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Analysis of surface subsidence due to longwall mining under weak geological conditions: Turgut basin of Yatağan-Muğla (Turkey) case study

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ABSTRACT
Accurate prediction of surface subsidence due to the extraction of underground coal seams becomes a significant challenge in engineering. For a projected longwall coal mining operation, conditions of weak cover rock and thick coal seams (6–12 m) in Turgut basin in Yatagan-Turkey are described and discussed based on the field data, using surface deformation prediction system software. This paper aims at predicting the subsidence values only numerically by evaluating the influence of subsidence on irrigation pipeline structure to be built on the ground for the cases with pillars left in the coal seam.

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KEYWORDS
Longwall mining; subsidence; weak rock; coal pillar; Turkey

1. Introduction

Surface movements are always caused by the application of longwall mining method, in the form of collapses in the mined out areas (goaf). The amount of surface movement is affected by several parameters, including the number and thickness of the coal seams that have been mined, dip of the seam(s), depth of overburden above the seam(s), the surface topography, the composition of the overburden rock and the presence of structural discontinuities [1–3].

As a general rule, total height of the coal seam is used to estimate the maximum subsidence, which ranges from 40 to 90% of the total mining height [4]. This approximation may result in different values for various coal basins. In general, in this particular coal basin that was studied, Turgut basin of Yatağan-Muğla, subsidence values were found to be 50–70% of the seam height, except over the pillars left to prevent the subsidence.

Although, these values yield a very rough estimate of the maximum subsidence, i.e. the subsidence that can be expected in the middle above a longwall panel or above a fully mined-out area, i.e. an area without any pillars or unmined zones. The value also is valid only in the case in which there are no major faults. In the central part above a longwall panel or above a fully mined-out area, it often is assumed that the new surface remains parallel to the original topography, so that no differential displacements occur. Around the edges of a mined area, the subsidence evolves from the maximum value in the central part to a subsidence of nearly zero at a certain distance away from the mined out area.

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Thus, the subsidence results in a curvature of the new surface. For a single panel, it can be assumed that a trough is formed [5,6]. This will lead to differential vertical displacements and to horizontal displacements (horizontal strain in tension and in compression) around the edges. Generally, it is assumed that damage to the infrastructure occurs mainly in such areas, i.e. where large differential vertical displacements and large horizontal strain exist.

Any subsidence analysis that utilises numerical modelling, when used as an adjunct to empirical techniques, can predict the subsidence, if a concrete knowledge of the geology, particularly the stratigraphy, and the behaviour of rock material of the subsurface strata are present. Hence, currently, the prediction of subsidence using numerical modelling may result in poor accuracy [7–10], and this stems in large part from a lack of understanding of the constitutive laws of the coal measure strata. Among the subsidence studies carried out formerly for a range of constitutive laws considering the behaviour of material [10–12], there has been no single work conducted to date that provides a comprehensive assessment of the effectiveness with which commonly used constitutive laws can predict surface subsidence and subsurface displacements. The present study includes the estimations acquired by modelling the coal seam and the overlying strata with constitutive laws of varying complexity using surface deformation prediction system (SDPS).

2. Study area

Study area is situated in north, north-east of Turgut basin of Yatağan County in Muğla Province (Turkey) and encompasses around 22 km^2.

2.1. Morhology

Topography of the study area is formed by Dipsiz Creek and other seasonal creeks in the east. Kemer Creek, Boğaz Creek, Kayırlı and Bulgurcu Creeks are among the seasonal creeks. This depressed area is surrounded by Yapraklı, Hacıbayramlar (N), Turgut (S), Zeytin-Zeytinköy (W) and Yava (E) and declines from west to east with the influence of the creeks (Figure 1).

2.2. General geological properties

Study area was examined based on the information published in the chapter entitled 'Lignite Reserves in Yatağan-Turgut basin of Muğla Province in Turkey Lignite Inventory Book', MTA [13] A section based on drillcore data along the NW-NE directional section was taken from the town of Turgut to north-east of Yaztepe along with the general geological map of the region. When this section and the geological maps prepared by the MTA [13–15] are jointly evaluated, crystallised limestone-marble was detected in the basement. On this metamorphic basement, Turgut Formation which consists of Middle Miocene aged blue-grey sandstone–siltstone–claystone is located. Lignite formations are located on the Turgut Formation and they are thinning towards the town of Turgut and it can be seen that they reappear locally due to the faulting to the side of the section. Following the lignite level, Sekköy Formation consisting of Middle Miocene aged blue-grey green marl–siltstone–sandstone is situated. This formation is unconformably overlain by the Yatağan Formation. Upper Miocene–Pliocene aged Yatağan Formation which consists of green-grey conglomerate–sandstone–tuff-marl–claystone is observed in the surface of the study area (Figures 2–4). According to the Turkey's lignite inventory published by the MTA [13], the lignite has a variable thickness between 0.75 and 12.05 m with an average thickness of 6.20 m in an area spreading to near 14 km^2. The mean depth of lignite seams is 255 m but it is stated that the depth is variable between 86.85 m (NE)-505.25 m (SW). Total reserves of 130 million tonnes have been reported, including proven and probable reserves, according to the borehole data obtained by MTA (General Directorate of Mineral Research and Exploration), TKI (Turkish Coal Enterprises) and Yatağan Thermal Energy Generation Inc.

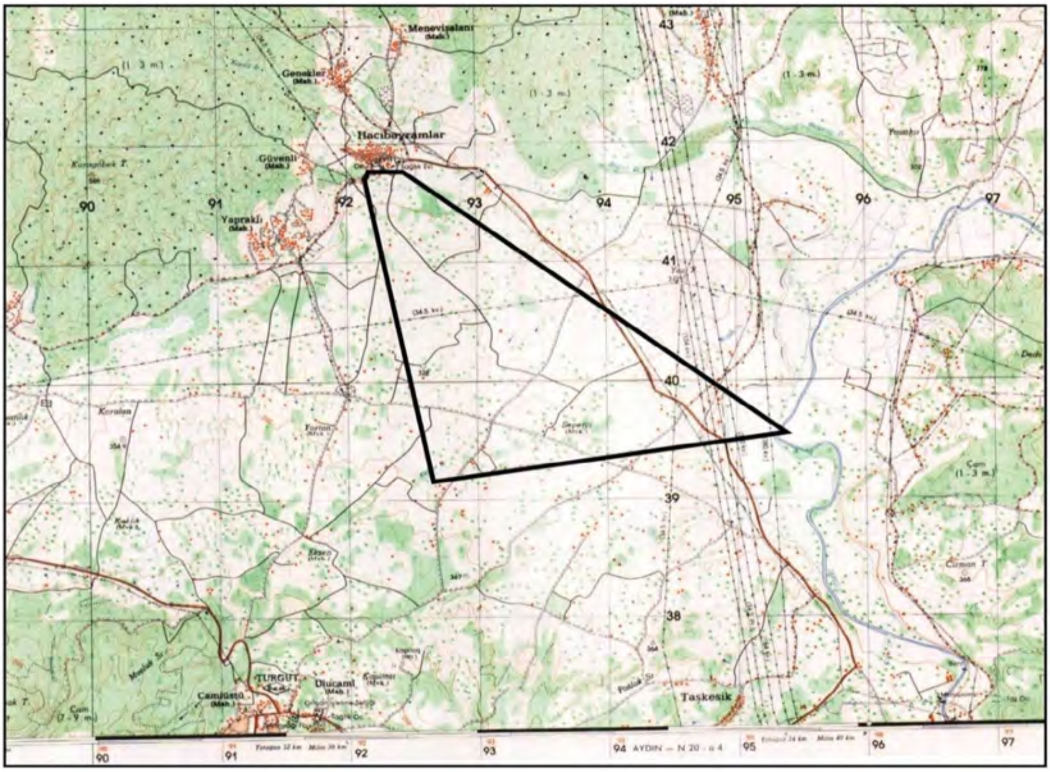

Figure 1. Topographical map of the area studied. Source: The Coal company.

