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ORIGINAL PAPER

Long-Term Stability of a 13.7 × 30.5-m (45 × 100-ft) Undercut Span Beneath Cemented Rockfill at the Turquoise Ridge Mine, Nevada

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Abstract
In 2001, researchers from the National Institute for Occupational Safety and Health (NIOSH) installed instruments at the Turquoise Ridge Mine in cooperation with Placer Dome, Inc. to monitor the geomechanical behavior and stability of a cemented rockfill (CRF) sill and the surrounding host rock during test mining of a large undercut span beneath backfill. Six parallel, adjacent drifts were mined and backfilled to construct a CRF sill, approximately 22.9 m (75 ft) wide by 30.5 m (100 ft) long. The sill was then partially undercut, successfully creating a 13.7-m (45-ft) wide by 30.5-m (100-ft) long span beneath the CRF. Only small vertical displacements were measured in the overlying host rock during mining, with most of the movement occurring at shallow depths in the mine roof. Because the back above the CRF sill remained stable, the majority of the mining-induced stress was transferred to the host rock abutments rather than to the backfilled drifts. During retreat mining of the undercut span, the CRF sill and the mine roof remained stable. Most of the measured vertical displacement was caused by separation of the backfill from the overlying host rock, or deflection of the CRF sill, which was comparable to the deflection of a monolithic, elastic plate having similar dimensions, material properties, and undercut spans. The CRF sill moved in mass as a single unit rather than as individual drift segments, and the vertical cold joints between adjacent backfill drifts did not adversely affect their stability. Additional measurements collected from the instruments have shown that the backfill span is still intact and in stable condition more than 16 years after the completion of undercut mining. Displacements in the mine roof and abutments have stabilized, and vertical stress and deformation within the CRF have generally leveled off or decreased. Although only slight mining-induced loads were transferred to the backfilled drifts, the CRF has confined the abutment ribs and mine roof, thereby improving their long-term stability. Results of compressive and tensile strength tests conducted with CRF samples from the test site indicate that the long-term compressive strength gain for CRF is similar to that of concrete, and that the tensile-to-compressive strength ratio for CRF is about 1/6 rather than 1/10. Assuming the in-place CRF gained strength at the same rate as the lab samples, an analytical analysis of the flexural stability of the CRF undercut span shows that the Factor of Safety for the span should have logically increased over time. By providing a better understanding of the long-term strength properties and geomechanical behavior of CRF, these research findings help improve the methods that are used for designing stable, long-term undercut entries beneath cemented backfill.

Keywords Underground metal mine · Backfill · Cemented rockfill (CRF) · Undercut span design · Geotechnical instruments · Long-term strength

1 Introduction

Cemented rockfill (CRF) is commonly used in conjunction with underhand cut-and-fill mining methods to provide ground support in weak rock mass conditions, particularly in the underground gold mines in Nevada (Seymour et al. 2013). The CRF supports the overlying material in the mine roof and also confines the surfaces of rock pillars and abutments, thereby enhancing their ground support capabilities.

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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If the CRF is designed, batched, and placed properly, it typically provides a safe, stable back for the next undercut. However, as wider undercut spans are implemented, a better understanding is needed of the engineered properties of this material and also the design methods that are used to evaluate its performance (Pakalnis et al. 2005; Tesarik et al. 2007; Barnard and Sandbak 2017). Recent placement of long-term infrastructure in undercut entries beneath CRF has created a need to understand not only the long-term strength of the CRF but also the long-term stability of CRF undercut spans. A previous backfill span study conducted at the Turquoise Ridge Mine has provided a unique opportunity for investigating both of these issues.

In 2001, the Turquoise Ridge Mine (then operated by Placer Dome, Inc.) conducted an instrumented backfill span study in cooperation with the National Institute for Occupational Safety and Health (NIOSH) Spokane Research Laboratory (SRL) to determine if a new mining method could improve productivity and reduce the exposure of mine personnel to groundfall hazards. An initial test was conducted to determine if a large undercut opening could be mined safely beneath several parallel, adjacent drifts that had been backfilled with CRF. Six drifts were mined and backfilled on an upper level off the TR 4145 heading, creating a CRF sill that was then partially undercut by mining three adjacent drifts on a lower level off the TR 4135 heading to successfully create a stable 13.7-m (45-ft) wide by 30.5-m (100-ft) long span beneath the backfill. NIOSH researchers were recently allowed to re-enter the area and collect manual readings from the instruments that were installed to monitor ground stability during the original test mining. Most of these instruments are still functioning, even though they were installed more than 16 years ago.

This paper provides background information regarding the original backfill span study, explains the initial response of the instruments during mining, and analyzes the long-term response of the instruments based on current instrument readings. Conclusions concerning the geomechanical behavior and stability of the host rock and backfill are supported by the results of long-term strength tests conducted with CRF samples from the test site as well as an analytical analysis of the flexural stability of the CRF undercut span.

2 Background

The Turquoise Ridge Mine is a joint venture between Barrick Gold Corporation and Newmont Mining Corporation, with Barrick as the operating partner. The mine is located in northern Nevada about 69 km (43 miles) northeast of Winnemucca. Gold mineralization is mined from a Carlin-style deposit hosted by Cambro–Ordovician mudstone and lesser carbonate with interbedded basalt. The area has

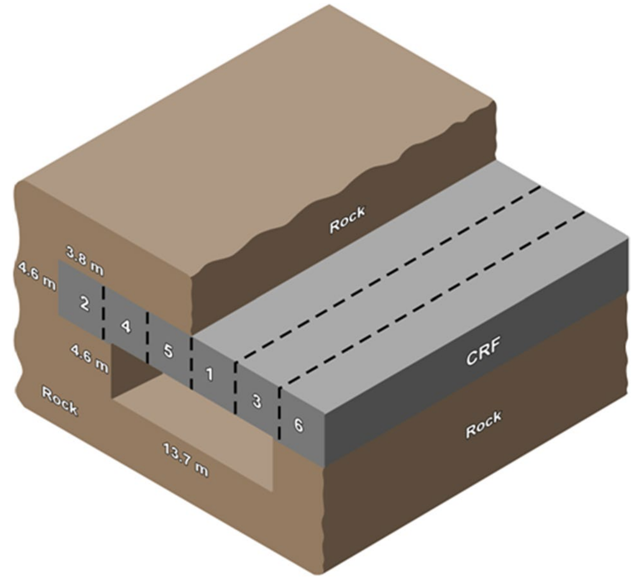

Fig. 1 Topcut mining sequence and final undercut span

undergone very complex structural disruption, both before and after gold mineralization was deposited. Cryptic metamorphism in the area is likely related to the intrusion of the Cretaceous Osgood granodiorite stock. Alteration associated with gold is characterized by the remobilization of carbon, decarbonatization of limestone beds, and argillization of basalt and dacite units (Seymour et al. 2018).

Production zones within the ore bodies are typically composed of highly altered and intensely fractured rock with Rock Mass Ratings (RMR) (Bieniawski 1989) less than 45 (Sandbak et al. 2012). Access drifts and infrastructure often intersect faults and altered material of varying thickness and geotechnical quality ranging from blocky competent rock to saturated soil-like material (Warren et al. 2016). Because of these weak rock mass conditions, CRF has historically been used in conjunction with underhand cut-and-fill mining methods (Sandbak et al. 2012; Barnard and Sandbak 2017).

3 TR 4145 Backfill Span Study

As illustrated in Fig. 1, a 22.9-m (75-ft) wide CRF sill was constructed by mining and backfilling six 3.8-m (12.5-ft) wide, 4.6-m (15-ft) high, and 30.5-m (100-ft) long topcut drifts on an upper level. Beneath this CRF sill, two 4.3-m (14-ft) wide by 4.6-m (15-ft) high undercut drifts were mined on either side of a 5.2-m (17-ft) wide pillar, which was in turn retreat-blasted in two separate stages to create a 13.7-m (45-ft) wide undercut span (Fig. 2). The mining and backfilling sequence for the six topcut drifts is shown in Fig. 1 along with the final undercut span on the lower level. Mining of the topcut drifts

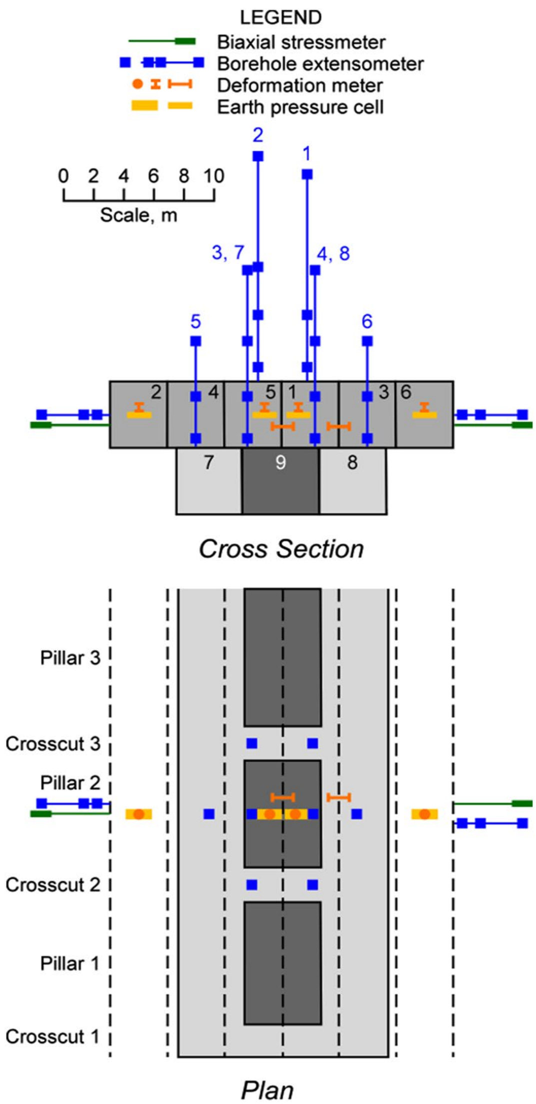

Fig. 2 Cross-section and plan views of the instrument locations

began in the fall of 2000, and the 13.7-m (45-ft) wide undercut span was completed in July 2001.

