Madencilik - Mining, 2023, 62(4), 159-166

BİLİMSEL MADENCİLİK DERGİSİ
SCIENTIFIC MINING JOURNAL

TMMOB Maden Mühendisleri Odası Yayını / The Publication of the Chamber of Mining Engineers of Turkey

www.mining.org.tr

Orijinal Original

Investigation of Subsidence Induced by the Production of Sublevel Caving Method in Divrigi Ekinbaşı Underground Iron Mine

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Received: 6 July 2023 • Accepted: 28 January 2024

A B S T R A C T

In this study, the subsidence induced by sublevel caving production method applied in the Divriği Ekinbaşı underground mine was investigated and evaluated. In this context, on-site observations and measurements were made in the underground mine. Two point cloud datasets with an approximately seven-month time difference were analyzed, and surface collapses, cracks, and fractures were plotted on the map for each periods, the fracture initiation and subsidence angles of hangingwall and footwall sides were determined. As a result of the analysis of first and second data sets, subsidence angle of the hangingwall side remained the same as 50.40°, in the footwall side 72.84° and 53.44° respectively. The areas of fracture and subsidence regions increased by 4.67 ha and 7.67 ha, respectively, over a period of around seven months.

Keywords: *Sublevel caving method, Subsidence, Fracture initiation and subsidence angles.*

Introduction

As is well known, the production methods commonly used in underground mining are classified into three main class as supported, non-supported, and caving methods. Ore geometry and shape (thickness, strike, inclination, depth, etc.), reserve and amount of production, grade and grade distribution, ore-wallrock contact condition, geologic and tectonic structure, strength of ore and wallrocks, groundwater condition, surface and economic conditions are all taken into account during the selection of underground mining method. With the acceptance of the surface subsidence, the caving methods can be selected and applied.

Sublevel caving has been widely used since its introduction in Sweden in the 1960s, particularly in metal mining, due to its advantages such as simple structure, flexibility, and high mechanization (Shuai et al., 2016). In sublevel caving method, the vein is divided into vertical slices that are quite close to each other, typically between 10-30 m (Figure 1). Production is carried out from top to bottom in the ore body, with sublevels prepared at regular intervals. Production galleries that have been driven perpendicular to or parallel to the orebody in the horizontal plane systematically form sublevel. In thick orebodies, sublevel production galleries are started from the footwall drift and driven up to the hangingwall drift. Sublevel caving is commonly used in deep and steep (>60°) orebodies, but it can also be applied to very thick and massive deposits. The hangingwall can be weak to strong, but it must cave spontaneously or be blasted after the ore is produced. Since there is no filling, the hangingwall must have caved towards the chamber of produced ore. This caving result in serious collapse on the surface and subsidence pits may appear. In this respect, continuous caving is crucial to prevent voids in wallrock, which leads to a sudden collapse that can damage the surface installations.

In this study, the subsidence induced by the production of sublevel caving method in Ekinbaşı underground iron mine was investigated. This underground mine is located within the borders of Divriği district of Sivas province. First, observations and measurements were both performed on the surface and inside the mine, and the results of the study were evaluated in light of the relevant literature.

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https://doi.org/10.30797/madencilik.1323500

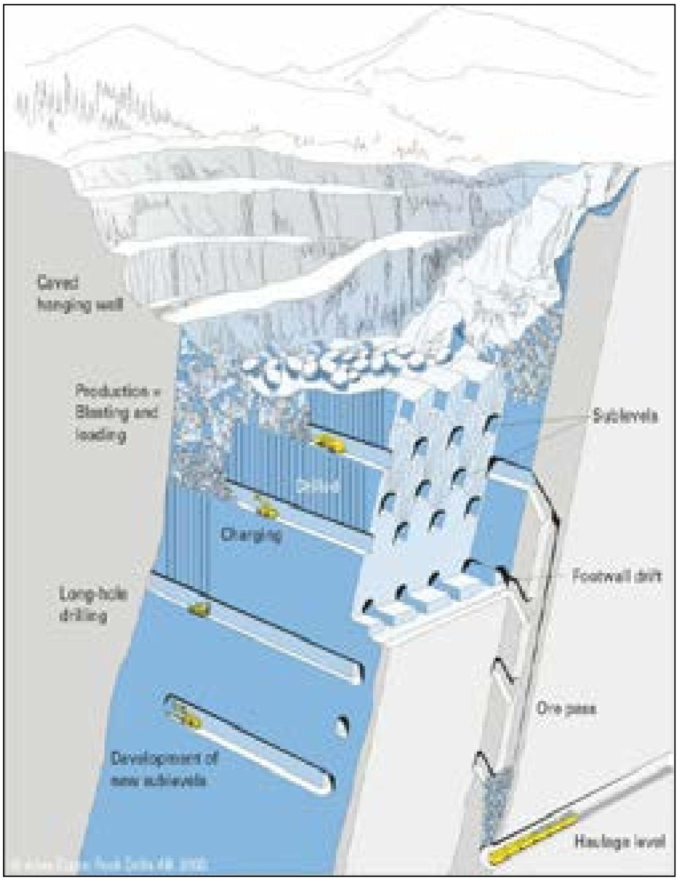

Figure 1. Sublevel caving mining (Hamrin, 2001)