Whateley et al. [16] determined the lignite reserve of Turgut basin using different methods. In this study, borehole data and geological maps prepared by MTA [14] were used. The researchers noted that the SW margin of the basin is limited to about 200 m strike fault in the NW-SE direction. They emphasised that Turgut Formation consists of claystones, siltstones, sandstones and conglomerate, which were incompatible with the basic units, and that they were exposed to the north and south of the basin. It is also emphasised that the Sekköy Formation consists of marl and limestone reaching a thickness of 150 m and the overlying Yatağan Formation consists of conglomerate, claystone, sandstone and tuffs, which can reach a thickness of 400 m. It is stated that lignite in this region has a thickness of 20 m between Turgut and Sekköy Formations. It is also stated that lignite is intersected by 73 of the 104 holes drilled by MTA in Turgut basin.

In this study, the coal which draws border with Turgut and Sekköy Formations will be evaluated. Whateley et al.[16] have calculated the coal reserve by changing the lignite co-thickness map which was prepared by Nakoman and İnaner [17] based on borehole drill data.

In the Turgut basin, in an area of 16.913.962 m^2, a total of 121 881 519 t coal reserve was calculated considering an average extractable seam thickness of 4.91 m. When Polygon Method and an average coal seam thickness of 5.42 m is considered, a total of 135 131 180 t coal reserve; when the inverse power of geostatistical method is used, a total of 137 508 503 t coal reserve; when Krigging Method is employed, a total of 138 825 164 t coal reserve was calculated (Figure 5).

When the tectonic features of the Turgut Basin are considered, it appears to be a graben-sedimentary basin developed due to normal fault activity. The faults limiting the basin are part of the NW-SE trending fault called Muğla-Yatağan Fault Zone in the literature (Figure 2) [16,18].The seismic movements

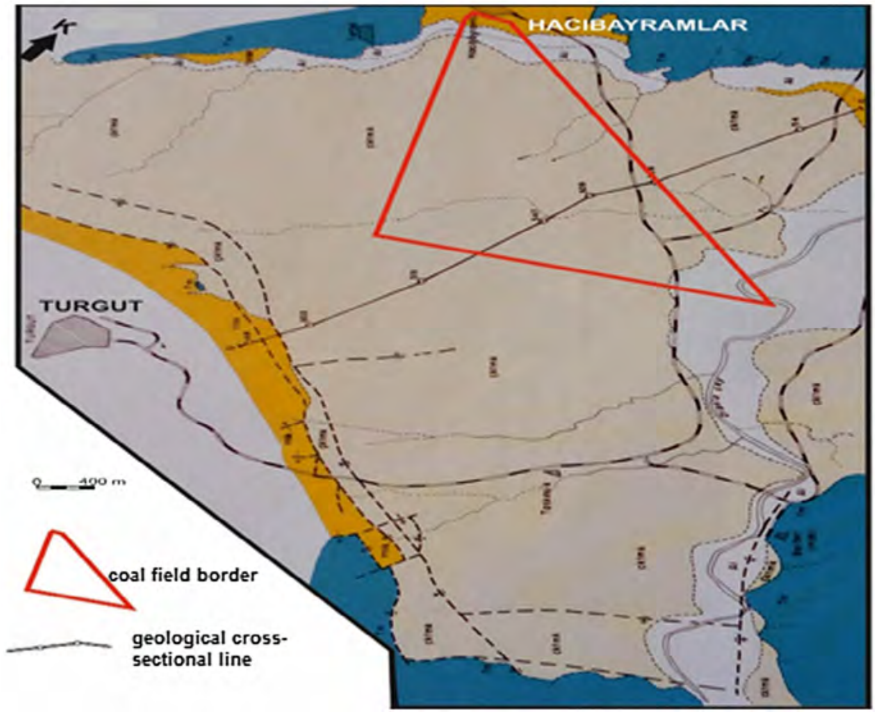

Figure 2. General geological map of the area studied [13].

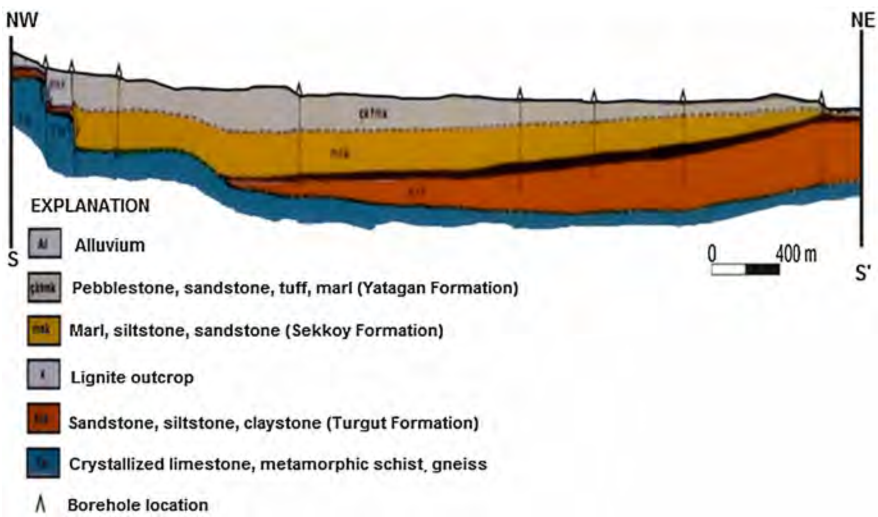

Figure 3. General geological cross-section of the area studied [13].

on this fault caused fallings, faults, folds, turns in blocks, openings, horizontal and vertical pulses in the Lagina antique region located at the SW boundary of the study area [18]. The age points to the existence of a great activity in the region in the fourth century. Based on the MTA data, it is reported that the strike due to these faults is about 200 m [16].

