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MINE DEWATERING: A VERITABLE COMPONENT IN MINE COST ANALYSIS IN THE DEVELOPMENT AND MINING OF THE LAFIA-OBI COAL, NIGERIA

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ABSTRACT

The impact of water in surface and underground mining activities is of great concern to Mining Engineers and Geoscientists to the effect that its accumulation in excess quantity can render mining of minerals ineffective. Surface and underground mines must therefore constantly be dewatered in order to forestall over-flooding and its attended effects on mining machinery, infrastructures industrial health, and productivity. In mine planning and design the cost of dewatering of mines is often captured as capital costs at the initial stage of mine development and afterwards in the cause of mining as operating costs both playing significant roles in profit or loss of Mining companies. Mines are often excavated below the water table where mine voids serve as low-pressure sinks inducing groundwater to move to the openings from the surrounding saturated rock. The result is the dewatering of nearby rock units via drainage of fractures and water-bearing strata in contact with the mine workings. There is also the potential for impacts to more remote water-bearing units and surface water bodies depending on the degree of hydrologic communication. The extent and severity of the impact on the local surface water and groundwater systems depends on the depth of the mine, the topographic and hydro-geologic setting, and the hydrologic characteristics of adjacent strata. The dewatering of mines and its cost implications starts from mineral exploration and mine development from where the rate of water flow is approximated thereby providing the initial clue to the choice of dewatering pumps and other drainage infrastructures. The paper dwells on the sources of water and its menace in surface and sub-surface mines, its control, and effects on the cost analysis of mineral investments.

KEY WORDS; Acid Mine Drainage, Underground Water, Dewatering, Room-and –Pillar, Cost Centers

Brief Geology

The study area is bounded by latitudes $8^0\ 25^1\ 43^{11}$ N and $8^0\ 20^1\ 40^{11}$N on its northern and southern boundaries, and by Longitudes $8^{\ 0}\ 48^1\ 80^{\ 11}$ E and $8^{\ 0}\ 55^1\ 55^{11}$ E on its eastern and western boundaries. It covers an area of $48Km^2$ and is located between Obi and Agwatashi Village located some 40 Km southwest of Lafia and 80 Km north of Makurdi by the River Benue.

The geology of the area has been studied by Falconer(1911) and Bain (1942) who in their regional studies provided information on the occurrences of brown coal, Farington (1956), Shell-BP (1957), Crachley and Jones (1965), the Mines Development Syndicate (1948, 1949), Offodile (1973, 1974, and 1976) and the Coal Group of N.S.D.A (1978). The various reports on the area included data and interpretation from an excess of 130 sunken boreholes and of two exploration pilot shafts 1 & 2 located at Agwatashi and ---respectively.

The stratigraphic sequence developed from previous studies on the Obi coal area provides the four distinct formations namely, Agwu, Keana, Ezeaku and Arufu Formations in deepening order respectively(Table 1). While these formations are overlain by about 400m of sediments, the Agwu formation which predominantly harbours the upper and lower coal measures has a total thickness of about 595m. The Keana sandstones and Arufu formation are underlain by the Precambrian basement at a depth beyond 995m. The 900m of dominantly shale, with subordinate limestone, sandstone and several coal seams constitute the main stratigraphic unit of the study area. This Formation (Agwu) is characterized by quick succession of shale and sandstone, limestone and coal seams indicating rapid change in positional depositional environment[11].

The upper coal measure is 355m thick it includes marine and non-marine sediments it consist of rapidly alternation of shale, sandstones, siltstone, and limestone with over 16 non-commercial seams in carbonaceous shale layers. The lower coal measures on the other hand, is 230m thick with the top 80m consisting of abundant coal horizons with shale intervals inter-bedded with siltstone, sandstone and occasionally limestone beds.

