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Investigation of possible causes of sinkhole incident at the Zonguldak Coal Basin, Turkey

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Abstract. The subsidence mechanism of ground surface is a complex phenomenon when multiple seam coal mining operations are carried out. Particularly, the coal mining beneath karstic formations causes a very special form of subsidence. The subsidence causes elasto-plastic deformation of the karstic layers and the collapse of cavities leads to dolinization and/or sinkhole formation. In this study, a sinkhole with a depth of 90 m and a width of 25 m formed in Gelik district within the coal-basin of Zonguldak (NW, Turkey) induced by multiple seam coal mining operations in the past has been presented as a case-history together with two-dimensional numerical simulations and InSAR monitoring. The computational results proved that the sinkhole was formed as a result of severe yielding in the close vicinity of the faults in contact with karstic formation due to multiple seam longwall mining at different levels.

Keywords: sinkhole, subsidence; karstic cave; underground coal mining

1. Introduction

Karst is a special landform formed by the solution of carbonate formations beneath the ground (Kohl 2001). The surface topography depends upon the solution characteristics of carbonate layers through ground water (Delle Rose and Leucci 2010, Ortiz and Crespo 2012). The solution of carbonate rocks results in various caves, dolines and swallets (Carrozzo *et al*. 2008).

Sinkholes are just one of many forms of ground collapse, or subsidence. Land subsidence is a gradual settling (as in the longwall mining) or sudden sinking (as in the room and pillar mining) of the Earth's surface owing to subsurface movement of earth materials. The principal causes of land subsidence are aquifer-system compaction, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost. Land subsidence can affect areas that are thousands of square miles in size (USGS 2017).

In shallow mining area, sinkhole subsidence is an abrupt local depression at the surface which can be hazardous to life and property due to its tendency to occur without warning. Shallow extraction, weak overburden and geological discontinuities are the main factors which cause them. Sinkholes occur due to the failure of a mine roof which migrates through the overlying strata until the failure zone intercepts the unconsolidated overburden. Alternatively they may occur by the creation of cavities in the overburden following the inflow of sand and soil from the overlying weathered and friable strata through faults. Overburden cavities eventually cave in and sinkholes appear at the surface (Singh and Dhar 1997).

Longwall mining operations may be affect the sub-surface streams, ponds, water table and aquifers to various degrees (Luo and Peng 2010). Especially, underground operations beneath karts areas would be problematic either mining operations or surface damage to the structures (Gongyu and Wanfang 1999, Yin and Zhang 2005). The structure of the cave could be affected by time and finally becomes a sinkhole depending on advancing of longwall panels. The cave system which have contact with a fault is even more affected by the mining activities.

The effect of mining on sinkhole occurrence in karstic regions is little known in literature. Although, there are some reports of major ground settlement in mined area including karstic caves (Li and Cheng 2012, Lei *et al*. 2015), the event occurred on January 1, 2012 in Zonguldak Coal Basin (ZCB) in Turkey has probably a unique case in the world so far. In addition, one may find many samples of sinkholes in the karstic region of various countries in the world, Aydan and Tokashiki (2013) investigated the stability of natural caves in Ryukyu limestone using analytical and numerical methods and developed some empirical guidelines how to assess their stability on the basis of numerous case history data.

Zonguldak Coal Basin has an important karstic topography in Northwest of Turkey (see Fig. 1). The coal seams were formed in Westphalian and Namurian stages of

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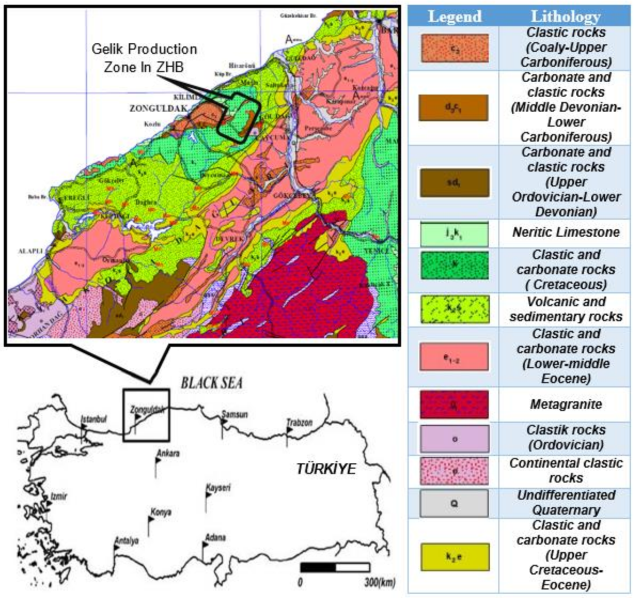