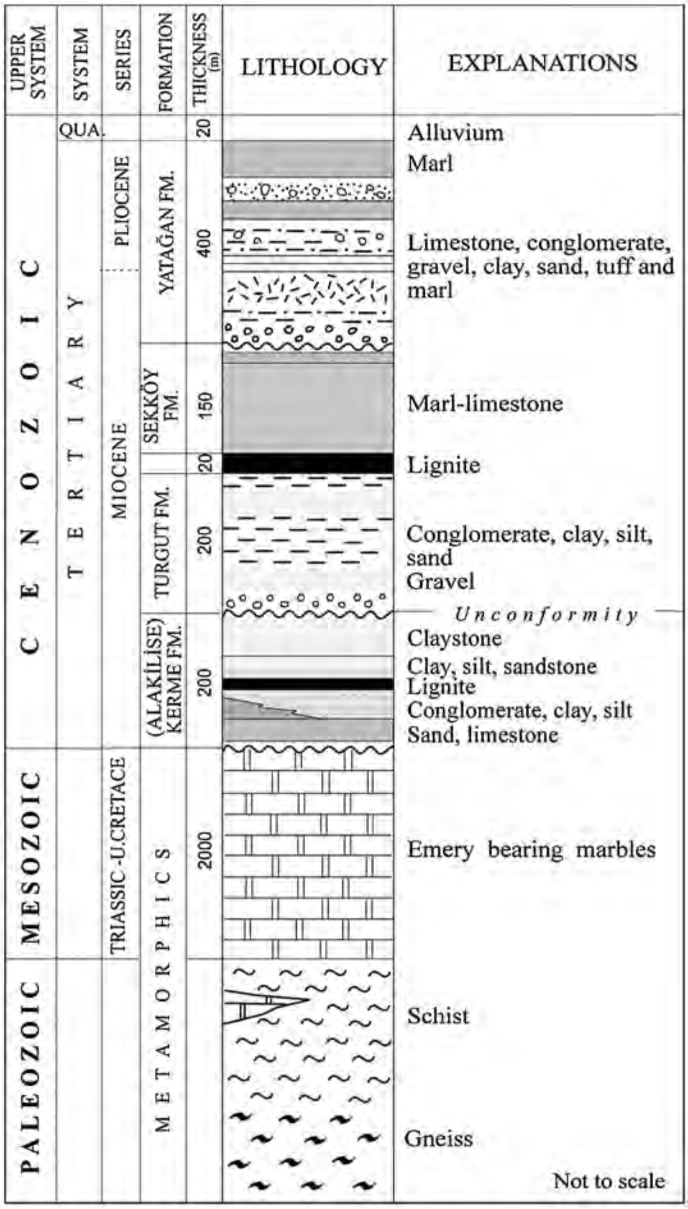

Figure 4. Generalised stratigraphical cross-section of the area studied (Courtesy of [16,22]).

3. Evaluation of the drill-hole data and *in situ* state of stress

In addition to drill holes driven by the MTA and TKI in the field of investigation, Yatağan Thermal Energy Generation Inc. has drilled a total of 32 new drill holes at depths ranging from 60 to 280 m. These holes were drilled in selected areas where there were no holes previously drilled by the MTA. In the upper parts of almost all of the drill holes, the units such as conglomerates, claystone, sandy siltstone belonging to Yatağan Formation have been identified. These units are followed by the Sekköy Formation, which consists of marl, silty sandstone and green claystone units. Claystone, sandstone and siltstone are also found in the lignite levels with thicknesses ranging from 0 to 23.1 m and with an

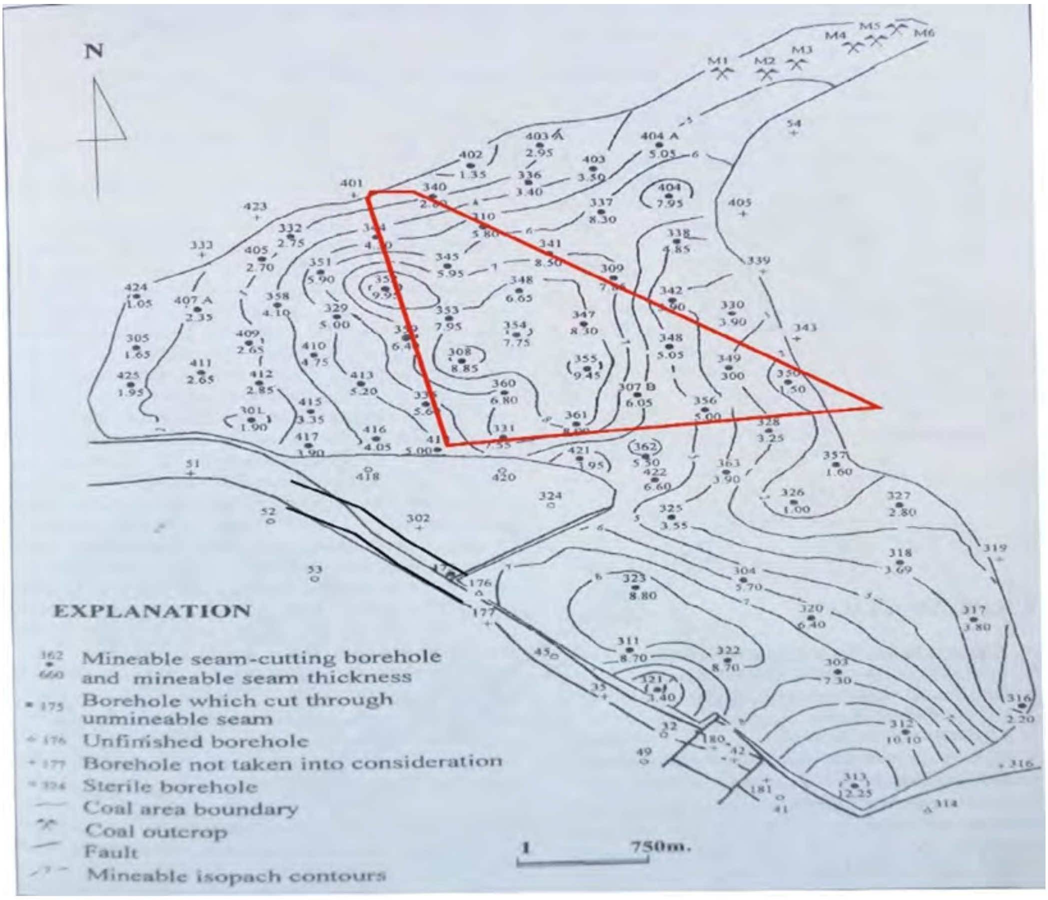

Figure 5. Isopach map of the coal seams [16].

average thickness of 10.4 m. Below these units, the Turgut Formation that consists of sandy siltstone and sandy clayey siltstone units is situated.

Average uniaxial compressive strength of the host rock in the basin was determined to be 3–7 MPa and classified as the weak rock, although the average uniaxial compressive strength of the conglomerate was determined to be 18 MPa. Conglomerate, as the stiffest formation in the basin, comprises a small percentage of overburden rock and will not influence the total subsidence over the mined out area. Hence, the subsidence after the extraction of coal seam is expected to be 60–70% of the coal seam thickness. In SDPS software, total subsidence was determined based on the percentage of hard rock in the overburden. In this study, the percentage of hard rock was introduced in the software as 10% considering the presence of conglomerate as the stiffest rock in the overburden.

In-situ vertical and horizontal state of stresses at the depth of longwall mine to be projected were estimated to be around 8–10 MPa and 2–4 MPa, respectively.