Primary ground support for the upper-level drifts consisted of 2.4-m (8-ft), #7 resin-grouted rebar installed in the mine roof on a 1.2-m × 1.2-m (4-ft × 4-ft) staggered row pattern. Additional surface support was provided by wire mesh spot bolted to the mine roof and down the ribs of the drifts to within 1.8 m (6 ft) of the mine floor with 1.8-m (6-ft) friction bolts. The ribs of the upper and lower level drifts were supported by 1.8-m (6-ft) friction bolts installed on a 0.9-m × 1.2-m (3-ft × 4-ft) staggered row pattern complementing the rebar pattern in the mine roof.

Table 1 Summary of host rock instruments accessible from TR 4145

Instrument	Type	Location
BSM1	Biaxial stressmeter	West abutment-topcut 2
BSM2	Biaxial stressmeter	East abutment-topcut 6
HBX1	Two-point MPBX	West abutment-topcut 2
HBX2	Two-point MPBX	East abutment-topcut 6
VBX1	Two-point MPBX	Back of topcut 1
VBX2	Three-point MPBX	Back of topcut 5

3.1 Upper Level Instruments

To monitor the geomechanical behavior of the host rock and backfill during mining, NIOSH installed several different types of instruments, including biaxial stressmeters (BSMs), multipoint borehole extensometers (MPBXs), earth pressure cells (EPCs), and deformation meters (DMs). Geokon vibrating wire instruments were selected because of their reliability and long-term monitoring capabilities. Groups of complementary instruments were installed in close proximity in the host rock and backfill to verify readings from the individual instruments, to ensure that essential data would be collected if some of the instruments malfunctioned, and to provide additional information for interpreting the behavior of the host rock and backfill.

Most of these instruments were installed via access from the TR 4145 heading during mining and backfilling of the topcut drifts that formed the CRF sill. Sixteen vibrating wire instruments were installed on the upper level along a vertical cross section near the mid length of the topcut drifts. BSMs were installed in the east and west abutments to measure stress change in the host rock as mining-induced loads were transferred to the abutments. To verify trends in these stress change measurements, MPBXs were installed near each BSM to monitor horizontal displacement or dilation (HBXs) as the abutments were loaded. Two additional MPBXs were installed overhead in the mine roof near the mid span of the topcut drifts to monitor vertical movement in the back (VBXs) as the overall mining span on the upper level was increased. A summary of the upper level instruments that were installed in the host rock is provided in Table 1.

As the topcut drifts were backfilled, EPCs and DMs were installed near the mid length of selected drifts to measure vertical loading and deformation, respectively, in the CRF. Longer DMs were installed to monitor potential movement or slip along vertical cold joints between adjacent backfilled drifts. A summary of the upper level instruments installed in the backfill is provided in Table 2.

Table 2 Summary of backfill instruments accessible from TR 4145

Instrument	Type	Location
EPC1	Earth pressure cell	Backfill-topcut 1
EPC2	Earth pressure cell	Backfill-topcut 2
EPC3	Earth pressure cell	Backfill-topcut 5
EPC4	Earth pressure cell	Backfill-topcut 6
DM1	Deformation meter	Backfill-topcut 1
DM2	Deformation meter	Backfill-topcut 2
DM3	Deformation meter	Backfill-topcut 5
DM4	Deformation meter	Backfill-topcut 6
DM5	Deformation meter	Across backfill cold joint between topcuts 5 and 1
DM6	Deformation meter	Across backfill cold joint between topcuts 1 and 3

Table 3 Summary of instruments accessible from TR 4135

Instrument	Type	Location
VBX3	Three-point MPBX	Through topcut 5 into back
VBX4	Three-point MPBX	Through topcut 1 into back
VBX5	Two-point MPBX	Through topcut 4 into back
VBX6	Two-point MPBX	Through topcut 3 into back
VBX7	Three-point MPBX	Through topcut 5 into back
VBX8	Three-point MPBX	Through topcut 1 into back

3.2 Lower Level Instruments

To monitor the stability of the CRF sill during retreat mining of the central undercut pillar, six additional MPBXs were installed overhead through the backfill and into the mine roof from undercut entries on the lower level. These vertical borehole extensometers (VBXs) were positioned along the longitudinal and lateral axes of the undercut span to provide the mine staff with a sequential assessment of the backfill's stability as each section of the central undercut pillar was mined. The spatial distribution of these instruments also supplied further information regarding the symmetry and consistency of displacement measurements in the backfill and overlying host rock. A summary of the instruments installed from the lower level is provided in Table 3. Cross section and plan views of the undercut test site are shown in Fig. 2, illustrating the approximate locations of the instruments.

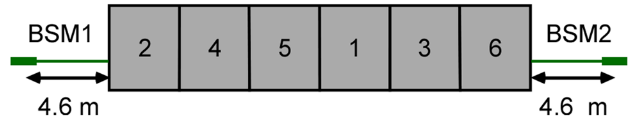

Fig. 3 Biaxial stressmeters (BSM1 and BSM2) installed in the west and east abutments, respectively

3.3 Data Collection

During the backfill span study, 22 vibrating wire instruments were installed in the backfill and host rock. Most of these instruments were also equipped with temperature sensors. Overall, 76 sensors were monitored—55 vibrating wire transducers and 21 thermistors. Data acquisition systems were set up underground on each level near the test site to collect readings from the instruments. The dataloggers were programmed to monitor the instruments every 2 h. During retreat mining of the central undercut pillar, the scan rate was increased to 10-min intervals so that the stability of the host rock and backfill could be analyzed in closer detail. The instruments were monitored by the data acquisition systems over a 13-month period from December 2000 to January 2002. Additional manual readings were collected from the instruments on January 30, 2002; September 15, 2005; July 10, 2007; and August 3, 2017. The last set of manual readings collected from the lower level instruments was on September 15, 2005. Since then, access through the TR 4135 heading has been blocked.

4 Response During Mining

A brief summary of the response of the instruments during mining and shortly thereafter is provided below. This analysis includes measurements from the upper and lower level instruments through their final DAS scans on January 9, 2002 and January 11, 2002, respectively.

4.1 Biaxial Stressmeters (Abutment Loading)

Geokon Model 4350-3 vibrating wire biaxial stressmeters (BSM1 and BSM2) were installed in the west and east abutments on the upper level to measure mining-induced stress changes in the host rock near the mid length of topcut drifts 2 and 6, respectively (Figs. 2, 3). Grouted in horizontal drill holes at a depth of 4.6 m (15 ft) into the abutments, these instruments were primarily intended to measure an increase in vertical stress as overburden loads were redistributed to the abutments during mining of the topcut drifts. A comprehensive description of the biaxial stressmeter and case study information regarding its use in mining applications is provided by Seymour et al. (1999).

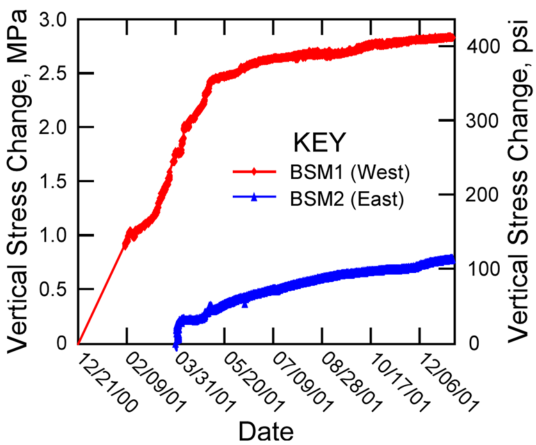

Fig. 4 Vertical stress change measured in the abutments by BSM1 and BSM2, during and shortly after mining

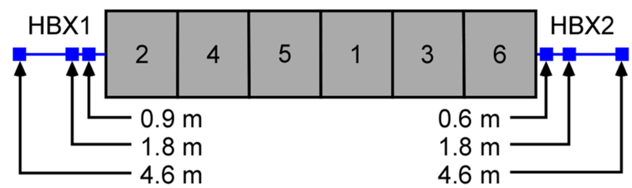

Fig. 5 Horizontal extensometers (HBX1 and HBX2) installed in the west and east abutments, respectively

