Effect of longwall mining on groundwater for underground coal extraction in Barapukuria, Bangladesh

Barapukuria is the first and only coal mine in Bangladesh. It deals with the groundwater monitoring and mine flooding with its practical applications to recognize the mining related geo-environmental hazards associated with the Gondwana Barapukuria coal basin of northwest Bangladesh. A summary and problems regarding the present research emphasizing on the general geologic understanding, hydrogeological, geotechnical, and tectonic setting of the study area have been focused and specially ground movement and water inrush/ inflow hazards into the mine. Water inrush in the mine generates adverse impacts on the exploration and underground multi-slice longwall mining in the Barapukuria coal deposits. It is also shown that current coal mining operations under a mega-aquifer in NW Bangladesh, and presents a case study of underground mining in Barapukuria and water inflow enhancements that result from these coal extraction operations.

Introduction

Coal mine of Barapukuria basin in Dinajpur district, Bangladesh, enters into the coal mining era for the first time. Geographically the study area lies between latitudes 25°31/N to 25°35/N and longitude 88°57/E to 88°59/E, included in the survey of Bangladesh topographic sheet No.78 C/14. The coalfield was discovered by the Geological Survey of Bangladesh (GSB) in 1984-85 and 1986-87 field season in the drill hole GDH-38, which encountered coal seams at a depth of 159 m. The coal reserve found in the Barapukuria is 303 million tonnes (Wardell Armstrong, 1991). In addition to that about 86 million tonnes is considered as inferred reserve. Studies suggest that coal mining is technically as well as economically feasible and concluded in favour of underground mining. On the basis of consultant opinion, the Government of Bangladesh decided to establish an underground coal mine at Barapukuria. In 1994, the Bangladesh government signed a contract with the Chinese contractor CMC (China National Machinery Import and Export Corporation) for the development of Barapukuria coal mine at a production rate of 1 million tonne per year in 25 years mine life by underground mining method. At present, the coal mine is facing enormous difficulties to meet the target.

Structure of the Barapukuria basin

Regionally, the Barapukuria coal basin is located in the Dinajpur shield (Fig.1) of Bangladesh and is surrounded by the Himalayan Foredeep to the north, the Shillong shield/ platform to the east, and the Indian peninsular shield to the...
west (Khan, 1991; Khan and Chouhan, 1996; Alam et al., 2003). Structurally, the Barapukuria basin is a long, narrow, and shallow permo-carboniferous intracratonic rift basin. The basin trends approximately N-S for over 5 km, ranges from 2 to 3 km wide, and is over 550 m deep. Steeply dipping normal faults bound tilted half-graben occurs below a prominent unconformity, covered by an unstructured pleistocene through tertiary clastic sequence, (Fig.2). The northern, western, and southern boundaries of the basin are also truncated by several small-scale normal boundary faults. Major basin-bounding faults are part of a zone of crustal weakness. The faults and igneous dyke decrease the cohesion and friction angle and reduce the shear strength through fault plane and filling materials. The overall structures of the Barapukuria basin imply a tectonically active highly disturbed zone (Wardell Armstrong, 1991; Bakr et al., 1996; Islam and Islam, 2005). The Barapukuria half-graben basin is assumed to be related to tectonic origin. The basin area is very close (about 200 km) to the convergence boundary of the Indian and Eurasian plates. As a consequence, the far field tectonic stress field is highly significant to the structure of this basin. A 5 km long eastern boundary fault of the Barapukuria basin is the best structural evidence for recent tectonic activity. In a gross sense, for the Barapukuria-type half-graben basin, displacement is greatest at the center of the fault and decreases to zero at the fault tips. The displacement of an initially horizontal surface that intersects the fault is greatest at the fault itself and decreases with distance away from the fault. This produces footwall uplift and hanging-wall subsidence, the later which creates the sedimentary basin (Gibson et al., 1989; Contreras et al., 1997).

It is apparent that the basin geometry is affected by fault propagation and displacement is accumulated on the boundary fault.

Geology and hydrogeology of the basin

Geologically, this basin area is a plain land covered with recent alluvium and pleistocene barind clay residuum. The geologic succession of this basin has been established on the basis of borehole data (Guha, 1978). The sedimentary rocks of Gondwana Group, Dupi Tila formation, barind clay residuum and alluvium of the permian, pliocene, pleistocene and recent ages respectively were encountered in the boreholes which lie on the pre-cambrian basement complex. A large gap in sedimentary record is present in between Gondwana Group and Dupi Tila formation, which is most probably happened due to the erosional or non-depositional phase exist during triassic to pliocene age (Khan and Rahman, 1992).