4. Subsidence

4.1. Subsidence theory

The overburden above an underground mine, such as longwall coal mine will induce caving, displacement of the overburden material owing to the weight of the ground above the undeground mine and will usually result in measurable movement, or subsidence, at the ground surface above the mine. The shape of the disturbed ground surface above a collapsed mine is called a subsidence. In this work, the term 'subsidence' refers only to the vertical displacement of the ground surface. In numerical analyses, although small amount of horizontal movement was observed, it was not treated as significant as to impact on the structure of the pipline system and was neglected. treated elsewhere. Subsidence above coal mines can be more accurately predicted where longwall mining has occurred as opposed to room-and-pillar mining, because it is more reasonable to assume that the mined cavities will collapse within a short time after mining activity has ceased.

In subsidence prediction methods, there are a number of important parameters on which many researchers who conducted studies on subsidence theory always agreed. Two of these parameters are directly measurable, geometric properties of the coal seam and the mine of interest. They are (1) the thickness of the coal that is extracted and (2) the vertical distance between the mined seam and the ground surface. These parameters can be symbolised and described as:

m: mined coal thickness

h: height of overburden

Two other significant parameters will be dependent on the location of the mine. They are empirical in nature and, when used in a predictive method, are often assumed to be equal to values back-calculated from similar, nearby mines. The first is referred to as the subsidence factor. This factor is used to determine another derived parameter (see below). The second is called the angle of draw. The angle of draw is the angle of the line, measured from horizontal, from the outer edge of a mined area to the outer edge of the subsidence trough. These two parameters will be symbolised and defined as:

a: subsidence factor

γ: angle of draw (°)

Several studies on subsidence theory can be seen to refer to two other derived parameters: The maximum predicted subsidence value depends on both the mined coal thickness and the subsidence factor. It indicates the amount of subsidence, which would be expected above a large mined-out area. The second derived parameter is called the critical radius. These last two parameters are symbolised and defined below and in Equations (1) and (2).

$$S_{\max} = a \cdot b \tag{1}$$

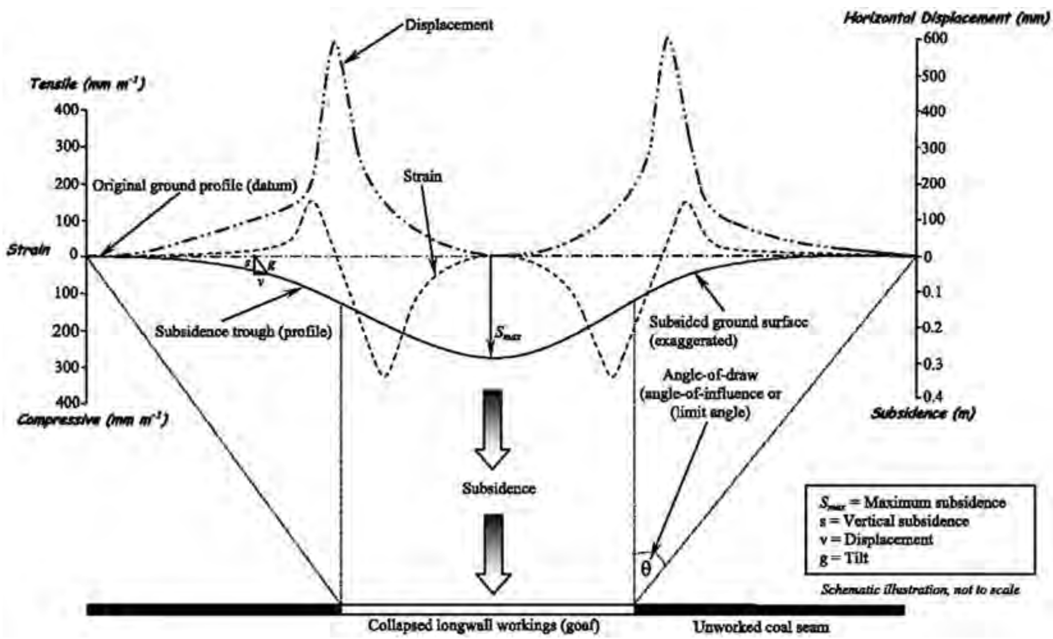

Figure 6. Typical section through workings, illustrating standard symbols for subsidence and slope [23].

where, S_{max} is the maximum predicted subsidence.

$$B = \frac{h}{\tan\gamma} \tag{2}$$

where, B is the critical radius.

The critical radius can be better understood by considering a horizontal coal seam extending infinitely in all directions below a horizontal ground surface. Half of the seam is extracted to one side of a straight line and the other half is left undisturbed. The surface above the extracted portion (far from the dividing line) could be expected to subside a distance equal to S_{max}. The surface above the undisturbed portion (far from the dividing line) would not be expected to subside at all. Close to the dividing line, however, the surface would likely be disturbed. The extent of the disturbance is quantified by the critical radius. Moving perpendicularly away from the dividing line, subsidence would be expected to become uniform (either zero or S_{max}) at one critical radius from the dividing line.

4.2. Prediction of subsidence

Subsidence, a universal process that occurs in response to the voids created by extracting solids or liquids from beneath the Earth's surface, is controlled by many factors including mining methods, depth of extraction, thickness of deposit, and topography, as well as the *in situ* properties of the rock mass above the deposit (Figure 6). The impacts of subsidence are potentially severe in terms of damage to surface utility lines and structures, changes in surface-water and ground-water conditions, and effects on vegetation and animals. Although subsidence cannot be eliminated, it can be reduced or controlled in areas where deformation of the ground surface would produce dangerous or costly effects.

4.2.1. Previous studies conducted to predict the subsidence

Subsidence prediction is highly developed worldwide where there are comparatively uniform mining conditions and a long history of field measurements. Much of this mining has been carried out beneath crowded urban and industrial areas where accurate predictions have facilitated the use of the surface and reduced undesirable impacts.

Empirical methods of subsidence analysis and prediction based on local conditions seem better suited to the current state of knowledge of the varied geologic and topographic conditions in domestic coal mining regions than do theoretical/mathematical/ numerical approaches. In order to develop broadly applicable subsidence prediction methods, more information is needed on magnitude and timing of ground movements and geologic properties.

Song et al. [19] have focused on the prediction of mining subsidence and its impact on the environment in the Hongqi mining area.on the basis of probability integral model, in first instance based on field surveys and the analysis of data collected from this area. Isolines of mining subsidence were drawn and the impact caused by mining subsidence on the environment was analysed quantitatively by spatial analysis with Geographic Information System. The results indicate that the subsidence area of the first working-mine can be as large as 2.54 km^2, the maximum subsidence is 3440 mm.

Xu et al. [20] have conducted a study to estimate mining-induced surface subsidence by means of the finite difference method. They aimed at making a judgement whether the extraction of the coal seam will have a negative impact on the dam nearby. First, they have estimated the initial values of the rock mass mechanical parameters using the available literature that relates intact rock and discontinuity properties to rock mass parameters. Then, based on available surface subsidence monitoring data on WUTONG's mined areas, they have determined the main mechanical parameters of coal and rock masses by a back analysis procedure that combines an experimental design technique with numerical simulations. Finally, the surface subsidence results in the mining area are numerically predicted for four different mining scenarios.