Fig. 1 Lithology and location of ZCB (MTA 2015)

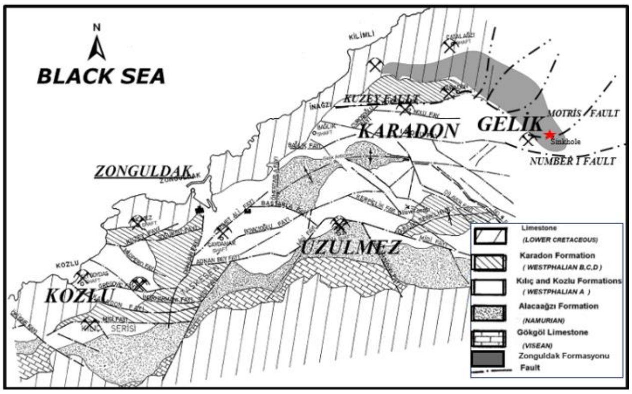


Fig. 2 Tectonics and formations of the region

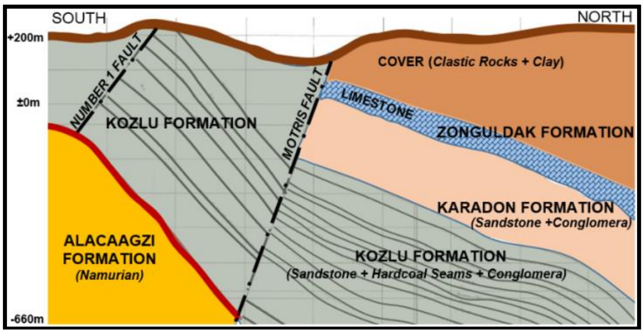


Fig. 3 Geologic cross-section of the region

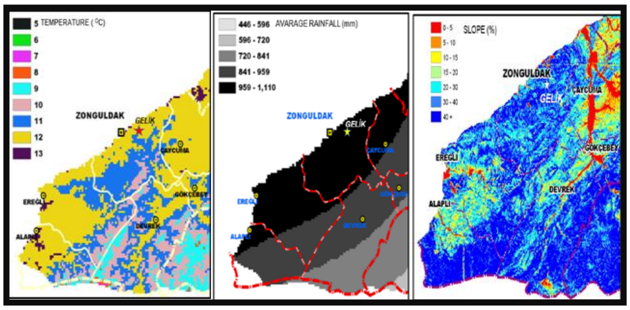


Fig. 4 Temperature, rainfall and slope maps (ÇŞB, 2007)

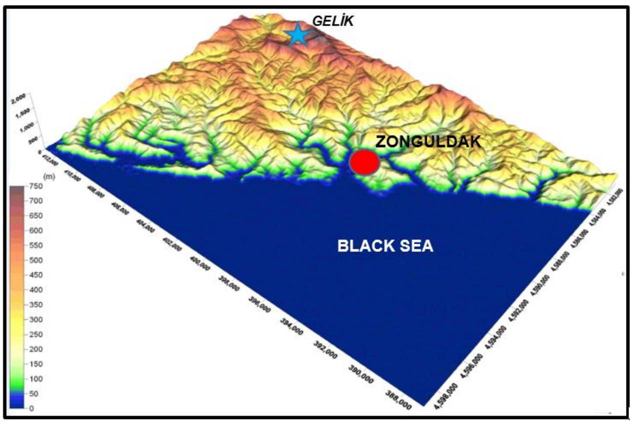


Fig. 5 Digital elevation model (DEM) of the region produced from SRTM data

Paleozoic-Carboniferous system and overlain by Cretaceous karstic limestones. Main four lithological units forming from top to bottom are Cenozoic-Quaternary, Mesozoic-Cretaceous, Mesozoic-Cretaceous and Paleozoic-Carboniferous respectively. Faults are the main tectonic features and they affect ground subsidence when they are in contact with karstic formations. One of the special subsidence forms is the sinkhole development.

In this study, the subsidence and sinkhole incidence in Gelik area have been presented and investigated using subsidence influence field modelling, surface deformation monitoring and finite element analysis.

2. Geology and hydrogeology of Zonguldak Coal Basin

The geology of the Gelik coal production panels, where the sinkhole is formed, consists of four formations, namely, Kozlu Formation, Karadon Formation, Alacaağzı Formation and Zonguldak Formation. The geological characteristics of the area of interest are as follow:

At the bottom of the study area, the formation consisting of Namurian age intercalated sandstone, siltstone, claystone with continental deposits is named as Alacaağzı Formation. This formation is followed by the other two coal-bearing Carboniferous Formations, respectively “Kozlu” and “Karadon”.

