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Improved Pull out Strength of Fully Grouted Roof Bolts through Hole Geometry Modification

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ABSTRACT

Rock bolt installation characteristics near roof falls have been identified as contributing to failure. One documented and regularly occurring failure mechanism is loss of anchorage between the grout and the rock wall of the bolt hole. Key contributors to the integrity of the grout interlocking with the rock mass are the diameter of the hole relative to the diameter of the bolt, resin versus cement type grouts, rock type, and condition of the hole. Smooth bolt holes consistently exhibit less rock bolt load bearing capacity than rough walled holes.

The goal of this study was to quantify the benefits of borehole conditioning and develop a systematic approach that would allow improvement of roof bolt performance. A new rock drilling technology, the Helical Drag Bit (HDB), was used in the early stages of this project to condition the borehole. The HDB cuts a prescribed helical groove in the borehole wall. When a bolt is grouted into a hole that has been conditioned using the HDB, the grout fills the helical groove and provides a stronger, more reliable mechanical lock between the rock and the grout.

This paper presents results of a series of tests conducted in the laboratory and in the field. Short encapsulation pull out tests have demonstrated considerable increase in pull out strength and more consistent bolt performance when hole geometry is modified using the HDB. The results have also shown that greater load bearing capacity improvements are obtained in mines with weak roof rock, where it is most needed. Additionally, bolts recovered for examination suggest that hole conditioning during roof bolting reduces the effects of finger gloving. Therefore, mines with stronger roof rock could also benefit from hole conditioning.

A new roof bolt that uses the HDB principle has been designed and tested. The new system works with existing bolting equipment requiring minimal modifications to the traditional procedure used for installation of fully grouted rebar bolts. The use of these higher anchorage capacity bolts will allow mines to reduce severe injuries and fatalities resulting from ground failures while maintaining or increasing productivity.

INTRODUCTION

Rock bolts are a primary support technique used to stabilize rock against roof falls in coal and hard rock mines [1]. Installation of roof bolts involves drilling holes into the rock and establishing a firm anchorage in those holes. Approximately 80% of roof bolts use grout as a means of anchoring, with the vast majority of the remaining percentage of rock bolts using mechanical anchors [2]. The widespread use of grouted bolts is attributed to the fact that they distribute their anchoring load on the rock over a greater area and generally have superior anchorage capacity.

As major contributors to a roof control plan, rock bolts have been studied to determine optimum installation spacing and length, to match geologic conditions. The main ways rock bolts support mine roofs are: beam building (the tying together of multiple rock layers so they perform as a larger single beam), suspension of weak fractured ground to more competent layers, pressure arch, and support of discrete blocks. Cable bolting, where cables are used in place of steel rods or bolts, performs a similar function. It is important to note that while rock bolts play a critical role in mitigating rock mass failure, many other mine design factors come into play to create a stable mine environment including, but not limited to, opening dimensions, sequence of excavation, matching of bolt anchor and length with opening and geologic conditions, and installation timing. Notwithstanding the importance of these other factors, if the bolts used in rock stabilization do not perform well, miners are at risk.

Bolt installation characteristics near roof falls have been identified as contributing to failure [3]. One documented and regularly occurring rock bolt failure mechanism is loss of grout shear bond to the rock wall of the borehole [4]. Key contributors to the integrity of the grout interlocking with the rock mass are the diameter of the hole relative to the diameter of the bolt, type of grout (resin or cement), rock type, and condition of the hole.

A fully grouted bolt anchors itself by frictional interlock between the resin and the rock. Smooth boreholes consistently exhibit a reduced bolt load bearing capacity over rough walled holes because the interlocking effect is reduced. To address this, drill bit manufacturers intentionally use wide tolerances in manufacturing and offset bit cutter inserts in such a way as to induce a wobble during drilling which, when combined with loose bit mounting to drill rod, results in ridges being left on hole walls.

This approach generally produces a sufficient wall roughness to increase anchoring capacity. However, even with these variations in borehole smoothness and anchorage capacity improvement, failure of the rock-grout interface is still common.