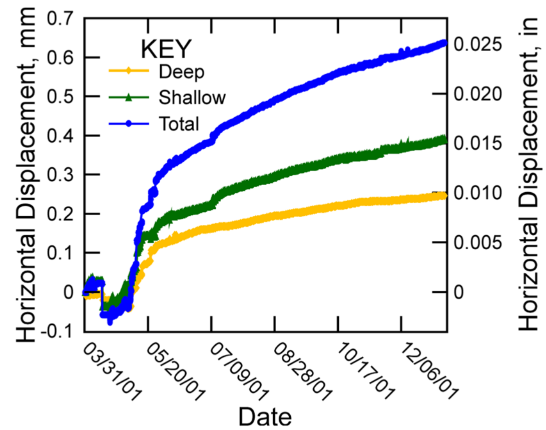

Fig. 6 Horizontal displacements measured in the east abutment by HBX2, during and shortly after mining

Stress change measurements from the BSMs indicated that most of the abutment loading occurred during mining of the upper-level drifts, particularly the excavation of topcuts 5 and 6, which significantly increased the total mining span. Because the two stressmeters were installed at distinctly different times in the mining sequence, the stress changes measured by these instruments were markedly different as shown in Fig. 4. BSM1 was installed in the west abutment from topcut 2 almost 100 days before BSM2 was installed in the east abutment from topcut 6. As a result, a much larger change in vertical stress was measured in the west abutment, 2.84 MPa (411 psi), than in the east abutment, 0.78 MPa (113 psi). Because topcut 6 was the last entry on the upper level to be mined, the stress change measured by BSM2 was primarily caused by undercut mining on the lower level. No appreciable increase in stress was measured by either of the biaxial stressmeters during retreat mining of the central undercut pillar. This indicates that the 5.2-m (17-ft) wide pillar was essentially de-stressed and that very little overburden load had been transferred from the mine roof through the CRF sill to this pillar.

4.2 Horizontal Extensometers (Abutment Dilation)

Two-point borehole extensometers (HBXs) were installed near each of the biaxial stressmeters to measure relative horizontal displacements in the abutment ribs (Fig. 5). These rib dilation measurements were intended to provide supporting information to help verify trends in stress change measurements from the biaxial stressmeters, to assess the rib support provided by 1.8-m (6-ft) split-set friction bolts, and to quantify the rib confinement provided by the CRF.

To prevent damage from mining equipment and blasting fly rock, the Geokon Model 1300 (A-9) extensometers were equipped with hydraulic anchors, fiberglass rods, and vibrating wire displacement transducers that were connected in series in the borehole. The collar anchors for these instruments were installed in competent rock at depths of 0.6–0.9 m (2–3 ft) in the drill hole, thus avoiding the blasting-induced fracture zone near the skin of the mine opening.

The HBXs measured only slight horizontal displacements in the abutments during mining. As shown in Fig. 6, HBX2 measured about 0.64 mm (0.025 in.) of total displacement in the east abutment over the 4.6-m (15-ft) length of the instrument. As illustrated by the normalized strain curves in Fig. 7, most of this movement occurred between the collar anchor and the shallow anchor, which was installed at a depth of 1.8 m (6 ft).

HBX1 measured even less horizontal displacement in the west abutment. These measurements were difficult to interpret and may have been overshadowed by the effect of temperature changes as the adjacent drifts were backfilled and as the CRF cured. Nevertheless, the small displacements measured by HBX1 and HBX2 indicate that the abutment ribs remained stable and provide evidence that the CRF restricted their dilation, thereby improving their long-term stability.

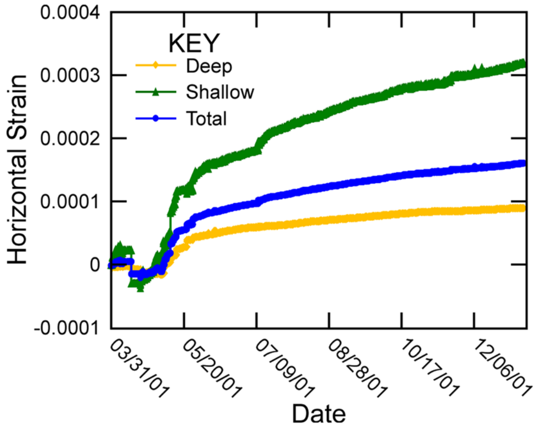

Fig. 7 Horizontal strain in the east abutment computed from displacement measurements by HBX2, during and shortly after mining

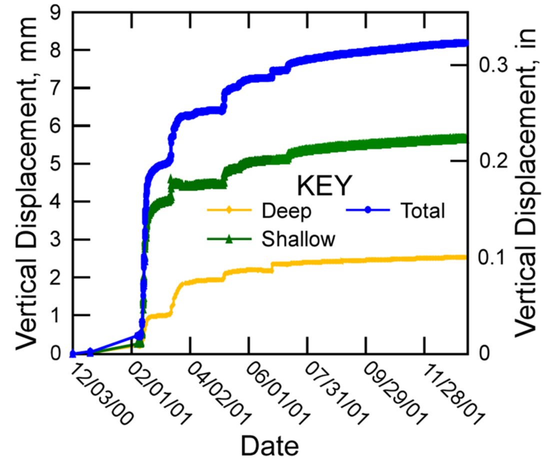

Fig. 9 Vertical displacements measured in the back above topcut 1 by VBX1, during and shortly after mining

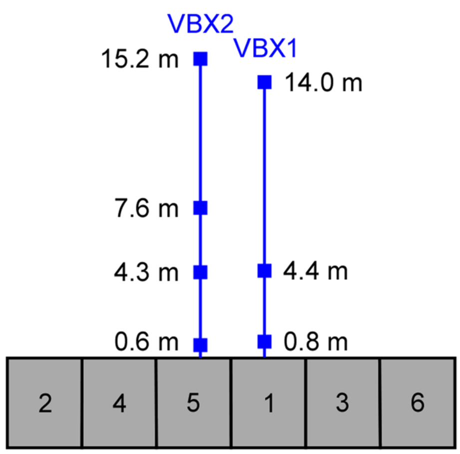

Fig. 8 Vertical extensometers (VBX1 and VBX2) installed overhead in the back

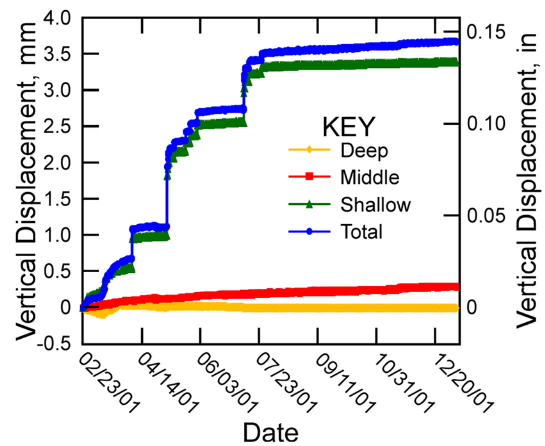

Fig. 10 Vertical displacements measured in the back above topcut 5 by VBX2, during and shortly after mining

4.3 Vertical Extensometers (Back Displacement)

Near the center of the 22.9-m (75-ft) wide mining span on the upper level, similar borehole extensometers were installed overhead in the mine roof to measure relative vertical displacements in the overlying host rock. These displacement measurements were intended to identify movement or separation across geologic features, to monitor the progression of arching and the loosening of rock in the mine roof during mining, and to provide an early warning of impending roof falls. As shown in Fig. 8, two-point and three-point extensometers (VBX1 and VBX2, respectively) were installed above topcut drifts 1 and 5. The deep anchors for these extensometers were installed about 14–15 m (46–50 ft) above the back of the upper-level drifts so that the vertical displacements measured by these instruments could be referenced from a stable horizon in the mine roof. To avoid fractured rock near the mine opening, the collar anchors of these instruments were installed in competent rock at depths of about 0.6–0.8 m (2–2.5 ft) up the drill hole.

Displacement measurements from these extensometers indicated that the mine roof was generally well supported and stable. Only small vertical displacements were measured in the overlying host rock, and most of this movement was located near the back of the topcut drifts within about the first 4.3–4.4 m (14–14.5 ft) of the mine roof. The largest displacements were measured by VBX1, the vertical extensometer installed overhead in the back of topcut 1. As shown in Fig. 9, VBX1 measured about 8.19 mm (0.323 in.) of total displacement during and shortly after mining. The majority of this movement, about 6.35 mm (0.25 in.), occurred as topcuts 5 and 6 were excavated, significantly increasing the mining span on the upper level. VBX2, on the other hand, measured only about 3.68 mm (0.145 in.) of total displacement in the back of topcut 5 (Fig. 10).