Kozlu formation is Carboniferous in age and consisting of altered sandstone, thick coal seams, shale and conglomerates and it is designated as the extractable coal units in the ZCB. The lower unit starting with sandstone and continuing with claystone (mudstone) is called as “Kılıç Unit”. Another unit is the “Upper Dilaver Unit” starts with conglomerate and consists of intercalated shale and sandstone. Conglomerates contain quartzite of various size, magmatic and metamorphic gravels. The grain size in sandstone ranges from very fine size to large sizes. The age of the unit is assigned as Late Namurian Westphalian-A age and it is about 750 m thick (Kerey 1982, Yergök *et al.* 1987). Kozlu Formation gradually passes upwards in to

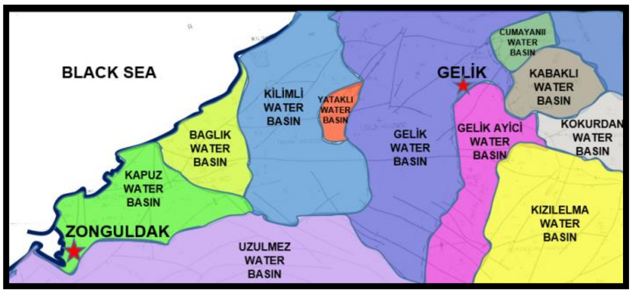


Fig. 6 Hydrogeological map showing groundwater basin in the region (Yergök *et al.*1987, MTA 1996)

Karadon Formation.

The deposits which appears to be similar to Kozlu formation in view of facies features is "Karadon Formation". Formation consisting of conglomerate, sandstone, claystone, diatomite and refractory clay layers (Schieferton) intercalated with coal which are of Westphalian B, C, D age (Alan and Aksay 2002).

Zonguldak formation is consists of Lower Cretaceous (Aptian-Barremian) karstic limestones discordantly overlays the Carboniferous formations. Zonguldak formation contains abudant caves, dolines and swallets (Yergök *et al.*, 1987).

Gelik Region is bounded by non-active faults, especially "Motris" and "Kuzey" are major faults in the Gelik Region (see Figs. 2 and 3). There are no constantly and regularly flowing rivers in the Gelik Region except small creeks fed by karstic caves and dolines. Statistical meteorological data indicate that annual average rainfall and temperature are about 1219 mm and 13.6℃, respectively. The dominant direction of winds is E-SE and the average wind velocity is about 2.4 m/s. The average morphological slope and topographic height of the area of interest in Gelik Region are 40% and 700 m, respectively. Maps of temperature, rainfall and slope maps are shown in Fig. 4. The digital elevation model with a contour interval of 30 m based on SRTM data are shown in Fig. 5. The topography of the region gradually increases in height from the sea towards the land (Karadeniz *et al.* 2009). The highest elevation is 845 m.

Formations in the region consist of both permeable and impermeable units. Rocks consisting of Paleozoic clayey and silty deposits with coal fragments in the middle of the region in the ZCB are impermeable. These units are found in Karadon, Kozlu and Alacaağzı Formations.

Zonguldak formation containing Barremian age lower dolomitic limestone unit is permeable and consists of active aquifers. Seepages are resulted mainly from the tectonic and lithologic structure of the region. Karstic structures are generally observed at locations where faults and fracture zones cross-cut each other and lithologic changes. Groundwater in this formation is shallow and consists of recent accumulations. The groundwater flow 600 m below the sea level is observed in Gelik Region. Fractured and large porous structures are observed in limestone and Carboniferous transition units. Caves and swallets are generally formed in these permeable units. Hydrogeologically there are two groundwater basins in the region which are named as "Gelik" and "Gelik Ayiçi". The distribution of groundwater basins are shown in Fig. 6. Underground water regime is of very important for mining operations and tunnels. There are so many researches about the stability and behavior of tunnels in karst area (Zhou *et al.* 2015, Yuan *et al.* 2016, Li *et al.* 2016).

3. Mining activities in the region

The Gelik is one of five active mining regions in ZCB. The thickness of the coal seams ranges between 1 m and 7 m in the Kozlu Formation having 20 coal seams and the 14 of these seams have been extracted using the longwall mining technique in the last 14 years with a total production of 915.033 tons (TTK 2015). The inclination of coal seam ranges between 10° and 40° with an extraction elevation ranging from +200 m to -400 m.

