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Mine Inundation:
A Proactive Approach

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Submitted to: Prof. Nuray Demirel
For
MINE 555
Advanced Mine Health and Safety Management

January 2019

ABSTRACT

Mine inundation is uncontrolled flow of water, brine or mud debris to active working of a mine from surface or underground source and remains immediate cause of quite a few mining disasters in the 21st century, regardless of regulations, legal sanctions and technological advance. Major accidents, like Ermenek in Turkey, Bagdigi, Godavari Kani, Central Sounda in India, Quecreek in the USA and Wang Jialing in China reveal the fact that investigation of the earliest mine inundation cases and lessons learnt from them were being insufficient in identifying hazards, assessing associated risks and finding out the root cause. Risk management system should be preventive rather than being reactive because controlling water inundation hazard in development and commissioning phase of a mine is more effective in minimizing the associated cost and prohibiting the fatalities. This paper aims to put forward the sources of inundation in underground mines, proactive control measures for controlling groundwater.

KEYWORDS: Accident Investigation, Mine Accident, Mine Inundation, Inrush, Water Control Methods, Underground Mining.

1.INTRODUCTION

The inflow of water into mine can be controlled with pumping, however, in some cases the volume of water is excess and dewatering is insufficient or impractical, which is described as "inrush" or "inundation". Inundation could be catastrophic when large bodies of water are in place (Holla, 1987). Mine inundations have different sources; from surface water or underground sources. In major mining countries such as the USA, Russia, Poland, Australia, Canada, Germany, India and the UK, the incidence of mine inundation can generally be attributed to sudden inflow of surface water, water entering into working face from strata, working close to outdated mines, presence of fault or other disconformities which can transmit groundwater from aquifer into mine working, ineffective sealing of shafts and boreholes, and bulkhead or barricade failure (Dunn, 1982; Wilson, 1985; Garritty 1983; Slatcher, 1985; SWA, 2011; Vutukuri and Singh, 1995). Apart from China, above countries experienced very few number of water inrushes from the floor, in contrast, more than 90% of water inrushes are due to inflow from karst aquifers through the coal seam floor in Chinese coalmines (Shi and Singh, 2001). Mine inundation accounts for 31% of all mine disasters in the history of Indian coalmines between years of 1899 and 2005 (Batra, 2008). Job (1987) stated that 162 out of 208 accidents were due to contact with abandoned old working during the period from 1851 to 1970 in the British collieries. In order to prevent reoccurrence of mine inundation accidents, unveil underlying causes and issue robust barriers, it is essential to classify inundation (Vutukuri and Singh, 1995)

2. CLASSIFICATION OF INUNDATION

Singh (1986) classifies mine inundation in three categories with reviewing mine inundation cases. He states that the first two types are mining induced, whilst the third is a natural phenomenon.

i. Event Controlled Inundation: This kind of inundation is owned by caved mine workings and succeeded by main and periodic falls in the roof strata. The flow rate of water decrease exponentially after reaching its highest point in a short time. These kinds of mine inundations are led by the fallowing factors:

- Subsidence patterns around caved mine workings.
- Rock mass hydrology.
- Geological structures and discontinuities.
- Major and periodic roof falls in the goaf.

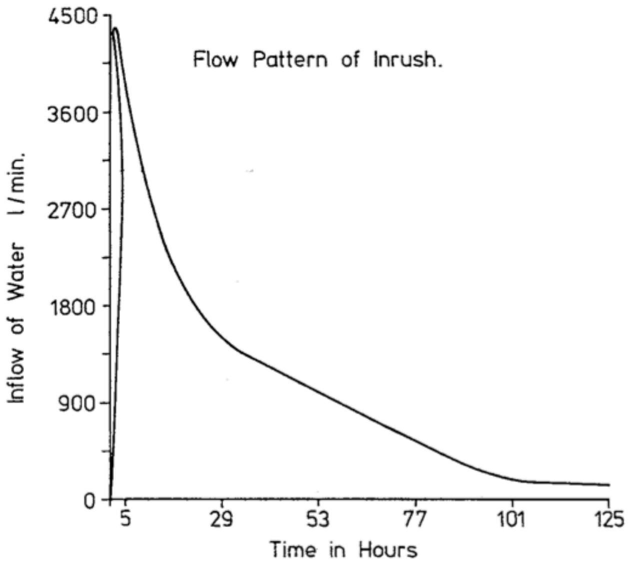

Figure 1. Flow Pattern of Event Controlled Inundations (Pugh, 1981)

ii. Accidental Inundation: This kind of inundation is a major root of accidents for mining industry and take place due to the factors below:

- Accidental contact with adjacent waterlogged mine working.
- Accidental contact with unstable fluidized strata or natural bodies of water.
- Sudden and unprecedented flow of surface water to active working of a mine (Davies and Baird, 1977).

Job (1987) states that accidental inundation take place due to different underlying reasons such as accuracy of old plans, inadequacy of communication or management systems. He identified eleven distinct reasons for inundation from old mines: ineffective barriers, incomplete plans of old workings, absence of plans, incorrect plans, incorrect interpretation of old plans, failure to obtain the abandonment plans, absence of protective boreholes, ineffective protective boreholes, failure to plug boreholes, unknown old workings, and incorrect seam correlation.

iii. Spontaneous Inrush: Spontaneous inrushes are natural events associated with mining in the proximity of karst aquifers. Usually an inflow takes place through a layer of protective barrier between the mining horizon and the aquifer; both due to intergranular flow or flow through a fault and other structural discontinuities. An inflow occurs if the following conditions are simultaneously fulfilled:

- Presence of large quantity of water.
- Development of high hydraulic pressures, sufficient to overcome pressure losses due to flow through the protective barrier or structural discontinuities.
- Thickness of the protective barrier.
- Development of fracture zone within the barrier.
- State of high stress within the barrier.