The principal constraints to the design of the BCMP relate to the great thickness (average 36 m) of seam V1, which contains some 90% of the reserves, and the presence of massive Gondwana sandstones and unconsolidated Dupi Tila formation. The later formation represents a major aquifer over the whole mine area with many thousands of square kilometers aerial extent. It is at least 100 meters in thickness reaching 185m in the southern part of the mine area and is overlain by barind clay residuum. The Dupi Tila formation and Gondwana sandstone are in hydraulic continuity with the coal seam V1 and represents a major potential hazard to the mine from water inflow.

Methods of study

Different types of meteorological data are important for interpreting groundwater level fluctuation and water level drawdown. Mainly rainfalls, temperature, humidity of the area were interpreted. Interpretation of data shows the mine areas climatic change and how does it affect the groundwater level. The collected meteorological data are from 2000 to 2010 from regional meteorological sub-division office, Dinajpur. The collected hydrogeological data are groundwater levels in dry and rainy seasons, hydrogeologic units and their characteristics, amount of mine inflow etc. For determining the groundwater level condition it is necessary to monitor different monitoring well data which are situated in the mine area. The water levels are monitored from 23 boreholes (now 2 test boreholes were sealed) in the Barapukuria coal mine.

Fig.2 Structural pattern of the Barapukuria coal basin, Dinajpur, Bangladesh (Wardell Armstrong, 1991; Bakr et al., 1996; Islam and Hayashi, 2008a; Islam et al., 2009)
area. These boreholes were installed by W.A. Company in 1991 for the study of hydrogeological characteristics, water level fluctuation and hydraulic relationships between aquifers. Barapukuria coal mining company collected monitoring well data daily basis. For graphical presentation daily data are converted to monthly basis from 2004 to 2010. Geotechnical data were collected from the existing underground mine documentation center to evaluate Barapukuria underground coal mine areas recent groundwater and other geotechnical problems. At the time of feasibility study for underground mine a detail geotechnical investigation was done by Wardell Armstrong (1991) and China National Machinery Import and Export Corporation (CMC), 1994, which is used as the main source for the present study. More than 20 boreholes were used to know the geotechnical properties of the rock types of Barapukuria area. The collected data includes shear strength properties of rocks (cohesion and angle of friction), moisture and saturated unit weight of rocks, consolidation test etc. The geotechnical data were collected from four formations viz. the Madhupur clay formation, Upper Dupi Tila formation, Lower Dupi Tila formation and Gondwana formation.

**Dupi Tila water level fluctuations and recharge**

Observed fluctuations at all monitoring sites show that groundwater levels respond to rainfall. The pattern of groundwater fluctuations were monitored from January to December and represents almost a complete annual cycle. The plots show a groundwater recession during January, February and early March (2006-2008), which was a period of negligible rainfall. Intermittent rainfall during mid-March and more continuous rainfall from mid-April onwards resulted in a significant rise of the groundwater surface.

Groundwater is within the Dupi Tila aquifer system in close to ground-surface throughout the year. Lowest observed natural groundwater levels during March were approximately 9m below the groundwater level during the monsoon season. During the monsoon the regional groundwater surface is within approximately 2m of ground surface. A 6-7m general rise of groundwater levels within the Dupi Tila recorded from the lowest levels during March to mid-June, high groundwater levels at or very close to ground surface was sustained during the monsoon season. In the mine area, where the Madhupur clay is relatively thick, infiltration may be limited by the permeability of the clay. Infiltration tests on Madhupur clays by BADC indicated a percolation loss during the monsoon season, would amount to a vertical recharge of 280mm. Studies by UNDP, 1982, suggest a minimum annual recharge for the Dinajpur region of 370 mm and a maximum of 660mm representing 18.5% and 33% respectively of the average annual rainfall of 2000 mm. Recharge occurs through infiltration of rainfall, flood waters, stream and canal flow, and irrigation returns. It mainly occurs between May and July, as indicated by the sharp rise of water levels during this period. After July, water levels remain stable suggesting rejection of recharge because the aquifer is filled to capacity.