Table1. Stratigraphic sequence of the Lafia-Obi coal Field

Sedimentary Environment	Thickness ,m	Name of Measure and Series(NSDA 1970)	Names of members	Formation
Marine	400	Argillite Series	Shale Member	Agwu Formation
Transitional	90	Upper coal measure	UPPER COAL MEASURES	,,
Shallow Marine	70	Upper non-coal bearing series	,,	,,
Transitional Shallow marine	140	Middle coal measure	,,	,,
Shallow Marine	65	Middle non-coal bearing series	,,	,,
Transitional	60	Zone of maximum coal occurrences		,,
	110	Lower coal measure	LOWER COAL MEASURE	
	60	Series underlying coal series	,,	
Delta and River	?	Sandstone		Keana Sandstone
Marine	?	Limestone and Shale		Arufu Formation Wamba Formation
	?	Precambrian Basement		Precambrian Basement

Water Transmission Underground

The expected groundwater in the Lafia- Obi is water located beneath the ground surface in soil pore spaces and in the fractures of sedimentary rock formations which characterizes the geology of the Middle Benue trough. Hydrological studies carried out on the deposit in 1973-1980 revealed that depending on the position of the mine shaft and the system of mining, the rate of total water flow into the mine shaft reaches 8 cu.m /hour. Whereas the rate of total water flows into the mine during the period of maximum mine workings can be 150 cu.m/hour. The result of the study also reveals the existence of several unconfined aquifers which are 13-15m in the argillite crust of weathering, 40m in fault zones, sub-incrops of limestone and sandstone along the Bui and Akpaid stream channels. The filtration parameters suggests that the transmissibility is very variable, increasing during the high water period with increase in the thickness of zone of aeration, pebble and gravel content [8] The transmissibility of the Lafia sandstone according to the study is considered equal to that of the unconfined aquifer because of its nearness to the surface. The water table is generally at a depth of 1-5m in the boreholes and stream channels in the rainy season and as much as 10m and bellow in the dry season. This underground water, or “groundwater,” is produced by seepage of rainwater, and stream waters into rocks and sediments. Groundwater commonly resides in fractures and holes in bedrock and sediments. The depth at which soil pore spaces or fractures and voids in rock become completely saturated with water is called the water table. These saturated water zones become the aquifers in which the water starts movement under pressure towards areas of low pressure. The characteristics of aquifers vary with the geology and structure of the substrate and topography in which they occur. Generally, the more productive aquifers occur in sedimentary geologic formations of which incidentally the Lafia- obi Coal belongs. By comparison, weathered and fractured crystalline rocks yield smaller quantities of groundwater in many environments. The results of investigation by the Steel Council as corroborated by the satellite image indicates that the influence of both sub-surface and surface drainages shall play a role in acid mine drainage in the process of development and mining of the Obi coal (Fig. 1). This image show river networks and lineaments which reveal highly fractured underlain rocks. Generally the Eastern part of the map is highly fractured as compared with the western part of the study area. The transmission of water to underground mine workings are more likely to affect the Obi coal area because of the presence of areas of high fractures which trend generally in the South- East; and North- West directions.

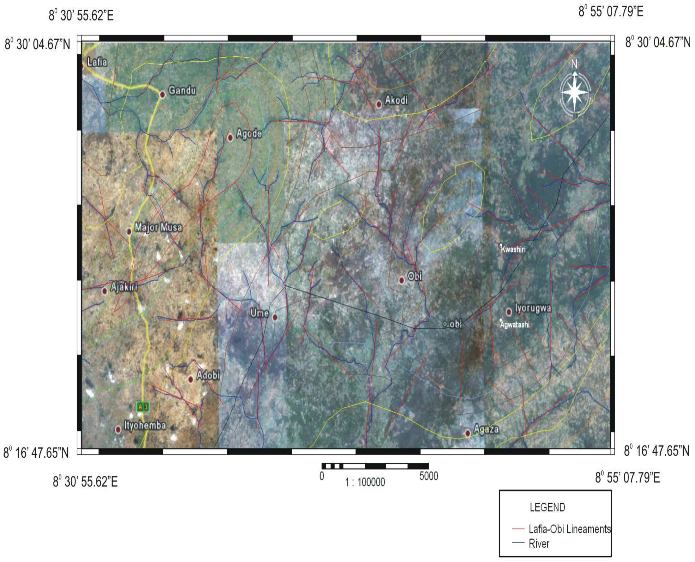

Fig.1 Location map of the study area showing drainages and fractures

Impacts of Underground Mining on Hydrology

The mining of coal can be accomplished by a variety of mining methods which are determined by the geotechnical properties of the rocks and coal. These methods include; the room and pillar, Longwall, advance and retreat mining methods amongst several others. Dewatering and mine water management are essential aspects of many mine and quarry operations. The cost of dewatering of the Lafia- obi coal mine will absorb a substantial part of both capital and operating cost of the investment.