3. INVESTIGATION OF GROUNDWATER SOURCE DURING DEVELOPMENT AND CERTIFICATION

In order to choose the best method for controlling inundation and understand its nature, the source of groundwater or its existence should be thoroughly and adequately investigated. Therefore, historical information of the mining area, engineering and scientific methods are combined to find the origin of water. Techniques can be categorized during development and certification of a mine as below (USDA, 2010; Hargrave *et al*, 2003):

Reconnaissance investigation

A reconnaissance investigation includes review of existing information and examination of surface features at the site. The reconnaissance gives investigator information regarding the nature and characteristics of surface features and conditions. Establishment of the correlations with existing map information are possible through observation and examination. Tentative interpretations regarding groundwater conditions can be formulated. Topography, geology and soil maps and literature concerning should be assembled together and studied. Data from a field reconnaissance should contain general descriptions and locations of the surface features and conditions, including the following items:

i. General geology of the project site
ii. Geologic conditions that influence groundwater movement and recharge
iii. Surface features resulting from groundwater movement, such as seeps, springs, and landslides
iv. General character of streams and valleys including volumes of flow, stream banks and bed, steepness of valley grades, and side slopes
v. Groundwater development, yields, quality, and use
vi. Water well logs
vii. Data and quality reports of groundwater.

Data of any previous mining work will be a good source for renaissance investigation.

Preliminary investigation

Available reconnaissance reports are reviewed in preliminary investigation phase including geologic literature of the area, groundwater reports and data, and well drilling data and records. The investigation should establish the nature and characteristics of the subsurface materials, groundwater conditions, probable yield, water quality, and other conditions and features. In this phase, all area related geologic, groundwater, and well drilling data and well records are evaluated.

i. Maps:
A study of available resource maps is an excellent way to start a preliminary groundwater investigation. Maps and other information may be obtained from government geological agencies, local or county water management agencies, universities, and government agencies such as the Natural Resources Conservation Service (NRCS)

ii. Imagery
Aerial photos and GIS data sets can be used to make initial interpretations of geologic structure, landforms, potential recharge areas, springs, land use, and vegetation patterns. Satellite imagery, as well as Light Detection and Ranging (LIDAR) data, may also be used if available for the area of study.

iii. Field study
The details of local structure and its relationship to possible aquifers in the geologic section must be determined in areas where stratified sedimentary rocks are exposed. Therefore, attitude (strike and dip) and exposed strata elevation are measured and plotted on the map of the area. Use of aerial photo contact prints is very beneficial and should be used wherever possible. Stereoscopic study of aerial photographs may reveal information about geologic features, such as faults, as well as losing and gaining streams. Well logs will enable the construction of structure contour maps, which are useful especially in cross-bedded and indefinitely sedimentary strata. Remote sensing technology, such as refraction seismograph or electrical resistivity equipment can be employed to indicate subsurface structure. Joint systems, faults, and the location and elevation of springs may be mapped. In areas of extrusive igneous rocks, the thickness of flow or series of flows and the elevation of the water table should be observed in addition to the characteristics of jointing and the presence of faults and springs.

iv. Mapping
A geologic map should always be prepared on the best available base map including: areal and surficial geology, structure of bedrock, stratification, folding, schistosity, faults, or fractures, surface groundwater features including springs, seeps, swamps, and marshes, sinkholes and disappearing or reappearing streams (in karst topography), legend listing all formations shown on map. This includes a brief description of characteristics of aquifers, aquicludes, and other pertinent information, locations of wells. Well record data and logs will be included in reports.

v. Geologic sections

To complete and interpret the information on a geologic map, one or more geologic sections and fence diagrams are prepared, based on logs of wells, test holes, geophysical studies, or other related information. The fence diagram is constructed in three-dimensional perspective from actual well logs to show geologic relationships.

Detailed investigations

Collection of data is required to make sound geologic interpretations in detailed investigation. Information from preliminary investigation, additional data collection, reports, logs, maps, fence diagrams and field test data are included in detailed investigation for review and study. Locations of wells, ambient and seasonal water levels, withdrawal areas, amounts of withdrawal, springs or other discharge areas, hydraulic gradients, and rate and direction of groundwater movement should be determined. Seismic or electrical resistivity tools and tracers may be used to determine flow directions and velocities. Drilling or the excavation of pits may be required to obtain more information, and to take samples of water and soil or rock materials. Field permeability tests, pumping tests, and pressure testing often are desirable. The installation of observation wells and piezometers may be advisable under some conditions. In conclusion, detailed investigation is composed of the elements below;

- Drilling, sampling, logging, description, and classification of all strata that will influence groundwater hydrology
- Pressure testing for in-place permeability and seepage through fractured rock and voids in soluble strata where control of seepage is important
- Ascertaining the influence of structural geology, faulting, folding, and fracturing on transmissibility of groundwater
- Installing piezometers or observation wells in hydrologically significant strata

Data collection

Geophysical survey; seismic or various types of electrical resistivity tools can be used to determine depths to bedrock and depths to a water table, as well as fracture zones. Multiple-probe seismographs are useful in rapid analyses, especially using variable shock sources and post processing software. Portable electrical resistivity meters can be used to perform rapid surveys over long traverses (USDA, 2010)

Seismic Method

Refraction and reflection are two methods used in seismic. Impact of heavy instrument or small explosive charge is used to create small shocks at the surface and the travel time of the shock, sound or wave is measured. Seismic waves follow the same laws of propagation as light rays and may be reflected or refracted at any interface where a velocity change occurs. Seismic reflection methods provide information on geologic structure within thousands of meters below the surface, whereas seismic refraction methods-of interest in groundwater studies are limited with 100 meters deep. The travel time of a seismic wave depends on the media through which it is passing through. The velocities are greatest in solid igneous rocks and least in unconsolidated materials. Based on these data, it is possible to allocate fractures, fissures, faults and lineaments (Balasubramanian, 2007)

Electrical Resistivity Method (ERM)

Resistivity of underground materials are measured and mapped with ERM. With transmitting and receiving electric current along various paths and measuring the associated voltage, it is possible to create image of the electrical features of the subsurface. ERM is based on the response between the earth and the flow of electrical current. It is sensitive to variations in the electrical resistivity of the subsurface measured in Ohmmeters. Resistivity measurement is conducted by inducing an electric current into the earth through two current (C1 and C2) electrodes and measuring the resulting voltage at two potential electrodes (P1 and P2). The apparent resistivity (pa) value can be calculated based on the current (I) and voltage (V) (Riwayat *et al*, 2018).

