Rock Mechanics for Industry, Amadei, Kranz, Scott & Smeallie (eds) © *1999 Balkema, Rotterdam, ISBN 90 5809 052 3*

Description of a large catastrophic failure in a southwestern Wyoming Trona Mine

R.K.Zipf Jr.
Department of Mining Engineering, University of Missouri-Rolla, Mo., USA

P.Swanson
Spokane Research Laboratory, National Institute for Occupational Safety and Health, Wash., USA

ABSTRACT: A large-scale collapse occurred in a room-and-pillar trona mine in southwestern Wyoming on February 3, 1995. An area measuring approximately 1 by 2 km (2800 by 7200 ft) collapsed abruptly without warning. This paper describes the resulting mine damage, airblast, gas emissions, and seismic event. The collapse is analyzed in terms of a cascading sequence of pillar-floor failure using established principles of failure stability. The dynamic nature of the failure is thought to stem from geological and mine geometry factors resulting in a "soft" pillar-loading system. While the specific mechanism initiating the collapse has not been identified conclusively, four candidate mechanisms are considered. Design methods to decrease the potential for large-scale collapse are summarized, and limitations in our ability to evaluate both the stability of old workings and long-term performance of new designs in this setting are described.

1 OVERVIEW OF MINING OPERATION

The Solvay Minerals mine (Green River, WY) uses the room-and-pillar method to produce trona from beds at depths ranging from 460 to 520 m (1500 to 1700 ft). Trona is an evaporite mineral composed of sodium carbonate, sodium bicarbonate, and water, and the beds lie within interbedded shales and marlstones. Figure 1*A* shows part of the overall mine layout. A set of east-west mains seven to eight entries wide and set of north-south mains provide access to the panels. Two shafts, one for intake and production and the other for exhaust, intersect the trona bed about 365 m (1200 ft) east of the north-south mains.

Initial production began in the southeast and northwest panels, and recent production came from the northeast, southeast, and southwest panels. The northwest panels had been backfilled completely with process plant waste. The northeast panels were being backfilled at the time of the collapse. The southeast and southwest panels were not backfilled because there was an insufficient amount of process plant waste.

Figure 1*B* shows the 13 panels of the southwest section that collapsed. The section measures approximately 1 by 2 km (2800 by 7200 ft). Chain and panel pillar designs changed as equipment use and mining practice evolved. Continuous-bore miners are currently used for production. Figure 1*C* shows typical layouts of rooms and pillars in the more recent southwest panels. Room width is about 4.6 m (15 ft), chain pillar dimensions are approximately 12 by 14 m (40 by 47 ft), and panel pillar width is about 3.8 m (12.5 ft). Rooms between panel pillars are driven about 70 m (230 ft) deep, making the overall panel width approximately 183 m (600 ft) between the edges of the panel isolation pillars. The isolation pillar between panels is for ventilation control since the mine is gassy. There is a 36-m (120-ft) wide pillar between panels 7W and 8W and an 18-m (60-ft) wide pillar between panels 8W and 9W. Barrier pillars range from about 30 to over 60 m (100 to 200 ft) wide along the south mains. The barrier pillar along the bleeders at the back of the southwest panels ranges from 12 to nearly 30 m (40 to 100 ft) wide.

2 COLLAPSE DESCRIPTION

The collapse occurred without any obvious short-term warning on the morning of February 3, 1995. Miners working near the southwest panels reported that they heard a rumbling, a big boom, and then a deafening sound lasting 5 to 6 sec in all. The collapse resulted in structural damage to the mine, an airblast, and ammonia and methane emissions.