While considerable research into rock bolting has been conducted to date, gaps still exist in areas that could lead to vast improvements in rock bolt performance. For example, a significant number of pull-test studies have been performed to identify optimal hole diameter to bolt diameter ratios for maximum anchorage capacity. Hole condition has also been identified as an important contributor [4, 5, 6, 7, 8]. A bibliographic search on the topic led to the conclusion that no study has been conducted on the specific influence of borehole conditioning by design to improve anchorage capacity.

Research dating back 30 years indicates that roof bolt anchorage failure is most likely when roof rock is weak, i.e. where roof support is most critical [9,10]. In view of the potential for improvement in rock bolt load bearing capacity by cutting grooves, or rifling, in the borehole, a testing program was developed to quantify the benefits of borehole conditioning and to determine the optimal hole characteristics to maximize such improvement.

Previous attempts to condition the borehole have proved impractical because of the difficulty of obtaining a consistent geometry. Helical drilling was selected as the method to produce the conditioned boreholes for validation of the concept. A preliminary analysis was conducted to define the desired borehole geometry and several sets of Helical Drag Bits were manufactured and evaluated with the goal of identifying the optimal configuration of the tool.

HELICAL DRILLING

Helical Drilling is a patented drilling technology that employs a drill bit with cutting members arranged in a helical pattern on the periphery of a central hub to form a helical groove or thread within a borehole. Applications of Helical Drilling include long horizontal slim-hole drilling, low energy-low reaction force drilling, and lithology characterization. A standard drag bit is used to create a pilot hole. The Helical Drag Bit (HDB) follows the drag bit and the helically arranged cutting members cut a "thread" within the pilot borehole. Several cutting members are typically incorporated into a HDB. Their function is to gradually increase the depth of the thread within the borehole until reaching the desired diameter. This gradual increment of depth helps reduce the size of the cuttings and maintain accurate borehole geometry.

Several operating variables determine the resulting geometrical characteristics of the final borehole. These variables need to be optimized for each particular application. The key operating variables illustrated in Figure 1 are:

Pilot hole diameter (D)
Helical Pitch (P)
"Thread" or groove depth (d)
"Thread" or groove width (w)

A HDB was designed that would cut a helical groove or "thread" to "condition" a standard 1 inch borehole. The helical pitch, and groove width were designed for weak rock with a compressive strength of about 500 psi and standard grout shear strength of about 2500 psi. The design values were such that the ratio of rock to grout area in shear is slightly larger than the grout to rock strength ratio of 5 to 1 therefore guaranteeing failure of the grout and not of the rock. The groove depth was limited by the amount of grout available in the cartridge. If the groove is too deep, the length of the grout cartridge required to fill the hole can be longer than the length of the hole. Figure 2 shows a picture of a conditioned hole in limestone resulting from use of the HDB.

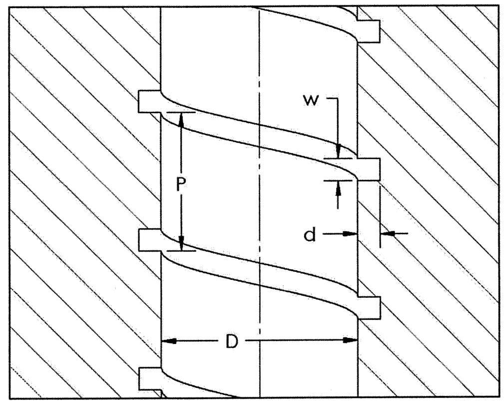

Figure 1. Section view of resulting borehole geometry after using the HDB.

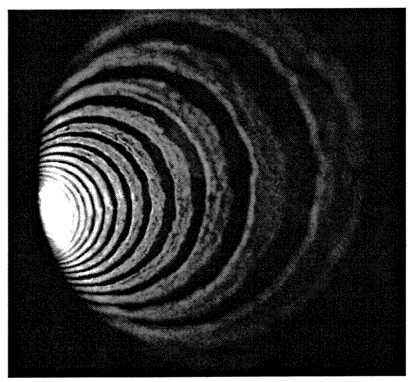

Figure 2. Conditioned hole obtained with the HDB

FIELD TESTS

Field-testing was conducted using the short-encapsulation pull test (SEPT) to make an evaluation of the effect of HDB hole conditioning on roof bolt anchorage. In a SEPT test, a roof bolt is grouted only in the top 12 inches, and then pulled using a hydraulic ram while recording load and bolt head displacement. The maximum load required to break the anchorage is also recorded. The effectiveness of the bolt-rock-grout anchorage is measured by the "Grip Factor" which is defined as the bolt's resistance to pull out per inch of bolt length. The Grip Factor is calculated as:

Grip Factor = Maximum SEPT load (tons) / 12 inches

A low Grip Factor (less than approximately 1 ton/inch) means that the bolt has low resistance to rock movement and is typical in mines with weak roof [6,10].

