International Journal of Mining Science and Technology 26 (2016) 471–476

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

# Analysis of roof and pillar failure associated with weak floor at a limestone mine

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ARTICLE INFO

*Article history:*
Received 7 June 2015
Received in revised form 16 August 2015
Accepted 3 November 2015
Available online 15 March 2016

*Keywords:*
Underground limestone
Ground control
Case study
Weak floor
Instability

ABSTRACT

A limestone mine in Ohio has had instability problems that have led to massive roof falls extending to the surface. This study focuses on the role that weak, moisture-sensitive floor has in the instability issues. Previous NIOSH research related to this subject did not include analysis for weak floor or weak bands and recommended that when such issues arise they should be investigated further using a more advanced analysis. Therefore, to further investigate the observed instability occurring on a large scale at the Ohio mine, FLAC3D numerical models were employed to demonstrate the effect that a weak floor has on roof and pillar stability. This case study will provide important information to limestone mine operators regarding the impact of weak floor causing the potential for roof collapse, pillar failure, and subsequent subsidence of the ground surface.


## 1. Introduction

Massive roof falls extending to the surface at a limestone mine in Ohio have been studied collaboratively by the National Institute for Occupational Safety and Health (NIOSH) and the mine owners. This paper provides a summary of the sequence of events leading to observed instability and presents a numerical modeling analysis that investigates the role a weak floor can have on roof and pillar stability.

This study builds upon previous NIOSH research in underground limestone mines undertaken by way of a survey that analyzed performance of pillars in 34 different stone mines in the Eastern and Midwestern United States between 2005 and 2009 [1]. This survey led to the development of underground stone mine pillar design guidelines based upon a "stability factor" for the pillar system. The factor is compared to operational experience to determine ranges of values that are typical of stable pillar systems. A software package titled Stone mine pillar design (S-pillar) was developed for easy application of these guidelines [2].

Weak floor in the present case study departs significantly from cases included in the previous NIOSH research, in that none of the 34 study mines had weak floor issues. Moreover, this case study is the first in which a weak floor has been monitored routinely as roof falls are occurring. A detailed report on the observations and measurements taken at the mine has been published [3]. The previous observations led to the conclusion that although there were weak bands in the pillar, the weak floor was the significant defect that led to the instability issues. The pillars were initially mined in 2004, approximately 10 years before the instability issues began to occur. The objective of this study is to use numerical models to analyze a variety of floor strengths and the impact of moisture content to find the critical point at which the floor becomes unstable, leading to long-term instability issues.

## 2. Site description and field observations

The study site is the Petersburg Mine, an underground limestone mine owned by East Fairfield Coal Company, located in eastern Ohio in Mahoning County. The mining horizon is generally from 60 to 75 m below the surface. The mine is developed from a box cut, with portals into the Vanport limestone seam with slightly less than 45 m of overburden. The surface is gently rolling, and the Vanport limestone remains near horizontal with maximum grades of less than three degrees. Geologically, the Vanport limestone is a part of the Allegheny Formation within the Pennsylvanian System. The lower Kittanning coal overlies the Vanport limestone and is typically 9–12 m above the top of the limestone.

The underground mine design incorporated a variety of pillar sizes, but generally consisted of 12 m wide drifts driven directly west with north–south crosscuts that were also 12 m wide. The pillars were 8 m wide by 18 m long. The resultant mine plan

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http://dx.doi.org/10.1016/j.ijmst.2016.02.016
2095-2686/

consisted of crosscuts on 30 m centers with drifts on 19.8 m centers. The initial mining height was approximately 5.5 m, leaving a 1.2 m beam of limestone in the immediate roof.

Typically, the mine leaves approximately 0.6 m of limestone in the floor. However, in the area of the instability, it was observed that less than 0.6 m of limestone had been left in the floor. The mine geologist indicated that the stone thickness at the bottom of the pillar changed irregularly due to dips, resulting in a thinner floor stone thickness than what was planned. Borehole logs in this area showed that a 1 m thick weak unit of moisture-sensitive fireclay was beneath the limestone but not present in other parts of the mine. The fireclay was a rock when it was cored, however, upon weathering it turned into a soft and crumbly material, as described by the mine geologist. This fireclay floor bed could not be tested for a uniaxial compressive strength test, because the core pieces were too small for analysis. However, the strength was estimated to be 3 MPa by NIOSH based on field evaluation methods [4]. Also during the field evaluation, the weak floor unit appeared to have a consistency of a stiff soil and contained clayey minerals. In a few areas, the pillars were standing directly on top of this weak bed. The site geologist also mentioned that this area had standing water multiple times in the past.