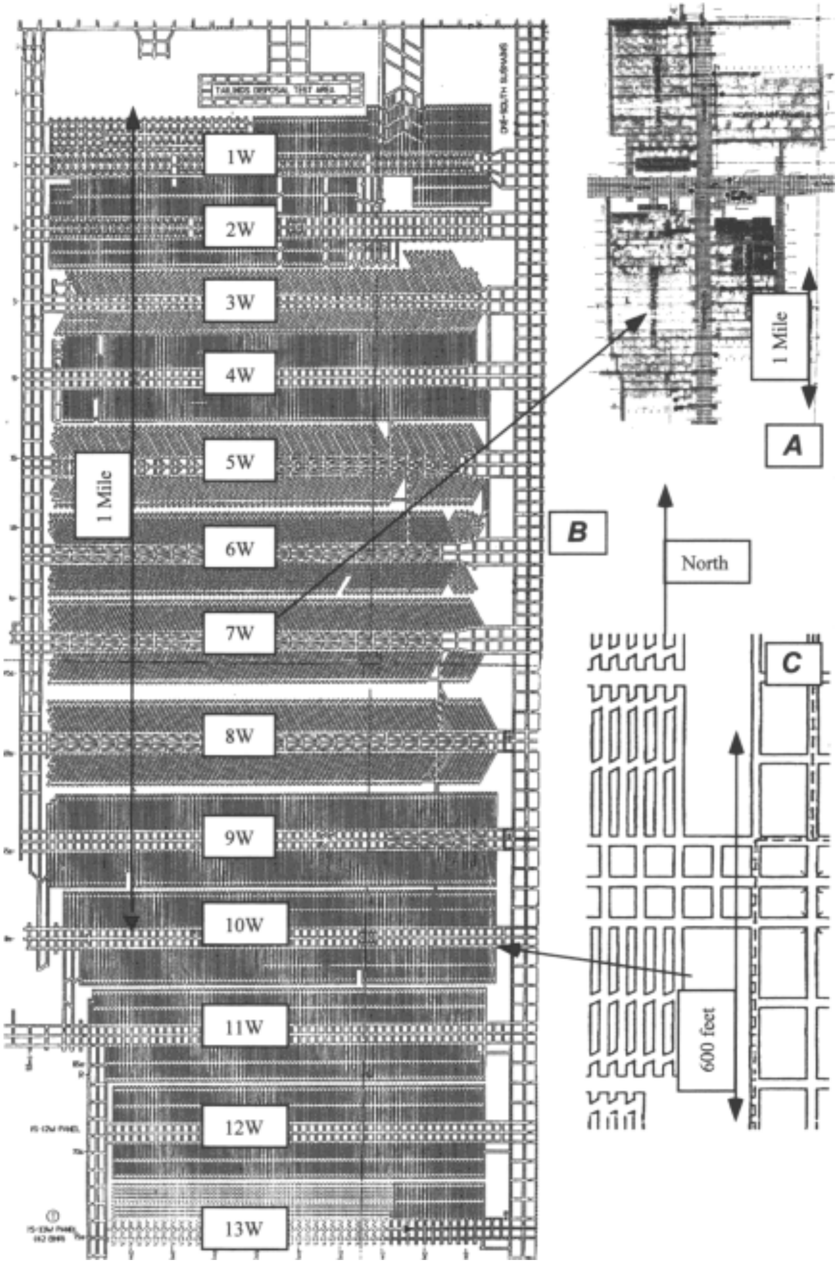

Figure 1. *A*, Overall layout for part of mine; *B*, layout of southwest panels that collapsed; *C*, details of typical panel (MSHA, 1996).

All 13 panels in the southwest section of the mine (Fig. 1*B*) collapsed completely or were severely damaged, except around the section perimeter. Panel entries in these areas were heavily damaged and generally not travelable. There was no collapse of panels elsewhere in the mine. The entire area over the southwest panels subsided between 0.75 to 0.9 m (2.5 to 3 ft), and maximum subsidence was estimated at 1.04 m (3.4 ft). Prior to the collapse, little subsidence was observed over the southwest section. Incidents of mine collapse usually entail failure of pillars; however, in this case the collapse involved failure of both the pillars and the immediate floor material. As observed around the perimeter of the southwest panels, the upper pillar and immediate roof rock in the production rooms remained intact, and failed rock erupted from the immediate floor and lower pillar. Cutter-type roof failure was generally observed in some gateroads, but not in production rooms. Gateroad pillars were shattered, and shear displacements between layers with contrasting mechanical properties facilitated movement of material from pillars into the gateroads.

The collapse produced an airblast that destroyed ventilation control devices throughout the south mains and short-circuited the ventilation in these areas. Air forced from the collapsing panels caused an airflow reversal and vented from both the exhaust and intake shafts for about 17 min.

The collapse liberated enormous quantities of methane (CH_4) and ammonia (NH_3) into the mine atmosphere. An estimated 2.8 million m^3 (100 million ft^3) of methane were liberated from the collapsed area, presumably from broken shales in the roof and floor, which served both as a source of methane and as a barrier to the migration of methane. The highest emission per day was about 0.85 million m^3 (30 million ft^3). In some underground areas, methane levels were above the 15% upper limit for an explosive atmosphere immediately following the event. In spite of the presence of possible ignition sources (diesel equipment) and destruction of the ventilation controls in the south mains, no explosion or ignition occurred. Methane emissions from the mine returned to normal levels of about 28,300 m^3/d (1 million ft^3/d) about 3 months after the event.