Type of Water	**Resistivity (ohm-m)**
Precipitation	30-1000
Surface water in area of igneous rock	30-500
Surface water in area of sedimentary rock	10-100
Groundwater in area of igneous rock	30-150
Groundwater in area of sedimentary rock	>1
Sea water	0.2
Fresh water	10-100
Drinking water (max. salt content 0.25%)	>1.8
Water for irrigation and watering (max. salt content 0.25%)	>0.65

Table 1. Resistivity values of some kinds of water (Riwayat et al 2017).

Vertical Electrical Sounding (VES)

The electrical resistivity survey involved vertical electrical sounding (VES) is based on measuring the potentials between one pair of electrodes while transmitting a direct current between another pair of electrodes. Depth of current penetration is proportional to the spacing between the electrodes in homogeneous ground, and varying the electrode separation provides information about the stratification of the ground (Koefoed, 1979).

Variation of resistivity with depth is determined in VES. Single VES should only be applied in areas, where the ground is assumed to be horizontal layered with very little lateral variation, since the sounding curves only can be interpreted using a horizontally layered earth (1D) model (Balasubramanian, 2007).

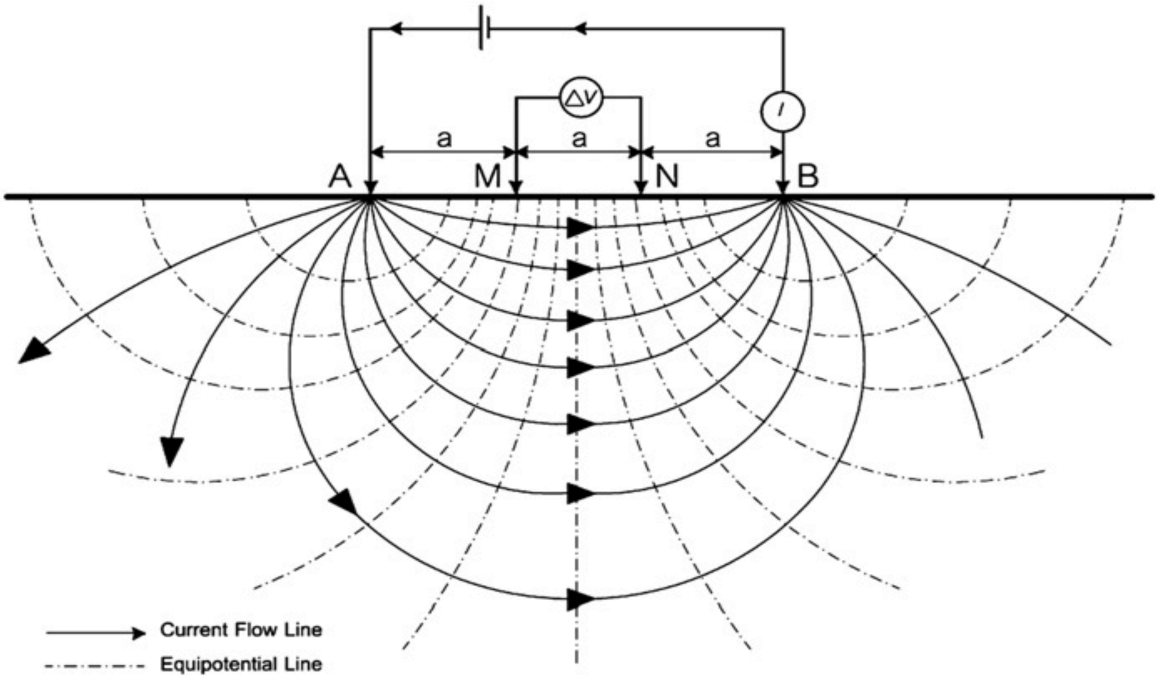

Figure 2. A Representation of ERM-Wenner Array (Wiwattanachang, 2011).

Electrical Profiling (EP)

In this method, entire array is moved along a straight line while the spacing between electrodes is kept fixed. This gives some information about lateral changes in the subsurface resistivity, but it cannot detect vertical changes in the resistivity. Interpretation of data from profiling surveys is mainly qualitative. The most severe limitation of the resistivity sounding method is that horizontal (or lateral) changes in the subsurface resistivity are commonly found. High resistivity is seen in igneous and metamorphic rocks and their resistivity changes with the degree of fracturing, and the amount of the water in the fractures. Due to the higher porosity and water content, sedimentary rocks have lower resistivity. There could be overlaps of resistivity of various rocks because their resistivity is dependent on different factors such as porosity, fraction of water saturation and amount of dissolved salt (Balasubramanian, 2007).

Surface Nuclear Magnetic Resonance Method

Surface NMR provides direct data about geometry, water content, hydraulic conductivity and resistivity of aquifer and known for being sole nondestructive exploration method. In order to collect underground water information, NMR measurements are combined with nondestructive surface acquisition approach that enables this method essential tool in hydrogeophysics in last decade. All NMR-based techniques share a common basic procedure in which an alternating magnetic field (the excitation or secondary field) at Larmor (resonance) frequency forces reorientation of the macroscopic magnetic moments of protons from their thermal equilibrium. After the excitation field is extinguished, the orientation of magnetization returns to the equilibrium state. This relaxation process generates a weak magnetic field that is measured and analyzed to determine properties of the materials. Surface NMR adopts the basic principles of NMR measurements, emitting an excitation pulse and recording the relaxation signals (free induction decays or FID), but it uses large surface coils to measure the induced decay (Yaramanci, 2004). The importance of the SNMR method lies in its ability to detect water directly and allowing reliable estimation of mobile water content and hydraulic conductivity (Yaramanci and Petke, 2007).

Remote Sensing Techniques

Remote sensing serves as a tool to interpret lithology, structure and groundwater occurrence. Thermograms are the best images for inventory of seeps and springs. Remote sensing can contribute an image base map or geologic and hydrologic parameters, derived from the image, to the multiple data sets in a hydrologic information system. These data sets could be used to form information through merging and integration techniques. It uses reflected and emitted energy to measure the physical features of remote objects and surroundings (Moore, 1982). Due to the optical characteristics of the parts of the earth, it reflects or emits different amount of energy in different wavelengths (Patra *et al*, 2016).