1. Subsidence in sublevel caving method

Surface deformations induced by underground mining have distinct properties that vary depending on the mining method used. During sublevel caving mining, a large-scale subsidence occurs on the surface of the hangingwall side and a smaller subsidence occurs on the footwall side (Herdocia, 1991; Lupo, 1996). The hangingwall subsidence area is divided into three zones: the caved zone, the fracture zone and the continuous deformation zone. (Figure 2). The caved zone is formed by large-scale movement of the wallrock surface layer. The size of the area can range from millimeters to several meters and is typically composed of irregular blocks.

Sometimes natural shafts may also be observed on this area. After ore extraction, these shafts are formed by caved rocks moving downward in the direction of the flow. The fracture zone is defined by stress cracks close to the caved area, fractures, benches and irregularly formed sinks near the caved area. The displacements in this area develop with horizontal and vertical movements ranging from centimeters to meters. Lupo (1996) described the nature of the movement in this zone as a combination of shear and toppling mechanisms similar to those seen in surface rock slopes. The blocks formed in the fracture zone can mix with the rocks in the caved zone. This area is defined as unstable and unsafe for civilian structures. The continuous deformation zone is defined by deformation development ranging from millimeters to centimeters. The surface area of the subsidence zone is usually larger than the extracted area (Blodgett and Kuipers, 2002). The extension of this zone varies depending on the production method and rate, the depth and size of the orebody, the fracture and crack structure of the hangingwall and footwall rocks, their strength, swelling factors, geological discontinuities, surface topography and groundwater level.

