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A REVIEW OF HYDROLOGICAL INVESTIGATIONS FOR DEEP COAL MINES, WITH SPECIAL REFERENCE TO PETROPHYSICAL METHODS

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INTRODUCTION

The presence of groundwater can have an important influence on investment decisions for deep coal mines. It is a hazard during shaft sinking, precautions may be needed when mining near large aquifers, and the development of special mining methods may be necessary. These can have a major effect on the viability of the project. With the tendency to mine deeper, e.g. 1200 m, with pre-mining groundwater pressures of up to 1200 bars, prior assessment of potential groundwater conditions is essential.

Groundwater conditions at such depths can only be ascertained from exploratory boreholes and hydrogeology studies must be commenced at the start of exploratory drilling. The additional costs involved are small compared to the hugh consequential losses that can occur if the presence of groundwater problems is not identified.

Groundwater conditions in boreholes may not be evident due to "mud walling" and by mud filtration into permeable formations which can be invaded to annular thickness greater than 300 mm where poor mud control occurs. Open hole rotary drilling methods adopted for most overlying strata also limits the accuracy of formation sampling. To avoid mis-interpretation hydro-geological assessment requires a multi-disciplinary approach combining ;

- regional geology
- borehole logging
- down-the-hole petrophysical logging
- geotechnical appraisal
- hydrological tests
- fully cored index holes, combined with laboratory tests

The need for surface water investigations should not be overlooked during early investigations. Surface conditions can impose constraints on mining and processing and a study of surface hydrology takes some time to complete if annual variations are to be considered [1].

Groundwater Regime

Exploration relating to mining is site-specific though the consequences of mining on the hydrological environment can extend well beyond the boundaries of the proposed mine take. The purpose of exploration is to provide a data base on mineral quality and conditions over a mining area with hydrology as an important aspect. A critical objective is to establish the existing hydrological regime against which the consequences, if any, of mining and processing can be calculated and effects beyond the mining area assessed.

The study of aquifer basins is not discussed here though regional hydrology and the situation of a mining area within the hydrogeological regime is a fundamental aspect in the assessment of hydrological conditions. Authoritative works are available [2].

Shaft Sinking

The cost of sinking and equipping deep shafts is (circa) 20% of the total investment cost for a mine. Several years lead time are needed for shaft sinking and furnishing before coal production and a return on investment begins. Groundwater is a major hazard and a potential delay factor in sinking (as high as one year is known) and can have a serious detrimental impact on project economics. Shaft investigations require to be specific to the immediate shaft area and an investigation borehole should be drilled within the shaft circle. The investigations must relate water conditions with rock characteristics and water quality.

The possibility of water flow into the mine workings, depending on magnitude, can increase the capital cost of mine development and reduce operating efficiency. Pumping rates from wet mines can be as high as $5 - 13 \times 10^6$ t/year.

The assessment of mining horizon water conditions from exploratory drilling has not been investigated comprehensively in the past. The resolution of mine inflow predictions is complex in that the vertical conductivity of a multi-layered strata sequence over a large areal extent has to be assessed along with predicted changes in permeability induced by future seam extraction [5].

Inflow must be related to the mining method proposed, the roof and floor conditions, the weathering characteristics of the exposed rocks etc. Dry but porous stratum in the vicinity of the coal seam which may provide hydraulic communication must be identified.

Barriers Against Water Hazards

Safety pillars are required against surface and underground water hazards in a number of mining situations. The specifications for such barrier pillars are generally defined by mining law [4,5] but hydrogeological investigations may be needed to determine boundary pillar characteristics and specific sub-surface conditions. Such situations include : projected mining under the sea or a large surface water body; major aquifers overlying or underlying the coal seam(s); cross-fault aquifers where displacement brings permeable ground against the mining horizon.

Unsealed or poorly sealed boreholes present an unacceptable hazard to underground mining and an effective method of sealing boreholes, before abandonment, is essential in any drilling programme, together with an exact borehole survey.

Surface Hydrology

A hydrological investigation must aim at obtaining all information needed for water management during and after mine operations including pollution control. A necessary part of the hydrological assessment of a mining area is a knowledge of regional geology, physiography, hydrocensus and climate; to which project factors of water abstraction, drainage and pollution factors can be applied.