Two mines with low Grip Factor were selected for testing the rifling concept using the HDB. Test Site One was in the NIOSH Bruceton Mine in Pennsylvania, with an average Grip Factor of

0.69 ton/in. Test Site Two was in the BHP Billiton San Juan Mine in Waterflow, New Mexico, with an average Grip Factor of 0.5 ton/in. Both Grip Factor measurements were documented for grouted headed rebar bolts using standard drilling techniques from previous studies conducted by others [6, 10].

Test Site One: 16 bolts were installed, 8 using a traditional or "standard" drilled hole and 8 using the HDB to condition the hole. Bolts used were 79 inch-long, #6, Grade 60, with a minimum nominal yield load of about 26,500 lb. They were installed in alternating standard and HDB conditioned holes, all in close proximity to each other to minimize the effect of any geologic variation at anchoring horizon.

Pull tests consistently showed that bolts installed in conditioned holes produced better anchorage than those installed in standard holes. There was an average increase in maximum load capacity of 66%, with a maximum difference of 107% between the bolt in the standard hole with the lowest load capacity and the bolt in the conditioned hole with the highest capacity. The average grip factor (GF) was 0.66 (ton/in) for standard holes vs. 1.1 (ton/in) for conditioned holes. Even though the GF standard deviation was nearly the same for standard and conditioned holes, in relative terms standard holes had a 9% variation in load capacity while only 5% variation was calculated for conditioned holes. This suggests that bolts installed in conditioned holes might have more consistent maximum load capacities than bolts installed in standard holes. Half of the bolts installed in conditioned holes reached loads that exceeded the nominal yield capacity of the bolt, while all of the bolts installed in standard holes exhibited a maximum load that was below 67% of the nominal yield load of the bolt.

An examination of the load vs. displacement graph for the pull tests, Figure 3, reveals that besides the better anchorage obtained by conditioning the borehole, the bolts installed in the rifled holes showed a steeper initial loading in the linear region of the curve. The implication is that by rifling the borehole a stiffer system is achieved and the bolt can reach higher loads with lower deflections, a desired characteristic in a passive roof control element.

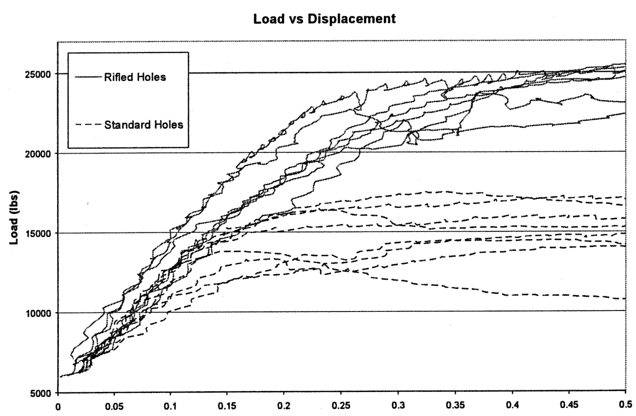

Figure 3. Comparison of pull tests between bolts installed in standard holes and bolts installed in rifled holes.

Two bolts were completely extracted for study, one from a standard hole and one from a neighboring conditioned hole (Figure 4). The bolt from the conditioned hole exhibited some apparent gloving where the plastic grout wrapper was forced into the rifled grooves, yet its load capacity was 82% higher than that of the neighboring standard hole, which had no signs of gloving. One possible explanation is that, since friction between surfaces is not the main bolt loading mechanism in conditioned holes, gloving does not present a problem affecting the load capacity of the bolt, provided there is adequate mixing of the grout.