Remote sensing shows an increasing role in the field of hydrology and water resources development. Remote sensing provides multi-spectral, multi-temporal and multi-sensor data of the earth's surface, which are suitable for mineral explorations, water resources evaluation, environmental monitoring and groundwater targeting. The high-resolution satellite images are interpreted to identify the groundwater potential zones (Balasubramanian, 2007).

Test drilling

Test drilling or exploration wells are unique in providing information regarding the underground conditions. Information regarding, movement of underground water, seasonal changes in water levels, outcome of flooding can be extracted from observation wells and piezometers. Particle sizes, composition, porosity and permeability, change in strata, horizon classification, material consistency, cementation and depth, elevation and location of the well should be recorded during test drilling. Exploration and observation wells will contribute to define gradation, storage capacity, permeability rates of unconsolidated materials and rock formations, and to correlate formation of rock. Core samples could also be collected and test to describe faults, solubility, composition, and permeability of the formation. All information collected will be helpful in defining water storage potential and production capacity of aquifer, and underground water transmissibility (USDA, 2010).

Logging methods

There are several techniques for logging wells for finding underground water sources, as well as the formation changes, depths, faults, and disconformities. These techniques are applied through a borehole. Electrical logging, gamma ray, neutron logs, sonic logs, nuclear magnetic resonance, flow meter, tracer logging, and caliper logging are widely applied methods. Keys (1968) suggested that logging technology developed thanks to petroleum industry could play an essential role in investigation of water source. He also adds that logging technology must be adapted to the requirement of ground water hydrology.

Tracer method

Tracer tests are very common in investigating groundwater in terms of its hydraulic feature, hydrodynamic conditions, flow pattern, connection with surface or other territories, and causes of inrushes (Käß, 1998; Wolkersdorfer *et al*, 2008). This technique includes injecting a tracer to water and observing it in time and space. It was first used for finding out the linkage between underground or surface water and the mine (Skowronek and Zmij 1977). In order to thoroughly explain and understand hydrodynamics of inundated mine, tracer method was firstly used in 1995 (Wolkersdorfer, 2007).

In order to conduct a tracer tests, there should be a direct access to intake area. In absence of access to intake and discharge locations, well or pits are needed to reach the source and the point of discharge like area to be mined (USDA, 2010)

Dyes, salts, stable isotopes, radioactive and neutron active, solid tracers, phages, bacteria, polystyrene beads, spores are commonly used materials in tests (Wolkersdorfer, 2008). Fluorescein, potassium permanganate, rhodamine “B”, methylene blue, aniline red aniline blue, and auramine yellow are most common dyes. Radioactive tracer will enable describing the flow pattern and speed of groundwater. Careful use of any tracers in terms of content and amount are strongly recommended and employment of radioactive tracers shall be avoided.

Correlation and interpretation

All the collected data should be interpreted for describing aquifer properties, strata variability and distribution, rock conditions, faults, fractures, disconformities and cavernous conditions. Maps including the barriers of the water zones, faults, discharge and recharge locations, formation and structure geology, contours, water flow patterns are constructed in the final stage.

4.SUBSURFACE AND SURFACE METHODS DURING OPERATION AND ABANDONMENT

Most of the methods used in finding origin of groundwater during certification and development phase of mine can be used in operation and abandonment phases as well. It is essential to find the source of water in developing control measures against water hazard. Drilling exploration wells, reconnaissance and preliminary investigation, maps constructed for underground water investigation, analysis of chemical content of water samples taken from active mine, adjacent water logged working, boreholes, water wells, dams, springs, rivers, application of tracer and electromagnetic methods can provide valuable information regarding the source and magnitude of water during these phases.

5. WATER CONTROL METHODS

There are several methods for controlling underground water such as dewatering, diversion, choosing barrier pillars, grouting, ground freezing, pumping. Controlling underground water against inundation is highly dependent on the source, capacity of the water, rock and formation properties and characteristics of the aquifer of the area to be mined. Therefore, in order to come up with remedial action, all geological and hydrogeological features of the water should be known. Morton and Mekerk (1993) state that besides its importance in increasing safety and preserving natural sources, controlling underground water decreases earth-moving costs, and increases useful life of machinery and improves slope stability. SWA (2010) suggest that control measures should aim to reduce risk level of inundation hazard; hence, its likelihood and level of severity should be decreased. There are five levels in hierarchy of controls:

1.Eliminate water hazard from system
2. Decrease magnitude of the hazard
3. Reduce event likelihood through engineering control.
4. Administrative controls or soft barriers
5. Reduced likelihood through warnings and PPE

In this chapter, only first three levels will be covered for controlling underground water. It is well known that the effectiveness of the control decrease from top to down. Elimination of the water hazard should be central concern in developing countermeasure against mine inundation.

Dewatering

Drainage of dewatering is the most widely used technique and includes removing the water from a location with decreasing water table. Dewatering techniques are dependent on the several factors, such as volume and the origin of water, availability and feasibility of tools, duration of drainage, and experience of the contractor or subcontractor. Before choosing a technique, information regarding the water bearing formation must be in place including aquifer characteristics (i.e. confined or unconfined, permeability, thickness, and depth), potential seasonal inflows, location of discharge and origin of recharge. Engineering approach should be supported by management for the best outcome, Dewatering methods includes dewatering wells, deep drill dewatering, drains, sump pumping and dewatering galleries (Morton and Mekerk, 1993). These methods can be applied to the adjacent water logged mines to avoid them being a hazard for active working of a mine.

Wells are drilled vertically to the water-bearing zone in order to dewater the zone and are very common. Vertical wells are advantageous and practical because drainage take place away from mining and doesn't interrupt operation, however, associated high cost of drilling and pumping, and existence of low permeable aquifer and vertical-fractured rock masses limit its application. Use of dewatering wells in Nevada underground mines couldn't successfully drain the underground water, but it was successful together with drainage boreholes drilled through mine. For deeper mines, deep wells can be drilled that are capable of removing excessive amount of water. Horizontal or directional boreholes are another technique applied widely and can be the most inexpensive one if merged with delineation or definition drilling. Drainage boreholes drilled above the stopes, or into the hanging wall from the access drifts. Konkola Mine in Zambia was known as one of the driest mine in the world due to the drainage borehole (Straskraba and Effner, 1998; Straskraba, 1983).