Yi et al. [21] have investigated the distribution of the final surface subsidence after longwall coal mining operations in inclined and flat coal seams. They have stated that subsidence induced by longwall operations in inclined coal seam could be significantly different from that in flat coal seam and demands special prediction methods. The authors have claimed that despite many empirical prediction

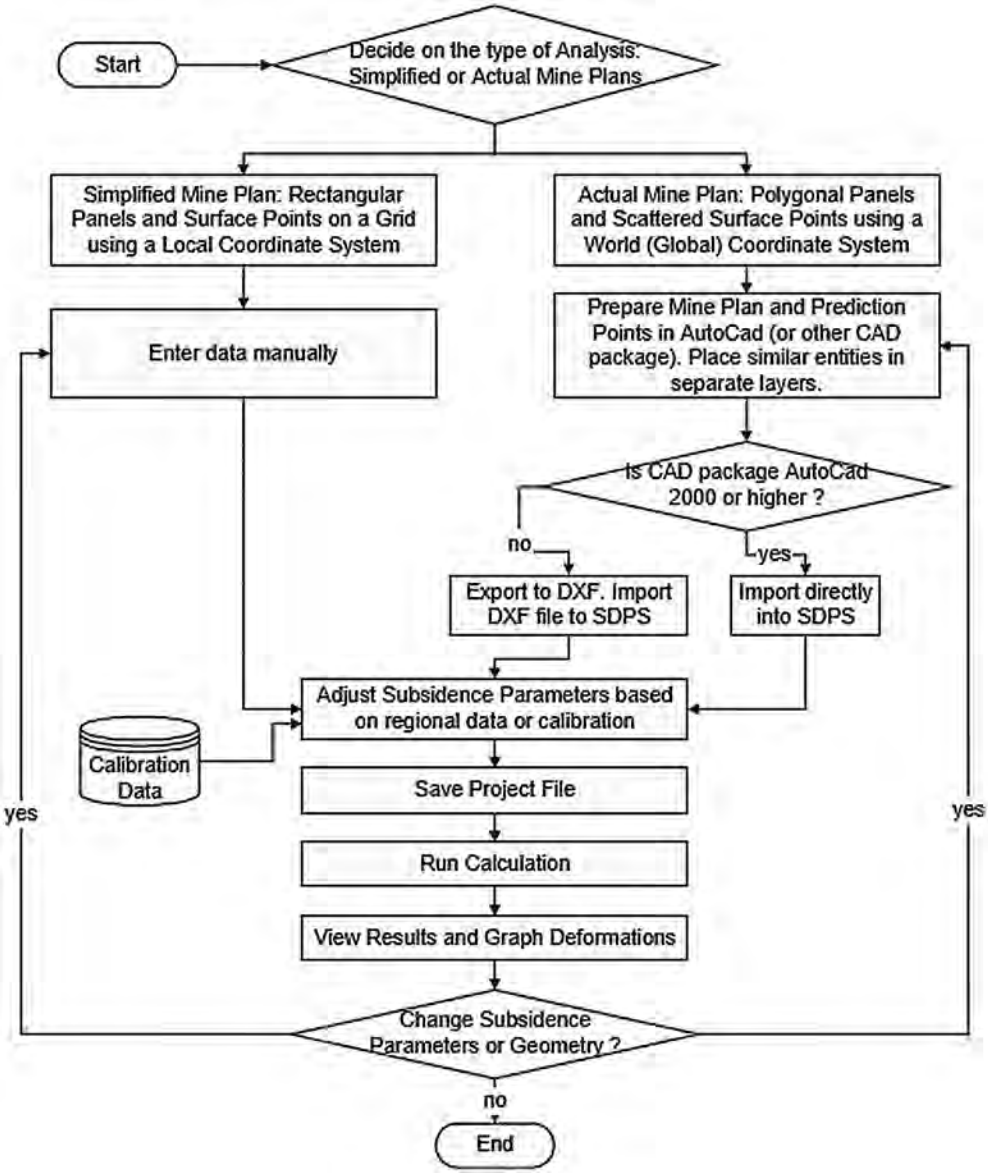

Figure 7. Flowchart diagram for the influence function method [24].

methods developed, these methods are inflexible for varying geological and mining conditions. Hence, they have developed an influence function method to take the advantage of its fundamentally sound nature and flexibility. Hence, they have made, significant modifications to the original Knothe function to produce an asymmetrical influence function. A corresponding computer programme has been developed and has been applied for a number subsidence cases for longwall mining operations in coal seams with varying inclination angles to demonstrate the applicability of the developed subsidence prediction model.

4.2.2. Subsidence prediction procedure performed in this study

In this study, subsidence was predicted via the software SDPS using influence function methods for subsidence prediction which have the ability to consider any mining geometry, to negotiate superposition

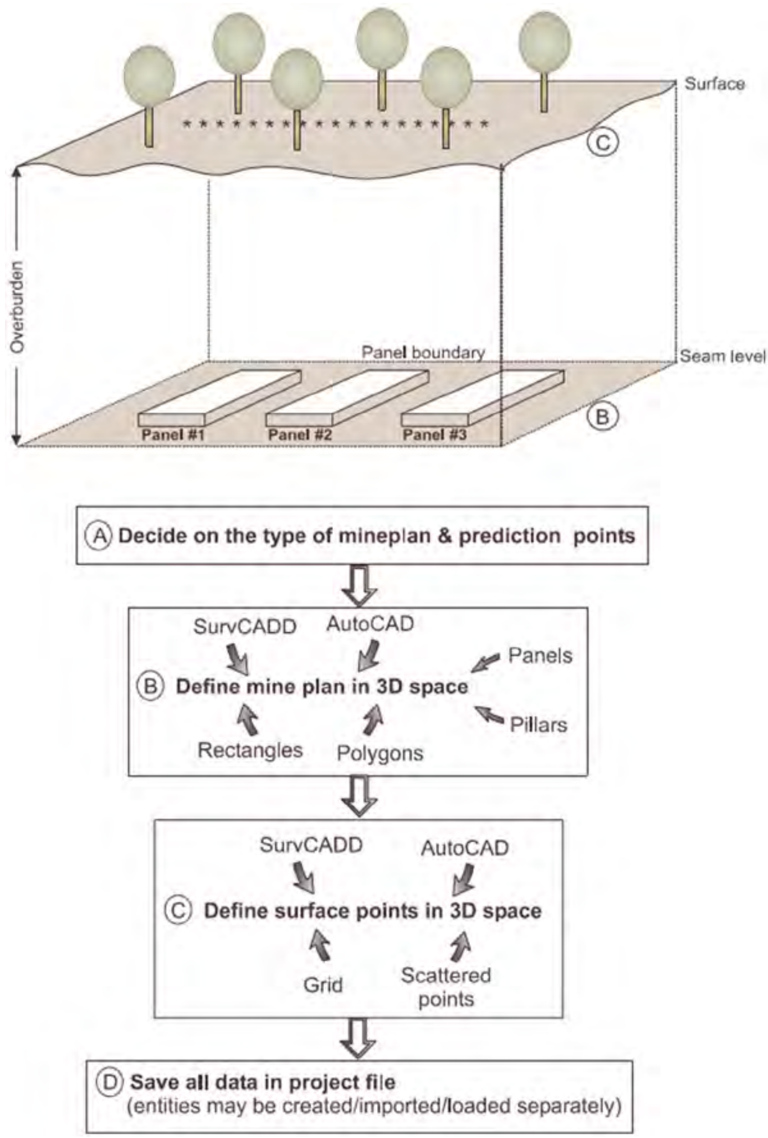

Figure 8. Steps required in defining a project [24].

of the influence from a number of excavated areas having different mining characteristics and, also, to calculate horizontal strains as well as other related deformation indices. The function utilised in SDPS is the bell-shaped Gaussian function.

