AMERICAN JOURNAL OF INNOVATION IN SCIENCE AND ENGINEERING (AJISE)

ISSN: 2158-7205 (ONLINE)

VOLUME 3 ISSUE 3 (2024)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Innovation in Science and Engineering (AJISE)

Volume 3 Issue 3, Year 2024
ISSN: 2158-7205 (Online)
DOI: https://doi.org/10.54536/ajise.v3i3.3275
https://journals.e-palli.com/home/index.php/ajise

Quantitative Analysis of the Subsidence Trough of the Barapukuria Coal Mine, Bangladesh

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Article Information

Received: August 28, 2024

Accepted: September 26, 2024

Published: September 30, 2024

Keywords

Angle of Draw, Geotechnical Properties, Influenced-Zone, Spatial and Areal Expansion, Surface Subsidence

ABSTRACT

Subsidence has been an ever-increasing concern of the Barapukuria coal mine for nearly two decades and has indeed called for quantification to predict the expansion of surface subsidence. The study has been undertaken to address this issue. Earlier studies only dealt with the horizontal expansion of the subsidence trough and were calculated based on a rudimentary rule of thumb. On this basis, about 646 acres of land have been acquired and marked as the Influence zone of the mine. However, the extension of the subsidence trough has moved further beyond the Influenced-zone boundary, severely damaging several houses around the mine . This study empirically measures the spatial extension of the subsidence trough identifying mining-induced cracks and joints in 37 affected houses around the mine that emphasized the modification of the rule of thumbs, particularly the angle of draw. It is revealed that the minimum and maximum limit angles are 42^{o} and 60^{o} respectively, and a distance of 378m to 727m (average 552m) must be considered to mark the influenced-zone boundary of the mine while the mining depth is 420m. To precisely quantify and predict the increasing progression of subsidence trough, it is imperative to determine an angle of draw, spatial and areal expansion, and the geotechnical properties for this specific mine.

INTRODUCTION

The Barapukuria Coal Mining Company Limited (BCMCL) started commercial production in 2005 using the Longwall mining method. Coal extraction from the 1st slice, 2nd slice, and 3rd slice have already been completed, and extracting coal from the 4th slice of the thickest coal seam VI (average thickness 36m). There exist 12 panels in the first slice, 9 in the second slice, 7 in the third, and extracting coal from the fourth slice. Around 646 acres of land have been acquired followed by coal extraction from the first slice, while land subsidence was observed first time in 2006 (Daily Star, 2016; BDNEWS24, 2016). The subsidence has gradually increased and reached beyond the influenced zone boundary as well as the land-acquired boundary during coal extraction from the 1214 face of the 2nd slice in January 2017. Agricultural land has been subsided, and cracks observed in the walls and floors of houses located around the mining area (north-eastern side of the mining area). The coal face 1214 is located beneath the acquired land where the average depth is 405m, the length of 440m, the width is 160m, and the coal extraction height is 6-7m. The land-acquired program was planned considering half of the mining depth (Rule of Thumbs). The influenced-zone boundary was marked according to the rule of thumbs i.e. a distance half of the mining depth. In this regard, around 210m distance from the mine panel was measured where the mining depth was 420m. with the angle of draw 26.5^{o}. The mining-induced subsidence analysis as well as prediction mostly depend on the projected and measured limit angles of the subsidence trough. The angle of draw or limit angles played a vital role in the planning and sanction stage of a mine. The areal expansion of subsidence is one of the most important factors to be assessed completely. Moreover, the dynamism of overburden strata with the geotechnical properties, and hydrogeological conditions play a prime role in appraising the limit characteristics of subsidence. The mining-induced subsidence prediction methods with various norms and their deriving equations that help to describe the spatial distribution of subsidence trough can be expressed through the Profile Function, Influence Function, and Empirical Methods, Numerical Models, and Stochastic Influence Functions. Among the practiced subsidence prediction methods and models, the Influence function was first proposed by Bals in 1931 and used to evaluate various subsurface geotechnical and structural factors. The Numerical models are powerful tools in the prediction of subsidence that are dependent on rock mechanics and mathematical theories. In mathematical modeling, rock deformation mechanisms are approximated by the physical behavior of overlying rocks. The Stochastic influence function is the advanced technique used in subsidence prediction to account for uncertainties in subsurface parameters, considering the hypothesis that the overburden strata are sequentially layered, separated by a series of cracks, joints, and fractures into numerous rock blocks whose dynamism has characterized by an arbitrary nature. The dislodgment of the stratified rock mass, as the summation of the movements of clastic particles, follows the laws of mathematical statistics (Litwiniszyn, 1957, 1972, 2014; Liu & Liao, 1965; Vulkov, 2001; Pataric & Stojanovic, 1994; Fei *et al.,* 2014; Valente, 2016; Cai *et al.,* 2016; Malinowska *et al.,* 2020). The present research has been carried out on the evaluation of geotechnical properties such as stress-strain parameters, and the geological conditions