Drainage galleries are not a common method for dewatering due to the associated high cost. It can be defined as ring tunnels intersecting and these galleries are used to remove water with artificial lifting (Morton and Mekerk, 1993).

Diversion
Diversion method means turning the ground water aside from active working of a mine. It aims to decrease inflow of groundwater to active working of the mine or eliminate it with placing a physical barrier between water hazard and active mine. This method includes grout curtains, grout injection, cover drilling and grouting piling, and bulkheads (Morton and Mekerk 1993, Harteis and Dolinar, 2006).

Grouting
Grouting provides a sealing barrier against water hazard with injection of cementing material through drilling holes to increase rock resistance. Grouting methods are applicable in all phases of mining, namely, development and decommissioning, operation and abandonment phases. It is very efficient is sealing off the water inflow from strata and it was successfully implemented in reduction of inflow. Due to high cost, it is used to seal smaller areas such as faults, disconformities, voids and fractures. It is also effective in controlling inflow from low permeability strata with using ultrafine and chemical materials (Straskraba and Effner 1998).

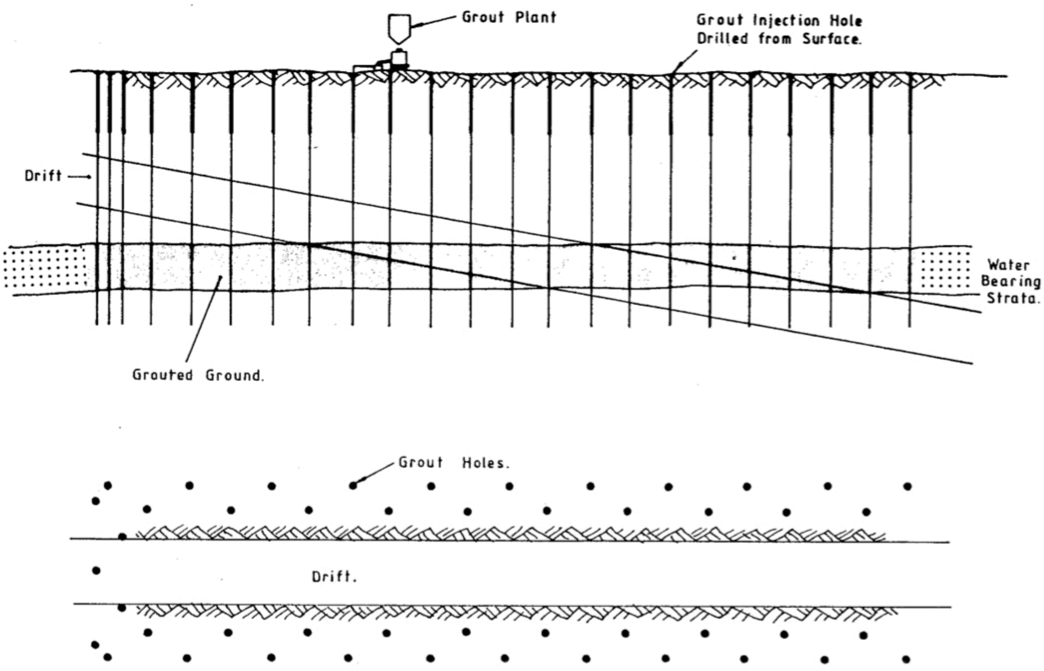

Figure 3. Typical arrangement of grouting from surface, drifts and tunnels (Daw and Pollard, 1986).

Grouting method and materials are highly dependent on the source and amount of the underground water hazard, formation permeability and strata properties, and the area and the depth of the application. The basic categories of grouting distinguished by the mode of entry into the soil or rock are: pre-grouting from surface, permeation grouting (intrusion, penetration), displacement grouting, compaction grouting (including slab-jacking), jet grouting (Keong, 2005).

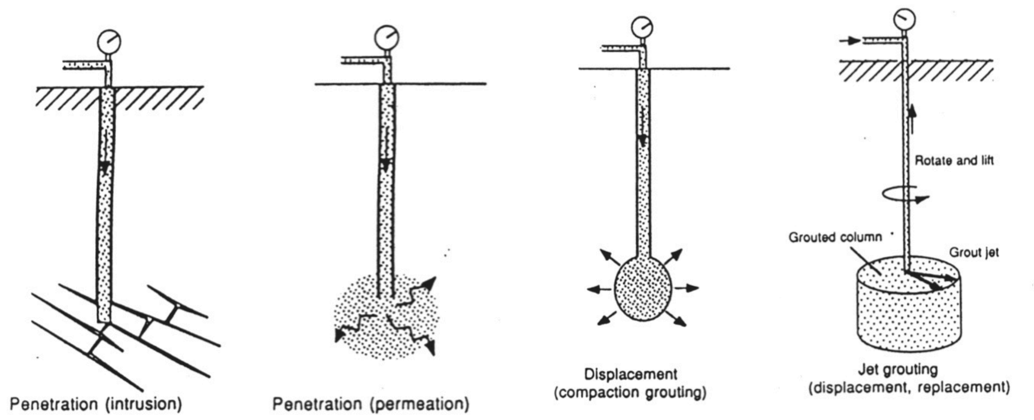

Figure 4. Modes of grouting

Pre-grouting technique is based on applying any grouting material from surface to underground through a shaft in order to isolate water-bearing zones from potential mining tunnels. It is applied to shallow depth up to 300 meters in the USA and England; however, greater depths were successfully grouted in Russia and South Africa (Dietz, 1982; Kipko *et al*, 1984).