Ammonia was also liberated in significant quantities. Its source is believed to be the broken trona and oil shales. Elevated levels of carbon monoxide (CO) were also present after the collapse. The CO is thought to emanate from the kerogen-rich layer of oil shale in the immediate floor. Three months after the collapse, gas concentrations at the bleeder connection for the southwest panels were CH_4 - 2.7%, CO - 110 ppm, and NH_3 - 18 ppm.

3 SEISMIC RECORD AND INTERPRETATION

Seismometers operated by the Bureau of Reclamation, University of Utah, U.S. Geological Survey, and other institutions recorded the collapse event, which registered 5.1 M_L (local magnitude) and was one of the largest seismic events ever associated with a mine collapse.

Early investigative efforts focused on understanding the source of the seismic event. As the southwest Wyoming trona district does not have a long history of notable mining-induced seismic activity, initial speculation targeted a natural earthquake as the cause of the mine damage. However, detailed seismological studies by Pechmann et al. (1995) and Swanson & Boler (1995) concluded that the seismic energy emanating from the vicinity of the mine was not a tectonic or natural earthquake, but rather the recorded seismic energy resulted from a mine collapse mechanism.

Figure 2 summarizes seismic event locations reported by the University of Utah, the Bureau of Reclamation, and the National Earthquake Information Center for this event. As this area is not associated with significant natural seismic activity, coverage by regional seismograph stations is sparse. One useful measure of the uncertainty in the location calculations comes directly from a comparison of the location coordinates reported by the different groups (Fig. 2). The consensus among seismologists is that the event location is consistent with the location of the damaged mine workings in the southwest section of the mine.

Focal mechanism analysis by Swanson & Boler (1995) and waveform modeling by Pechmann et al. (1995) show that an implosional (mine collapse) source mechanism rather than a faulting-type source mechanism best explains the observed seismic radiation. Furthermore, the observed seismic energy release is about one-tenth the gravitational potential energy loss due to subsidence. These studies concluded that the mine collapse released sufficient potential energy to account for the observed seismic energy without additional sources from natural earthquakes.

During initial investigations of the cause of the seismic event, the possibility was suggested that a small tectonic earthquake triggered the large-scale mine collapse. This earthquake trigger would necessarily involve shear-slip through some part of the earth's crust near the mine. Swanson & Boler (1995)

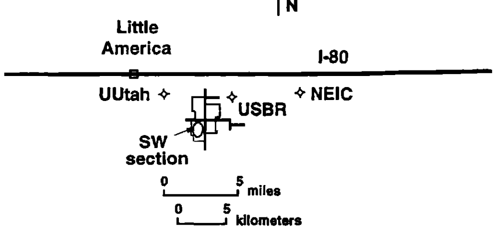

Figure 2. Calculated epicenter for Feb. 3, 1995, event (Swanson & Boler, 1995)

present an analysis of this possibility and conclude that a small tectonic earthquake trigger was unlikely.

4 COLLAPSE MECHANISM

Researchers at the U.S. Bureau of Mines (USBM) suggested that the mine collapse was a "progressive pillar collapse," also known as a "domino-type failure." Because of its rapidity, Swanson & Boler (1995) coined the name "cascading pillar failure" (CPF). In this mechanism, when one pillar fails, the load that it carried is transferred rapidly to adjacent pillars, causing them to fail and leading to the rapid collapse of very large areas of a mine. Once CPF has begun, it becomes self-propagating. Loads on intact pillars immediately adjacent to the failure area increase as the extent of the failure increases, thereby driving the failure. CPF continues until all pillars in the array have failed or when a solid abutment or substantial barrier pillar is reached. No other failure mechanism has emerged to explain the mine collapse and the ensuing seismic event, airblast, and explosive gas release.

The principles governing failure stability are well known from laboratory-scale rock testing. Rock failure has been shown to be stable or unstable depending upon the relative stiffness of the testing machine and rock sample (e.g., Cook & Hojem, 1966). Using a simple spring model to describe such laboratory experiments, Salamon (1970) formulated the general stability condition of the loading machine-rock sample system in terms of system stiffness and the slope of the sample's load-displacement, or stress-strain, curve. Whether a rock specimen fails in a stable, nonviolent manner or in an unstable, violent manner is determined by this stability criterion. When the slope of the post-peak load-deformation curve becomes more shallow than loading machine stiffness (Fig. 3), failure is unstable.