Water Budget

The water budget of a mine area within a regional system can be an important area of study. Drought patterns, annual flows in rivers and streams, water quality, existing water wells and current water abstraction can be established where local records are available. The water demand for mine and plant operation against water availability from the water resources study is inevitably needed for planning application or permits. In water deficient regions water reservoirs and/or the piping of water over long distances to ensure supply may need investigation. The sharing of sometimes scarce water resources with other users can be a sensitive feature of planning.

In low rainfall regions the build-up of dissolved solids in rivers can be high. As mine and plant water discharge can also be high in solids, it is not always possible to totally discharge directly into such rivers without detriment to downstream users and closed mine water systems for part of the mine outflow may need investigation. Water quality is therefore an important factor in water budget investigations, as well as for shaft freezing or grouting investigations.

Water Management Planning

At the mine commitment stage the start of a series of ongoing hydrological studies will be required which expand on the initial exploration data base. The studies include :

- Environmental baseline study
- Water Management planning
- Mine operational hydrogeology
- Post mining hydrogeology

REMOTE SENSING

Aerial photo interpretation and satellite imagery verified by the use of reliable ground data have important applications in hydrological and environmental surveys of a region. The first earth resources satellite capable of sensing and recording electromagnetic radiation reflected from or emitted by the earth surface was Landsat 1 launched in 1972 and had a RS resolution factor of 70 m, the present Landsat 4 has a resolution of 30 m and future European and USA satellites will improve resolution of 10 m. Satellite images are received digitally and converted into user format including false colour, image restoration and image enhancement.

A combination of aerial photography of the mining area with satellite imagery can be a useful tool in some hydrogeological and environmental baseline surveys. Vegetation, land form and use, erosion, run-off patterns, colour and ground features, e.g. terraces, gravel pits, etc. can be identified from aerial photographs and provide indications of sub-surface conditions. Many major coal fields are however "concealed" under thick alluvial cover.

PETROPHYSICAL LOGGING

General practice in exploratory drilling is to open-hole drill to above the coal seam and core drill the coal seam; although sometimes when a hard abrasive overbuden is present the option of total coring may be adopted. The use of wire line logging, correlated to index (cored) holes, in open holing provides a relatively low cost means of determining geological logs, identification of core loss material in cored sections, correlation between boreholes (petrophysical fingerprint) and determining of some mineral quality parameters [6,7]. The logs can also provide an indirect qualitative measurement of permeability. This may be achieved by correlating the different log responses with a hydrological index from a combined groundwater - petrophysics - geotechnical test borehole.

A logging suite for coal exploration may comprise :

- Standard density log with source-detector spacing 45 cm
- High resolution density log with source detector spacing 15 cm
- Natural radioactivity log (Gammar Ray)
- Borehole caliper log
- Acoustic velocity log (compressional wave only)
- 3 electrode laterolog (focussed resistivity)
- Standard Neutron-Neutron log (source-detector spacing 45 cm)
- Verticality log
- Spontaneous Potential Log (S.P.)

This suite of logs may be expanded with

- Absolute and differential temperature
- Short spaced neutron-neutron (source-detector spacing 25 cm)
- Acoustic device which measures the compressional and shear wave velocity
- Microresistivity
- Dipmeter.

The logging devices perform their measurements going up-hole. Their logging speeds are dependent on the requirements of the client and may vary between 1-2 m/min. The lower the logging speed of statistical devices (gamma ray, density, neutron) the higher their accuracy and resolution.

All logs should be carefully calibrated to guarantee repeatability and universal meaning.

Devices using radioactive sources (density, neutron) require special caution whilst handling. Most countries have strict legislation requirements for the handling and use of sealed radioactive sources which have to be adherred to. In case radioactive sources are lost down a borehole, all efforts should be directed to get it recovered. If left behind, legislation requires the designation of a protective zone around it, which will result in the sterilisation of a substantial pillar of coal.