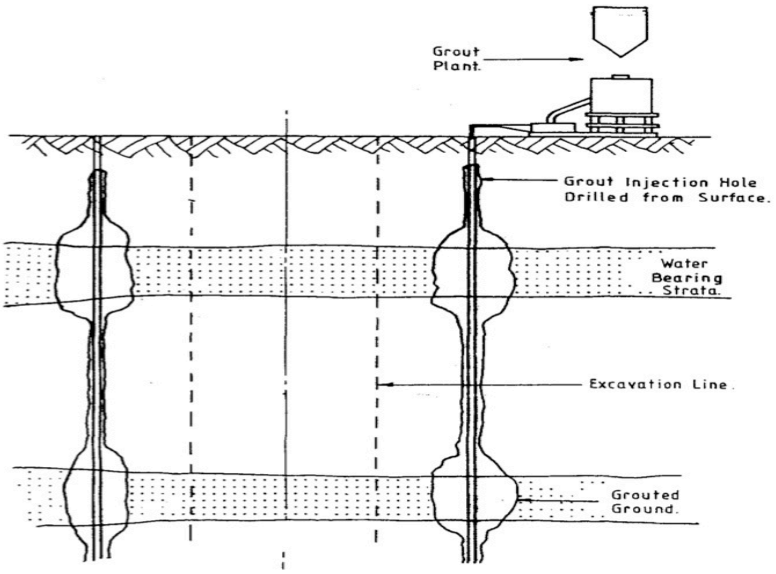

Figure 5. Typical arrangement of pre-grouting from surface shaft

Perme

ation grouting includes replacing the pore fluid of the soil or rock, and filling void pores and fissures with injected cementing material. Its penetration depends on the permeability of the ground and limited with clean sands and gravel or open fills that can be penetrated with low-viscosity cementing materials. Permeability and porosity of the aquifer, cost and strength, and permanence requirements are describing factors in choosing the cementing chemicals. Cement-based materials can be used for the fissures having more than 2x 10^{-4} width. In first phase of grouting, injecting of cement-based materials will be cost saving. In secondary treatment, other chemical can be used to achieve more control over inflow. In some instances, permeation grouting is insufficient, especially in fissures having low permeability. In order to fill these fissures, overpressurized grouting material is injected down hole and the existence fissures are canalized or new fissures are created (Keong 2005, Daw and Pollard 1986). Hydrofracturing method can be utilized in combination with permeation grouting technique in order to minimize to cost.

Figure 6. Randolph Mine grout face on belt slope

In order to grout the unconsolidated rock encountering high groundwater pressure, squeeze-grouting technique can be implemented. This technique includes pumping the high-pressure grout material through holes to build a grout bulb or deliberate hydrofracture and utilize consolidated formation by increasing its density and shear stress. Several grouting materials such as chemical and neat cements can be used together to achieve better isolation (Greenwood and Hutchinson, 1982).

Backwall grouting aims to grout the void between shaft and excavated rock face with continuous injection of grout material in different phases until realization of complete isolation. In the first phase of backwall grouting, void filling takes place and channels of bleeding are locked with curtain grouting through holes to strata in the second phase (Daw and Pollard, 1986).

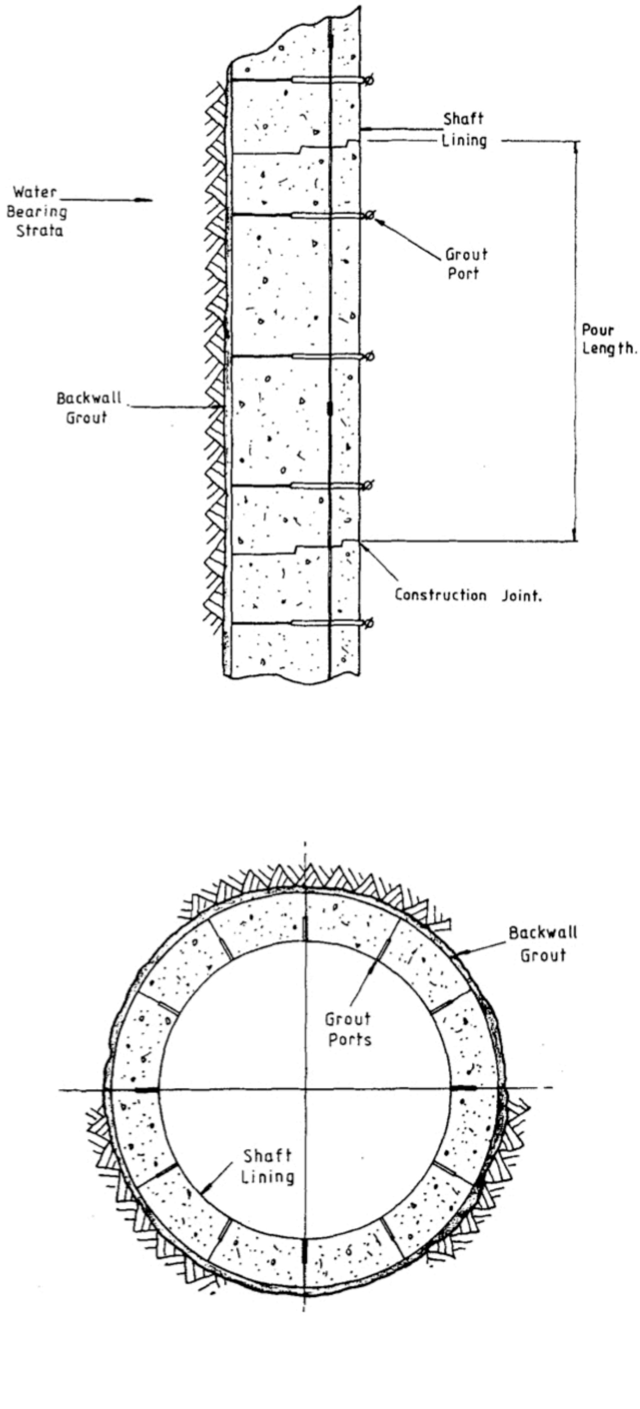

Figure 7. Backwall Grouting (Daw and Pollard, 1986).

Cover or curtain grouting is an ideal method for sealing off multiple leaks to mining surface. Holes are drilled and low viscous material is injected to face of drift, which forms an impermeable barrier and block water inflow (Bezuijen and Talmon, 2006).

Grout Materials

According to the material used in grouting, it is classified as suspension grouting, sodium silicate grouting, chemical solution grouting, and asphalt emulsion grouts. Suspension grouts are neat or aerated mortar cement, clay-cement, clay, bentonite, and clay-bentonite-cement and are widely used grouting material.