This method assumes that the influence function for the two-dimensional case is given by:

$$g(x,s) = \frac{S_0(x)}{r} \exp\left\{-n\left(\frac{(x-s)^2}{r^2}\right)\right\} \tag{3}$$

where, r is the radius of principal influence ($h/\tan\beta$), h is the the overburden depth, β is the angle of principal influence, s is the coordinate of the point P, where subsidence is considered, x is the coordinate of the infinitesimal excavated element and $S_0(x)$ is the convergence of the roof of the infinitesimal excavated element.

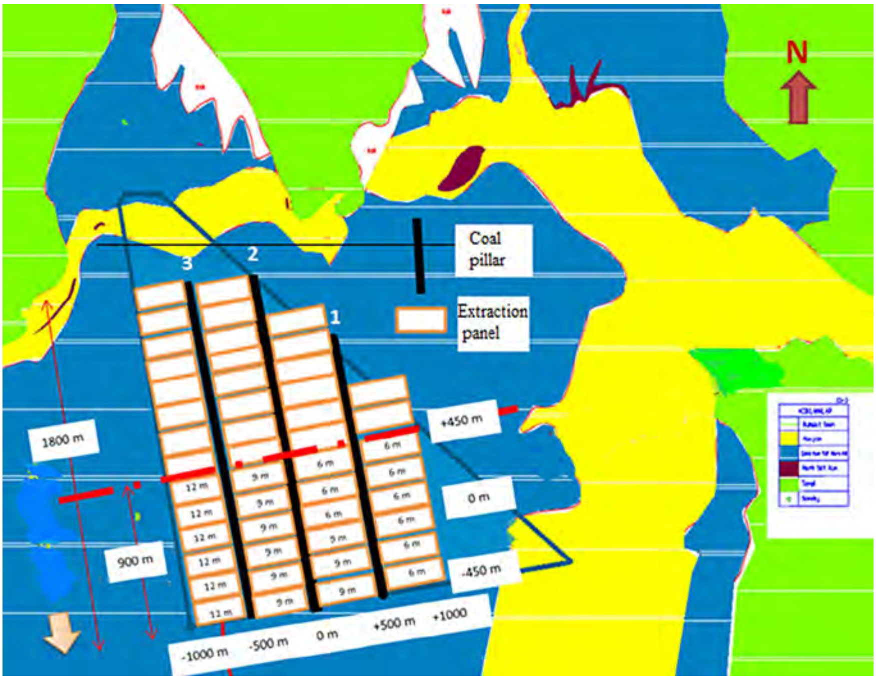

Figure 9. Planning of coal extraction panels and panel dimensions. Source: The Authors.

Subsidence at any point $P(s)$, therefore, can be expressed by the following equation:

$$S(x, s) = \frac{1}{r} \int_{-\infty}^{\infty} S_0(x) \exp\left[-n\frac{(x-r)^2}{r^2}\right] \tag{4}$$

where, $S_0(x) = m(x)\, a(x)$, $m(x)$ is the extraction thickness and $a(x)$ is the roof convergence (subsidence) factor.

This model is sensitive to the maximum subsidence factor for the area (S_{max}) and the distance of the inflexion point from the rib. The maximum subsidence factor can be calculated as a function of the percentage of hard material in the overburden (per cent of hardrock). The position of the inflexion point can be calculated as a function of the overburden depth. Both estimations are based on statistical procedures used to evaluate data from Eastern U.S. coalfields and should be used for predicting subsidence movements over areas with similar characteristics.

Horizontal strains and displacements are also calculated s as well as other related deformation indices. The value of this factor is directly related to the magnitude of the calculated strains and curvatures over an undermined area. It can be empirically estimated by the average ratio of measured strain and curvature over a set of surface points.

In this profile function formulation, the magnitude of the maximum subsidence factor is not affected by the position of the inflexion point. Thus, the same maximum subsidence factor is obtained using either an average or a conservative estimate of the position of the inflexion point. The position of the inflexion point, however, determines the distribution of the subsidence profile with respect to the rib of the excavation. It should be emphasised that the profile function developed for this area may not be applicable for subsidence predictions over other coalfields with different characteristics. The factors that influence subsidence behaviour include, but are not limited to; overburden depth, makeup of overlying geologic strata, coal seam thickness, longwall panel geometry (width, length, etc.).

Using the influence function method, surface deformations are calculated following the typical steps required as shown below. The corresponding flowchart is also shown in Figure 7, which presents typical distributions for the deformation indices that can be calculated by the influence function method. Figure 8 presents a schematic diagram for creating the input data.

- Load the Influence Function Programme
- Input Data
- Mine Plan Data
    - Prediction Point Data
    - Empirical Parameters
- Select calculation options
    - Subsidence
    - Horizontal Strain
    - Horizontal Displacement
    - Slope
    - Curvature
- Save Project File
- Calculate Surface Deformations
- Load Graphing Programme
- View Calculated Deformations

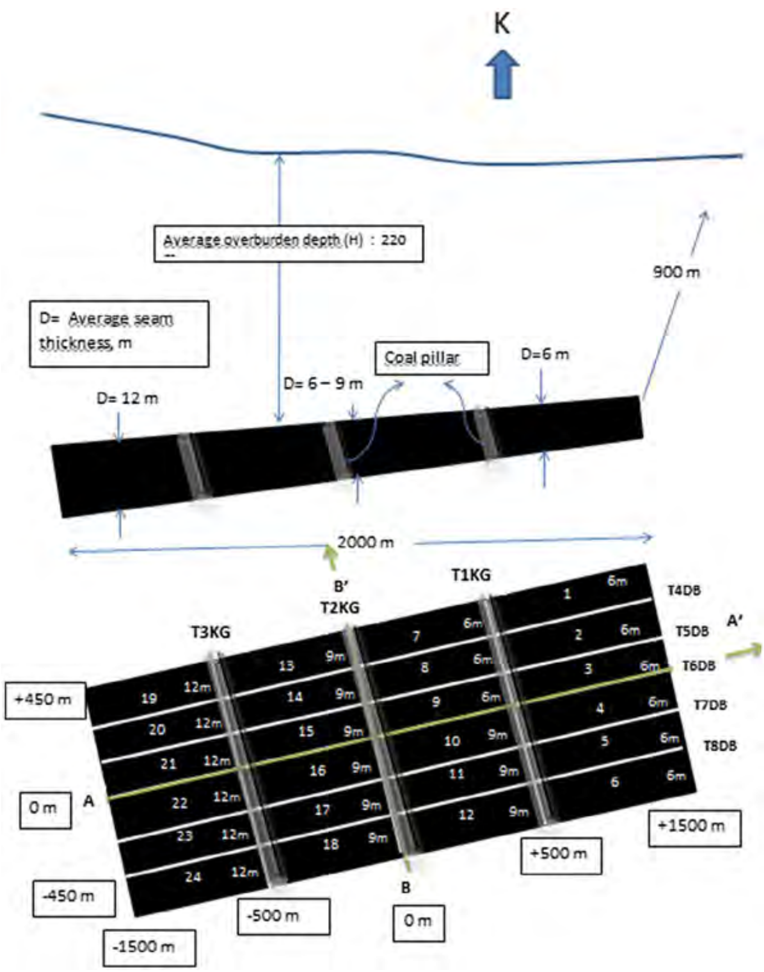

Figure 10. Plan view and cross-sections of coal extraction panels and average coal seam thicknesses.

