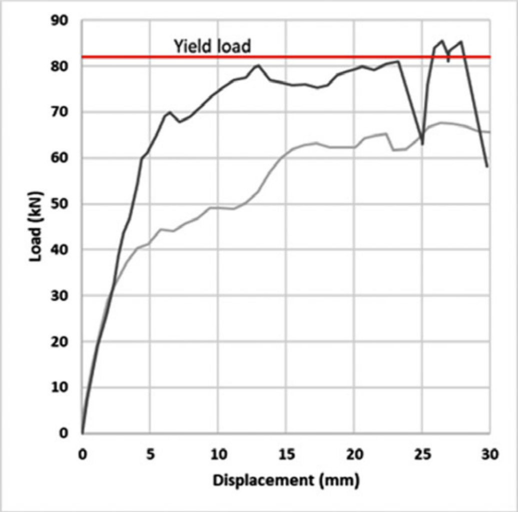
The SEPTs conducted in the NIOSH Safety Research led to the conclusion that if an optimal rotational speed were employed during bolt installation, it is likely that the anchorage capacity of rib bolts, as measured by SEPT, would be equivalent to yield load of steel rebar, irrespective of the bolt diameter.

PARTIALLY GROUTED PULL-OUT TESTS (PGPTS)

Following the same procedure adopted for conducting SEPTs, partially grouted pull out tests (PGPTs) for rib bolts were tested in two mines. The rotation speed during bolts installation was not regulated in all the PGPTs. Unfortunately, the RPMs of the roof bolter were not recorded in those tests. In Mine-B, two anchorage lengths were tested (0.61 m and 0.914 m) for No. 5 bolt with bolt length of 1.219 m. Figure 6a shows the load-displacement curves of PGPTs in Mine-B. It shows that all PGPTs experience steel rebar yielding with stiffer loaddisplacement



a) Mine-B, No. 5 Rebar



b) Mine-C, No. 5 Rebar

Figure 6. Load-displacement curves of PGPTs with solid lines denoting a 0.61 m anchorage length and dashed lines indicating a 0.914 m anchorage length

Table 2. Key features of PGPTs for bolts with a length of 1.219 m and rebar diameter of 15.875 mm

Mine	Coal Seam	Number of Tests	Anchorage Length (m)	Average 1st peak load (kN)	1st Peak Load Range (kN)	Average 1st Peak Displacement (mm)
B	Pittsburgh	3	0.610	98	95–103	17
		2	0.914	92	87–92	10
C	Pittsburgh	2	0.686	59	40–77	6

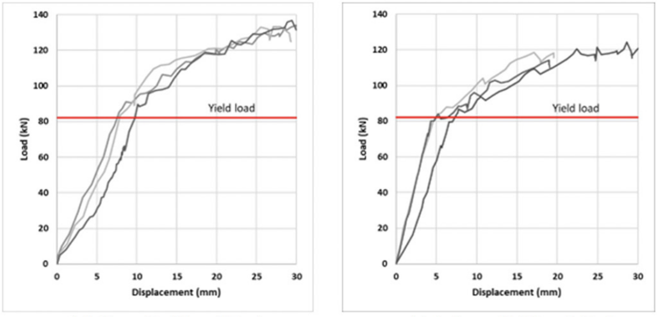
curves for longer anchorage length of 0.914 m. Figure 6b illustrates the load-displacement curves of PGPTs carried out in Mine-C. In one of the tests, the yielding capacity of steel rebar was reached, while in the other test, the peak load reached approximately 83% of the yield capacity of a steel rebar. Table 2 summarizes the key features of all conducted PGPTs extracted from Figure 6. The anchorage capacity of rib bolts, as determined by PGPTs, primarily relies on the yielding of the steel rebar, irrespective of unregulated rotation speeds that adopted during their installation.