The total reserves of coal in the region are about 410 million tons. 131 million tons of coal are found to be between the ground surface and the elevation of –460 m. The typical coal mining is based on the longwall method with caving. The distribution of underground galleries and shafts cover an area of 8.5 km^2. The excavation method is not mechanized and the support of mine is wooden. The mechanical pick hammer is used and transportation is done through the chained conveyor. The longwall advance rate is about 1 m per day.

4. The interaction between mining and karstic structures in relation to Gelik sinkhole occurance

There is A sinkhole formed unexpectedly on January 1, 2012 in Gelik Region of the ZCB. The sinkhole has 25 m width and 90 m depth approximately (see Fig. 7). The sinkhole occurred at 280 m NW of the swallet is associated with Koca Osman creek. Koca Osman creek is one of the most important hydrogeological features in the Gelik Ayiçi Groundwater basin. The hydrogeological regime is associated with seasonal rainfalls and disappears into underground through a swallet. It collects its water via two dolines.

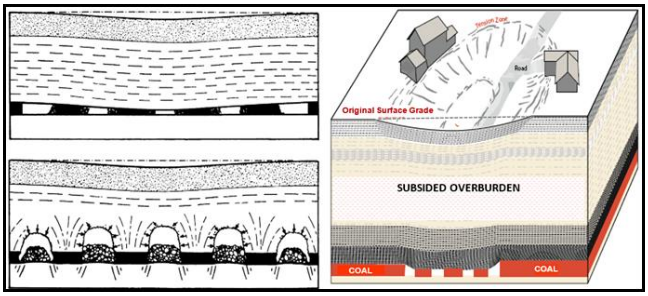
Surface water enters cave system and is stored in the Zonguldak aquifer. Motris and Kuzey Faults next to the swallet act as conveyors of groundwater into the cave system. It has been founded by the Mineral Research and Exploration General Directorate (MTA) that the groundwater associated with swallet permeates into the cave system, two mine shafts and Cumayanı creek through tracer test (MTA 1996).

The region, where the sinkhole is formed, is one of the important cave systems in Turkey as well in the world (see Fig. 8). These systems have been determined by on-site measurements and mapping studies conducted by the MTA between 1990 and 1996. There are coal mines below these caves. Underground mining is carried out in the coal seams named as "Acılık", "Sulu" and "Çay" of the area bounded by No. 1 Fault and Motris Fault between +200 and -360 levels.

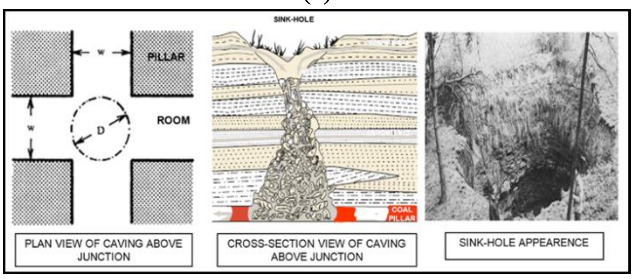
The sinkhole incident which is associated with mining

Fig. 7 Sinkhole development on January 1, 2012 in the investigation area.

Fig. 8 The relation with the sinkhole development of caves and creek in the region



(a)



(b)

Fig. 9 (a) Surface subsidence formed by pillar failure and (b) Sink-hole develeopment above 4-way junction (illustrated by combining of Whittaker and Reddish 1989, Admunson *et al*. 2009)

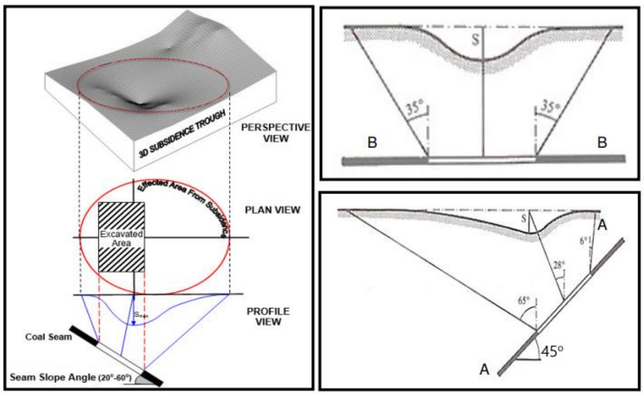


Fig. 10 The subsidence profile associated with coal mining of inclined seams

generally occurs when the extraction is carried out by using room and pillar mining techniques (Bonetto *et al.* 2008). The subsidence associated with room and pillar technique occurs in two patterns. One of them is caused by the failure of pillars and the failed body moves into the center of the caved region and the subsidence is not very large (see Fig. 9 a). Another mode of subsidence is the combination of several caved region at the junctions as Fig. 9(b) (Whittaker and Reddish 1989, Unlu 1994, Admunson *et al*. 2009). On the other hand, the mining using longwall mining method results in subsidence over an area larger than the area of the panel (see Fig. 10).