Drawing example from the coal seams of America, the flat-lying sedimentary rocks of southwestern Pennsylvania, underground mining is routinely accompanied by rock fracturing, dilation of joints, and separation along bedding planes. Rock movements occur vertically above the mine workings and at an angle projected away from the mined-out area. Mining-induced fracturing within this angle can result in hydrologic impacts beyond the margins of the mine workings. The zone along the perimeter of the mine that experiences hydrologic impacts is said to lie within the "angle of dewatering" or "angle of influence" of the mine. Angle of influence values of 27 to 42 degrees have been reported for the coalfields of northern West Virginia and southwestern Pennsylvania (Carver and Rauch, 1994; Tieman and Rauch, 1991).

These changes to the rock mass can change the water transmitting capabilities of the rock by creating new fractures and enlarging existing fractures. This typically results, at least temporarily, in detectable changes in permeability, storage capacity, groundwater flow direction, groundwater chemistry, surface-water/groundwater interactions, and groundwater levels. Depending on the ratio of overburden to seam thickness and the type of mining, measurable surface subsidence may occur. As previously discussed, this surface movement ranges in type from broad troughs approximating the area of coal extraction (typical of longwall mining) to complete collapse of overburden from the mine to the surface, e.g., sinkhole subsidence (generally associated with shallow room-and-pillar mining).

The various underground mining techniques have distinctly dissimilar impacts on local water resources. In short, the impacts of room-and-pillar subsidence tend to be localized, irregular, and often long delayed; whereas those of Longwall subsidence are immediate, pervasive, systematic, and ultimately predictable (Booth, 1997).

Potential Hydrologic Effects: Underground mine openings of the Obi coal seams are expected to intercept and convey both surface water and groundwater as indicative from the geological and hydro-geological findings around the Kwashiri and Agwashiri prospecting shafts. The Upper coal measures are below the depth of 400m, which is very far below the existing water table even in extreme dry season conditions. When excavated below the water table, mine voids serve as low-pressure sinks inducing groundwater to move to the openings from the surrounding saturated rock. The result is the dewatering of nearby rock units via drainage of fractures and water-bearing strata in contact with the mine workings. There is also the potential for impacts to more remote water-bearing units further away from the boundaries of the study area and surface water bodies depending on the degree of hydrologic communication. The extent and severity of the impact on the local surface water and groundwater systems depends on the depth of the mine, the topographic and hydrogeologic setting, and the hydrologic characteristics of the adjacent strata. Additionally, the amount and extent of mine subsidence-related changes to the rock mass is expected to govern the impacts of underground coal mining on surface water and groundwater.

Effects on Streams and Surface Waters: The study area is composed of numerous streams as earlier mentioned whose discharges vary with seasons of the year. The impacts of underground mining on surface waters can range from no noticeable impact to appreciable diminution, water ponds, and/or diversion. The formation of subsidence-induced cracks, surface depressions, and/or sinkholes at the bottom of, or adjacent to, surface water bodies, such as these streams, ponds, can lead to complete or partial loss of water due to leakage to the underlying strata. The resultant changes in surface slope can adversely impact drainage along irrigated fields, and the existing natural streams especially those Obi town and environs (Bhattacharya and Singh, 1985).