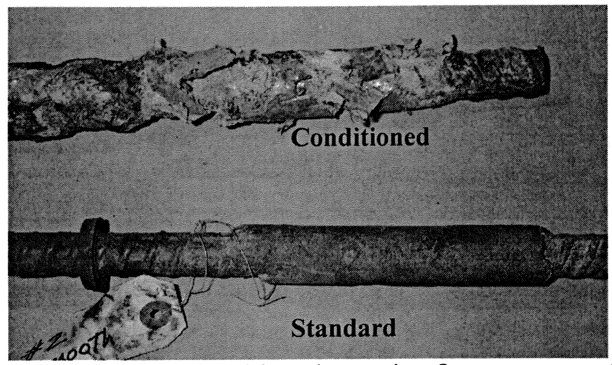

Figure 4. Bolts recovered from the test site. One was recovered from a "conditioned" hole (top) and the other was recovered from a standard hole (bottom).

Test Site Two: Results at site two also showed a dramatic increase in load capacity when boreholes were conditioned using the HDB. 26 bolts were installed; half of them using standard and the other half using conditioned boreholes. In contrast to Test Site One, four different bolt lengths were used in order to determine the effect of conditioning the holes in various anchoring horizons. Bolts used were #6, Grade 60, with lengths of 4, 5, 6 and 7 feet. Bolts were installed in alternating standard and conditioned holes, in groups of equal length to ensure similar anchorage horizon geology. Cores were obtained near each group of bolts in order to characterize roof composition. The 4-foot bolts had an anchorage horizon in a region consisting of carbonaceous mudstone and shale with abundant coal stringers. The 5-foot bolts found anchorage in a region with weak grey mudstone rich in clay. The 6-foot bolts had anchorage horizon within a combination of rock types. From the bottom to the top, there were 5 inches of coal, 2 inches of carbonaceous mudstone, and 5 inches of fine-grained sandstone. The 7-foot bolts had an anchorage horizon in fine-grained sandstone.

Similarly to Test Site One, bolts installed in conditioned holes consistently exhibited higher load capacities than those in standard holes as shown in the pull test results presented in Figure 5.

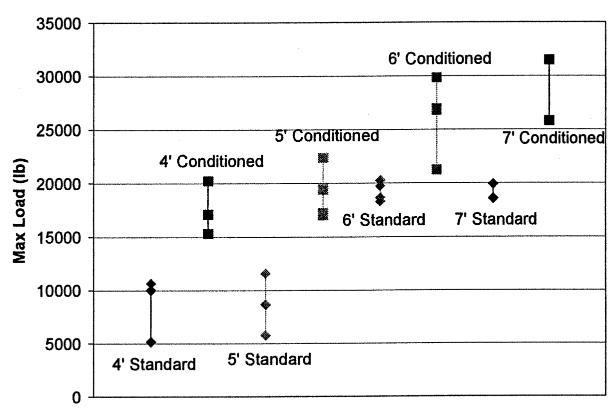

Figure 5. Comparison of maximum anchorage load between bolts installed in standard holes and bolts installed in HDB conditioned holes for the various anchorage horizons tested.

Calculation of the average Grip Factor for each group of bolts installed shows consistent improvement in holes conditioned using the HDB. Results are shown in Table 1. Bolts installed in weaker rock, as evidenced by the low Grip Factors of the 4- and 5-foot anchoring horizons, saw the greatest percentage increase in load capacity. Bolts in the relatively more competent rock (6- and 7-foot anchoring horizons) saw a lower percentage increase in load capacity. The improvement however, was sufficient to bring the average Grip Factor above the threshold value of 1 ton/inch, which is the value under which a mine roof is classified as weak. Four of the bolts installed in conditioned holes exceeded their nominal yield capacity. One of them was further loaded during the test until it reached its ultimate strength, breaking at the base of the head, something never seen before at this mine during a 12 inch encapsulation test. These high anchorage loads were obtained with the 6- and 7-foot bolts that were anchored in a relatively more competent rock than the 4- and 5-foot bolts.

Table 1. Average Grip Factor for bolts installed in standard and conditioned holes for each of the anchoring horizons tested.

	4 feet	5 feet	6 feet	7 feet
Standard	0.37	0.36	0.81	0.8
Conditioned	0.75	0.81	1.11	1.19
% change	103	125	37	49

Two bolts were completely extracted for study, one from a standard hole and one from a neighboring conditioned hole. The bolt from the standard hole presented a smooth surface similar to the one obtained from Test Site One. The bolt recovered from the conditioned hole showed clearly where the grout threads had been sheared during the pull test. An over-core of one of the bolts was obtained and the cured grout exposed to reveal the geometry of the hole (Figure 6).