5. Subsidence influence field modelling and remote sensing studies on ground surface settlements

The areal effect of subsidence associated with the coal mining of “Sulu” and “Acıklık” seams during 2005 and 2008 have been computed and the results of some of computations for coal mining for Sulu and Acılık seams between the elevations of –160 m and –360 m were shown in Figs. 11(a) and 11(b). It was found that the coal mining of “Sulu” and “Acıklık” seams between the elevations of –160 m and –360 m affected the sinkhole formation. The inclination of the seam was about 45^{o}, the length and width of the panel were 530 m and 200 m respectively while its average depth was 330 m in the computations. The area of surface subsidence was computed using the subsidence limit angle shown in the cross-sections of A-A and B-B shown in Fig. 10. From computational results, the sinkhole development was affected by the mining nearest and deepest to the sinkhole location.

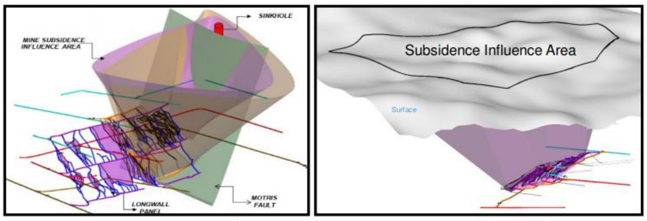


Fig. 11 The modelling of subsidence due to mining at multiple seams during 2005 and 2008 affecting the sinkhole location

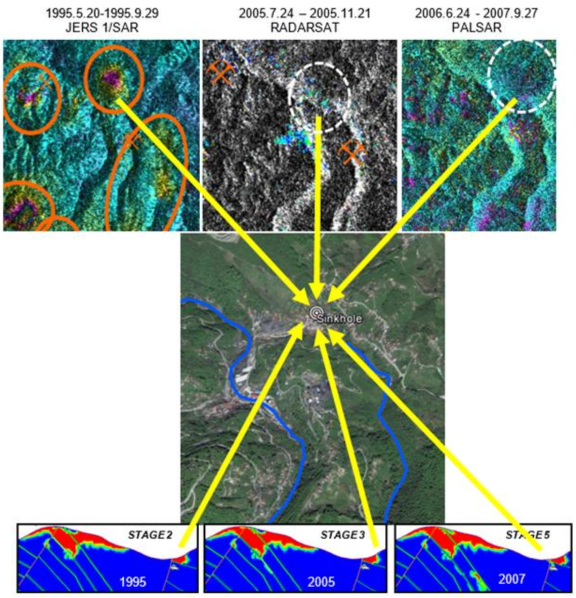


Fig. 12 Surface settlement inferred from DInSAR image analyses

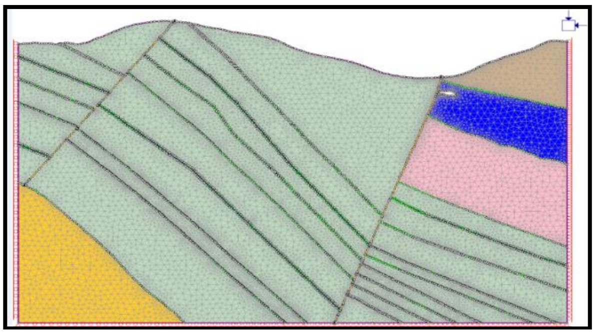


Fig. 13 Finite element mesh used in numerical analyses

The ground surface settlements due to mining activities in ZCB are obtained from DInSAR satellite observations at the date 1995, 2005 and 2008. The satellite images obtained from 1995 JERS1/SAR, 2005 RADARSAT and 2007 PALSAR were used for this purpose. Some ground settlements at the site of sinkhole formation were determined by DInSAR image analyses.

RADARSAT images using C-Band signals evaluated deformations in the urbanized areas while JERS1/SAR and PALSAR images with L-Band signals could evaluate the settlements below the vegetation. Within this context, 2005 DInSAR analyses which were conducted by using RADARSAT images indicated to ground surface settlement in the urbanized areas. Initiation of the ground surface settlement appeared due to mining between the elevations of +100 m and –60 m in 1995 in view of inferences from InSAR image analyses. InSAR analyses dated 2007.09.27 demonstrated that the ground surface settlement caused by the longwall mining at Sulu and Acılık seams between –160 m and –360 m elevations (see Fig. 12).