Room-and-pillar mining is generally less disruptive to nearby surface waters than high-extraction methods of Longwall mining. Individual openings have only minimal localized draining impacts due to self-supporting roof members which span the opening to form a compression arch, with the support pillars serving as abutments. This "pressure arch" limits not only the deformational, but also the hydraulic influence of the opening (Booth, 1986). As additional entries are driven, the network of intersecting drains act as a planar under drain, inducing downward leakage from overlying units. However, due to its built-in system of support pillars and limited mining-induced fracturing, significant drainage is typically limited to near-mine units. Many detrimental impacts of room-and-pillar mining take years or even decades to occur as weak coal pillars deteriorate over time (Sgambat, 1980). Deteriorating or under-sized pillars that fail over time result in vertical extension of mine-induced fracturing. Dewatering impacts under these conditions can reach to a few hundred feet above the mine collapse areas (Rauch, 1985).

Rauch (1985) provides the following description of the dewatering impacts of room-and-pillar mining in the north central Appalachians."…Typically the greatest groundwater inflow rates occur near the working face of the mine where groundwater is being drained from storage, especially from fractures in mine roof rocks. In older mine sections, long term groundwater recharge to the mine is under more or less steady state conditions, originating ultimately from infiltration of precipitation or surface water. …'' This water typically enters the mine along rock fractures that intersect the mine ceiling, especially along vertical fracture zones. Groundwater inflow is especially great in areas of mine ceiling collapse due to the retention of too little roof rock support or to weak ceiling rock where fracture zones intersect the mine.

Effects on Wells and Springs: Wells and springs in proximity to room-and-pillar mining have the potential of being adversely impacted. Commonly the mechanism is direct draining of groundwater to the mine. Generally, where the support pillars are stable, these impacts are localized. From mine practices, dewatering of mining coal environments typically extends to 20 to 100 feet (6 to 30.5 m) above the mine workings. Wells that terminate at depths greater than 100 feet (30.5 m) above the mine roof are generally safe. In cases where support pillars fail, additional subsidence may result in more extensive fracturing. In these instances impacts may be up to 200 (61 m) or even 300 feet (91.5 m) above the mine roof. Subsidence impacts may be extended where mining is close to vertical fracture zones.

Potential Effects on Structures: Damages to structures are generally classified as cosmetic, functional, or structural. Cosmetic damage refers to slight problems where only the physical appearance of the structure is affected, such as cracking in plaster or drywall. Functional damage refers to situations where the structure's use has been impacted, such as jammed doors or windows. More significant damages that impact structural integrity are classified as structural damage. This would include situations where entire foundations require replacement due to severe cracking of supporting walls and footings.

Water Control and Remediation

The working conditions with excessive water is to be avoided for the following reasons; unsafe working conditions; difficulty in ore handling; possibility of slope instability; reduced operating life span of machinery; nuisance factor and possible floor heave [Morten 2010] . The potential impact of ground water inflow to a mine can often be assessed at the pre-feasibility stage. This stage can be designed to include a preliminary hydrological appraisal(or Phase one investigation) can include a desk study and borehole census of the area to determine the regional hydrology and assess its potential impact the mine on one hand, and of the mine on the ground water. Phase two would aim to determine a preliminary estimate of aquifer parameters such as the volume of ground water in storage, flow characteristics and the dimension of the aquifer or aquifers in the study area. The objective of Phase three is to plan an initial design to either divert or dewater the planned excavation. Once the required information is available Phase three can be accomplished through computer modeling and/ or simulation. Where necessary, the trial dewatering can be set up. If the ground water is shown to be a significant problem, it can be removed or diverted [Morten 2010].

The presence of numerous fractures, surface streams and aquifers in the study area can constitute a formidable water drains to underground openings. The flow of water in underground mines can constitute immeasurable sociological and financial menace. Preventive techniques are quite effective in abating abandoned mine drainage originating from surface mines. Diverting water away from the mine site and land reclamation of the disturbed area are relatively inexpensive and effective techniques. Since only about 11 percent of abandoned mine drainage originates from surface mines, it can be abated by relatively dependable, inexpensive and effective techniques as follows.

Diversion- This can be accomplished through the following; Grout curtains; Grout Injections; cover drilling; diverting water from mine entries and grouting pilling. It must however be pointed out that subsequent pressure built ups could be dangerous.

Dewatering- Dewatering entails removal of ground water from an area through the lowering of the water table. This can be accomplished through wellpoints, Deep boreholes; dewatering galleries; Drains; Sump pumping or a combination of one or two of the above.