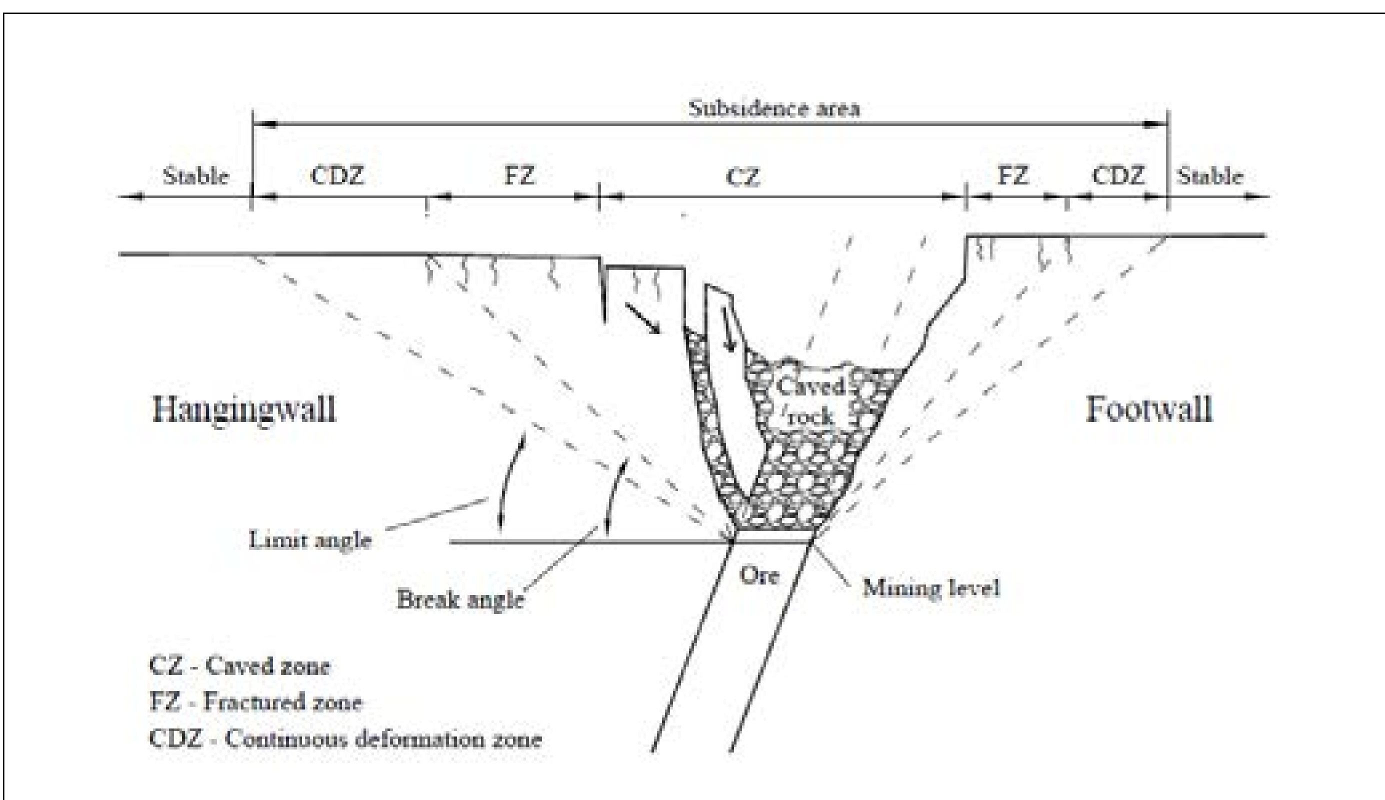

Figure 2. Surface deformation zones at mines with sublevel caving mining method (Barba, 2008)

The angle of fracture, which is used to define the boundary of the fracture zone, is mostly determined using the equilibrium limit method. On the other hand, the expansion of the subsidence area is determined by analyzing the recorded data. The equilibrium limit method is based on assumptions similar to those used in rock slope stability analysis. This approach was utilized by Hall and Hult (1964) with the assumption that failure happened along a single plane between extraction and surface (Barba, 2008). Following this idea, Hoek (1974) developed an equilibrium limit approach to estimate the hangingwall failure for great extraction depths. Hangingwall was supposed to be a rock slope whose base was the bottom of the excavation. As the mining goes downwards, the extraction at the base gradually caves in the hangingwall. It was assumed that there would be a planar shear failure from the extraction bottom to the tension crack on the surface, adding the effect of collapsed rocks. This failure is assumed to occur under static conditions. Sensitivity analyses of the Grängesberg iron mine in Sweden, where the sublevel caving method was used, showed that the fracture angle is highly influenced by the rock mass properties and the depth of mining (Hoek, 1974). Subsidence had occurred in the Swedish-Kiirunavaara underground iron mine due to the using of sublevel caving method, affecting certain areas of Kiruna city, the railway, and the power station. (Villegas et al., 2011). Brown and Ferguson (1979) developed the equilibrium limit method, which takes into account the inclined ground surface and shear plane and the water pressure in the stress crack (Figure 3). Lupo (1996) improved Hoek's equilibrium limit method by accounting the tensile forces occured during ore extraction and the interaction between the hangingwall and the footwall. When the ore is extracted, the caved rocks create tensile forces that will increase the shear stresses on both sides.

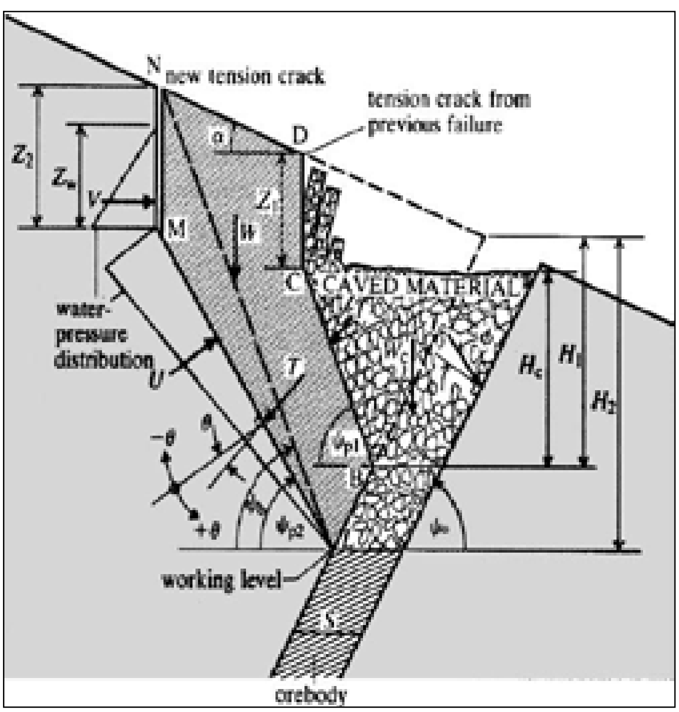

Figure 3. Idealized model used in limit equilibrium analysis of progressive hangingwall caving (Brown and Ferguson, 1979)