6. Numerical analyses of Gelik sinkhole incident

In order to investigate whether the sinkhole was caused by the extraction of coal using the longwall panels, numerical analyses considering the multiple seam coal mining were carried out and the yielding conditions were investigated. The numerical analyses are also widely used in mining engineering similar to the other engineering disciplines (Zhang *et al*. 2014, Wang *et al*. 2015). The numerical analyses enable the engineers to evaluate stress concentrations, as well as yielding locations and their effect to the adjacent structures.

Table 1 Rock material properties (modified from ZEDEM, 1994)

Formation (Rock units)	UCS* (MPa)	Deformation Modulus, Ei* (MPa)	Poisson ratio	mi**
Alacaagzi Formation (Sandstone + Claystone + Coal)	60	20000	0.22	14
Kozlu Formation (Sandstone + Claystone)	61	13000	0.21	18
Karadon Formation (Sandstone + Conglemera + Claystone)	40	7000	0.20	21
Zonguldak Formation (Limestone)	45	7510	0.25	8.5
Coal in Kozlu Formation	7	3000	0.32	4
Cover material	10	5700	0.15	5
Goaf material	2	110	0.30	5

*Average value
** mi: Hoek-Brown material constant

Table 2 Rock mass properties used in numerical analyses

Formation (Rock units)	Unit Weight (MN/m^3)	Cohesion (MPa)	Friction angle	Tensile strength, (MPa)	Deformation Modulus, E_m (MPa)	GSI
Alacaagzi Formation (Sandstone + Claystone + Coal)	0.027	2.84	30.4	0.047	3193	40
Kozlu Formation (Sandstone + Claystone)	0.025	4.89	41.5	0.353	9526	70
Karadon Formation (Sandstone + Conglemera + Claystone)	0.023	2.16	33.9	0.021	1117	40
Zonguldak Formation (Limestone)	0.022	1.49	23.3	0.027	611	30
Coal in Kozlu Formation	0.014	0.64	30.2	0.387	2641	80
Cover material	0.015	0.272	19.3	0.010	464	30
Goaf material	0.015	0.042	16.5	0.001	5	20

Computer code (Phase2) based finite element method was used to investigate the stress and deformation response of multiple seam coal extraction as a two-dimensional problem (Rocscience 2012). The domain is discretized into either triangular or rectangular elements. The code includes the yield functions such as Mohr-Coulomb and Hoek-Brown for rocks and Cam-Clay for soils. The rock material properties is given Table 1. In the computations, the yielding of rock mass was assumed to obey Mohr-Coulomb criterion together with elastic-perfectly plastic behavior. Equivalent angles of friction and cohesive strengths for each rock mass and stress range is determined using proposed method by Hoek *et al*. (2002). The generalized Hoek and Diederichs equation (Hoek and Diederichs 2006) utilizes the modulus of the intact rock (E_i), Geological