Deep mine drainage abatement techniques are generally quite costly, dependent on suitable geologic and hydrogiologic conditions, and less predictable in their effectiveness than preventive methods. These factors, combined with possibilities of deep mine seal failures, which could constitute a safety hazard in residential areas, make draining abandoned deep mines one of the most perplexing water control problems.

The selection of the dewatering systems would come under the Phase three hydrological investigations. This selection of dewatering systems depends on the following factors;

Hydrological conditions; length of time pumping is required; Volume of water to be removed; Whether pumping equipment can be installed in the operation area; Availability of drilling and dewatering equipment and the Contractor or professional experience. The design of the dewatering system will depend on the characteristics of the water bearing formations and these include;

1. Whether the aquifer is confined or unconfined,
2. The transmissivity and storage coefficient of the aquifer,
3. The static water level,
4. The seasonality of potential inflows,
5. The depth and thickness of the aquifer and
6. The sources of recharge of the aquifer and locations of these sources.

Cost Analysis of Underground Mine Drainage System

The Estimation of Capital Costs and Operating Costs of dewatering of Mines are given by cost Formulas where the numerical value of the main factor or factors affecting these costs is incorporated into an algebraic expression

$$\text{COST}=KQ^{x} \quad \text{or} \quad \text{COST}= KQ^{x}\, T^{y}$$

where K is a constant, Q and T represent the numerical value of factor or factors which have the greatest influence on the costs , x and y are exponents (normally between 0.0 and 1.0) that assure the rate at which changes in the value of Q and T results in changes in costs (SME mining Engineering Handbook, 1992). The major factors that affect capital and operating costs of dewatering of mine include the following; Size of Mine, Production Capacity of a Mine, T/day; T/y etc, Cross-Sectional Areas of Shafts, Adits, Cross- cuts, Shaft Stations, Haulage Roadways, Mining Stopes, Mine Lay-out Areas, S/gravity, Depth of Shafts, Open-

Pits/Quarries in addition to Heights and Widths of major Structures / openings of Surface and Underground Mines.

In mine cost analysis major areas where costs can be incured are traditionally grouped into Cost Centers. The dewatering of the Obi coal mining area therefore constitutes an important Cost Center which cannot be ignored. This center shall consist of drainage systems notably amongst which are underground sumps, multistage pumps, inflow water controls, standby pumps, and Piping networks. The cost of this system is a function of the total installed horse power of the operating pumps which is in turn a function of the total of gallons per minute(liters per second) multiplied by the pumping head of the in feet(meters) for each of the installed pumping stations. The study area from fig1 indicates a highly fractured underground trending generally to the South-East; and North –West direction. The rate of water inflow into the mine shall be highly dependent on the presence of faulted water-bearing zones. Consequently, the rate of pumping in litres per minute for each pump is several times the inflow at each station sump, and the pumping head will typically be between 120 to 450m.

The expected total pump system Horse Power,

$$H_p = \text{Total of (Gallons/minute x } H_{d\,/}\ 2350\text{(for all pump stations)}$$

Where H_d is the pumping head. The above formula provides the total installed pumping system, however if the pumping system has not been planned in detail, the installed horse power can be approximately estimated from the following formulae.

Installed horse power $H_p = 8.0T^{0.5}$ for dry mines with little inflow and mine depth less than 1000 feet (300m).
$H_p = 26\ T^{0.5}$ to $32.0T^{0.5}$ for mines with medium inflow and 1500 3000 ft (460 to 900m) depth.
$H_p = 62T^{0.5}$ for mines with heavy inflow. The depth of the Obi coal mine is about 900m, however to be on the safe side and particularly in view of the highly fractured nature of the study area, the third formula can be considered in the determination of the installed horsepower. This total value of the pump Horse power is an important variable in the determination of cost of dewatering of mines. The Horse power also depends on the production capacity of the mine in terms of daily tonnage T.