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that influence the surface subsidence of the mine area. First of all, the research work has collected all required data and methods used in the calculation of geotechnical properties of rock from the respective mine authorities, studied carefully, and independently calculated all the parameters to cross-check and evaluate correct parameters using updated techniques. Accordingly, the research work included the evaluation of the geotechnical properties of rock; analysis to be tallied with the practiced and proven techniques; procuring the existing underground mine layout; monitoring subsidence of the mine for its spatial expansion, and predicting mine sustainability of the mine. The present study aims to consider the angle of draw as a vital issue from both a statistical and an analytical point of view.

Asymmetrical Basin Geology of Barapukuria

The Barapukuria Coal Mine (BCM) covers approximately 6.68 km^2 and is an asymmetrical basin in which coal deposits at shallower depth at both edges (north-south) and deeper at the middle portion. So far, the coal has been extracted from the first and second slices by longwall and Longwall Top Coal Caving (LTCC) system following a descending slicing path.

Half-graben Structure

The asymmetrical syncline basin has been developed with various boundary and intra-basinal faults (Armstrong, 1991; Bakr *et al.,* 1996). Most of the faults have a similar N-S direction (Figure 1a). Actually, the Permian coal of the Barapukuria basin has been deposited within the early-developed synclinal basin. The thick depositional sequence might have taken place due to simultaneous subsidence on the down-thrown block in the Archaean basement and forms the eastern boundary of the coal basin (Figure 1b-d). Within the Barapukuria coal basin, around 37 basinal faults have been identified in seismic interpretation (Armstrong, 1991) which affect the Gondwana Sequence. The longest intra-basinal fault 'Fb' with a displacement of up to 40m (Islam & Hayashi, 2008), and the eastern boundary fault 'Fa' have controlled sedimentary deposition within the basin. The positions and orientation of the faults located in the basin influence the formation of a half-graben with huge deposition to the east as well as the southeast portion of the basin (Armstrong, 1991; Bakr *et al.,* 1996)

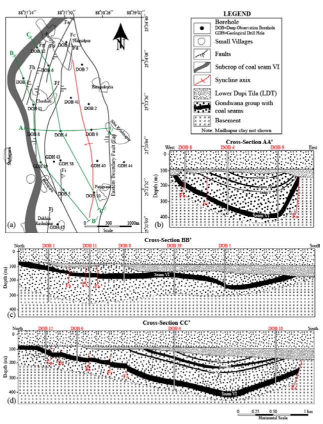

Figure 1: Major faults, structural pattern, stratigraphy, and distribution of coal seams of BCM (After Armstrong, 1991)

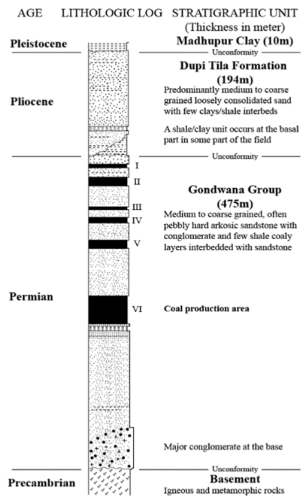

Figure 2: Summary litho-log with major stratigraphic units of Barapukuria basin (Imam, 2013).