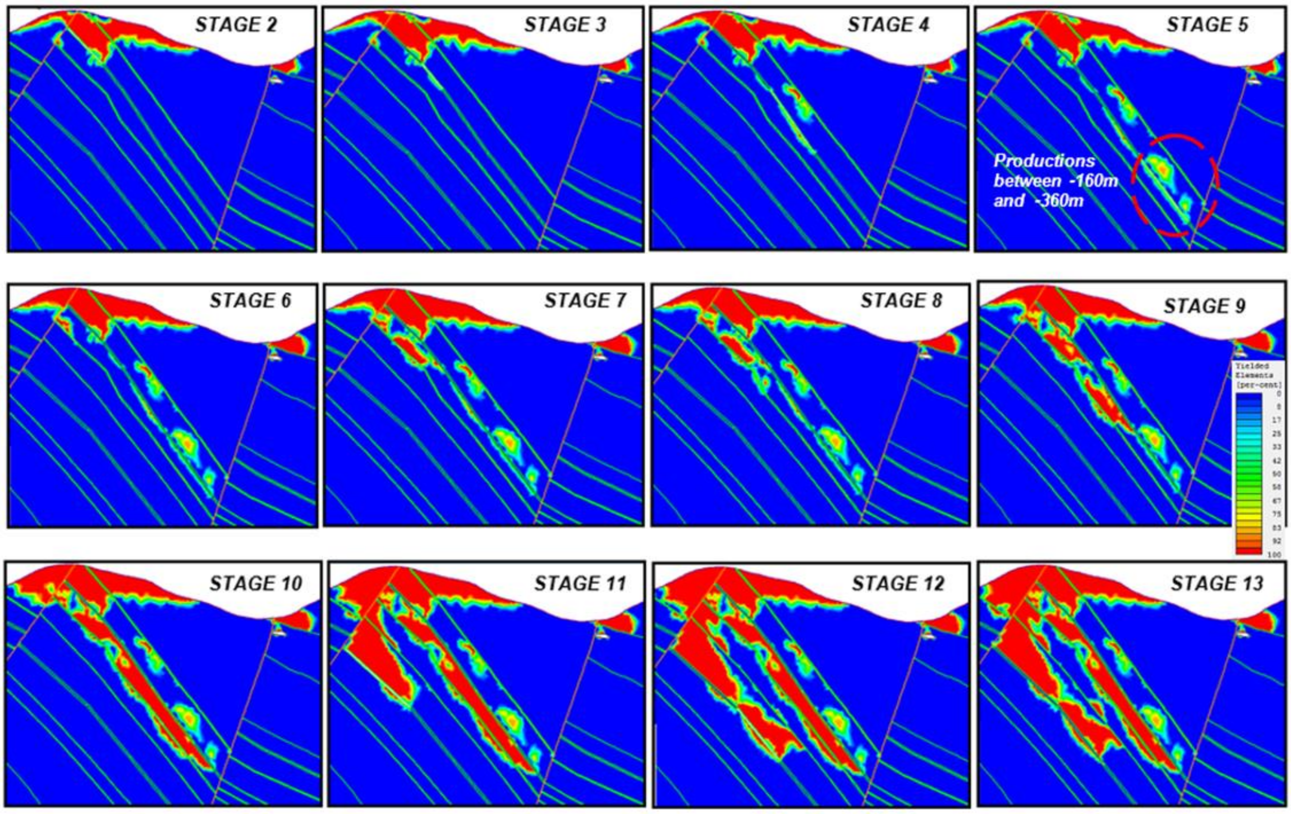


Fig. 14 Numerical analyses results for different stages

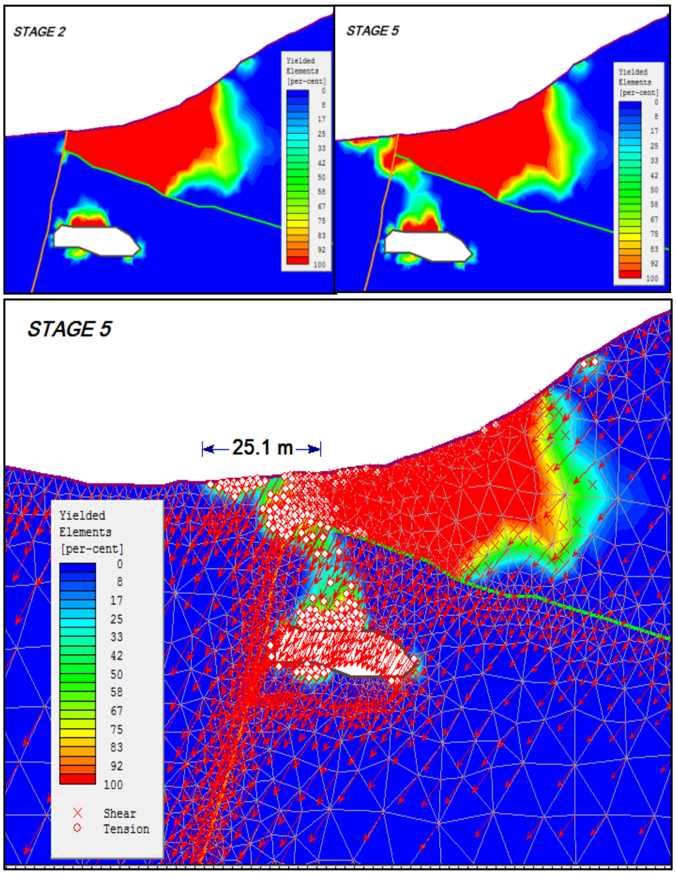


Fig. 15 Yielding zones and deformation vectors at the 5th stage of numerical analyses associated with sinkhole development

Strength Index (GSI) and damage factor (D) to compute the rock mass deformation modulus (E_m) (Eq. (1))

$$E_m = E_i \left(0.02 + \frac{1 - D/2}{1 + e^{[(60+15D-GSI)/11]}} \right) \quad \text{(MPa)} \quad (1)$$

D is assumed to be zero. Rock mass properties used in the analyses are given in Table 2. Fig. 13 shows the automatically generated finite element meshes for the geologic cross-section shown in Fig. 3.