Fully Grouted Pull-out Tests (FGPTs)

Pull-out tests were carried out on fully grouted bolts in four mines. The rotation speed during bolts installation was not regulated in all the FGPTs. These tests were conducted until the bolts failed for some tests, with strict adherence to safety protocols throughout the testing process. Figure 7 shows the head portion of one of fractured bolts showing the necking behavior induced during the pull-out test. Figure 8 illustrates the load-displacement curves of all FGPTs. Table 3 lists a summary of the key features of all conducted FGPTs as extracted from Figure 8. As anticipated, the load-bearing capacity of rib bolts within all FGPTs primarily relies on the yielding characteristics of the steel rebars, regardless of the unregulated rotation speed employed during their installation.

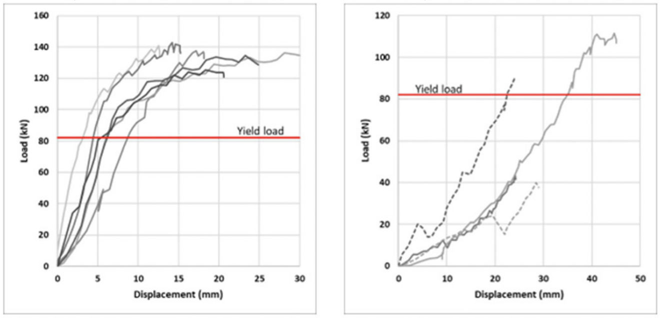
In a prior investigation focused on the performance of mechanically anchored rib bolts within underground coal mines, significant findings highlighted the substantial influence of coal mass strength on the observed bolt capacity (Mohamed, et al., 2019).

In our ongoing research, we initially hypothesized a similar influence of coal mass strength on the measured capacity of resin-grouted bolts. However, our findings did not support this hypothesis. Instead, we discovered that coal mass strength does impact the measured stiffness of grouted bolts, with stronger coal seams exhibiting a stiffer bolt behavior. This observation was quite evident in MineE when rib bolts were tested within the soft Pocahontas No. 3 coal seam.



a) Mine-B, No. 5 Rebar

b) Mine-C, No. 5 Rebar



c) Mine-D, No. 5 Rebar

d) Mine-E, No. 5 Rebar

Figure 7. Load-displacement curves for FGPTs, where solid lines correspond to a 1.219 m bolt length and dotted lines correspond to a 1.524 m bolt length

Figure 8. Head portion of fractured bolt showing necking behavior induced by FGPT

Table 3. Key features of PGPTs for bolts with rebar diameter of 15.875 mm

Mine	Coal seam	Number of tests	Bolt length (m)	Average 1st peak load (kN)	1st peak Load range (kN)	Average 1st peak displacement (mm)
B	Pittsburgh	3	1.219	94	89-96	10
C	Pittsburgh	2	1.219	85	84-87	6
D	Kellioka	6	1.219	95	81-106	7
E	Pocahontas No. 3	2	1.219	n/a	n/a	n/a
		2	1.524	110	n/a	41

SUMMARY

Coal ribs play a crucial role in maintaining the stability of underground coal mines. Rib bolting systems are widely employed for their effectiveness in enhancing rib stability and averting dangerous collapses. Inadequate rib bolt design can lead to instability, posing serious safety risks. Researchers are trying to develop an engineering-based approach for more reliable rib bolting designs. Pull-out tests, measuring the force required to extract a bolt, are invaluable for evaluating bolt anchorage and bond strength, aiding in rib bolting designs.

This study involved conducting 73 in-situ pull-out tests on rib bolts, situated across different coal mines in the eastern US. The tests spanned various coal seams and focused on grade 60 bolts with a tensile strength of 414 MPa, mainly No. 5 bolts with a 15.875 mm diameter. Three anchorage types were examined: Short Encapsulation (SEPT), fully grouted (FGPT), and partially grouted (PGPT) bolts, with varying anchorage lengths.