Major Stratigraphic Units

The surface subsidence predominantly depends on the geologic sequences of a basin. In the BCM, four major formations namely Madhupur Clay, Dupi Tila (Upper and Lower), Gondwana Group, and Pre-Cambrian Archaean Basement (Figure 2), have been correlated based on age and lithology (Bakr *et al.*, 1996). The immediate roof rock of the coal panels at Barapukuria is of Permian Gondwana Coal and Sandstone that undergoes subsidence and reaches up to the surface through lower and upper Dupi Tila and Madhupur Clay. Here the coal is extracted from Seam VI and the extracted panels started leaving around 18m of coal at the top of Seam VI. In this case, coal becomes the immediate roof before the sandstone. The Gondwana Group contains coal (Seam I-V), sandstone, siltstone, shale, and various carbonaceous-argillaceous thin laminations. The lower Dupi Tila is a thin impermeable layer that is not present throughout the basin which is covered by a thick layer called upper Dupi Tila. The Upper Dupi Tila is well known as a water-bearing formation in the Barapukuria basin area.

MATERIALS AND METHODS

The rock sequences of the basin and mining horizon are considered in an equilibrium state before the mining activities. An early inequality of stresses around the opening is developed due to ore extraction which leads to redistribution of the ground stresses and deflection of overlying strata takes place due to stress redistribution. The continuous caving followed by ore extraction in longwall mining, moves upwards and spreads the caving to develop the subsidence trough. The extremely complex working procedure in longwall mining, and subsidence mechanism have many considering factors including the panels' geometry, geological structure and strength of overlying rocks, and groundwater conditions (Whittaker & Reddish, 1989). In nature, the stratigraphy of a basin is seldom homogeneous having a series of different types of rock of different origins, thicknesses, and strength properties. The reflection of subsidence trough on the surface solely depends on the panel width as well as the rock strength of the overlying strata. The roof may not deflect if the panel width is not sufficient with hard roof rocks, and a negligible amount of subsidence is observed. Otherwise, roof rock caves in, and ground deformation travels from the extraction level and moves up to the land surface. The noticed land subsidence and ground movement are the result of the collective response to the impact of underground excavation as well as the properties of the overlying strata. The angle of draw shown in Figure 3, is one of the most important parameters that defines the areal expansion of subsidence trough at the surface due to underground mining. The removal of infinitesimal mineral resources at the longwall panel develops a simple cave at the surface within the angle of draw and is also supposed to have minimum effect at the surface outside the limit line.

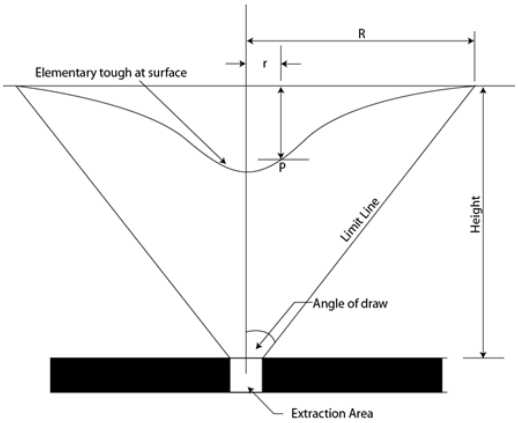

Figure 3: Effect of infinitesimal extraction element on surface.

The influence function (Whittaker & Reddish, 1989) of the infinitesimal extraction can be mathematically defined as:

$K_z = f(\gamma)$ .... (1)

Where Kz=The effect of an infinitesimal extraction, and γ=The angle of draw in the range $0 \leq \gamma \leq \theta$. Among different influence functions, the stochastic influence function illustrated in Eq. 2 is the most successful solution employed for subsidence modeling and prediction (Whittaker and Reddish, 1989).