1. Cost of Mine Pumping System

The cost of mine drainage system depends on total installed horsepower H_p as highlighted earlier. The cost includes the concreting of dams, and pump stations, the installed cost of pump, the cost of standby pumps, the installation of piping from pump stations to shafts, pump control equipment and sludge removal equipment. The pumping system cost is calculated from;

PSytemCost = $ 1,400Hp$^{0.7}$ for little inflow of water(Depth:
Less than 300 m).
= $ 3, 400Hp$^{0.7}$ for medium water
inflow(depth: 460-910m)
= $ 5,800Hp $^{0.7}$ for Mines with heavy water---(1)
inflow at depth of less than 300 m

In choosing the approximate cost of mine system for the Obi coal, the second formula shall be adopted.

2. Cost of Water Supply System

In underground mines water supply is necessary. The Obi coal mine shall incur some cost of water supply system which depends on the amount of drilling and types of drills used for mine development. The equipment includes small jacklegs and stoppers for drilling and large jumbo drills for large bore-hole drilling in stopes and development openings. From experience, a typical 500tpd mine uses about 43,00 gallons of water daily while a typical 8000tpd mine uses about 230,000 gallons per day.

Cost of water supply = $5,300 T$^{0.4}$, where T is tons of coal mined daily.---(2)

3. Cost of Water Distribution

For water to get to the underground development and mining work faces it has to be distributed through piping. The cost of piping network to distribute water to all working places in the mine depends on the length of lateral development. The length of lateral development L is usually a function of daily mined tonnage T and stope width W;

Length of lateral development L in ft = $1276T^{0.5} / W^{0.4}$

Cost of pipe installation underground = $\$2\text{-}80L^{0.9} C^{0.3}$ ---------(3)

Where C, is the rate of water flow in the pipe in cubic feet per minute for underground water supply. This cost however, does not include the cost of surface water diversion and possible run-offs.

4. Cost of water Supply to Coal Washer System

The capital cost of fresh water pumping plants, reclaim water plants, fire protection, and portable water supply, varies according to the local topography, the proximity and the nature of nearby sources of year round supplies of water. If there is a suitable source of water within two miles of the mill, and the intervening topography is moderately level, the water system would cost;

Cost of water supply to Coal Washers System = $\$14,000\ T^{0.6}$ -------(4)

Total Capital Cost = (1) + (2) + (3) + (4)

$=\$ 3,400Hp^{0.7} + \$5,300\ T^{0.4} + \$2\text{-}80L^{0.9} C^{0.3} + \$14,000T^{0.6}$

The above capital cost does not include operating cost which is also vital in the determination of the profitability of a mining project. The total cost of mining is broken down into three categories as these individual costs relate to production process: [1] costs that can be directly identified with the production process [direct costs], [2] costs that are not directly identified with the production process but is required for the production process [indirect costs] and [3] costs that are not related to the production process but are part of the overall operation [overhead costs]. Direct costs include costs of direct labor [e.g. face crew on pumping equipment] and direct materials [e.g. lubricants, fuel] that can be directly associated with a particular production process.

Indirect costs include costs of indirect labor [e.g. pump maintenance crew, pump operators] and indirect materials [e.g. maintenance supplies, tires].Overhead is a very broad term which encompasses "those expenses which cannot be allocated specifically to particular cost units, but which must be apportioned or absorbed by unit cost centers." Three kinds of overheads are recognized: [1] production overhead [e.g. superintendent salary, mine office personnel, mine office supplies, refuse disposal, etc.], [2] selling and distribution overheads [salesmen, wages of truck drivers, insurance, dispatch personnel, commissions, etc.] and [3] administrative overhead [general office costs, stores, taxes, legal and accounting, etc.].

CONCLUSION

The structure of the Obi coal environment is heavily fractured indicating that the rate of water flow is expected to range from medium to heavy inflow. In underground mining such a coal mine, the consequences of inaccurate estimation of capital and operating costs in initial feasibility studies may include the commitment of major amounts of capital funds before it is realized that the mining project will not be profitable. or the rejection of a mining project that would otherwise be profitable. In this cost estimate, the costs associated with dewatering of the Obi coal mine and water supply constitutes an important component that should not be ignored in the initial mining cost analysis.

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