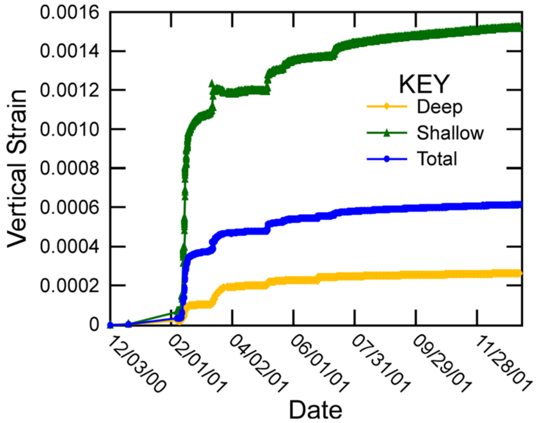

Fig. 11 Vertical strain in the back above topcut 1 computed from displacement measurements by VBX1, during and shortly after mining

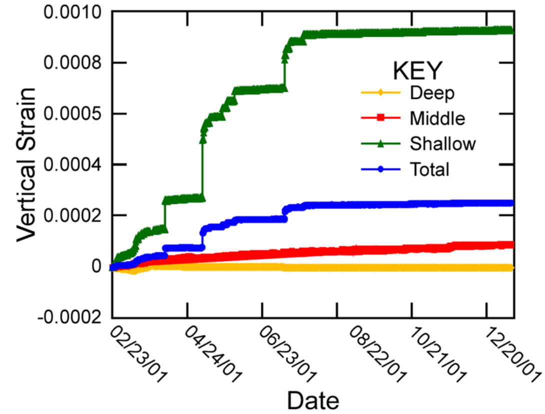

Fig. 12 Vertical strain in the back above topcut 5 computed from displacement measurements by VBX2, during and shortly after mining

Even though both of these extensometers were installed near the middle of the 22.9-m (75-ft) mining span on the upper level, their displacement measurements were significantly different due to the sequence in which the upper-level drifts were mined. Topcut 1 was excavated much earlier in the mining sequence than topcut 5. As a result, VBX1 was installed about 82 days before VBX2. Prior to the installation of VBX2 in the back of topcut 5, VBX1 measured mining-induced displacements in the back of topcut 1 that were caused by the excavation of topcuts 2–4 and, especially, topcut 5 (Fig. 9). Although VBX1 measured larger displacements during the mining of topcut 6, VBX2 measured twice the amount of total displacement during undercut mining on the lower level. Furthermore, VBX2 provided a more definitive response to face advance during undercut mining and exhibited less time-dependent deformation in its displacement measurements (Fig. 10). As a result, the host rock in the back above topcut 5 appeared to be more intact or at least less disturbed by prior mining events than that of topcut 1. This may explain why the backfill in topcut 1 appeared to be loaded more by the mine roof than the backfill in topcut 5. Conversely, the confinement provided by the CRF in topcut 1 may have restricted further movement of the mine roof and, thus, limited the response of VBX1 during undercut mining.

As shown in Figs. 11 and 12, most of the vertical displacement measured by VBX1 and VBX2 occurred between the collar anchors and the shallow anchors installed at depths of 4.4 m (14.5 ft) and 4.3 m (14 ft), respectively, in the mine roof. During retreat mining of the central undercut pillar, VBX1 and VBX2 measured vertical displacements of 0.13 mm (0.005 in.) and 0.57 mm (0.022 in.), respectively, at these depths. However, during retreat mining, neither extensometer measured any significant movement in the mine roof above the depth of the shallow anchors, less than 0.01 mm (0.0005 in.) of vertical displacement.

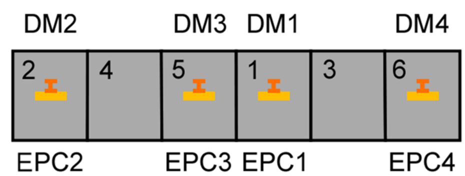

Fig. 13 Earth pressure cells (EPC1–EPC4) and deformation meters (DM1–DM4) installed in backfilled topcut drifts

4.4 Earth Pressure Cells and Deformation Meters (Backfill Loading and Deformation)

As topcuts 1, 2, 5, and 6 were backfilled, EPCs and DMs were installed near the mid length of these drifts to measure vertical loading and vertical deformation, respectively, within the CRF (Fig. 13). The Geokon Model 4800 vibrating wire earth pressure cells were equipped with 6.9-MPa (1000-psi) pressure transducers, and the Geokon Model 4430 vibrating wire deformation meters were configured to measure 6.35 mm (0.25 in.) of relative displacement (primarily compression) over the 30.5-cm (12-in.) length of the instruments. Relative vertical displacements measured by the DMs were used to calculate vertical strain. These strain calculations were in turn converted to changes in vertical stress using an in situ deformation modulus for the CRF of 1.315 GPa (190,700 psi). The modulus value was determined using a validated FLAC3D numerical model of the CRF sill as explained by Tesarik et al. (2007). To avoid point-loading or damaging these instruments, they were typically precast in forms using backfill that was screened to remove the plus 2.54-cm (1-in.) aggregate. After the backfill hardened, the forms were removed, and the precast instruments were positioned at their desired orientations near the center of the topcut drift on a bench that was formed about 1.5–2.1 m (5–7 ft) high in recently placed CRF using an underground loader or

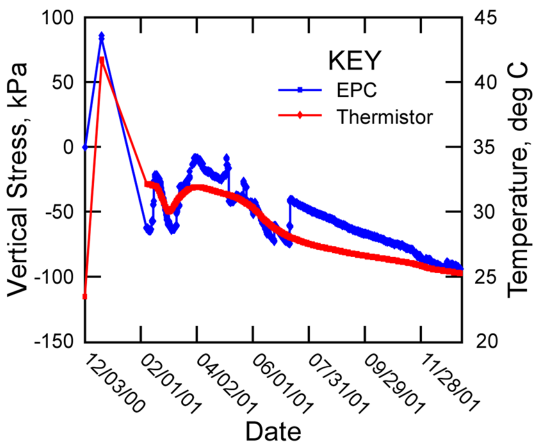

Fig. 14 Vertical stress measured in the CRF in topcut 1 by EPC1, during and shortly after mining

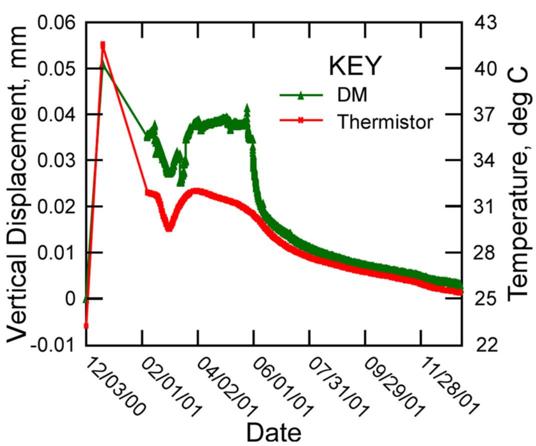

Fig. 15 Vertical displacement measured in the CRF in topcut 1 by DM1, during and shortly after mining

scooptram. Shotcrete was then applied over the instruments and their readout cables to maintain the orientation of the instruments and prevent inadvertent damage from mining equipment, as the remainder of the drift was backfilled.

The EPCs and DMs installed in topcuts 1, 2, 5, and 6 measured only small increases in stress and deformation within the CRF during mining. The vertical stress change measured in the backfill typically ranged from 68.9 to 206.8 kPa (10–30 psi) and was only slightly larger than the initial load estimated for the weight of the overlying CRF, 68.9 kPa (10 psi). Since these stress and displacement measurements were so small, the instruments' responses were often masked by changes in temperature as the CRF hydrated and cured (Tesarik et al. 2006). As shown in Figs. 14 and 15, the stress and displacement measurements from these instruments generally tracked the measured trends in temperature. In addition, these instruments were also significantly

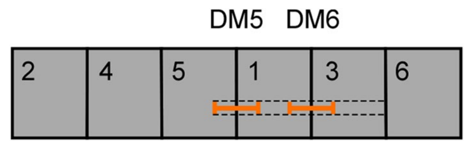

Fig. 16 Deformation meters (DM5 and DM6) installed across vertical backfill cold joints from topcut drift 6

influenced by time-dependent behavior as evidenced by the decreases in stress and displacement following each mining event or face advance. Because of these complicating factors, it was difficult to interpret the data from these instruments and to accurately compute the changes in stress and displacement caused by mining. Nevertheless, these instruments indicated that no substantial ground support loads were transferred to the CRF sill through the mine roof and, therefore, confirmed that the majority of the mining-induced load was redistributed to the abutments.

4.5 Deformation Meters (Horizontal Displacement Across Vertical Backfill Cold Joints)

To monitor potential movement or slip along vertical cold joints between adjacent backfilled drifts, two Geokon Model 4430 vibrating wire deformation meters, 2.44 m (8 ft) in length, were installed to measure horizontal displacements across the cold joints between topcuts 5 and 1 and topcuts 1 and 3 (Fig. 16). These large DMs were configured to measure a maximum relative displacement of 10.16 cm (4 in.), primarily in tension, and they were grouted in a single horizontal borehole that was drilled through the CRF from topcut 6. Because these instruments measured horizontal displacements across the cold joints rather than vertical displacements along these interfaces, they provided merely a rough approximation or indirect indication of the relative movement between adjacent backfill drifts. The primary purpose for installing these instruments was to provide an early warning of slip along the cold joints and, thereby, alert the mine staff to a possible collapse of the backfill during undercut mining on the lower level.