1.1. Some underground mines applied sublevel caving method

In the sublevel caving method applied in the Kiruna underground iron mine that is owned by the LKAB in Sweden, the hangingwall is continuously caving while the ore is drawn. This condition results in large-scale subsidence on the surface. The most serious condition in the Kiruna mine is that large-scale collapsing problems have begun on the surface side of the footwall. Ventilation shafts, ore passes, and parts of the haulage level and ramp located near the orebody have been subjected to substantial instability. (Sjoberg, 1996). The Malmberget iron mine, which has rather large orebody and uses the sublevel caving method, is also held by LKAB. Hangingwall collapses caused widespread surface subsidence, similar to the Kiirunavaara mine. Especially, the Kapten section of the orebody has caused extensive subsidence and thus the affected parts of Malmberget city had to be replaced. Kapten part of the orebody had been initially operated as an open pit mine. However, unlike the Kiirunavaara mine, no failures were observed at the footwall side here. (Sjoberg, 1996). Large-scale failures have also happened in other underground mines in Sweden that used sublevel caving, such as the Grängesberg mine. Similarly, an unpreventable large-scale failure occurred on the hangingwall side of the Långsele mine. The underground mine reached and merged with the surface as a result of the failure recorded in the form of crack and significant displacements which developed very quickly (Sjoberg, 1996). Woo et al. (2013) compiled subsidence data for some underground mines applied sublevel caving/shrinkage stoping/top slicing mining methods in the world. (Table 1).

2. Evaluation of subsidence

2.1. Ekinbaşı underground iron mine

Investigations and measurements were conducted on the surface of the Ekinbaşı underground iron mine (Figure 4), as well as in sublevels, footwall drifts and haulage level, as part of this study (Erdem et al., 2019). Sublevels of Ekinbaşı underground iron mine were opened with the advancement of ore connected footwall drifts. The orebody properties taken into account during evaluation of applied mining method are given in Table 2. These galleries with a cross -sectional area of 22.5 m^2, were opened in the footwall which were parallel to the ore boundary and advanced to the point where the mineralization ends. Then, the galleries with 10 m intervals, in the same size as the footwall drift were continued until the boundary of the ore. Ore boundaries were determined by vertical or inclined drilling to the drift face or side walls and taking into account the traces of ore in the sublevel maps (Ceylanoğlu et al., 2022).

The ore production operations initiated from 1260 level in Ekinbaşı underground mine were advanced down with 12 m level intervals. The produced ore was transported to the ore well, which has a total length of 121 m, and then to the underground crusher, which has a capacity of 700 t/h and is located in the 1108 level. The underground crusher crushed the ore to -170 mm, which was then moved to the conveyor in the main haulage gallery and delivered to the processing plant. Ore production in the Ekinbaşı underground mine was started from 1260 level, it was advanced with a distance of 18 m intervals until the 1170 level, and after this level, it was extended to the 1134 level with 12 m intervals (Figure 5). Thus, 126 m part of ore was produced, from top to bottom.

Table 1. Subsidence data for some underground mines applied sublevel caving/shrinkage stoping/top slicing mining methods (Woo et al., 2013)