Soil group	Sandy gravels Coarse Sands	Medium and fine sands	Silty or clayey sands Silts
Grain diameter d_{10} [mm]	>0.5	0.02 to 0.5	<0.02
Dispersion degree S [cm^{-1}]	<100	100 to 1000	>1000
Coefficient of permeability k [cm/s]	1×10^{-1}	1×10^{-1} to 1×10^{-3}	1×10^{-1}
Grout Type	Bingham (plastic) suspensions Emulsions	Colloid solutions	True solution
Strengthening	Cement (k>1×10^{-1}) Aerated mortars	Hard Silicates (k>1×10^{-1})	Aminoplasts Phenoplasts
Watertightness	Clay-cements Aerated mortars Bentonites Asphalt emulsions	Semi-hard silicates Soft silicates	Aminoplasts Acrylamide

Table 2. Grouts suitable for various conditions (after Caron)

Sodium silicate grouts are made through dilution of colloid solutions with water and a gel structure is formed. It must have some fluidity and gelation setting time to travel throughout the long holes, and strength to increase rock stability (Weiser, 1950).

Chemical solution grouts are chosen from monomers that can be polymerized in water to get low viscosity products. Different catalysts and retardant are added to solution to control setting time (Flory, 1953; Charpentier and Monnerie, 1960; Vollmert, 1973). Carbamide aminoplasts are suitable for acidic formations in which oxalic acid used as catalyst and retardant in water solution (Rosenberg, 1975). For alkaline formation, phenoplasts can be employed to build strength (Caron, 1963; Warner, 1972). Acrylamide and methylene-bisacrylamide monomers and polyester resins are other types of chemical grouting materials used to build up strength, hence, eliminate water inflow (Fern, 1963; Karol, 1968; Askey, 1971).

Asphalt emulsion types grouts provide sealing of wider fissures and include selection of cationic asphalt emulsion as primary grouting material and followed by cement type grouts. Due to the negative charged surface of the large channels, asphalts having positive charge are merged with them. In flowing groundwater, pulverized fuel ash is used to agglomerate with the emulsion, when it breaks, to seal the pores (Bitumen, 1973; Gebhart, 1972).

Ground Freezing

Ground freezing consists of freezing the water producing formation and turns it to an ice wall. It increases overall strength of the face to serve as a barrier between water hazard and mine. It is used to stabilize earth for excavation, abandoned mineshafts and to control groundwater thanks to impermeable walls as barriers (Bažant, 1979).

In order to freeze the ground, pipes are run to the ground and heat is decreased below to freezing point through theses isothermal pipes. Because of its high cost it is practical to use for short-term applications and small-scale areas (Patel *et al*, 2014; Trupak, 1954).

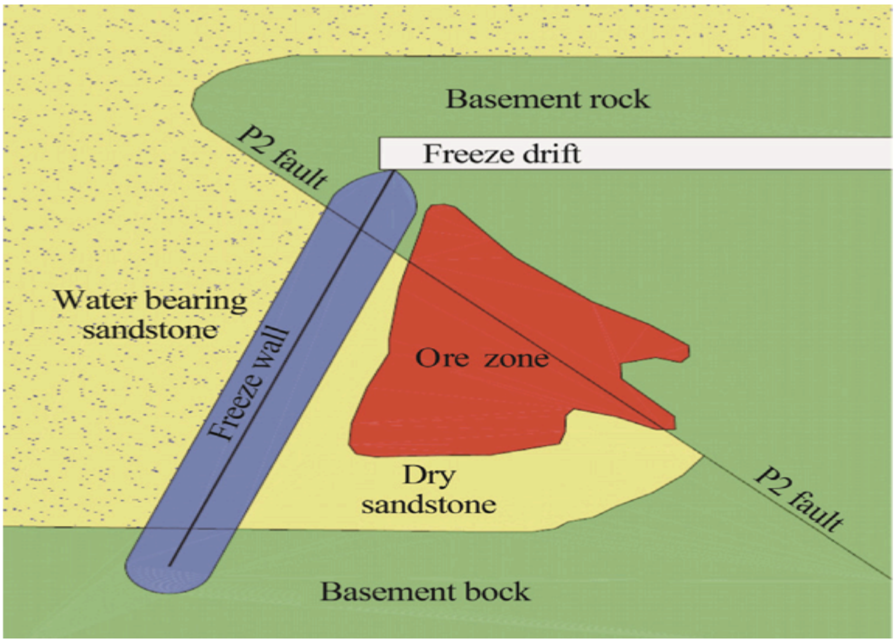

Figure 8. Typical freeze wall insulation situation with three freeze walls in the McArthur River uranium deposits (Xiaoyou, 2017)

Bulkheads

Bulkheads are widely used as a physical barrier to seal off the abandoned mine working and to protect neighboring active mine from explosion. They can also be used to control underground water originated from waterlogged strata, shafts and adjacent abandoned mine workings. Chekan (1985) lists some of the factors that should be considered during design and construction phases to control water inflow:

i. Bulkheads should be designed to endure maximum hydrostatic pressure of water
ii. Bulkheads should be designed from proper material to withstand wear, abrasion and corrosion due to water
iii. A proper bulkhead thickness should be selected and properly installed after a cover or curtain sealing of the mine face.

Chekan (1985) also classifies bulkheads into five groups:

i. Control-bulkheads are designed and constructed beforehand to plug abandoned mine working and to stop water flowing to active working. Pressure gauge is also installed to monitor the change in hydrostatic pressure.
ii. Emergency- bulkheads are employed to control emergency water inflow.
iii. Precautionary- bulkheads are installed in main entries and haulage roads to avoid inundation.
iv. Consolidation- bulkheads are utilized throughout grouting and consolidation of ground, and are temporary structures.
v. Open dam walls- these type of walls are used to store the underground water for reuse and conservation, and are restricting the water level to below the dam height.