As explained by Tesarik et al. (2007), DM5 measured only a minimal amount of horizontal displacement across the vertical cold joint between backfilled topcut drifts 5 and 1, about 1.02 mm (0.04 in.). This particular cold joint is located at the center of the undercut span and, therefore, should have been more susceptible to movement or slip than the other two vertical cold joints that were exposed during undercut mining (Figs. 17, 18). Even though DM5 provided only an indirect indication of vertical displacement along this cold joint, the small horizontal displacements measured by this instrument logically indicate that a limited amount of movement occurred along this interface. Unfortunately,

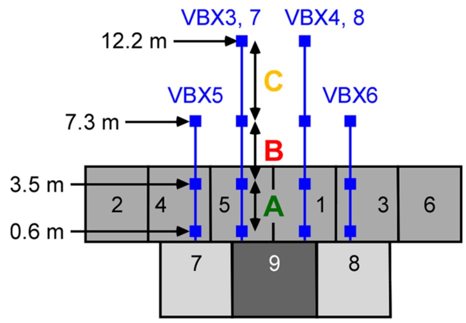

Fig. 17 Cross-section view of vertical extensometers (VBX3–VBX8) installed in the CRF sill and back from the undercut entries

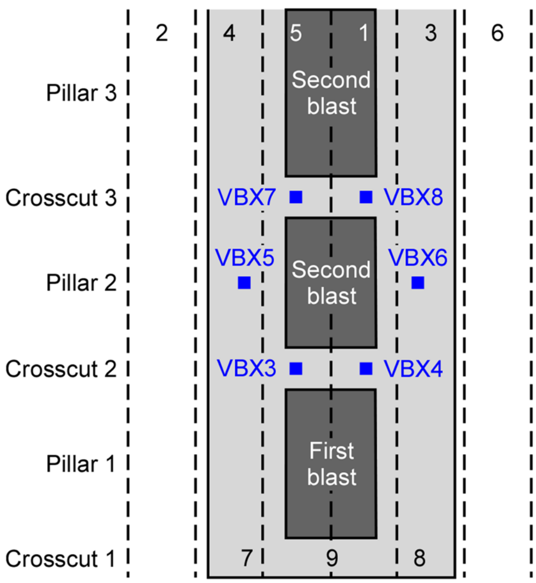

Fig. 18 Plan view of vertical extensometers (VBX3–VBX8) installed in the CRF sill and back from the undercut entries

this conclusion could not be verified by supplementary data from the other deformation meter installed across the cold joint between topcut drifts 1 and 3. The displacement transducer for DM6 stopped functioning about 36 days after the instrument was installed, more than 2 months before the central undercut pillar was mined. Nevertheless, no apparent movement or slip was observed along these cold joints during undercut mining even though three of these vertical interfaces were exposed along the entire 30.5-m (100-ft) length of the undercut span at the completion of mining.

4.6 Undercut Vertical Extensometers (Backfill Displacement, Deflection of CRF Sill, and Back Displacement)

To monitor the stability of the CRF sill and mine roof during retreat mining of the central undercut pillar, six additional vertical extensometers were installed overhead through the backfill and into the mine roof from undercut entries on the lower level. The configuration and location of these instruments are shown in Figs. 17 and 18. Two-point vertical extensometers (VBX 5 and VBX6) were installed near the mid length of topcut drifts 4 and 3, respectively, along the same cross section as the upper level instruments. Four additional three-point extensometers were positioned symmetrically along the longitudinal and lateral axes of the undercut span to provide a sequential assessment of the backfill's stability as each section of the central undercut pillar was mined. VBX3 and VBX4 were installed from the second crosscut in the central undercut pillar through topcut drifts 5 and 1, respectively. VBX7 and VBX8 were installed from the third crosscut in the central undercut pillar in a similar manner (Fig. 18). The spatial distribution of these instruments was intended to provide an advanced warning of a potential backfill collapse and to supply further information regarding the symmetry and consistency of displacement measurements in the CRF sill and overlying host rock.

To prevent damage from fly rock during retreat mining, the extensometer collar anchors were typically installed up the borehole about 0.6 m (2 ft) from the bottom surface of the backfill. To monitor vertical displacements and potential slabbing within the backfill, the shallow anchors for these extensometers were installed in competent backfill near the top of the CRF sill, usually about 1.07 m (3.5 ft) below the back of the upper-level drifts. Depending on the number of measurement points for the extensometers, additional anchors were installed at depths of approximately 2.44 m (8 ft) and 7.62 m (25 ft) in the overlying host rock so that vertical displacements could also be monitored in the mine roof (Fig. 17). Installing the extensometer anchors in this configuration not only enabled vertical displacements to be measured in the CRF and mine roof, but also allowed the vertical deflection or separation of the CRF sill from the overlying host rock to be measured during retreat mining of the central undercut pillar.

A summary of the vertical displacements measured by these extensometers during and shortly after mining is listed in Table 4. As indicated in column A of this table, most of the extensometers installed from the lower level measured only small vertical displacements in the CRF sill during retreat mining of the central undercut pillar. The sole exception was VBX7, the vertical extensometer installed overhead in topcut drift 5 from the third crosscut in the central undercut pillar (Figs. 17, 18). VBX7 measured 1.85 mm (0.073 in.) of vertical displacement in the overlying CRF, whereas the other five extensometers measured displacements of 0.19 mm (0.007 in.) or less in compression. The anomalously large displacement in the CRF at VBX7 may indicate that a slab was beginning to form in the backfill at this location following the second undercut blast. However,

Table 4 Summary of displacement measurements from undercut extensometers, during and shortly after mining

Vertical extensometer	Vertical displacement (mm)		
	A[a]	B[b]	C[c]
VBX3	−0.19	3.44	−0.05
VBX4	−0.10	4.49	0.07
VBX5	−0.06	1.36	NA
VBX6	−0.06	1.79	NA
VBX7	1.85	1.69	0.00
VBX8	−0.01	4.43	−0.13

Columns A, B, and C correspond with displacement measurements shown in Fig. 17. Tension is denoted as positive displacement

[a]Vertical displacements measured within the CRF sill

[b]Vertical displacements measured between locations near the top of the CRF sill and depths of about 2.44 m (8 ft) in the overlying host rock

[c]Vertical displacements measured in the overlying host rock between depths of about 2.44 m (8 ft) and 7.62 m (25 ft)

if a backfill slab was present, it appeared to be stable because no obvious time-dependent increase in strain was measured in the backfill over the next 6 months. Previous experience with similar borehole extensometers has demonstrated that these instruments can be used not only to identify slab formation but also to successfully predict the likelihood of a roof fall (Seymour et al. 1996).

During retreat mining of the central undercut pillar, the largest displacements measured by the vertical extensometers generally occurred between an anchor installed near the top of the backfill and an anchor installed at a depth of about 2.44 m (8 ft) into the mine roof, as indicated by the displacements listed in column B of Table 4. Although these displacement measurements were relatively small, less than 5 mm (0.2 in.), they were substantially larger than the vertical displacements measured at greater depths in the mine roof and, except for VBX7, were significantly larger than the vertical displacements measured in the CRF.

To create the 13.7-m (45-ft) wide undercut span, the central undercut pillar was retreat-blasted in two separate stages. During the first stage of retreat mining, the front section of the pillar between the first and second crosscuts, south of VBX3 and VBX4, was blasted (Fig. 18). During the second stage, the remaining two sections of the pillar, north of VBX3 and VBX4, were blasted at the same time. The responses of VBX4 and VBX7 to these two undercut blasts are shown below in Figs. 19 and 20.

As clearly shown by these figures and the vertical displacements listed in column C of Table 4, only slight movement was measured in the mine roof at anchor depths greater than 2.44 m (8 ft). Consequently, most of the vertical displacement that was measured in the mine roof by these extensometers occurred close to the back of the topcut drifts

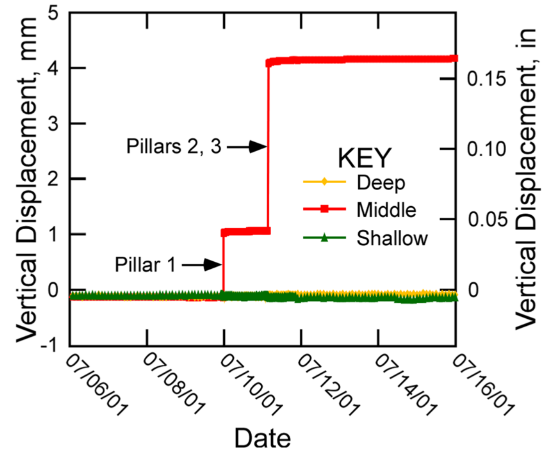

Fig. 19 Vertical displacements measured in the back and topcut 1 by VBX4 during retreat mining of the central undercut pillar

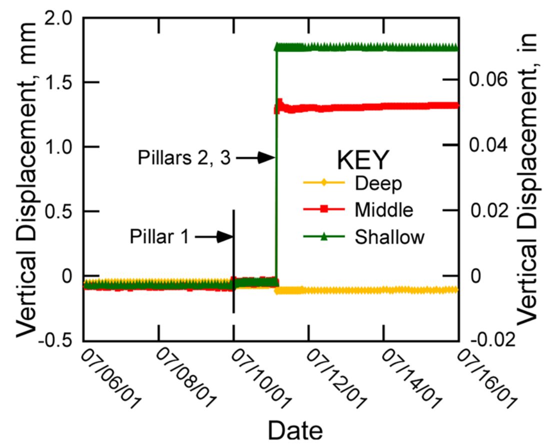

Fig. 20 Vertical displacements measured in the back and topcut 5 by VBX7 during retreat mining of the central undercut pillar

below a horizon of about 2.44 m (8 ft) in the overlying host rock. The displacements listed in column B are also much larger than the vertical displacements measured by VBX1 and VBX2 during retreat mining of the central undercut pillar. As noted previously, VBX1 and VBX2 measured vertical displacements of 0.13 mm (0.005 in.) and 0.56 mm (0.022 in.) at depths of 4.4 m (14.5 ft) and 4.3 m (14 ft), respectively, in the mine roof during retreat mining. Based on the vertical strains calculated from these displacement measurements, only 0.08–0.38 mm (0.003–0.015 in.) of vertical displacement should have occurred in the first 2.44 m (8 ft) of the mine roof. As a result, a majority of the displacement listed in column B was caused by separation or deflection of the CRF sill from the overlying host rock.