The laboratory system stability criterion was then extended by Salamon (1970) to full-scale mine pillars using the concept of local mine stiffness (LMS). This criterion compares local mine stiffness to post-failure pillar stiffness. LMS, represented by the slope k_m in Figure 3, depends on both the modulus of the rock mass and the size, spacing, and spatial arrangement of pillars. The presence of barrier and other large pillars tends to increase local mine stiffness, whereas smaller pillars mined under higher extraction ratios tends to decrease local mine stiffness. Unstable failure of brittle materials is promoted by the decreasing stiffness of the loading system.

Laboratory tests show that the stiffness of the shale (Young's modulus ~ 3.5–10.3 GPa [0.5–1.5 million psi]) and oil shale (Young's modulus ~ 2.1–7.0 GPa [0.3–1.0 million psi]) in the immediate roof and floor, respectively, is approximately one-sixth that of the trona (Young's modulus ~ 21–35 GPa [3.0–5.0 million psi]). The combination of low-modulus roof and floor materials and small pillars provided low load system stiffness over a large expanse of the southwest section. Unfortunately, measurements of the strength, modulus, and post-failure behavior of full-scale trona pillars with an oil-shale foundation are unavailable for analyzing in situ conditions rigorously.

5 COLLAPSE INITIATION

If indeed CPF was the pillar collapse mechanism, a more difficult question arises as to what initiated or triggered it. During investigations into the collapse, four different trigger mechanisms for the collapse evolved.

(1) Long-term degradation in the strength of the pillar-floor system.

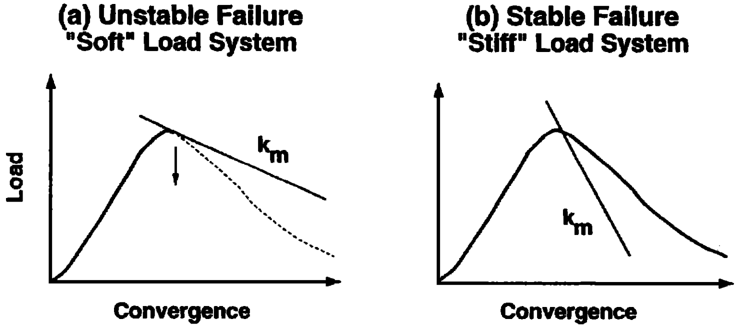

Figure 3. Unstable violent failure (*A*) versus stable nonviolent failure (*B*) (Swanson & Boler, 1995)

(2) Failure of the barrier pillar between the 7W and 8W panels.
(3) Failure of the Tower Sandstone bed and collapse of the pressure arch.
(4) Gas pocket collapse in the floor in the anomalous zone.

Understanding exactly what triggered the mine collapse is essential for assessing the likelihood of this event happening in other parts of the mine and perhaps other mines in the trona mining district. Also, understanding the triggering mechanism may influence the choice of preventive measures to decrease the risk of another collapse elsewhere. Table 1 summarizes the four triggering mechanisms considered by MSHA investigators, major supporting evidence, contrary evidence, and possible measures for preventing a reoccurrence of this type of event.

The first candidate for a triggering mechanism is the simplest of those which have been suggested —gradual degradation of strength in the panel pillars. Production rooms throughout the mine are commonly associated with floor heave and pillar degradation that increases with time following mining. Some of the stress and convergence monitoring data collected from the northern end of the southwest section, as well as visual observations, are consistent with pillars slowly loading up and failing with time. Local loss of pillar-floor load-bearing capacities, which further reduced mine stiffness in the immediate surroundings, initiated the unstable progression of pillar-floor failure.

Sudden failure of the 36-m (120-ft) wide barrier pillar and pillar foundation between the 7W and 8W panels (Fig. 1*B*) represents the second candidate mechanism. Upon failure, overburden loads carried by this centralized pillar were suddenly transferred to the smaller adjacent panel pillars, and large-scale instability ensues. Evidence of failure in the barrier pillar and the barrier pillar roof and floor was not found in direct borehole and seismic reflection investigations.

The third triggering mechanism is sudden failure of a strong roof member that initially shielded the pillars from overburden loads through the formation of a pressure arch. The pressure arch transferred overburden stresses to the solid abutments and barrier pillars. Such a candidate stratum would be the 85-m (275-ft) thick Tower Sandstone located 105 m (350 ft) above the trona seam. Sudden failure of the strong roof member resulted in sudden loading of the panel pillars, thereby initiating cascading pillar failure.

The last triggering mechanism is proposed on the basis of some of the unusual properties associated with an anomalous region in the southwest end of the southwest section. In this scenario, the anomalous region, where small pockets of high-pressure gas were observed, served as a structural trap for "formation gas." A large volume of formation gas is assumed to have emerged from the floor shortly before the collapse, resulting in localized floor subsidence. The unusually strong roof in the anomalous zone supported the additional load until it failed suddenly, loading the unusually weak pillars and subsequently initiating large-scale failure.