$K_z = \frac{1}{R^2} e^{\frac{-\pi r^2}{R^2}}$ .... (2)

Where R=The distance between the center of subsidence trough and trough edge, and r =The radial distance between the center of trough and point P. From the above influence function Eq. 2, it is realized that R is the predefined function depending on the angle of draw (see Fig. 9).

$R = H \tan \theta$ .... (3)

Where H= The depth of extraction, and θ = The angle of draw.

Subsidence Mechanics and Theoretical Profile

The void that has been created due to the collapse of roof rock is referred to as 'goaf'. Primarily, the working spaces and the machinery along the coalface are shielded from the deflecting strata by the canopy of Armored Face Conveyors (AFC). The subsidence trough generally develops while the roof rock breaks down into the goaf area through continuous cracking, jointing as well as fracturing, then settlement of rocks progress through overburden-rock and subsidence takes place up to the ground surface. While the overburden strata are sufficiently strong and the extracted panel width is small, no deflection takes place and no noticeable subsidence is observed at the surface. However, the wide panels are being selected to extract maximum resources due to economic reasons, and, in almost all cases, the roof rock fails to sustain the overburden. When a series of panels are mined out leaving unmined rib pillars underground, the panels usually reach their critical width while the optimum subsidence occurs.

The Rule of Thumb in Theoretical Subsidence Mechanics

Longwall caving method always encourages surface movements due to the strata (overburden) failures in the mined-out areas (goaf). To predict the spatial expansion of a subsidence trough, the rule of thumbs often is used as a function of the coal seam thickness, and it shows different values in various coal basins ranging from 40% to 90% of the total mining height (Wagner & Schumann, 1991; Sheorey *et al.*, 2000). Moreover, the rule of thumbs is also used to evaluate the typical angle of draw (Brady & Brown, 2006), considering a point on the surface far from the panel edge is equal to half of the mining depth. Where the limit angle is calculated as the outward angle between the normal to the panel edge and a line connecting the panel edge up to the location on the surface where subsidence is considered zero. Fig. 4 shows a general subsidence profile of a longwall panel depending upon the rule of thumb and it is easily observed that the highest subsidence occurs above the center of the longwall panel and attenuated gradually.

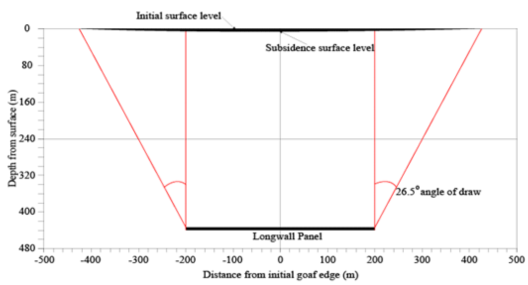

Figure 4: Typical subsidence profile is drawn to a scale (MSEC, 2007)

The Influence Function in Subsidence Mechanics

The theoretical angle of draw that has been considered according to the rule of thumb for the BCM is 26.5°, shown in Fig. 4. The influence of the surface subsidence moved beyond this point as coal extraction continues and reached the highest value. The mining-induced subsidence progresses upwards from the panel depth to the surface and the affected width (i.e., panel width) increases up to the surface. Sometimes the subsidence trough is found as an area greater than the geometry of the extracted panel. Though the research is expected an angle range from 55° to 60°, but a standard value of 45° often has been used in the past to predict the angle of draw of a subsidence trough. Although it is well-known that the rule of thumb has limitations, but the theoretical concept still has value today and applied to determine approximate subsidence. Based on the expected angle of draw, the areal extend of the subsidence trough is much more than the vertical depth of the coal seam, shown in Figure 5.