These deflection measurements are reasonably consistent in magnitude, and they are symmetrical with respect to the final dimensions of the undercut opening. As shown in

Fig. 21 View of final 13.7-m (45-ft) wide backfill span from the TR 4135 access (July 2001)

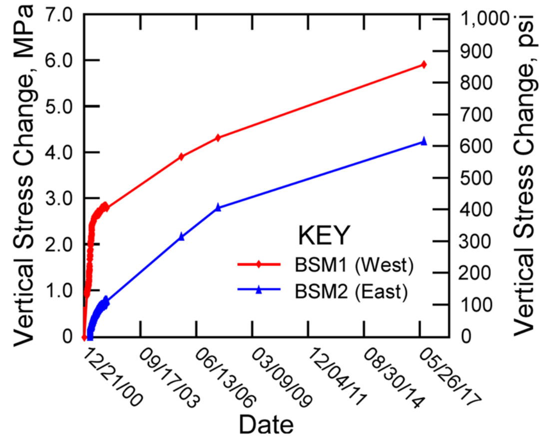

Fig. 22 Vertical stress change measured in the abutments by BSM1 and BSM2, 16 years after mining ceased

Fig. 18, VBX5 and VBX6 are located closer to the abutments on the lower level. As a result, these instruments measured smaller vertical displacements than the other extensometers. Except for VBX7, the displacements measured by the remaining extensometers were comparable in magnitude because these instruments were located approximately equidistant from the center of the undercut opening. The symmetry and consistency of these deflection measurements and the results of numeric modeling (Tesarik et al. 2007) indicate that the CRF sill behaved as a homogeneous, elastic beam or plate and moved in mass as a single unit rather than as individual drift segments. This symmetrical elastic behavior in turn, indicates that only minimal mining-induced loads were transferred to the CRF and that the shear strength along the vertical cold joints was sufficient to restrict differential movement along these interfaces. The final 13.7-m (45-ft) wide undercut span is shown in Fig. 21, shortly after the completion of undercut mining.

5 Long-Term Response

The data acquisition systems, which were monitoring the instruments, were removed from the mine in January 2002. Since then, manual readings have been intermittently collected from the instruments. The latest set of manual readings was collected from the upper level instruments via access from TR 4145 on August 3, 2017. An analysis of these readings indicates that most of the instruments and their electronic transducers are still functioning and providing valid measurements. A brief summary of the long-term response of the instruments based on this latest set of readings is presented in the sections that follow.

5.1 Biaxial Stressmeters (Abutment Loading)

Since the completion of undercut mining, the biaxial stressmeters have continued to measure a steady increase in vertical stress in the abutments (Fig. 22). BSM1 and BSM2 have measured long-term vertical stress changes of 5.91 MPa (856 psi) in the west abutment and 4.22 MPa (612 psi) in the east abutment, respectively.

While the magnitude of these stress changes is reasonable, it is doubtful that the vertical stress has continued to increase in the abutments over the past 16 years without additional mining near the test site. The increase in abutment stress since undercut mining was completed may simply reflect some unknown degradation of the vibrating wire sensors. However, the consistency in the calculated stress changes from these two instruments is striking.

5.2 Horizontal Extensometers (Abutment Dilation)

In contrast to the vertical stress increases measured in the abutments by the biaxial stressmeters, the horizontal extensometers have measured only slight changes in displacement, indicating that dilation of the abutment ribs has stabilized. An increase in vertical stress in an abutment would typically be expected to cause horizontal dilation of the abutment rib. However, if the abutment is confined by backfill, the amount of this dilation could be reduced. Previous NIOSH studies have demonstrated that backfill confinement limits pillar dilation and enhances the ground support characteristics of mine pillars (Seymour et al. 1998; Tesarik et al. 2003).

HBX2 measured an increase of about 0.11 mm (0.004 in.) of total displacement in the east abutment since its last manual reading on July 10, 2007 (Fig. 23). As shown by the horizontal strain plot in Fig. 24, most of this displacement occurred at a depth of less than 1.8 m (6 ft), and over the

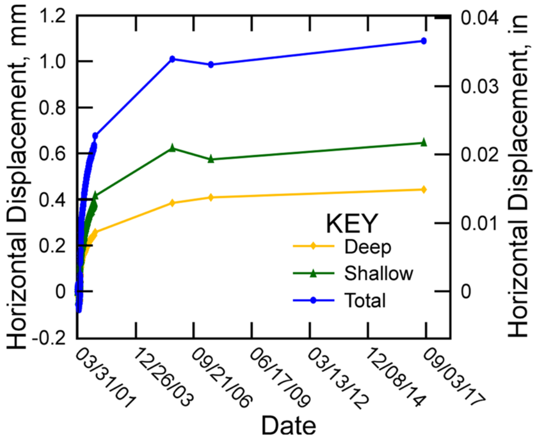

Fig. 23 Horizontal displacements measured in the east abutment by HBX2, 16 years after mining ceased

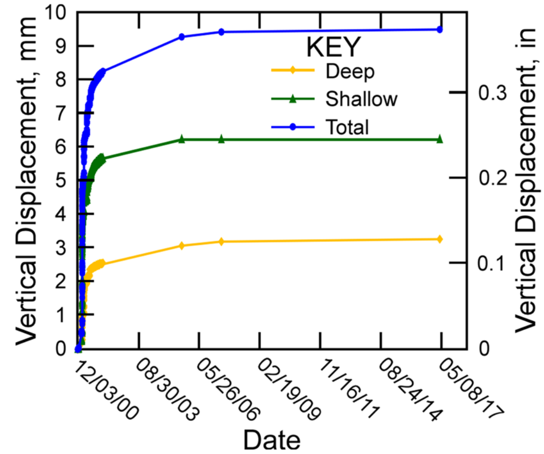

Fig. 25 Vertical displacements measured in the back above topcut 1 by VBX1, 16 years after mining ceased

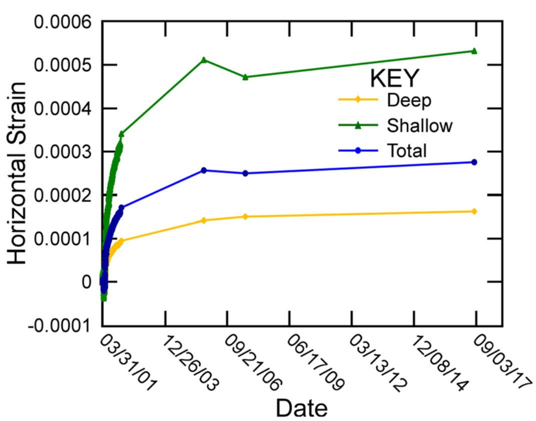

Fig. 24 Horizontal strain in the east abutment computed from displacement measurements by HBX2, 16 years after mining ceased

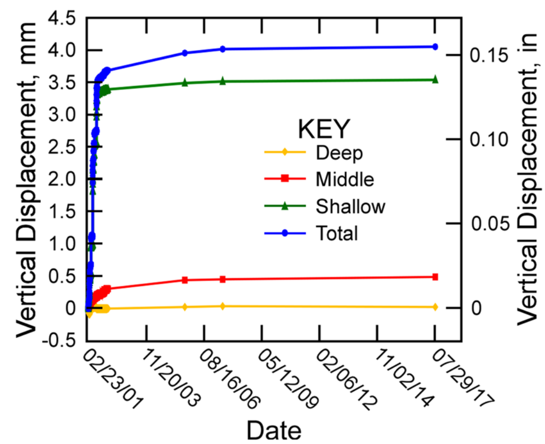

Fig. 26 Vertical displacements measured in the back above topcut 5 by VBX2, 16 years after mining ceased

past 12 years, this movement has stabilized. The horizontal displacement measurements in the west abutment have also stabilized. Overall, the small displacements measured in both abutments over the past 16 years indicate that the CRF has confined the abutment ribs and restricted their movement, thereby improving their long-term stability.

5.3 Vertical Extensometers (Back Displacement)

As shown in Figs. 25 and 26, the two vertical extensometers (VBX1 and VBX2) installed in the back above topcut drifts 1 and 5 have measured hardly any movement, less than 0.07 mm (0.003 in.) of total displacement, since their last readings on July 10, 2007.

This indicates that the mine roof at these locations has been stable over the last 10 years and that additional ground support loads have not been transferred to the CRF sill through the back. As discussed in the next section, this conclusion is also supported by the latest readings from the pressure cells (EPC1 and EPC3) and deformation meters (DM1 and DM3) installed in the backfill beneath these instruments. As shown by the vertical strain plots in Figs. 27 and 28, most of the displacement measured in the back by VBX1 and VBX2 has occurred at shallow depths in the mine roof, less than 4.4 m (14.5 ft) and 4.3 m (14 ft), respectively. This movement has clearly stabilized since the completion of mining 16 years ago.