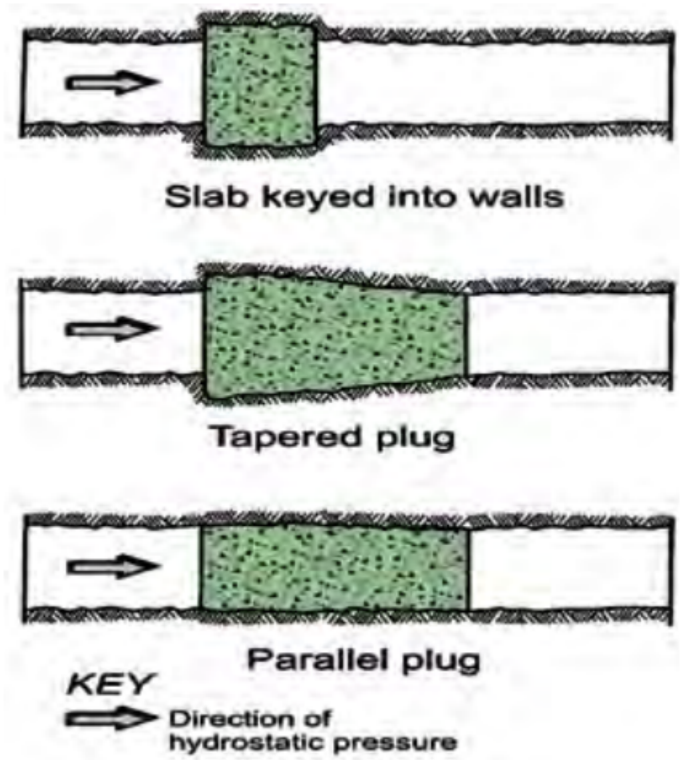

Figure 9. Three basic designs used for bulkheads in underground coalmines (Garrett and Campbell Pitt, 1958).

Water Barrier Pillars

The role of water barrier pillar is to prevent sudden water inrush to active working of a mine and is known as protective rock layers between ground water and active working of a mine. These barriers are effective if mechanical stability of the rock resists against water hydrostatic pressure (Kesserü, 1982).
Kesserü (1982) stated that there are two criteria required for selection of safety pillars: mechanical stability of rock mass and its hydraulic resistance.

Two methods are used in design of pillars (Rangasamy and Brummer, 2001):
Rock samples are analyzed in laboratory to find its strength and compared with the expected load in traditional method, however, in second method, numerical analysis aims to figure out the stress distribution within pillar.

Dunn proposed the earliest method in 1846 for selecting barrier pillar width depending of the depth. This method is not valid today because it undersized the pillar width with ignoring the seam thickness and side loads applied by water.

$$W = \frac{D - 180}{20} + 15$$

Where;
W = barrier pillar width (ft.)
And D = depth of mining cover (ft.)

Minimum pillar width is 15 feet for depth of 180 feet according to Dunn equation.

Pennsylvania Mine Inspector' s Formula uses depth of cover and thickness of seam to find safety pillar width.

$$W = 20 + 4T + 0.1D$$

Where;
T is the coal seam thickness (ft.)
D is the depth of mining cover or height of hydrostatic head acting against the barrier (round up to the nearest 100 ft.), whichever is greater.

Pressure Arch Method uses pressure arching principle and spans over which loads are transferred. Minimum width of pressure arch is a function of overburden depth. 75% of the minimum pressure arch width is recommended as panel width. Introduced in 1950's with using empirical observations of coalmines (Kendorski and Bunnell, 2007).

$$\mathrm{W} = 2.625(\frac{\mathrm{D}}{20} + 20)$$

Field data indicate that the strata comprising the overburden influence the maximum width of the maximum pressure arch, whereas the minimum width of the maximum pressure arch is primarily a function of the overburden depth. It is from the minimum width of the maximum pressure arch that the minimum barrier pillar width and maximum allowable span of the workings can be calculated (Koehler *et al*, 1995).

North American Method uses cover depth and adjacent panel with as variables, which were found as a result of observations in the USA and Canada.

$$W = \frac{D \times P}{7000 - D}$$

Where;
P is the width of the adjacent panel (ft.)
D is the cover depth (ft.)

Old English Barrier Pillar

$$W = \frac{H \times T}{100} + 5T$$

Where;
H = hydrostatic head or depth below drainage level (ft.)
T = coal seam thickness (ft.)

Holland Convergence Method

$$W = \frac{5\log(50.8C)}{E\log e}$$

Where;
C is the estimated convergence on the high-stress side of the barrier pillar in inches.
E is the coefficient for the degree of extraction adjacent to the barrier.
e = base of the natural system of logarithm
E = 0.07 should be used if adjacent workings are hydraulically backfilled, value E = 0.08 should be used if strip pack walls are built next to the barrier pillar, value E = 0.085 should be used if partial extraction is practiced, and value E = 0.09 should be used if complete caving will occur in adjacent panel

C is calculated as:

$$C = 0.001333 \times D \times \frac{T}{7} \times \frac{3000}{\sigma_c}$$

Where;
σ_c is unconfined compressive strength of a coal sample (psi).
T = seam thickness.

6. RECOMMENDATIONS AND CONCLUSION

There were many cases of mine inundation in the history of underground mining and these accidents led many fatalities and major loss of mines. Twenty first century also experienced mine inundation disasters regardless of advanced technology and knowledge from former cases. These cases revealed the fact that investigations were insufficient in figuring out the root cause of accidents. Several causes were introduced as cause of the accidents such as approaching too much to adjacent water logged mines, using outdated maps, choosing incorrect water pillar width, and etc. These are not the root cause of the accidents because these also unveil the fact that advanced technology and engineering practices were not practiced in this mines. The level of culture is the root cause of the accidents because technology and engineering practice would be effective in avoiding almost all these accidents in this century. A proactive culture should be implemented to reach zero mine inrush accidents level. A proactive risk assessment in mines is also cost efficient because indirect cost of the accidents are excessive such as compensations, loss of valuable mine sources.

To act proactively against mine inrush odds, the nature of groundwater and formation should be investigated thoroughly. Initial and detailed investigations are very efficient in finding the origin of groundwater and formation properties. These investigations include collecting historical data, mapping, geophysical surveys, test drilling and logging. Then, the best practice and method should be implemented according to hierarchy of controls. Dewatering of the ground water could be selected as an elimination method before operation phase of a mine. Diversion methods can be employed to minimize the water hazard. Using pumping, as a control measure against water rush is the least effective way, which has no control over any accidental and spontaneous inrush.

7. ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to Prof. Nuray DEMİREL for her continuous help and support during the course of this study.

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