To assess grout anchorage capacity while preventing steel rebar yielding, SEPTs with a fixed 0.305 m anchorage length were conducted, Results from SEPTs in various mines indicated diverse load-displacement patterns. Notably, No. 5 bolts exhibited a wide range of peak loads, while No. 6 bolts were more consistent. Unexpectedly, some SEPTs experienced steel yielding. To investigate these issues, controlled SEPTs were performed at the NIOSH Safety Research Mine, testing two bolt sizes and two rotation speeds (170 rpm and 780 rpm). The controlled SEPTs illustrate how rotational speed during bolt installation profoundly influences SEPT anchorage capacity, with higher speeds resulting in reduced anchorage capacity.

Pull-out tests were conducted for fully grouted bolts (FGPT) in four mines, with rigorous adherence to safety protocols to assess their resistance to fracture. Like the PGPTs, the anchoring strength of tested bolts, as determined by FGPT, depend on the yielding of the steel rebar, irrespective of the rotation speed employed during the bolt installation.

STUDY LIMITATIONS

In this study, pull-out tests were carried out on rib bolts within several eastern coal mines. The research focused on the performance of Grade 60 steel rebars, specifically No. 5 and No. 6. The conclusions derived from the experimental results are limited to the mechanical properties of the coal seams tested, and the properties of the bolts that were used. A more comprehensive study would have to be conducted to make any conclusions on the overall contribution of rib bolts to entry stability. It's important to note that this study does also does not account for potential external factors like bolt corrosion, timedependent deterioration of the ribs, or bolt grade.

The quality of grouted bolts is not solely determined by a single parameter. Rather, it depends on a complex interaction of various factors. These factors include resin speed, applied thrust and torque, as well as the mixing time. Excessive mixing can have a detrimental effect on anchorage quality, as illustrated in Figure 5b. Further experiments are required to establish the rotation speed and the mixing time thresholds beyond the manufacturer's recommendations that can adversely affect the quality of fully grouted bolts.

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DISCLAIMER

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24-038

Experimental and Numerical Analysis on Failure of Soil Slopes Induced by Increasing Pore Water Pressure

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ABSTRACT

Slope failures very commonly occur during a long period of heavy rainfall and groundwater rise. The failures pose a substantial risk to people, infrastructure, and equipment downslope. In the recent past, the mining industry has faced an increase in tailings dam failure due to several reasons including pore pressure increases in the dams. Many failures have been observed to occur during times of water level fluctuations but the critical factors that influence the initiation of slope failures still need to be adequately clarified. To investigate these factors, laboratory experiments were conducted on model sandy slopes to determine pore pressure-induced slope failure initiation.

This study also presents a method to examine water seepage through soil slopes using an ultraviolet (UV) dye and a UV flashlight. The small-scale model test simulation demonstrated failures induced by either water percolation from the upslope tank at a constant level or by raising the water level at intervals. A bottom chamber fully filled with water to replicate groundwater rise was also simulated. The soil slope was monitored at every stage to study the deformations and behavior until failure occurred.

Results gathered from the controlled laboratory conditions were useful for the verification of the numerical modeling method created in the computer program Slide. The analysis showed that slope failure always occurred when the toe was fully saturated. High pore pressures and seepage forces reduce the shear force at the toe to almost zero causing it to slide. A comparison of slope height to water level also indicated an average of 96% water level to cause a failure. At this point, the soil slope is fully saturated and has no matric suction. The findings in this study show that, by monitoring the moisture content of slopes, failures can be predicted.

INTRODUCTION

Soil has so many uses in our day-to-day life. Designing structures in soil requires engineering judgments and calculations. Soil particles naturally create friction between grains, and when this bond is broken, there is instability. Evaluating the causes of soil slope failure is essential in civil and mining engineering, and a significant cause of this is an increase in pore-water pressure. From this, it is necessary to perform laboratory tests to understand better how such failures occur. Several techniques are available to induce slope movement and failure, such as rainfall, using a shake table, and increasing pore-water pressure. All these methods require a laboratory set-up, which is time-consuming and requires precision. These tools can prove useful if the monitored slope is visible and not significantly affected by massive external physical contact such as shaking of the monitored slope. Any physical contact with an observed