Mine	Orebody	Period Reported	Undercut Depth (m)	Caving Angle (°)	Fracture Initiation Angle (°)	Angle of Subsidence (°)	Data Confidence/Comments
Copper Mountain (B.C., Canada)	Contact block	1937-1949	350	79-90	69-74	65	Good (cross-section with scale bar).
	122-East Block	1941-1949	210	82-90	67-74	-	Good (cross-section with scale bar). Lower angle in range aligns with dipping fault.
Copper Queen – Queen Hill (Arizona, USA	Queen Hill Block	1913-1933	100	78	78	78	Marginal (cross-section without scale bar but with mine levels and depths; assumed to be drawn to scale). Caved block is bound on all sides by faults, along which the block drops and across which subsidence is limited.
Kiirunavaara/ Kiruna (Sweden)	700 Level	1965-1995	465	60-94	53-74	40-60	Marginal (subsidence map but without indication of the sublevel depth; sublevel depth estimated from other sources).
Kiirunavaara/ Kiruna (Sweden)	785 Level	1965-2000	500	50-82	50-60	40-50	Marginal. Angles on the footwall side are shown to coincide with one another at 50°.
Gath's (Rhodesia/ Zimbabwe)	99 Level	1971-1976	60	50-75	50-75	-	Good (cross-section with caving angles reported). Lower angles correspond with dip of orebody; steeper angles correspond to caving in dipping hangingwall.
	158 Level		120	50-65	50-65	-	
	183 Level		145	50-56	50-56	-	
Havelock (Swaziland)	Level 1	1952-1972	135	52-82	52-78	-	Good (cross-section with scale bar). Lower angles in range controlled by dip of bedding in footwall. Deformation in hangingwall develops through flexural toppling and shearing along bedding.
	Level 2	1963-1972	180	52-90	52-64	-	
	Level 3	1966-1972	225	52-90	52-60	-	
Miami (Arizona ,USA)	Main orebody	1910-1925	180	60-84	60-68	-	Good (cross-section with scale bar). Mostly mined by top slicing and sublevel caving. Caving limits controlled by vertical boundary drifts. Lower angles are subparallel to foliation of schist.
Mt. Lyell (Tasmania)	Cape Horn (#5 Stope)	1972-1980	160	70-86	70-72	-	Marginal (cross-section without scale bar but with sublevel depths; assumed to be drawn to scale). Lower angles coincide with dip of footwall (70°).
Perseverance (Australia)	10030 Level	1996-1997	490	66-87	63-90	-	Marginal (subsidence map without scale bar; depths determined from secondary information and used to calculate angles; assumed to be drawn to scale). Sublevel caving beneath large open pit. Lower caving and fracture initiation angles extend beyond pit limits on hangingwall side of orebody.
	9920 Level	1997-1998	600	73-81	63-81	-	
	9870 Level	1998-1999	650	74-80	63-80	-	
	9860 Level	1999-2000	660	70-80	62-80	-	
	9850 Level	2000-2001	670	70-83	62-83	-	
	9815 Level	2001-2002	705	73-85	65-85	-	
	9760 Level	2002-2003	760	72-84	66-83	-	
Rajpura Dariba (India)	South 465 Level	-	185	70-90	55-70	-	Poor (no data provided; angles cited in text). 70° angle coincides with dip of footwall.
San Giovanni (Italy)	Contatto Ovest	1985-1990	100	75-92	-	-	Marginal (subsidence map and cross-section without scale bar but with mining levels and depths; assumed to be drawn to scale).

Figure 4. Fractures formed on the surface of Ekinbaşı underground iron mine

Table 2. The parameters taken into account during the evaluation of actively applied mining method (Ceylanoğlu et al., 2022)

Parameters	Ekinbaşı underground iron mine
Orebody thickness (m)	40-70
Orebody length (m)	410
Depth to orebody top (m)	140
Depth to orebody bottom (m)	300
Dip angle (°)	50-55
Grade (% Fe)	52-56
Type of deposition	Scarn
Contact condition of ore-wallrock	Medium undulation
Strength of orebody	Fair-good
Strength of hangingwall	Poor-fair
Strength of footwall	Poor-fair
Groundwater (L/min)	10
Total proven reserves (tonne)	5 080 000
Production rate (tonne/yr)	600 000
Remaining life of mine (yr)	< 10
Surface conditions for subsidence (Buildings, private property areas, power transmission lines, rivers etc.)	Suitable

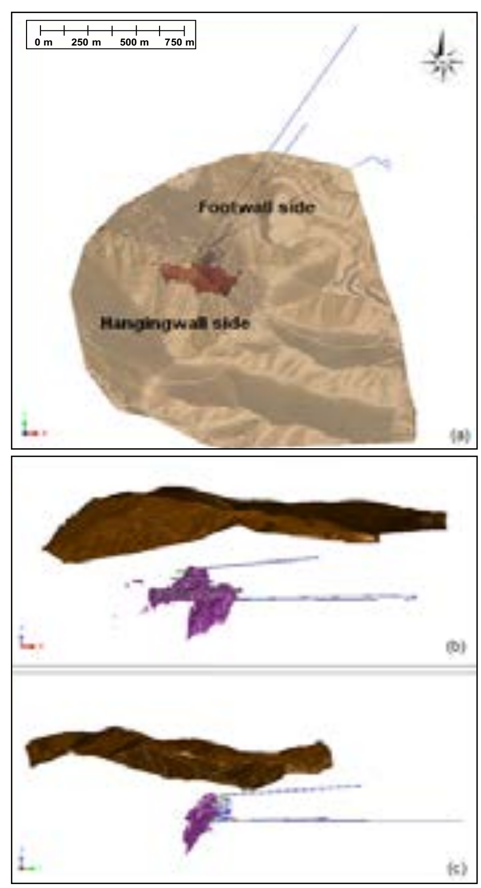

Figure 5. Ekinbaşı orebody, production levels and topography (a) Plan view, (b) Section view (towards north), (c) Section view (towards east)

2.2. Evaluation of subsidence

Similar to other underground mines around the world, the rooms created by ore production in Ekinbaşı underground mine were not filled with waste rock or other sorts of materials, but were left to cave. Due to the nature of the method, wall rock strata cave instead of produced ore. The caving of the wall rock strata activates the overburden layers towards the surface, resulting in large-scale surface subsidence.