Mud density and mud resistivity must always be measured to enable a proper assessment of borehole effects. Such effects are inevitable as petrophysical measurements are made in boreholes and are therefore affected by the borehole environment, i.e. the geometry of the borehole, the mud type and density, the mud invasion and the concurrent forming of mud cake. Obviously the degree of impact of such effects on the measurements can be minimised by proper drilling practise on one hand and proper sonde design on the other. Sondes are presently employed which are virtually unaffected by borehole diameter and mud density variations, whilst the concurrent measurement of the same physical parameter by means of devices with different depth of investigation enables the measurement to be corrected for mud cake and invasion effects. In general the log with the lowest depth of investigation will experience the largest borehole effect, whilst it exhibits the highest vertical resolution.

Two different ways of recording the petrophysical information are normally used :

1. Analogue chart paper traces, of which the layout normally complies with API standards. Two depth scales are generally used, one small scale to record the full borehole length and a large scale to present a detailed picture of coal seams.

2. Digital tape recordings, from which data can be entered into computer for further processing and computer evaluation.

Log Interpretation

The theoretical basis for the interpretation of most petrophysical logs is complex and outside the scope of this paper. Fortunately in most mining surveys it is possible to make satisfactory quantitative interpretations in terms of engineering parameters using site specific empirical relationships. Such relationships do exist because significant changes in geological or engineering characteristics will always be evident through at least one physical parameter which can be detected by log(s) and because any change in log response is indicative for a change in at least one geological parameter.

The establishment of above mentioned empirical relationships requires the drilling of fully cored "indexation" boreholes. The petrophysical parameters should then be correlated against lithological, geotechnical and hydrological parameters. Some uncertainties can emerge where core measurements are point tests, which are to be correlated with petrophysical logs representing running averages. Averaging such point measurements with a running average filter, similar to the effective filter mechanism of the logging probe, makes both measurements readily comparable.

The main logs to be used in the location of potential groundwater zones are : S.P., Resistivity, Gamma Ray and the porosity logs (density, neutron and sonic). After identification of above zones hydrological tests are being performed resulting in hydrological indices for the zones of interest which can be correlated to the log responses to obtain empirical relationships which may enable the prediction of those indices from logs.

Whilst porosity can be derived from logs with a high degree of accuracy, permeability is not directly obtainable as this depends on such "elusive" factors like pore space geometry and rock texture. It is therefore that one has to resort to empirical relationships which through their very nature are site specific.

Short description of logging techniques

Self Potential (S.P.)

The S.P. is recorded as the potential difference between a single moving electrode and another electrode earthed at surface. As the surface electrode has a constant potential, the S.P. curve shows the variations in the potential of the downhole electrode, which are caused by S.P. currents flowing in the mud column. The origin of such current are of an electrochemical or electrokinetic nature. Its major use is in the detection of permeable beds, however the magnitude of the S.P. deflection is not a measure of permeability.

Resistivity

A wide range of measuring devices exist. All of them use coil(s) or electrode(s) emitters to send an electro-magnetic- or current-signal into the formation. Receivers in the form of electrode(s) or coil(s) measure the formation response. The depth of investigation varies with tool design from a few centimeter to several metres.

The following logs are often employed in coal logging :

- The single point log, a simple 1 electrode system. Its response is strongly influenced by borehole effects.
- The Laterolog produced by a horizontally focussed sonde, provides high vertical resolution and low sensitivity to borehole effects.
- The Microlog, i.e. the response of a 1 cm^2 focussed sidewalled, current electrode. This log provides extremely fine vertical resolution. Multiple measurement of the microlog froms the measurement principle of the dipmeter.

Resistivity tools in combination with porosity tools (sonic, neutron, density) are used quantitatively in the evaluation of pore fill of sedimentary strata.

Density

In essence the density device consists of a radio-active source, a detector and amplification electronics. The source emits a constant flux of gamma quanta. These quanta are scattered by interaction with the electrons they encounter in the formation. Some of these scattered quanta arrive at the detector. Their number per second is a measure electron density and therefore proportional to the density of most rocks. Most present day sondes are run sidewall to minimise borehole effects.

An important use of this log is its application in porosity evaluation.

Neutron

The working principle of this type of device is similar to that of the density in that a source emits a flux of particles (neutrons) and a detector measures the response of the formation (gammas or thermal neutrons). The neutron response is directly related to the concentration of hydrogen in the formation. A high H concentration gives a low neutron count rate and vice versa. As the neutron log provides and H-index, its response is often used in porosity evaluation.