**Gondwana hydrogeology**

Groundwater movement is complex in Gondwana formation. Levels are higher in the north where the formation is in contact with Dupi Tila sands. The eastern extent of the aquifer is defined by a major fault bringing the aquifer against basement strata which acts as a barrier to flow. Other faults that affect the Gondwana basin do not appear to exhibit either enhanced or reduced permeability along the fault line, although they may cause some discontinuity to flow. There is presently insufficient data to predict groundwater flows in the south of the area. Reacharge is by vertical leakage from the overlying Dupi Tila aquifer. Where no lower Dupi Tila is present the recharge is via direct percolation. This process is progressively attenuated as the lower Dupi Tila aquitard increased in thickness towards the south and centre of the basin. Recharge can be calculated at 1 liter/second or 0.21 liter/second per km² width of an aquifer. Where the Gondwana and Dupi Tila aquifer are not separated by any Dupi Tila there is a good hydraulic connection. The Gondwana aquifer is confined by the underlying Tillie and basement strata. It comprises a poor leaky semi-confined aquifer with recharge by downward percolation from the overlying Dupi Tila aquifer.

**Gondwana groundwater abstractions**

During the development period (2001-2004) of the mining tunnels in Barapukuria, it was observed that the water inflow rate increased simultaneously with the mining. The water inflow rate in August 1998 was about 620 m³/hr when the underground mine tunnel length was about 1200 m. In November 2004, it increased up to about 1300 m³/hr, while the developed tunnel length was about 19,000 m (Islam and Islam, 2005). At present, the total inflow rate is about 1750 m³/hr (Monthly Progress Report, Barapukuria Coal Mining
Initially water inrush was predicted by the geologist and mine planer presumably at 500 m$^3$/hr. But over the time with high production rate of coal, roof caving propagate the fracture to the direct roof and indirect roof and that may be reached up to lower Dupi Tila and upper Dupi Tila which may cause of the water inrush volume almost triple. At present mine authority discharging nearly 1500 m$^3$/hr. This trends indicates that there is a direct relationship between the opening of the underground mine face and the inflow rate of water from the Dupi Tila formation through coal seams into the excavated mine face. A detail groundwater modelling should be carried out for avoiding such incidence in the underground mine.

**Impacts of longwall mining on groundwater**

During subsidence the strata undergoes fracturing and opening of existing fractures and joints and also a separation of the bedding planes, which causes an increase in fracture permeability and porosity (Booth, 2003). These changes in turn cause variations in hydraulic heads, gradients, and groundwater flow patterns (Dawkins, 1999; Booth et al., 1998; Aston and Singh, 1983) which can have significant impacts in nearby wells and on water supplies in the surrounding communities (Karaman et al., 2001). Although there is some potential for fracturing in the overlying aquifer to cause or increase drainage into the mine, it is generally accepted that variations in hydraulic gradients and groundwater levels are due to the changes in fracture porosity and permeability caused by longwall mining subsidence (Booth, 2003; Karaman et al., 1999; Booth et al., 1998). Normally, mine drainage only impacts wells that penetrate the lower fractured zone, and/or other zones where natural fractures are present (Booth, 2006).

The overburden above a longwall panel can be described as three zones (modified after Booth, 2002; Booth, 2003; Judall, Platt, Thomas and Associates, 1984):

1. Fractured zone (Gondwana formation): the lowest, most severely fractured zone, which greatly increases permeability and drains directly into the mine. The height of this zone can be described as a third to a half of the width of the panel, or between 20 and 60 times the extraction thickness. The fracture zone is typically dewatered; thus wells completed across this zone typically lose their water.

2. Aquiclude zone (lower Dupi Tila formation): An intermediate compressional zone that subsides with little

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**Overall geological and hydrogeological environment**