A team of NIOSH researchers made routine visits to the mine to collect data and gain insight into the causes behind the instability. Through previous observational and numerical analysis detailed in Murphy et al., the major factors that led to the instability are as follows [3]:

(1) Less than 0.6 m of limestone was left in the floor in some areas, leading to the exposure of a weak, moisture-sensitive fireclay unit below;
(2) Yielding of the weak floor induced tensile fracturing in the bottom section of the pillar;
(3) Due to the tensile fracturing, the pillar began to slough off at the corners and major blocks fell off from around the pillar;
(4) A weak band located near the mid-height of the pillar was able to squeeze out, inducing more tensile fracturing in the upper portion of the pillar. In some cases, the upper portion also experienced sloughing or scaling;
(5) Due to the decreased size of the pillar through sloughing, the effective footprint of the pillar and its load-bearing capacity were reduced. Thus the pillar was able to punch further into the floor, resulting in floor heave;
(6) After a number of adjacent pillars began to punch into the floor, a wide area roof collapse occurred. Due to the weak shale above the limestone roof beam, the fall extended to the surface.

## 3. Stability analysis

The NIOSH developed S-pillar software was initially used to estimate the stability of a typical pillar found in the Vanport limestone seam using the mining dimensions at the Petersburg Mine. The S-pillar analysis does not take into account the defects within the pillar or the weak floor, but will give a stability factor for a solid pillar on top of a competent floor. S-pillar was also used to find the estimated stress in the pillars, due to the depth and excavation, which could be expected at the Petersburg Mine.

After the stability was determined for the solid pillar, the S-pillar software was the starting point to calibrate a series of FLAC3D Mohr–Coulomb strain softening numerical models. To begin, a FLAC3D numerical model was created to represent a limestone pillar with a similar Uniaxial Compressive Strength (UCS) measured from the Vanport limestone seam. The objective was to match the strength of the solid pillar calculated in S-pillar to the strength of a solid pillar simulated in the FLAC3D numerical model. In this study, a solid pillar is defined as a Vanport limestone seam pillar with intact rock and does not include any defects such as a weak band.

Once the solid Vanport limestone seam pillar was calibrated in FLAC3D, the weak band defects were added into the model. The pillars that included the weak bands were representative of the typical pillar structure found in the areas of instability at the Petersburg Mine. For this study, the pillars that included weak bands observed in the areas of instability were defined as the Vanport limestone seam pillars with defects.

Initially during this analysis, the floor remained competent and strong. The objective was to analyze the reduced stability due to the weak bands prior to analyzing the impact of a weak floor. Next, a series of models were analyzed where floor directly below the pillars with defects had its strength slowly reduced. The objective was to find a critical floor strength that caused instability to the full system (roof, pillar, and floor). Finally, a series of models were analyzed where increasing moisture content and pore-pressure effects were simulated by decreasing the effective friction angle inthe floor. The objective was to analyze the impact of moisture in the floor to the instability in the full system.

### 3.1. S-pillar strength calculation for the solid Vanport limestone seam pillar

The S-pillar software uses an empirically based method to calculate a stability factor for stone mine designs. Included in the S-pillar analysis is an equation used to calculate the pillar strength that takes into consideration the laboratory uniaxial compressive strength, large discontinuities, pillar width, and pillar height. S-pillar was used as a starting point for this study to estimate the strength of a solid Vanport limestone seam pillar and the tributary area stress caused by the excavation dimensions and depth used at the Petersburg Mine.

After adding the mining dimensions of the Petersburg Mine and geotechnical properties of the Vanport limestone seam into S-pillar, the software estimated the pillar strength to be 39.4 MPa, as shown in Fig. 1.

The factor of safety using these mining dimensions and seam properties was calculated to be 5.87. Therefore, the tributary area stress approximation could be back-calculated using the pillar strength. The approximate stress in the pillar was calculated to be 6.71 MPa. For the scenarios analyzed in this study, the critical floor strength was determined at the value that caused the pillar strength to fall below 6.71 MPa.

### 3.2. FLAC3D calibration of the solid Vanport limestone seam pillar

A FLAC3D Mohr–Coulomb strain softening numerical model was created to estimate the strength of a solid Vanport limestone

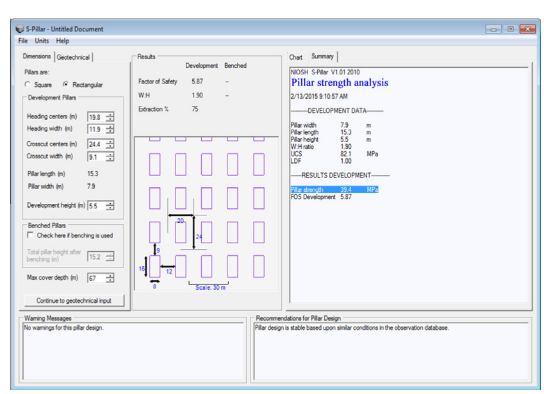

**Fig. 1.** S-Pillar strength analysis results for a solid Vanport limestone seam pillar.