Production activities in the mine were initiated from a certain roof level and continued towards the lower levels. As production progressed, the gap created by the obtained ore was filled by the immediate roof rock. Since the gap widens as it goes deeper, more wallrock yields and fills the rooms of the produced ore. Since the caving mechanism usually reaches the earth, subsidence, initially shows itself as minor cracks on the surface, later transformed into wide open major cracks, fault type fractures, and ultimately dolin type collapses.

Light detection and ranging (LIDAR) systems are sampling tools that emit numerous pulses in a short amount of time. After collecting each individual reading, the LIDAR system processes them into point cloud data, which includes pulses of light. From another aspect, point clouds are collections of spatial (3D) data points. They can be used to create digital elevation models of ground surfaces in mining. At its most fundamental level, a point data consists of x, y, and z coordinates that represent a specific location on earth. Point clouds can store attribute information about intensity, color, and time. Therefore, they can be used to monitor changes on the ground over time. Two point cloud data sets with high accuracy and resolution that permitted the investigation of the surface topography at the Ekinbaşı mine were taken over a period of almost seven months (203 days). The data was analyzed using a geographic information system software application in accordance with the Cartesian coordinate system, utilizing the ED50 datum and the 6° slice middle meridian. Surface collapses, fractures, and cracks could be detected and plotted on the map due to the high resolution of the data sets (Figure 6 and Figure 7). The collapse zone (CZ), major cracks (FZ), minor cracks (CDZ), and orebody projection (Coordinates to be Y and X; Northwest corner: 418363, 4365506; Northeast corner: 418768, 4365409; Southeast corner: 418715, 4365307 and Southwest corner: 418364, 4365394) were all processed on both figures. In the discontinuous deformation zone, there are large-scale collapse zones corresponding to the mine's projection on the surface. In proportion to the projection of the ore on the surface, wide-opening fracture cracks develop in common centered and ellipted. These are surrounded by narrow-opening deformation cracks. It was seen that in the period of approximately seven months between the dates of the first and second point cloud data, the effects of subsidence intensified, the collapse zone began to mature and the major fracture area and the minor crack area spread.

The Surpac mine planning package (https://www.3ds.com/products-services/geovia/products/surpac/) was used to determine the angles that characterize the subsidence occured on the surface of the Ekinbaşı underground mine (Table 3). The angles of fracture initiation and subsidence can be regarded to be consistent with the literature. The angles, on the other hand, decreased from the first to the second measure (203 days), and the cone base expanded. As the collapse zone expands in the following periods, the fractures around it will widen and turn into benches.

They will also be able to develop both downwards and towards the collapse zone that serves as the subsidence's center. On the other hand, since the continuous deformation zone is likely to spread further, this region, which limits the subsidence effect, should be monitored with displacement measurements that are repeated at regular intervals taking seasonal conditions into account. The subsidence basin generated on the surface is still in the maturation phase due to the activities carried out in the Ekinbaşı underground mine.

In a period of about seven months, the areas of fracture and subsidence regions increased by 4.67 ha and 7.67 ha, respectively. The development of these areas should be monitored at regular intervals using surface and/or air equipment capable of providing high-accuracy coordinate data via measurement stations placed in certain characteristic points on the surface, and surface motion vectors should be revealed. Thus, detailed information can be obtained about the development of the subsidence basin and will be able to make future predictions.

Sjoberg (1996) stated that the effects of subsidence were seen on the surface of the footwall side of the Kiruna underground mine, which operates in Sweden and produces approximately 27 million tonnes per year, and the most serious situation in the Kiruna mine was the larger - scale instability problems in the mine's footwall. Due to the fact that ventilation wells, ore passes, and some parts of the main entrance ramp were located so close to the orebody, they had subjected to significant instability (Sjoberg, 1996).