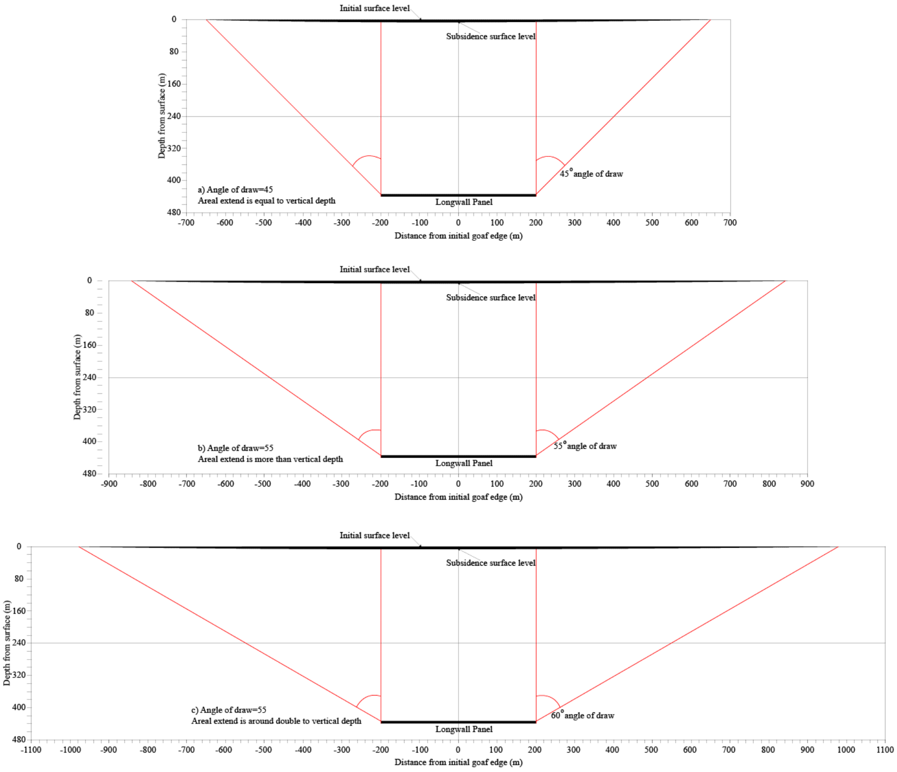

Figure 5: Areal extends in relation to the angle of draw-a) horizontal extension is equal to vertical depth of coal seam; b) areal extends is more than vertical depth and c) areal extends is almost double to the vertical depth of coal seam.

The subsidence models have been widely used successfully to analyze spatial expansion of a subsidence trough. Among all the techniques used, one of the prime parameters, the angle of draw (i.e., the limit angle) is often overlooked, which measures the horizontal expansion of subsidence trough. The angle of draw dealt with the subsidence trough is spread out through a complete cycle of compression and tension strain toward the limit of subsidence at the surface (see Figure 6).

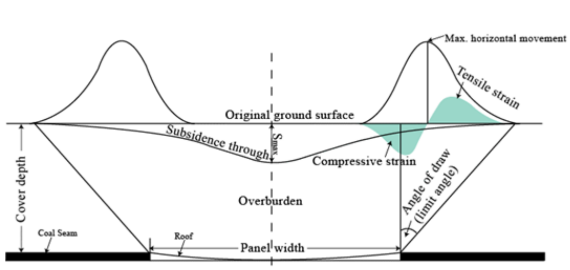

Figure 6: Mining subsidence terminology (MSEC, 2007).

Investigation of Cracks and Joints Around the Mining Area

To calculate the angle of draw for a specific subsidence trough, a subsidence settlement limit value needs to be assumed. In some countries, a random value of 20mm settlement is considered as an accepted limit, and minimum subsidence to the accepted limit is considered as a negligible effect on the surface, is also noted by Brady and Brown (Brady & Brown, 2006).

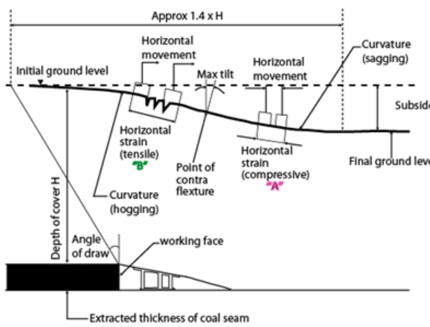

Figure 7: Development of subsidence through (Debono, 2007).