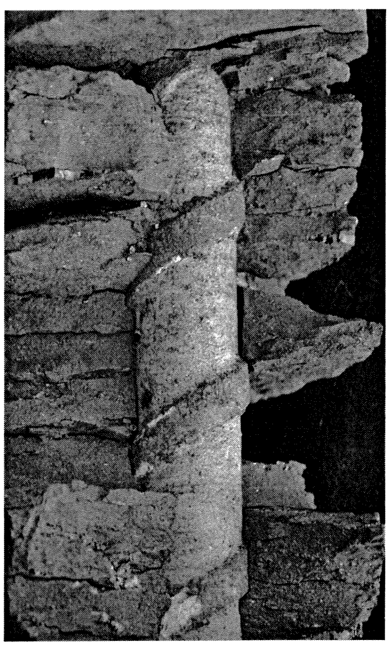

Figure 6. Over-core of the bolt reveals borehole geometry obtained by using Helical Drilling.

HELICAL ROOF BOLT

The test results presented above demonstrated that dramatic bolt load capacity gains can be achieved by conditioning the borehole. Realizing that the addition of an extra process step during bolt installation is impractical, a new roof bolt was designed. The Helical Roof Bolt (HRB) cuts a helical groove in the borehole as part of the installation process. A prototype HRB that incorporates helical cutting technology into a standard rebar bolt was manufactured and tested in the field. HRB bolts are installed following a procedure similar to the standard roof bolt installation with the difference that the bolt insertion is done in such a way that rotation and feed are coordinated so that the desired helical pitch is obtained. This feed-rotation coordination can be automated by making a simple modification to the bolter hydraulic system. Field testing continued this time using the HRB.

Test Site Three: Five standard bolts and 14 HRB bolts were tested using the SEPT test at the NIOSH Bruceton Mine in Pennsylvania. Bolts used were 79 inch-long, #6, Grade 60, with a minimum nominal yield load of about 26,500 lb. They were installed in an alternating sequence, with approximately one standard bolt for every three HRB bolts, all in close proximity to each other to minimize the effect of any lithology variation at the anchoring horizon.

Maximum loads obtained during pull tests are presented in Figure 7. HRB bolts exhibited higher load capacities than standard bolts consistent with the results obtained during both borehole conditioning tests. An average Grip Factor of 0.92 ton/inch was calculated for the standard bolts at this particular test location. A 17% Grip Factor increase was obtained with the use of the HRB bolts. This Grip Factor percent increase is consistent with previous observations indicating that greater gains in anchorage capacity are obtained in weaker roof rock.

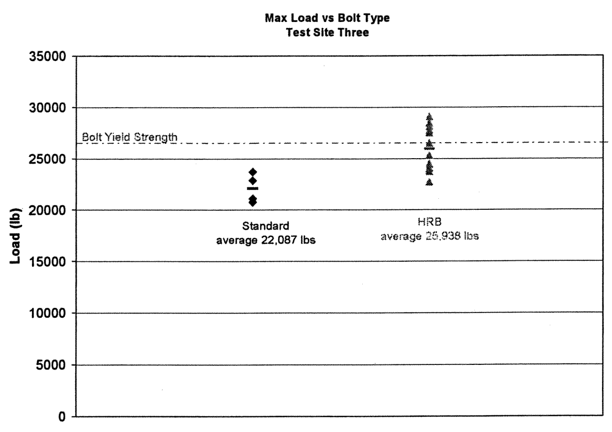

Figure 7. Comparison of maximum anchorage load between Standard bolts and HRB bolts.

There appears to be a linear relationship between the roof rock strength and the percent increase in load capacity after rifling the borehole or using the HRB bolts, as indicated in Figure 8. The percent increase of GF is greater in weak rock where the measured GF for standard bolts is low. The GF improvement diminishes linearly as the rock strength increases.

Test Site Four: Testing was conducted in an eastern Kentucky coal mine with competent shale roof. Two HRB and two standard bolts were installed and tested. Pull test results revealed that the GF obtained with the HRB and the Standard bolts was equal to 1.0 for both types of bolts. Although based on limited data, this result is consistent with results from previous tests as shown in Figure 8 indicating that no anchorage benefit is gained from the HRB when GF reaches a value of 1.0 for standard bolts.