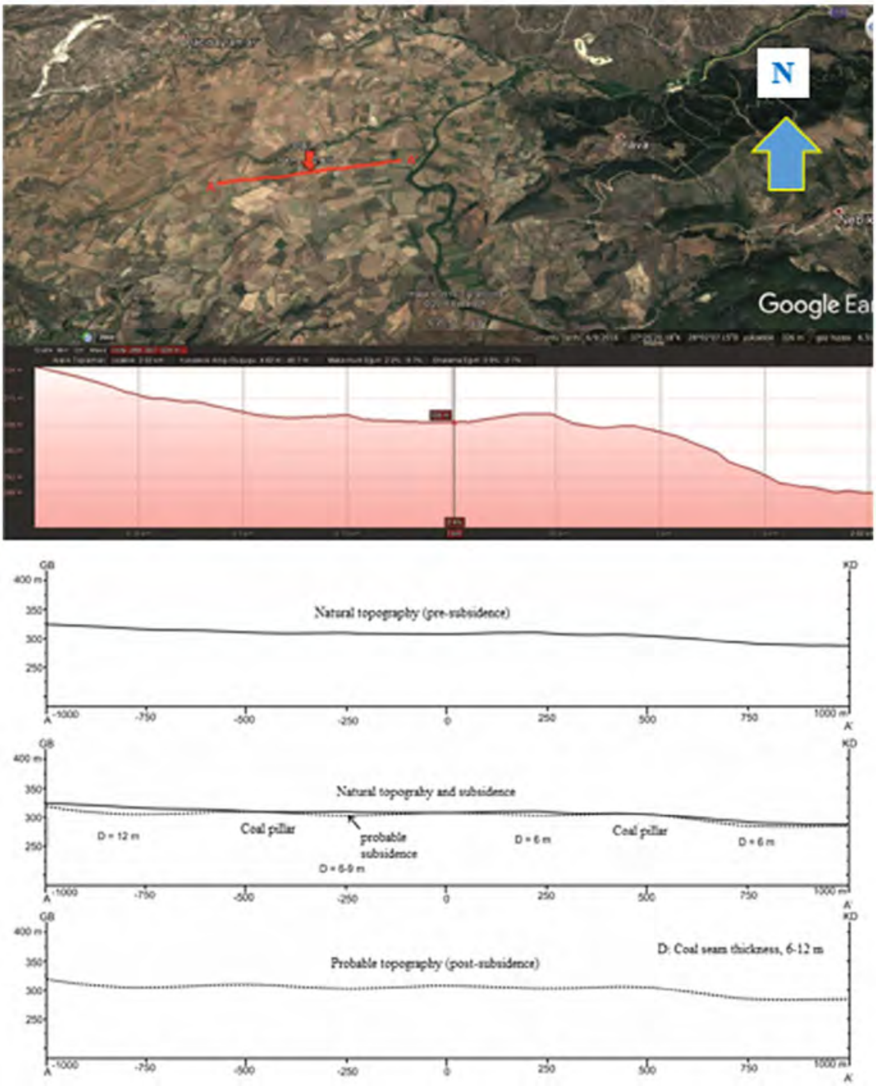

Figure 11. Natural topography in the E-W direction showing the site's Google Earth image, the trajectory of subsidence depending on the coal seam thickness, and the probable topography that will evolve after the subsidence. Source: The Authors.

5. Planning of longwall panels for Turgut basin coal measures

A total of twenty-four longwall panels were projected for the extraction of coal seam in the area of nearly 1 800 000 m^2 as shown in Figure 9. Coal extraction panels were dimensioned to be 500 m long and 150 m wide (length of the longwall face). No backfilling will be applied after the extraction of the coal seam. Longer axes of the panels were aligned E-W direction, in order to designate the coal pillars along N-S direction. Hence, the pipe network to be projected for the irrigation of the plain could be installed aligned with longer axes of the pillars without being subject to any damage that may occur owing to the subsidence. Subsidence analyses were realised using the SDPS software in the configured area (Figure 9) leaving coal pillars of several widths, such as 20, 30 and 40 m. Economically, the least subsidence was predicted in the result of analyses for coal pillar with a width of 30 m. However, an increase of 10 m in the width of coal pillar (40 m) did not yield any significant decrease in the subsidence.

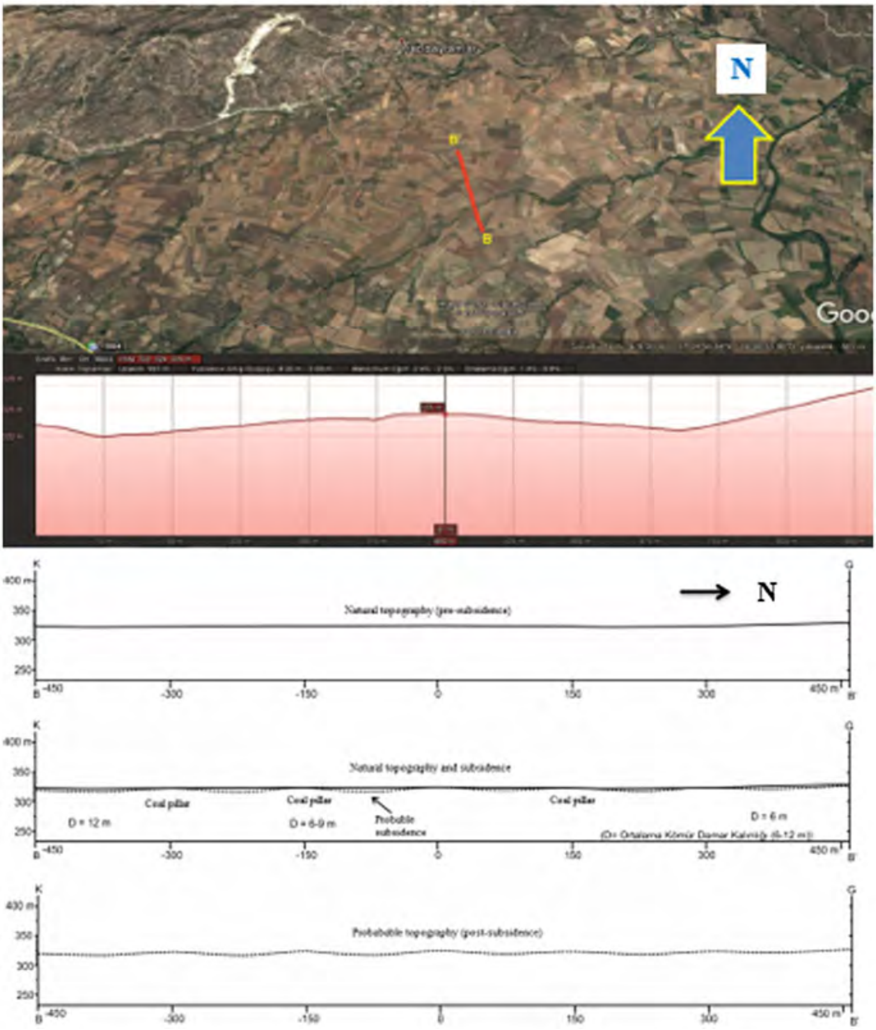

Figure 12. Natural topography in the N-S direction showing the site's Google Earth image, the trajectory of subsidence depending on the coal seam thickness, and the probable topography that will evolve after the subsidence. Source: The Authors.