Therefore, it is generally accepted that the attenuated subsidence is insignificant and negligible beyond the area where subsidence limit is less than 20mm. The characteristics of cracks developed due to compression and tension are shown in Figure 7. The surface subsidence increased following the extraction of resources and advancement of the longwall panel.

The compressional cracks are found around the mid-point of the panel (“A” marked in Figure 7) and tensional cracks around the panel’s wall area (“B” marked in Figure 7). In field investigation, the nature of cracks and joints in the households around the mining area has been closely observed and quantified.

Investigation Target

The subsidence influences attenuated followed a compressional and tensional cycle and the angle of draw is considered at the tip of this cycle. The limit also depends on the geotechnical properties of overlying strata and mining geometry. The field survey has been conducted to find out the affected houses around the mining area.

Investigation Instruments

During the field investigation, the following simple instruments are used- a) steel tape to quantify the cracks and joints, b) a camera to record the images of the cracks and joints, and c) Global positioning system (GPS) to locate the position of the cracks and joints.

Outcome of Field Investigation

Depending on the investigation, 37 houses in and around Barapukuria Bazar, have been identified which are located on the northeast side of the mining area and the east side of the 1214 panel. The specific location, size,

Table 1: Positions of affected households around the Barapukuria coal mine area.

S.N	Latitude	Longitude	S.N	Latitude	Longitud
1	25°32’59”	88°58’ 38”	20	25°32’51”	88°58’ 55”
2	25°32’57”	88°58’ 37”	21	25°32’50”	88°58’ 50”
3	25°32’56”	88°58’ 37”	22	25°32’47”	88°58’ 49”
4	25°32’53”	88°58’ 38”	23	25°32’42”	88°58’ 53”
5	25°32’55”	88°58’ 37”	24	25°32’35”	88°58’ 52”
6	25°32’50”	88°58’ 45”	25	25°32’33”	88°58’ 45”
7	25°32’49”	88°58’ 40”	26	25°32’51”	88°58’ 56”
8	25°32’49”	88°58’ 46”	27	25°32’49”	88°58’ 50”
9	25°32’44”	88°58’ 43”	28	25°32’49”	88°58’ 51”
10	25°32’32”	88°58’ 44”	29	25°32’44”	88°58’ 52”
11	25°32’34”	88°58’ 43”	30	25°32’40”	88°58’ 48”
12	25°32’41”	88°58’ 47”	31	25°32’36”	88°58’ 45”
14	25°32’31”	88°58’ 43”	32	25°32’34”	88°58’ 47”
14	25°32’34”	88°58’ 39”	33	25°32’58”	88°58’ 23”
15	25°32’36”	88°58’ 37”	34	25°32’41”	88°58’ 38”
16	25°32’29”	88°58’ 42”	35	25°32’58”	88°58’ 23”
17	25°32’38”	88°58’ 52”	36	25°32’55”	88°58’ 34”
18	25°32’34”	88°58’ 47”	37	25°32’41”	88°58’ 38”
19	25°32’37”	88°58’ 51”			

and alignment of the cracks and joints in houses were recorded. The coordination of the affected houses is shown in table 1.

The coordinates of the cracks in the house walls and floors have been collected through a field survey and plotted on the map (Fig. 8) called ‘Position of affected households of Barapukuria coal mine’ to visualize the spatial impacts of land subsidence followed coal extraction from Barapukuria underground coal mine. The map shows that the impacts of land subsidence have been extended beyond the influenced zone and land acquisition area of Barapukuria Coal Mining Company