5.4 Earth Pressure Cells and Deformation Meters (Backfill Loading and Deformation)

All of the pressure cells (EPC1–EPC4) and deformation meters (DM1–DM4) installed in the topcut drifts are still operating correctly, with the exception of the thermistor for EPC4, which stopped functioning in April 2001 shortly after

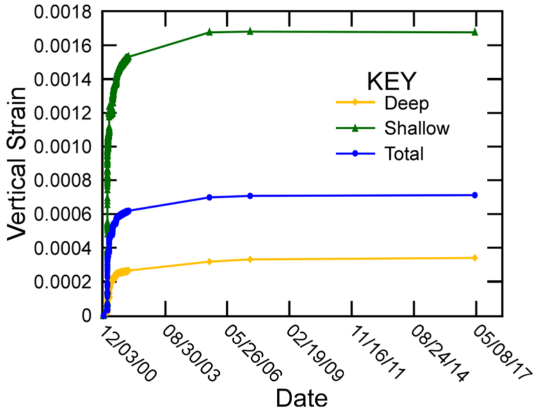

Fig. 27 Vertical strain in the back above topcut 1 computed from displacement measurements by VBX1, 16 years after mining ceased

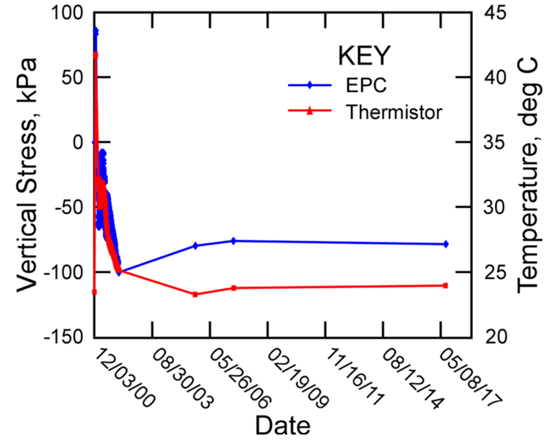

Fig. 29 Vertical stress measured in the CRF in topcut 1 by EPC1, 16 years after mining ceased

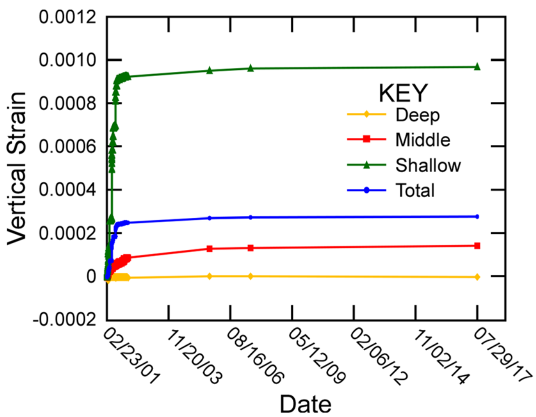

Fig. 28 Vertical strain in the back above topcut 5 computed from displacement measurements by VBX2, 16 years after mining ceased

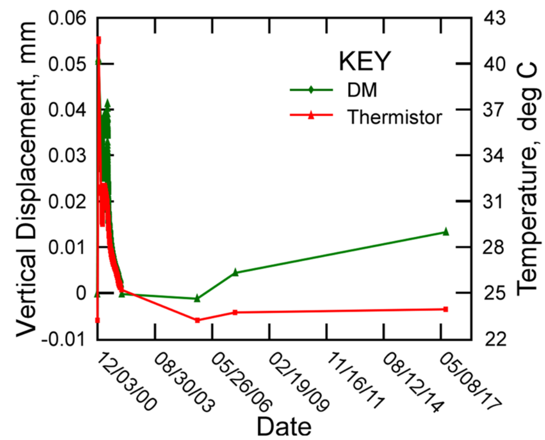

Fig. 30 Vertical displacement measured in the CRF in topcut 1 by DM1, 16 years after mining ceased

the instrument was installed. This indicates that the CRF sill is still intact and in stable condition because a collapse of the undercut span would likely damage the instruments and sever their readout cables.

As shown by the response of EPC1 in Fig. 29, the small amount of vertical stress that was measured in the CRF during mining has either leveled off or decreased since manual readings were collected from these instruments in July 2007. In a similar manner, the small vertical displacements measured in the CRF have generally decreased, except for a slight increase in the displacement measured by DM1 (Fig. 30). These small changes in vertical stress and displacement within the CRF indicate that no significant ground support loads have been transferred to the CRF sill since undercut mining ended 16 years ago. This conclusion is in turn supported by the lack of movement measured in the mine roof by VBX1 and VBX2 over the past 10 years.

5.5 Deformation Meters (Horizontal Displacement Across Vertical Backfill Cold Joints)

Neither of the large DMs were able to provide displacement readings on August 3, 2017. The displacement transducer for DM6 had previously stopped working in April 2001 shortly after the instrument was installed, but DM5 did provide a valid displacement reading in July 2007. Although the vibrating wire displacement transducers on these instruments are not functioning, their associated thermistors are still operating correctly. This indicates that the instrument cables are still intact and that the vibrating wire transducers have somehow been compromised. While the exact cause of this malfunction is not known, the operating thermistors indicate that the backfill cold joints are stable.

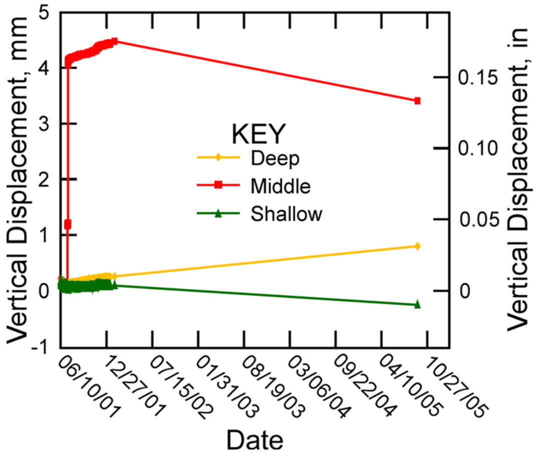

Fig. 31 Vertical displacements measured in the back and topcut 1 by VBX4, 4 years after mining ceased

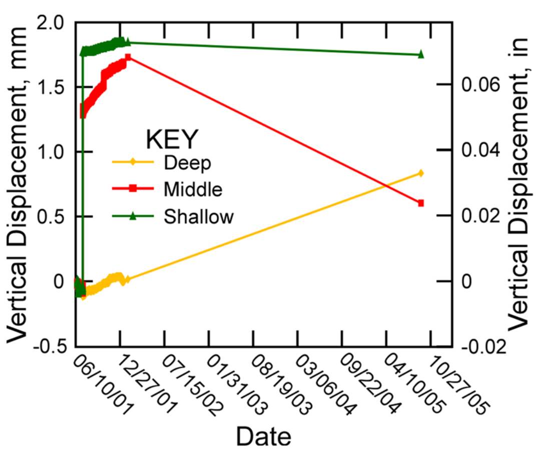

Fig. 32 Vertical displacements measured in the back and topcut 5 by VBX7, 4 years after mining ceased

5.6 Undercut Vertical Extensometers (Backfill Displacement, Deflection of CRF Sill, and Back Displacement)

The last manual readings were collected from the six undercut extensometers (VBX3–VBX8) on September 15, 2005. Visual observations and instrument measurements confirmed that the backfill span was stable at that time. As shown by the responses of VBX4 and VBX7 in Figs. 31 and 32, the deep transducers for the undercut extensometers generally measured an increase in vertical displacement at depths of between about 2.44 m (8 ft) and 7.62 m (25 ft) in the mine roof, whereas the middle transducers generally measured a decrease in vertical displacement between anchors near the top of the CRF sill and at depths of about 2.44 m (8 ft) in the mine roof.

These measurements indicate that the mine roof is gradually moving downward towards the sill and decreasing the initial deflection of the CRF sill in response to undercut mining. Nevertheless, the backfill does not appear to be loading because the vertical displacements measured in the CRF by the shallow transducers are generally stable. Additional readings from the undercut extensometers would help quantify the geomechanical behavior of the CRF sill and address questions regarding slabbing in the backfill and the long-term deflection of the sill.

6 Long-Term Backfill Strength

During backfilling of topcut drift 6 on March 28, 2001, in-stope samples of the CRF were collected by NIOSH researchers in standard 15.2-cm × 30.5-cm (6-in. × 12-in.) cylinder molds. The samples were transported to the NIOSH Spokane Research Laboratory and stored in a fog room at room temperature and 100% humidity until they were tested. Unconfined compressive strength (UCS) tests were conducted with the samples after they had cured for 708 days and 5927 days or about 2 and 16 years, respectively. Results of the 2-year tests were previously reported by Tesarik et al. (2007). These NIOSH test results were combined with historic 7- and 28-day UCS test data collected for quality assurance and quality control (QA/QC) purposes from batches of the same backfill mix by Placer Dome, Inc. A comparison of the average results from these tests is provided in Table 5. As shown by the trend line for the data plotted in Fig. 33, CRF samples under controlled curing conditions continue to gain strength with age. As with concrete, the rate of this strength gain gradually diminishes with prolonged curing time.