The data suggest that as the strength of the roof rock (as represented by its GF) increases, the mechanical interaction between the grout and the subtle variations in hole diameter created during drilling of the pilot hole becomes more effective in anchoring the roof bolt. Beyond the point where the GF equals 1.0, the interaction of the grout with an un-rifled hole apparently becomes equivalent to that obtained from rifling. There is no reason to believe that the anchorage capacity could be reduced when HRB bolts are properly installed in mines with GF greater than 1.0.

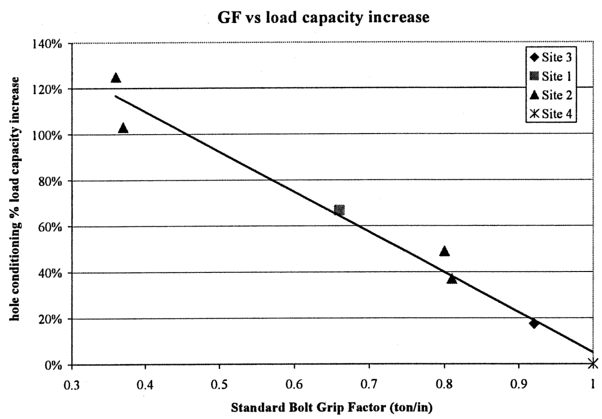

Figure 8. GF percent increase obtained by conditioning the borehole as a function of the GF measured for standard roof bolts.

HRB INSTALLATION AND BENEFITS

HRB bolts are installed following a procedure similar to the one used for standard headed rebar roof bolts. Resin cartridge size, borehole diameter and depth are the same as those required for the equivalent size standard bolt. Once the pilot borehole is drilled, the grout cartridge is inserted followed by the bolt. The bolt is then installed using a coordinated feed rate and rotation prescribed specifically for the mine where the installation takes place. No additional grout is needed for HRB installation because the rock particles produced by cutting the helical groove become part of the resin mix. Grout manufacturers have indicated that mixing of rock cuttings with the resin does not present a problem. When the bolt head reaches the roof, it is spun and held according to the same parameters specified for standard bolts. A hydraulic modification to the bolter, consisting of a bypass circuit with a proportional valve that feeds oil to the feed cylinder and drill head motor, can provide the coordination of feed and rotation needed for HRB installation. When the bypass circuit is turned off, the bolter operates in the standard manner.

Besides improved anchorage, the HRB has many other benefits. As the HDB is installed, the helical cutters cut the grout cartridge wrapper and enhance mixing of the resin, thereby preventing finger gloving. Another common roof bolt installation problem which is eliminated by using HRB bolts occurs when the pilot hole annulus is large enough to allow the cartridge to remain intact even after the bolt is inserted and spun. This is the case when #5 bolts are used in a 1" hole or #6 bolts are used in a 1-3/8" hole. Because the helical cutters of the HRB extend beyond the nominal hole diameter, it is not possible for the grout cartridge to remain intact during bolt installation. Additionally, because of the configuration and location of the cutters, the body of the bolt remains centered within the borehole reducing the potential for corrosion that arises when the body of the bolt ends up touching the wall of the borehole after the resin has cured.

CONCLUSIONS

Investigations have demonstrated that bolt anchorage capacities can be substantially increased, by more than 120% in some cases, when the borehole is rifled using helical drilling technology during roof bolting. Mines with weak roof, where demonstrated load capacity improvements are greater, can benefit the most from use of the hole rifling concept. Even mines with more competent roof could improve bolt performance by reducing the negative effect of gloving.

A new roof bolt, the HRB, that uses the helical drilling principle has been designed and tested. Pull testing of the HRB showed increased pull out capacity when compared with standard roof bolts. Additional benefits include reduced potential for bolt corrosion, by centering the bolt in the borehole, and gloving, by effectively destroying the grout wrapper and promoting mixing. The new bolt works with existing bolting equipment making minimal modifications to the traditional procedure used for installation of fully grouted rebar bolts. The use of these higher anchorage capacity bolts will allow mines to reduce severe injuries and fatalities resulting from ground failures while maintaining or increasing productivity.

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