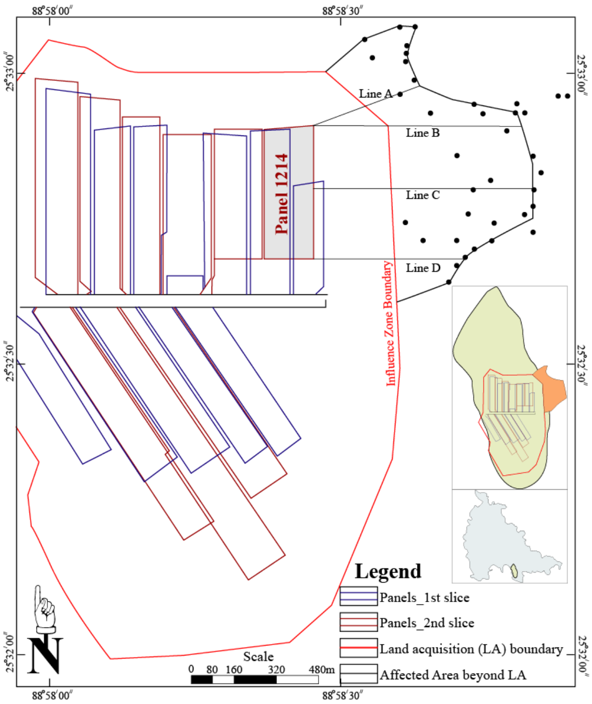

Figure 8: Positions of affected households beyond the influenced zone of the Barapukuria coal mine.

Table 2: Observed angle of draw in different Asian countries (Modified after Singh & Singh, 1998; Li *et al.,* 2007; Waddington & Kay, 1995)

Name of Country	Angle of draw	Overburden	References
Japan	40° - 50°	-	Singh & Singh, 1998; Li *et al.,* 2007; Waddington & Kay, 1995; Moebs & Barton, 1985
India	40°	>62% clays in overburden	Singh & Singh, 1998;
China	32.9°	-	Li *et al.,* 2007; Cui *et al.,* 2001
Australia	19° - 50°	Mostly strong overburden strata; sandstone and massive conglomerate	Waddington & Kay, 1995; Holla, 1997

Limited. The boundary line drawn from the map is 190-475m from the land acquisition boundary and 375-725m from panel 1214.

Moreover, the vertical depth of the mining horizon also influences the limit angle. Many researchers have been reported the amount of limit angle ranges from 11° to 50° (see Table 2) and characterized the type of overburden strata investigating subsidence troughs of various coal fields.

Angle of Draw and Unconfined Compressive Strength of Overburden

Observing stratigraphy from boreholes DOB-10, GDH-40, DOB-9, DOB-2, DOB-7, and DOB-13 the average depth of Alluvium, Madhupur clay, Dupi Tila formation, and Gondwana group is of 142.08m and mostly weak sediments. There is a water-bearing zone (aquifer) called Dupi Tila Formation. Moreover, a north-south lineament fault (200m down thrown) is located eastern side of the mine. The panel 1214 is developed into the highest depth 380-450m., and extracted coal by the Longwall Top Coal Caving (LTCC) mining method. The panel is 161m wide, 434.15m long, and 7.39m high. So highest land subsidence would be a general issue around the area. The Unconfined Compressive Strength (UCS) of the overburden of the BCM area is between 10.28 MPa and 55.32 MPa (Table 3).

Table 3: Unconfined compressive strength of Barapukuria coal mine (Armstrong, 1991).

Borehole No.	Sample Depth (m)	UCS (MPa)	Average UCS (MPa)
DOB 12	136	24.73	22.53
DOB 05	211	55.32	
DOB 05	245	25.13	
DOB 06	248	26.38	
DOB 02	265	12.66	
DOB 10	277	33.40	
DOB 04	312	19.83	
DOB 10	312	21.30	
DOB 10	328	10.28	
DOB 09	358	15.17	
DOB 09	369	13.04	
DOB 09	376	16.38	
DOB 09	425	19.31	

Table 4: Relation of UCS and angle of draw (Yao *et al.,* 1991)

2	27
4	29
6	33
8	35
10	45

The angle of draw increased as well as the UCS and it is greater than 450 while UCS is greater than 10 (Table 4). Depending on the relation between the angle of draw and UCS, it can easily be noted that the angle of draw in the BCM must be more than 45^0. From the field survey and plotted coordination of the affected houses, four lines have been drawn from panel 1214 (A, D, B, and C Line in Fig. 8). Based on the angles developed from the normal of panel 1214, and the four affected houses are 42°, 50°, 58.5°, and 59.9° (Figure 9).