6. Natural topography (pre-subsidence) and predictions of probable topography (post-subsidence) for Turgut coal measures

Results of the subsidence analyses for the coal extraction panels formed based on thickness of the coal seam are shown in Figures 9–11 as the natural topography (pre-extraction/subsidence) and probable topography (post-extraction/subsidence). In the evaluations, natural topography E-W (Section A-A′) and N-S (Section B-B′) directional sections were extracted while the current topography of the region was given with GoogleEarth image. Variable coal thicknesses (6–12 m) were processed under the topography. It is obvious that there is an increase in the subsidence from north to south-west depending on the increase in the coal thickness. However, the results obtained from the analyses suggest that a negligible amount of subsidence is expected to occur above the coal pillars of 30 m width, left between the coal extraction panels (Figures 11–13).

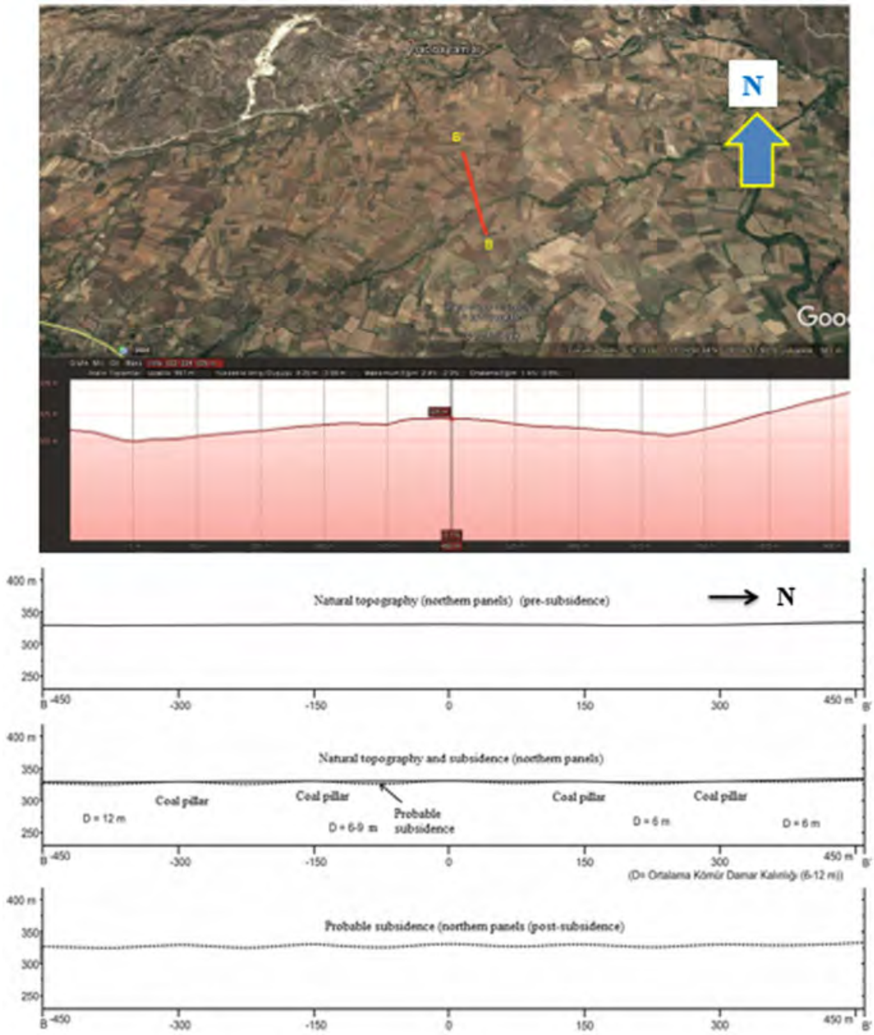

Figure 13. Natural topography in the N-S direction showing the site's Google Earth image, the trajectory of subsidence depending on the coal seam thickness, and the probable topography that will evolve after the subsidence. Source: The Authors.

7. Discussion and conclusions

As a result of underground mining operations with no backfilling, 'subsidence', which is called 'collapse' or 'seating', can occur naturally also owing to underground water movement and geological disasters and can damage surface structures and infrastructure from time to time. The amount of subsidence resulting from underground mining operations can be estimated as a result of some analytical and numerical analyses.

In this study, subsidence analysis was carried out using SDPS software according to the plan of coal extraction panels as shown in Figure 9, in which the width (W) and length (L) of the panel were determined as 150 and 500 m, respectively. The ratio, $W/H = 0.7$ is determined to be below the critical value of 1.2 ($W/H = 1.2$). At the eastern end of the panels where the average thickness of the coal seam is about 6 m ($D = 6$ m), nearly a maximum of 3.5 m of subsidence is anticipated to occur in this area, except above the 30 m wide coal pillar (T1KG) left to prevent subsidence (Figure 8). In the mid-section of the area, average coal seam thickness varies between 6 and 9 m ($D = 6–9$ m). In this section, a maximum subsidence of 5 m is expected to occur except above the coal pillar (T2KG) (Figure 10). In the western part where the coal seam thickness is near 12 m ($D = 12$ m), nearly 7.5 m of subsidence is predicted, however, above the coal pillars slight subsidence of maximum 0.5 m may be observed near the western border of extraction panels (Figure 10). The subsidence values over the coal pillars of 10 m wide in E-W direction were less than 0.3 m and negligible.

In this study, horizontal strains and deformations were also calculated along with the subsidence by the SDPS software based on the input data. However, magnitudes of horizontal strains and deformations were small and negligible when compared to that of subsidence. Hence, no impact of lateral deformations was expected on so the pipeline network to be installed on the surface.

When the drill-hole data and the data obtained from previous studies are examined, it is observed that clay units bear low strength and tend to display ductile deformation feature. Loose clay, sandy, silty and pebbly units are mostly over the lignite levels. It can be envisaged that these units will have a controlled subsidence that will gradually develop over the time, instead of sudden deformations that will cause catastrophic subsidence. Following the commencement of underground mining operations, it is important to monitor the movements through the displacement observation points to be created within the study area.

Disclosure statement

No potential conflict of interest was reported by the authors.

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