All developments, including transportation and ventilation wells, spiral ramp, and access galleries, are made on the footwall side of the steeply dipping ore body, while the hangingwall side is left to cave, according to the sublevel caving method used in the Ekinbaşı underground iron mine. Thus, the surface subsidence begins on the hangingwall side, and the fracture starting and subsidence angles on this side are characterized by lower angles corresponding to a wider area. This can be seen from Table 3 for the Ekinbaşı mine. During the field studies, access galleries and spiral ramp were investigated and there was no deformation in the well-gallery system due to subsidence. As production continues deeper, similar effects may occur on the footwall side. Hence, transport and ventilation wells, spiral ramp, and galleries should be monitored for these effects.

Table 3. Fracture initiation and subsidence angles at hangingwall and footwall sides of Ekinbaşı underground iron mine

Region	First measurement		Second measurement	
	Fracture initiation angle (°)	Subsidence angle (°)	Fracture initiation angle (°)	Subsidence angle (°)
Hangingwall side	61.45	50.40	54.57	50.40
Footwall side	73.65	72.84	62.65	53.44
Fractured zone area (ha)	14.28		18.95	
Subsidence area (ha)	39.50		47.14	

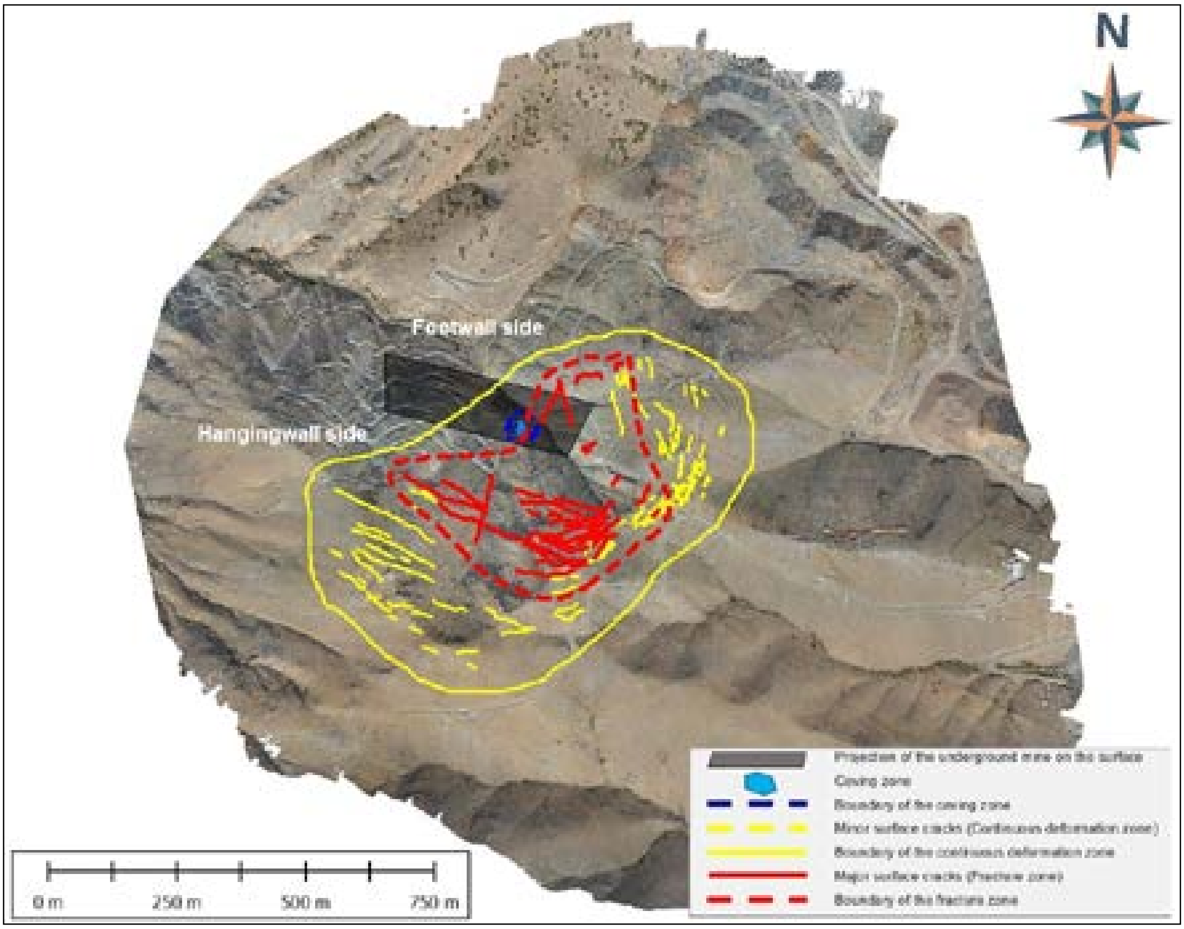

Figure 6. Fractures formed on the surface of Ekinbaşı iron mine (Using cloud data of first point)