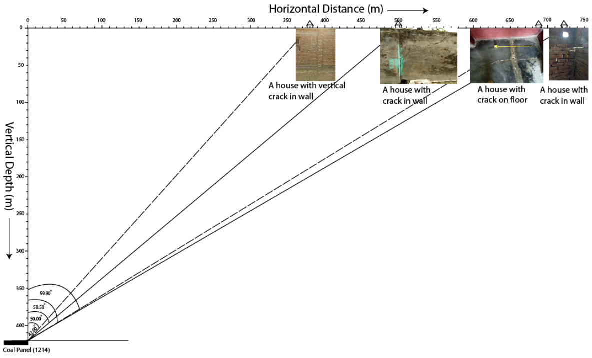

Figure 9: The probable angle of draw from Panel 1214 to the affected household located east of the mine.

The Zone of Influence of The Underground Mine Could be Calculated as

Zone of influence = tan θ × Panel depth

While θ = 42°, Depth 420; then

Zone of influence = 378.16 m

While θ = 60°, Depth 420; then

Zone of influence = 727.46 m

So, the location of affected houses of Baddyanathpur, Shibkrishnapur, Patrapara, Mathurapur villages would be 378-727m from panel 1214 (while the angle of draw considered 42^0 to 60^0).

RESULTS AND DISCUSSION

The only underground coal mine BCM in Bangladesh faces numerous challenges in extracting coal that is located near the surface due to the absence of hard roof rock. The only roof rock 'Permian sandstone' failed to sustain the overburden load which allowed subsidence on the extracted top up to the surface. Amstrong (1991) considered influenced zone of subsidence area would be half of the mining depth based on the rule of thumbs. However, the influenced zone went far away from the proposed and measured influenced zone and developed cracks and fractures in the households located in and around the mining area as the subsidence trough increased due to the advancement of coal extraction horizontally and vertically. In BCM, the angle of draw is around 42° to 60° (Figure 9), based on the field analysis considering panel 1214 and the affected houses around the mining area. The observed limit angle for the BCM basin is more than the reported average angle of draw (i.e. 30.5°) in various underground coal mines operating in Asian countries (ranging from 11° to 50°) and particularly in Australian mines is 34.5° (ranging from 19° to 50°). A close relation between the Unconfined Compressive Strength (UCS) of the roof rack and the angle of draw prevails. It is revealed that the angle of the draw is 45° while UCS is 10 MPa. So, the angle of the draw must be more than 45° as the average UCS of Barapukuria is 22.53 MPa.

CONCLUSION

Longwall and its moderated version Longwall Top Caving Coal (LTCC) always allow deformation of the overburden strata to settle down the extracted void. The subsidence reached up to the surface and developed cracks and fractures in the house walls, and floor and sometimes damaged households in and around the mining area. The mine-induced surface subsidence has been observed in and around the BCM area following coal extraction commenced in 2006. The surface subsidence has taken place after coal extraction from the first panel (1101) of the first slice. The areal distribution of the subsidence is being increased according to coal extraction from the ground year after year. The roof rock (Permian Sandstone) strength, angle of draw, and the overburden strata supported the areal distribution of the subsided area. According to the measured angle of draw 42° to 60° the influenced zone should be calculated and land acquisition must follow accordingly. Therefore, it may be concluded that the spatial analysis and prediction of subsidence in an underground mine required many parameters to investigate and determine the subsidence trough as well as the areal distribution. Finally, it is recommended that subsidence monitoring must be started from the beginning of the mining operation, and subsidence monitoring stations must be started at the beginning of the mining operation, and subsidence monitoring stations be installed throughout the panel length. Moreover, convergence monitoring systems should be strong enough to collect data from the beginning to the end of ore extraction.

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