In the Barapukuria basin, although seam VI is fairly flat-lying and extensive, the main problem is that the entire basin is affected by numerous faults and fractures. As described above, the basin is an intracratonic half-graben basin that is crossed by normal faults. The coal bearing permian Barapukuria formation of the Gondwana Group forms a plunging syncline that subcrops below the plio-pleistocene Dupi Tila formation, which is the water-bearing formation overlying the mineable coal seam. Two major extensional faults (Fig 2), Fa and Fb, are major controlling factors for water seepage into the mine (Wardell Armstrong, 1991). The Dupi Tila deposits comprised poorly consolidated to unconsolidated sands with high permeability ranging from 4.81 mD to 558 mD. Permeability within the Gondwana is considerably less (3.67 mD to 75 mD) than that of the overlying Dupi Tila aquifer. The upper coal seams have permeability between 9.8 mD and 137.8 mD because these seams are comparatively soft and, to a varying extent, are in hydraulic continuity with the upper Dupi Tila aquifer. Seam VI has permeability in the range from 13 mD to 119 mD (Wardell Armstrong, 1991; Islam and Hayashi, 2008a). Wardell Armstrong Mining Consultants of the United Kingdom and China National Machinery Import and Export Corporation (CMC) carried out pump-tests to estimate the hydraulic conductivity of the Dupi Tila aquifer and the Gondwana aquifer, respectively. In the Dupi Tila aquifer, the estimated results range from 160-260 m/d for the entire thickness of about 110 m (borehole DOB#5). Estimated hydraulic conductivity for the Gondwana aquifer is 31 m/d for the entire thickness of about 100 m. The permeability value of the lower Dupi Tila aquiclude is about 0.15 mD (Wardell Armstrong, 1991) and (CMC 1994).
3. Surface zone (upper Dupi Tila formation): It is the uppermost zone and consists of shallow strata subject to extensional stress and fracturing. Aquifers are affected by in situ fracturing but not necessarily by drainage into the mine from which they are hydraulically separated by the aquiclude zone. Fracturing and dilation of joints and bedding planes in the subsidence areas causes an increase in aquifer void volume and porosity. This in turn increases the aquifer permeability and storage coefficient (Dawkins, 1999), which creates a drop in water level and a hydraulic gradient towards the depression over the local potentio-metric depression (Booth, 2006; Karaman et al., 1999). Groundwater levels can begin to fall even before a longwall panel passes under a well, as drawdown is transmitted through the aquifer ahead of the longwall mining. Groundwater typically flows along the induced hydraulic gradient towards the depression over the subsiding zone (Fig.4) due to any or all of the following (Booth, 2003; Hill and Price, 1983):

- Direct drainage to the mine, if the well bottom is within the lower fractured zone.
- Increases in fracture porosity in strata, which causes large head drops in confined bedrock aquifers because of their low storativity and low fracture porosity.
- Increases in fracture permeability, causing decreases in hydraulic gradient from the site. Groundwater levels in wells may rise and groundwater discharges in mine increase.
- Draining of upper level aquifers through fractured aquitards down to lower levels.
- Drawdown expands outwards from the primary potentio-metric flow.

**Impacts on hydraulic properties**

During longwall mining, rock mass deformation and water/gas flow processes interact dynamically. Flow is controlled by the permeability of the porous medium, which remains a highly non-linear function of mining induced stress and resulting fractures (Adhikary and Guo, 2005). Therefore, any predictive methods to determine hydraulic behaviour requires the capability to accurately determine mining induced rock mass deformation, fractures and resulting changes in fluid flow parameters (Wook, 2005).

**Conclusion**

A variety of studies have documented the environmental impacts of longwall coal mining, including serious effects on aquifers, land subsidence, and the hydraulic properties of the mined strata. These studies also show that the impacts of longwall mining arise not only due to the drainage of groundwater into mined panels but also from changes in the overburden stress regime. Such groundwater hazards present a risk to mine safety that is a common concern of both mine operators and researchers. It is of vital importance to study mining-induced strata failure and the hydraulic parameters of these strata in order to predict and prevent water inflow in coal mines (Hill and Price, 1983; Booth, 1986; Zhang and Shen, 2004).

In the Barapukuria coal basin, six coal seams have been discovered, among which only seam VI (about 36 m thick) has been considered for mining. If the coal thickness was around 3-10 m, single-slice to double-slice mining methods are promising. Single to double-slice mining is not economically beneficial due to high thickness of coal in Barapukuria. Thus, the China National Machinery Import and Export Corporation (CMC) planned to use the multi-slice longwall mining method. For its operation, CMC divided seam VI into 16 panels with 6 slices. Seam VI is blocked out into a panel averaging nearly 120 m in width, 550 m to 900 m in length, and about 3.5 m in height, by excavating passageways around its perimeter. The ultimate height of the fracture zones would be about 22 m for the panel thickness of 3.5 m. The first-slice coal production commenced in 2005 and is continuing with different hazardous environments such as high temperature, humidity, large-caving on the roof, and huge water inflow from the roof.

The coal-bearing Gondwana Group in the Barapukuria basin, as well as the other basins in Bangladesh, is located under a “mega-aquifer” which is named the Dupi Tila formation. It is a prolific groundwater reservoir extending over larger areas of Bangladesh. Numerous high-angle normal faults, X-shaped joints, and fractures characterize the basins. During a seismic survey carried out by Wardell Armstrong Mining Consultants of the United Kingdom, about 37 faults were detected. At the time of tunnel development (2001-2004), numerous faults with 1-3 m throw were observed.