The binding quality of Portland cement is caused by the chemical process of hydration. An increase in strength with age will normally continue as long as unhydrated cement is

Table 5 Average UCS test results at different curing ages for 15.2-cm × 30.5-cm (6-in. × 12-in.) samples of CRF from the same backfill mix at the Turquoise Ridge Mine

Curing time (days)	Samples tested	Avg UCS (MPa)	Std dev (MPa)	CV (%)	Fraction of 28-day UCS
7	28	3.95	1.06	26.8	0.65
28	28	6.11	1.54	25.2	1.00
708	3	9.61	1.45	15.1	1.57
5927	4	11.28	1.28	11.4	1.85

Avg UCS average unconfined compressive strength, *Std dev* standard deviation, *CV* coefficient of variation

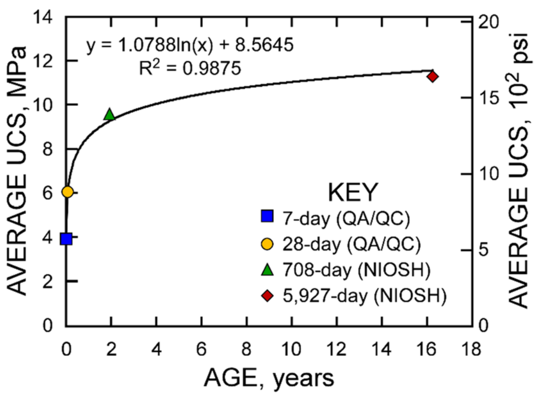

Fig. 33 Average UCS versus curing time for CRF samples from TR 4145 trial undercut

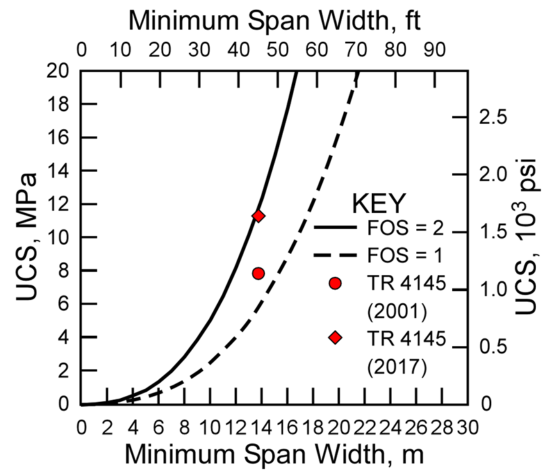

Fig. 34 TR 4145 CRF undercut span plotted against Mitchell equation for flexural stability (adapted from Pakalnis et al. 2005)

present, provided the relative humidity within the concrete remains above about 80% and the temperature remains above freezing (Kosmatka and Panarese 1990). If the curing conditions become unfavorable, the hydration reaction will halt, limiting the strength of the concrete. While favorable conditions are likely present at the TR 4145 site, the strength gain of CRF in an underground environment may be less than that of samples cured under controlled conditions (100% humidity and room temperature) in a laboratory. Nevertheless, a reduction in CRF strength should not occur unless some other adverse factor is present, such as one of the causes of concrete deterioration listed by the Portland Cement Association, which include corrosion of reinforcing steel, freeze–thaw deterioration, chemical attack, alkali-aggregate reactivity, abrasion/erosion, fire and heat, restraint to volume changes, overload, and impact (PCA 2002).

Splitting tensile strength (STS) tests were also conducted with several of the 16-year samples to quantify the long-term tensile strength of the CRF and determine an average tensile-to-compressive strength ratio. For the 16-year tests, the average UCS was 11.28 MPa (1636 psi), and the average STS was 1.90 MPa (276 psi), thus producing an average STS-to-UCS ratio of about 1/6. This ratio is significantly larger than the ratio of 1/10, which is typically assumed for undercut span design using limit equilibrium equations to analyze flexural stability (Mitchell 1991; Stone 1993; Pakalnis et al. 2005).

As noted by Stone et al. (2019), there are currently no established standards for preparing and testing cemented backfill samples. As a result, standards for other materials such as concrete are loosely applied to backfill. The CRF sampling methods and testing procedures, which were used for the UCS and STS tests mentioned above, roughly followed guidelines developed for concrete by the American Society of Testing and Materials (ASTM) and the American Concrete Institute (ACI). Values for coefficient of variation (CV) listed in Table 5 are typical for test results with cemented backfill, as explained by Stone et al. (2019).

7 Flexural Stability Assessment

As explained by Tesarik et al. (2007), the CRF in the topcut drifts had cured between 136 and 218 days prior to undercut mining. Using the strength gain equation for the trend line of the plotted data in Fig. 33, the CRF sill should have had a UCS of between 7.50 MPa (1088 psi) and 8.01 MPa (1162 psi) when the undercut span was completed in July 2001. The average of these two values, 7.75 MPa (1125 psi), compares closely with the average UCS of 7.83 MPa (1135 psi), which was calculated for the CRF sill in a similar manner by Tesarik et al. (2007) using an augmented concrete strength gain curve (Kosmatka and Panarese 1990). Based on the results of the 16-year tests conducted in June 2017, the CRF sill should now have a UCS of at least 11.28 MPa (1636 psi). A plot of the 2001 and 2017 average UCS values versus span for the TR 4145 undercut is shown in Fig. 34, along with a plot of the Mitchell flexural stability equation based on case history data collected by Pakalnis et al. (2005).

When the CRF sill was undercut in 2001, the 13.7-m (45-ft) wide span initially had a factor of safety (FOS) of about 1.4. Assuming that the emplaced CRF gained strength at the same rate as the 16-year samples, the current FOS should be about 1.9 for the undercut span. However, this analysis assumes that the tensile strength of the CRF is about 1/10 of its UCS, rather than the 1/6 ratio determined through STS testing. On the other hand, the strengths obtained through standard QA/QC tests may not accurately reflect the in situ strength of the emplaced material, as a result of other complicating factors such as compaction, density, unintended changes in mix design, and scale effects (Warren et al. 2018). Nevertheless, this analytical analysis of the flexural stability of the CRF sill does support the conclusions from the instrumentation measurements, indicating that the undercut span is likely still intact and in stable condition. A more thorough discussion of the flexural stability of CRF undercut spans at the TRJV is provided by Barnard and Sandbak (2017).

8 Conclusions

In 2001, 22 instruments, encompassing 55 vibrating wire transducers and 21 thermistors, were installed at the Turquoise Ridge Mine to monitor the geomechanical behavior and stability of a CRF sill and the surrounding host rock during test mining of a trial undercut span. This backfill span test was conducted in an isolated area of the mine, consisting of relatively competent, highly metamorphosed limestone. The back of the upper-level drifts were well supported by 2.4-m (8-ft) resin-grouted rebar bolts and steel mesh, as evidenced by the relatively small displacements that were measured in the overlying host rock by the vertical extensometers. Most of the movement in the back occurred at shallow depths in the mine roof and did not appear to be significantly influenced by geologic structure. Because of the competent ground conditions and effective roof support measures, the back remained stable over the 22.9-m (75-ft) mining span on the upper level. As a result, the majority of the mining-induced stress was transferred to the host rock abutments rather than to the backfilled drifts. Biaxial stressmeters measured significant mining-induced stress changes in the abutments, whereas the instruments installed in the backfilled drifts measured only minimal loading and deformation within the CRF. Although only slight mining-induced loads were transferred to the backfilled drifts, the CRF confined the abutment ribs and mine roof, thereby improving their long-term stability.

During retreat mining of the central undercut pillar, the backfill drifts and mine roof remained stable. Only small vertical displacements were measured in the cemented rockfill and overlying host rock. The vertical extensometers installed from the undercut entries clearly indicated that most of the measured displacement was caused by separation of the backfill from the overlying host rock or deflection of the CRF sill. An analysis of the extensometer data and numeric modeling results indicated that the behavior of the CRF sill during undercut mining was comparable to the deflection of a homogeneous elastic plate having similar dimensions, material properties, and undercut spans. Because only minimal mining-induced loads were transferred to the backfill, the stability of the CRF sill was not adversely affected by the vertical cold joints between adjacent backfill drifts.

Additional manual readings have been intermittently collected from the instruments after undercut mining ended in 2001. These measurements have indicated that while vertical stress has continued to increase in the abutments, displacements in the mine roof and abutments have stabilized, and vertical stress and deformation within the CRF have generally leveled off or decreased. The most recent readings from these instruments indicate that the backfill span is still intact and in stable condition. These conclusions are also supported by the results of recent laboratory tests, which measured the long-term compressive and tensile strengths of CRF samples collected during the original backfill span study and by an analytical analysis of the flexural stability of the CRF sill.

Although manual readings were collected from 16 instruments on the upper level via access from the TR 4145 heading in August 2017, access to additional instruments on the lower level via the TR 4135 has been blocked by waste rock. Reopening this heading would provide visual confirmation of the long-term competency of the backfill span and enable manual readings to be collected from six additional vertical extensometers installed in the backfill and mine roof. Measurements from these instruments would provide valuable information regarding vertical deformation and slabbing within the CRF, vertical displacements in the mine roof, loading of the CRF through contact with the back, and deflection or separation of the backfill sill from the overlying host rock.

These research findings are important because they (1) quantify the long-term compressive strength gain for CRF, demonstrating that it is similar to that of concrete, (2) report measured indirect tensile strength values for CRF, indicating that the tensile-to-compressive strength ratio for CRF is about 1/6 rather than 1/10, and (3) provide an analysis of a unique instrumented case study, documenting the long-term stability of a 13.7-m (45-ft) wide by 30.5-m (100-ft) long undercut span beneath CRF. This information provides a better understanding of the long-term strength properties and geomechanical behavior of CRF, and thus helps justify the use of undercut spans beneath CRF for permanent mine infrastructure.

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