Gamma Ray

This device consists only of a gamma-ray detector and a pulse amplification unit. It measures the intensity of the gamma radiation which the formation naturally emits. The activity measured in sediments is usually caused by the presence of uranium, thorium and/or potassium. These elements are preferentially absorbed by clay particles, which is an important fact for the lithological interpretation of its response.

Sonic

This device measures the speed of sound. It emits several times per second a very short sound wave. At several receiver "stations", the effects of the short sound bursts are recorded. The difference in arrival time of the first wave front arriving at the different detectors is a measure of the compressional wave velocity.

An empirical linear relationship in consolidated sands between porosity and acoustic velocity, makes that this log is often used in porosity evaluations. The presence of shale and its distribution, complicate the interpretation as with all porosity devices.

Caliper

This device measures the borehole diameter using arm(s). The variations in diameter are reflected in a movement of the arms, which causes a potentiometer to change resistance. Besides its requirement to calculate borehole effects on other sondes, it provides useful supplementary information on hole stability which relates to lithology.

Density Log

This is produced by a sonde which measures the formation response to a continuous bombardment of gamma quanda. Basically the device consists of a detector plus amplifier and radiation counter, measuring the response of radioactive source (emitting the gamma radiation), and a detector with amplification electronics. The system measures the electron density of strata which is approximately proportional to the bulk density of the strata. Most present day sondes are run sidewall to minimise borehole effects. An important use of this log is its application in porosity evaluation.

Resistivity Logs

A wide range of measuring devices exist. All of them use emitter(s) (coil or electrode) to send a signal into the formation (current or e.m. field). A receiver measures the formation response by means of coil(s) or electrode(s). The depth of investigation varies with the system from a few centimetres to many metres. The following logs are often seen. The single point log, a simple electrode system with a shallow depth of investigation. Its response is strongly influenced by borehole effects. The laterolog, a horizontally focussed sonde giving good depth of investigation and high vertical resolution. Resistivity provides good structural information. The measurement principle of the dipmeter is based on the fine vertical resolution of the micrologs (= the response of a 1 cm^2 focussed current electrode).

The evaluation of pore fill in sedimentary strata is based on Resistivity and Porosity logs (= Neutron, Sonic, Density).

Sonic Log

The basic sonic log involves the transmission of acoustic energy pulses into the formation and the measurement of transit time(s) from the transmitter to the detectors at fixed distances from the transmitter. A typical multi-sonde comprises two transmitters 900 mm above and below two receivers spaced 300 mm to 900 mm apart. By measuring velocity of sound waves through rock matrix and pore fluid the sonic log provides an index for porosity determination in the 5 to 30% range and a means of detecting secondary porosity such as fractures and cavities. Used in conjunction with the density log, a porosity determination can be enhanced.

Other Tests

A number of ancillary tests can have an application in a mining field exploration, including borehole temperature logging and tracer logging [11].

HYDROLOGICAL TESTING

General

Borehole conditions dictate the methodology for aquifer testing. Slim hole drilling at the diameters common in mineral exploration are subject to a number of "as drilled" conditions which restrict their degree of communication with groundwater, these include incomplete connection with secondary fissuring plus mud walling and mud fluid infiltration of permeable zones. Hydrological tests during exploration work are commonly carried out as single well tests because of wide borehole spacing in exploration and the need for site-specific measurements in shaft test boreholes. Pump-in or falling head tests are not normally used for deep hole testing since the resultant reverse flow to the aquifer is contrary to the developing of permeable zones, can create additional fouling and the use of pump-out tests are preferred. Core drilling of a selected number of boreholes, geotechnical logging of the core and correlation with petrophysical logging of all boreholes, provides a base for planning the hydrological test programme. Where boreholes are suitably located a multi-hole observation test will provide better information on reservoir conditions and anomalies. However the problem of combining pump tests using packers with multi-observation wells is in isolating the corresponding horizon in all wells to observe the effect of pumping. The main groundwater test methods for boreholes include :

- Conventional pump-out recovery test
- Drill steam packer test
- Pump-out packer test
- Borehole flow meter test
- Injection tests for shaft investigations

Borehole preparation for hydrological testing may include cleaning and development of the well by water jetting, reaming or flushing the well to reduce drilling mud contamination. Excessive development should be avoided as wall washouts may occur in weaker zones. The drilling mud should be replaced with clean fluid of minimum viscosity to retain hole stability. Unconsolidated strata at depth if unstable can present problems for testing and can limit open hole testing to stage tests requiring progressive screening and casing as drilling proceeds. Casing perforation methods used for oil exploration are not practical in groundwater tests.