Numerical model was used to evaluate stress and deformation distribution of the cave as a result of mining activities nearby. The finite element mesh was graded with the consideration of mining and the collapsed cave. The finite element mesh consisted of 37338 nodal points using the triangular elements. The excavation area and sinkhole cave were discretised using smaller finite element meshes. The initial stress state of the mining area was obtained through gravitational loading. The overburden vertical stress (Pv) was computed from the depth and average unit weight of rock mass. As there was no in-situ stress measurement at the site, the lateral stress coefficient was assumed to be 1.

The excavation of 4 coal seams nearby the sinkhole location was modelled in 13 stages. The seams were assumed to be excavated without filling. The properties of the goaf material were assigned at later stages. The cave was assumed to exist before the mining operations started.

Yield zones (i.e., plastic zone) obtained from the numerical analyses are shown at different stages in Figure 14. Numerical analyses indicated that complete yielding occurs in the vicinity of the cave at the 5th stage. The yielding does not further propagate at later stages. Fig. 15 shows both yielding zones and deformation vectors of the ground. This result implies that the mining at Sulu seam between the elevations –160 m and –360 m was the main cause of the sinkhole formation. Multiple seam mining in the area with a contact of the existing fault might have also affected the stress state and yielding at a natural underground opening in contact with the same fault. Maximum total displacement above the cave are calculated as 4.5 cm and 20 cm at the Stage 2 and Stage 5 by numerical solution respectively. In addition, the total displacements obtained as 8 cm at Stage 2 and 17 cm Stage 5 from the DInSAR analysis. This results obtained from two different methods are compatible with each other.

7. General remarks

In this study, a sinkhole incident occurred at Gelik on January 1, 2012 was investigated. The causes, which may have some roles on the sinkhole incident, may be summarized as follows:

• The region has a complex hydrogeologic and geological structure. Furthermore, the region receives heavy rainfall throughout the year. As a result, it is quite possible to conclude that sinkhole incidents in karstic Zonguldak formation are likely in the region. Nevertheless, there was no report on the sinkhole development before this incident.

• The underground coal production in this region is about 915033 tons per year. The yielding at ground surface may develop as a result of underground mining might have also caused some effects on the sinkhole occurrence.

•There are many faults in the region. Especially “Motris” fault is nearby the sinkhole site. The cave system in contact with this fault might have been affected by the coal seam extractions in contact with this fault.

• It is very likely that the sinkhole incidence might have been caused by the combined action of the causes mentioned above.

8. Conclusions

The conclusions from subsidence influence field modelling, surface deformation monitoring by interferometric SAR methods using radar images and finite element analysis, in relation to the sinkhole development are as follows:

• Study of the subsidence influence field modelling techniques showed that surface subsidence occured due to production of multiple seam caving longwall at -160 m/-360 m level during 2005-2007 years and it covered at the area of sinkhole location.

• The multi-stage finite element analyses of coal extraction between 1995 and 2012 years, the extraction of coal in 2005, which corresponds to Stage 5, indicated that a complete yielding occurred around the cave and it propagated towards the ground surface.

• The subsidence effect of the longwall mining panels has disturbed to the hydrological balance of the karstic structures above the coal seams. The structure of the cave could be affected by time and finally becomes a sinkhole depending on advancing of longwall panels. This phoneme has been proven by numerical solution and DinSAR image analysis. Additionaly, it is determined that the cave system which have contact with a fault is affected by the longwall mining production. As results, maximum total displacement above the cave are calculated as 4.5 cm and 20 cm at the Stage 2 and Stage 5 by numerical solution respectively. In addition, the total displacements obtained as 8 cm at Stage 2 and 17 cm Stage 5 from the DInSAR analysis. This results obtained from two different methods are compatible with each other.

• After seven years than 2005 year, a sinkhole occurred in 2012. This is probably reason that yielded rock mass has been load bearing capacity and also the shape of failure zone propagated towards the ground surfaces (stage 5 of the Fig. 14) is of curvature. This curvature shape of failed rock mass could be providing that broken rock blocks interlocked to each others. This feature might be one of reason of delayed sinkhole incident.

• While Koca Osman creek disappears into a swallet 300 m behind the sinkhole site, there should be another cave in relation to the swallet system. The investigation in the area confirmed the existence of such a cave system. The amount of the surface water seeping into the cave system is the highest in January (the average rainfall is 136.4 kg/m^2 and 18 days are rainy during January for a period of 1950-2014). This feature might have also been another factor which explains the reason why the sinkhole occurred in January.

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