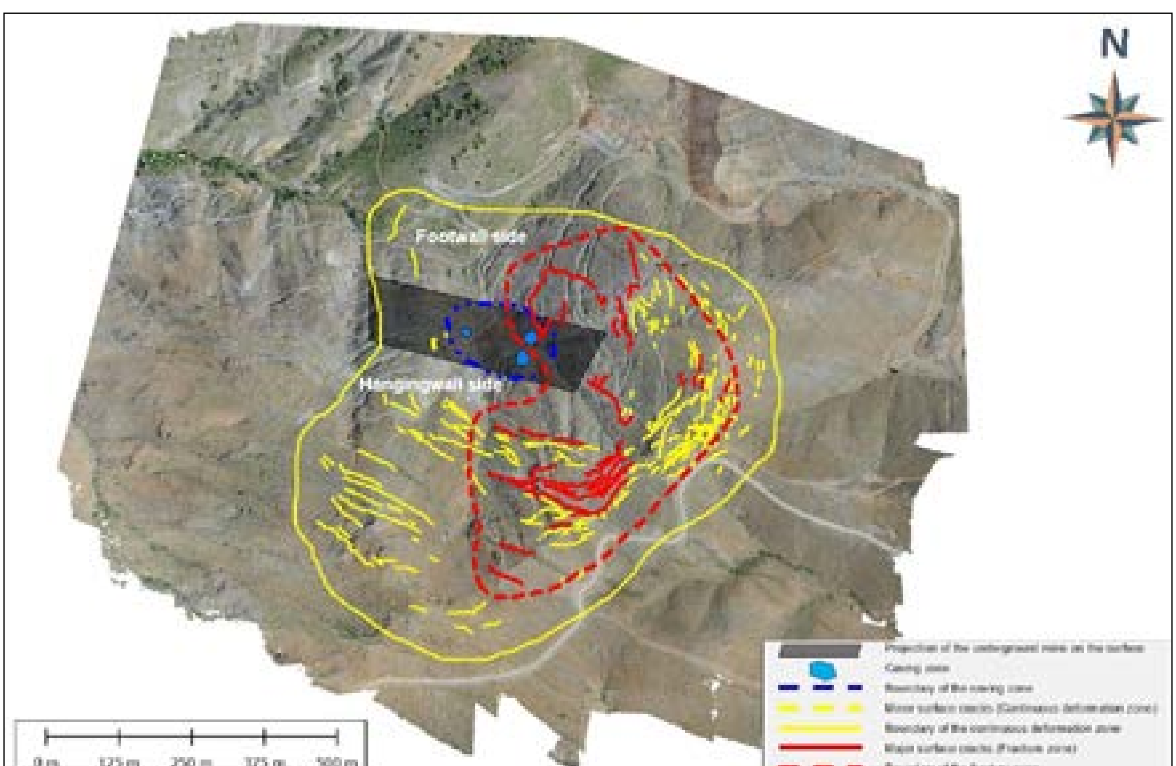

Figure 7. Fractures formed on the surface of Ekinbaşı iron mine (Using cloud data of second point)

3. Conclusions

In this study, the subsidence occured due to the sublevel caving mining method used in Ekinbaşı underground iron mine was investigated and evaluated. In accordance with the sublevel caving production method, since the rooms of produced ore were not filled with waste rock or other types of materials, but were left to cave. Due to the nature of the method, upper rock layers cave instead of the produced ore. The caving of the wall rock layers activates the upper layers towards the surface, causing a large-scale surface subsidence.

For Ekinbaşı underground mine, two point cloud datasets with a time difference of about seven months (203 days) were evaluated, and surface collapses, cracks, and fractures were shown on the map. By using the Surpac mine planning package, the fracture initiation and subsidence angles of hangingwall and footwall sides that characterize the subsidence occured on the surface of the Ekinbaşı underground mine were determined for each periods. The fracture initiation and subsidence angles of hangingwall side were determined as 61.45° and 50.40° and footwall side's were 73.65° and 72.84°, respectively for the first data set. For the second data set, the subsidence angle of the hangingwall side remained the same as 50.40°, where the fracture initiation angle was 54.57°. Therefore, in a period of about seven months, the areas of fracture and subsidence regions increased by 4.67 ha and 7.67 ha, respectively.

Due to the activities carried out in the Ekinbaşı underground mine, the subsidence basin occurred on the surface is still in the maturation period. To make future predictions about the subsidence basin, development of this area should be monitored at regular intervals.

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