6 CONCLUDING REMARKS

Mines utilizing the room-and-pillar method should seek layouts robust enough to resist uncontrolled collapse regardless of how it is initiated. One design approach is "containment" in which small panel pillars are surrounded by large barrier pillars. The barrier pillars shield the panel pillars from full overburden stresses and thereby increase their safety factor and decrease their probability of failure. The panel pillars can still undergo a cascade-type failure; however, should such failure be initiated, the design prohibits propagation beyond the surrounding barrier pillars. A second approach is "prevention," in which only large pillars are developed. The panel pillars are sufficiently strong and have desirable post-failure characteristics (i.e., satisfy the local mine stiffness stability criterion) and therefore cannot fail violently. These two design approaches effectively stiffen the loading system. The third approach is "full-extraction mining" that eliminates the possibility of pillar collapse altogether by ensuring complete opening closure (and surface subsidence) upon completion of retreat mining. In lieu of barrier pillars, a layout can utilize strategic placement of stiffening backfill to decrease the risk of runaway failure.

While the principles behind CPF are fairly well understood, there are practical limitations to our ability to use numerical models to evaluate both long-term stability of old workings and performance of new mine designs. The limitations stem from a lack of—

- Suitable information on the strength, modulus, and post-failure behavior of composite, full-scale roof-pillar-floor sequences,
- Knowledge of in situ material properties and deformation mechanisms under dynamic loading conditions,
- Simple assessment techniques to delineate and monitor how stresses are structurally transferred between production room pillars, gateroad-barrier pillars, and solid abutments in large panel sections.

Table 1. Summary of supporting and opposing factors for four triggering mechanisms and their preventive measures (MSHA, 1996)

	Long-term strength degradation of panel pillars	Barrier pillar failure between panels 7W and 8W	Pressure arch collapse	Gas pocket collapse
Supporting factors:				
1	Degradation of panel pillars observed	Degradation of panel pillars observed	High stresses at panel edges before failure	Large gas pockets observed in trona
2	Pillars highly stressed	Models show violent failure of 7W-8W barrier pillar is possible	Models show this a possibility	Alternate account for methane release
3	High stresses at panel edges before failure	Gives "big kick"	Gives "big kick"	Gives "big kick"
4	Models show this a possibility	Failure goes in two directions		
Opposing factors:				
1	No precursors seen	Violent failure of barrier pillar unusual	Bridging distance	Degradation of panel pillars observed
2	Failure propagated over 7W-8W barrier pillar	Abutment pillars have not failed	No evidence of stress shielding of panel pillars	Failure propagated over 7W-8W barrier pillar
3	Gradual failure does not give "big kick"	Corehole does not show failure		
Preventative measures:		Seismic reflection shows this pillar intact		
1	Alternate mine plan	Alternate mine plan	Alternate mine plan	Alternate mine plan
2	Backfill southeast panels	No backfilling needed in southeast panels	Backfill southeast panels	No backfilling needed in southeast panels
3	Monitor stress and convergence	Monitor stress and convergence	Monitor stress and convergence	Probe for gas pockets

- Opportunities to field test model simulations all the way through to the unstable failure stage.

Such rock mechanics knowledge is critical for utilizing the design approaches discussed. However, we must recognize the limits of such knowledge, conduct proper risk assessments, and plan mining systems accordingly.

REFERENCES

Cook, N.G.W. & J.P.M. Hojem 1966. A Rigid 50-Ton Compression and Tension Testing Machine. *J. S. Afr. Inst. Mech. Engr.* 1:89-92.

Mine Safety and Health Administration, US Dept. of Labor 1996. Report of Technical Investigation, Underground Nonmetal Mine, Mine Collapse Accident.

Pechmann, J.C., W.R. Walter, S.J. Nava, & W.J. Arabasz 1995. The February 3, 1995, M_L 5.1 Seismic Event in the Trona Mining District of Southwestern Wyoming. *Seismo. Res. Let.* 66(3): 25-34.

Salamon, M.D.G. 1970. Stability, Instability, and Design of Pillar Workings. *Int. J. of Rock Mech. & Min. Sci.* 7:613-631.

Swanson, P.L. & F. Boler 1995. The Magnitude 5.3 Seismic Event and Collapse at the Solvay Trona Mine: Analysis of Pillar/Floor Failure Stability. U.S. Bur. Mines Open File Rep. 86-95, 82 pp.

Laboratory testing