Fracture intensity within the rock strata of the Gondwana Group ranged from 7-10 per meter, whereas joints ranged from 1-3 per meter. Thus, the coal-bearing Gondwana Group is connected directly or indirectly with the overlying water-
bearing Dupi Tila mega-aquifer by diverse joints, faults, and fractures (Islam and Islam, 2005; Islam and Hayashi, 2008a). In addition, there is an open window that is located at the northern extremity of the present mine plan. The hydrogeological conditions in the Barapukuria coal mine are very complex. The most serious issue affecting the safe operation of the coal mine is water inflow from the unconsolidated upper Dupi Tila (UDT) aquifer. Flooding of the mine from breaches in the upper Dupi Tila aquifer occurred frequently in different time during the mine development and production time.

Faults and fractures in the Barapukuria basin have created a groundwater flow network between the water bearing Dupi Tila aquifer and coal-bearing Gondwana rocks (Wardell Armstrong, 1991). Wardell Armstrong Mining Consultants of the United Kingdom investigated the hydraulic gradient and the general direction of groundwater inflow in the Barapukuria area. A moderate hydrodynamic balance appears to exist between the upper Dupi Tila aquifer and the underlying Gondwana units, with an almost flat hydraulic gradient (0.0004–0.0006). Average transmissivity, specific yield, and velocities were 1200 m²/day, 25% to 30%, 0.0004, and 0.02 m/day, respectively (Wardell Armstrong, 1991; Islam and Hayashi, 2008). The main lineaments (faults and shear zones) and dikes overlie the Archaean basement in the study area. Fb is absent within the Dupi Tila formation, and the general direction of groundwater is NE-SW. If Fb was within the Dupi Tila formation it could act as an important conduit, rather than as a barrier to groundwater flow. Conveniately, Fb is located within the Gondwana formation, where the general direction of groundwater is NW-SE, W-E, and SW-NE. The hydraulic gradient and the general direction of groundwater flow are almost at right angles with the trend of Fb in the mining regions. Therefore, Fb could act as a barrier to groundwater flow, i.e., the effect on the aquifer.

Another important geological feature in the Barapukuria coal deposits is an igneous intrusion (dike) that trends NE-SW. Studies have shown that not only faults, but also dikes, can play important roles in groundwater flow.

Dikes can be either barriers or conductors for groundwater flow if they consist of fine-grained rock. The effect of dikes depends on their trends in relation to the hydraulic gradient and the density of the fracture systems in the dikes. Transverse dikes act both as groundwater barriers and as conductors (Babiker and Gudmundsson, 2004). In case of the igneous dike in the Barapukuria basin, it was observed during the mining development that the dike acts as a barrier rather than a conductor for groundwater flow. A very small amount of water flows through some fracture systems of the dike; however, it was insignificant (Islam et al., 2009).

Despite these geological and hydrogeological complexities, a multi-slice longwall mining plan has been considered for a 34 year mine lifetime, with a target production of 1 million tonnes per year. If the mine is successfully operated, about 10% of the total coal reserve (about 37 million tonnes) (Islam and Hayashi, 2008a) will be extracted. At this point, our basic question is whether it is possible to accomplish longwall mining accurately in the Barapukuria basin considering its geological and hydrogeological characteristics. The primary purpose of this study is to focus on hydrogeological complexities that might be encountered in an overlying aquifer during multi-slice mining excavation. Under natural conditions, groundwater is introduced into coal seams by infiltration at the sub-crop with Dupi Tila sands and by vertical movement through the surrounding Gondwana host rocks.

Drainage of mining excavation sites located within these seams will cause a redistribution of stress patterns and readjustment of the natural groundwater flow patterns. In general, a lowering of the groundwater potential at the excavation site will lead to the following important changes:

- A higher rate of infiltration from the Dupi Tila into the seam excavation.
- A lower groundwater potential within coal seams relative to surrounding lithologies that will cause increased convergence of groundwater towards the seams.
- Groundwater within the coal seams will converge on the area of excavation and will cause increased movement toward the main cavities including lateral flow along the coal seams.

Longwall mining is sometimes considered to be destructive or environmentally unsafe because it causes the land above the mined-out panel to sink. At present, large-scale land subsidence has occurred at Kalupara village, south-southeast of the Barapukuria mine, due to extraction of a 3 m high section of mining panel 1101. It is to be mentioned that some of the Kalupara village is located just above the 1101 mining panel, from where coal extraction had already been completed by 2006. The 1101 mining panel is about 900 m length. At present, the 1103 mining panel, which is parallel and just east of the 1101 panel, is under consideration for extraction. If in the future multi-slice (about 18 m thick) coal is extracted, an equal heights of land subsidence can be expected to occur and cause of new fracture in the Gondwana formation which increase permeability increasing water inflow level in the underground mine face.

References