The main data required in borehole hydrological tests are : location of water bearing horizons; assessment of transmissivity, fracture systems, pore matrix and communication, hydrostatic pressure, water quality, solubility of calcareous rock units, etc. For shaft investigations additional rest requirements must provide the data needed for planning the ground treatment of permeable zones by cement or chemical pregrouting or freezing. The presence of saline water may preclude freezing. Such tests include identification of rock fracturing and rock matrix types.

Pump-out Well Tests

A conventional drawdown/recovery test by bailing, borehole pump or air lift can be carried out in stages as drilling proceeds or after hole completion and provides a first evaluation of the presence and magnitude of water problems. The method is however too general for specific design use as variations in porosity over a sequence of strata cannot be accurately determined.

Drill Stem Packer Tests

Packer test systems provide the most diagnostic method for evaluation of formation groundwater [11,12,13]. The method provides for single packer or double packer "stradle" type test units which are suspended in the borehole by the drill steam against a pre-selected horizon to isolate that horizon for pressure testing. The packers, typically rubber sleeves, may be inflatable by a down-the-hole mud pump operated by drill rod rotation or by a compression type which is set mechanically by applying mass from the drill stem. The basic double packer test unit comprises packers, perforated inlet pipe between packers, pressure recorders or transducers, test valve, equalising valve and choke. The spacing between packers can be varied. The single packer unit for bottom tests is similar in content to the above. The minimum hole diameter for standard packer tests units is typically 130 mm and the maximum 400 mm. Special slim units can be manufactured if required but are costly and require proving tests before use. For relatively shallow mine hydrology testing the drill stem unit can be modified for inflation of packers from the surface and automatic and continuous recording at surface of test pressures.

The test programme measures the hydraulic profile stage by stage over the full depth of hole, the location of a good packer seating for each stage being predetermined from the petrophysical log.

In a test the packer unit is run into the borehole with valve closed and drill stem dry. Packers are inflated at the selected test horizon and tested by pull back from surface and by observing mud level in the annulus during testing. To begin the flow test the main valve is opened by drill stem weight or rotation and water from test section flows into the drill stem through a choke to control flow rate. After a predetermined test period the test valve is closed and pressure allowed to rebuild in the test section. Pressure recorders monitor drill stem pressure during the in low period and reservoir recovery pressure during the shut-in test period. Two sets of tests are commonly carried out per programme. Air expelled from the drill stem during testing gives indication that the test is successfully operating and an ancilliary pressure gauge or transductor may be fitted to the top of drill stem to give preliminary observation of the test. The down-the-hole memory recorder from deep tests is normally not recovered until the withdrawal of the unit at the end of a test series but mine exploration units are surface monitored.

During deep test runs the packer system is subject to severe pressure from the mud column and for strength a minimal clearance is allowed between the deflated packer and borewall thus when running the unit in the borehole the speed has to be controlled to avoid swabbing. After the completion of a test, inflation type packers can be deflated and the unit reset for the next test, the drill stems being swabbed by wire line bailer to empty the stem for next test. Resetting is more difficult with mechanical packers.

Test interpretation is based on Darey's law as developed by Theim, Thiess, Jacob and Cooper [14,15,16] and others. The mathematical relationships for non-equilibrium conditions are complex but quantitative evaluations which determine formation flow can be graphically resolved. The shut-in pressure recovery data is plotted as a semi-log graph of log time $\frac{t+\Delta t}{t}$ against pressure change and assumes a constant flow rate for the preceeding inflow period. The semi-log plot gives a straight line approximation but commonly deviates with anomalies for near borehole effects and longer term leaky aquifer and boundary effects. The transmissivity for a typical confined aquifer pressure recovery test is determined by the slope of the straight line graph over one log cycle and related pumping rate [17].

Flow tests can be analysed by type curve solution [18] if they are of adequate duration.

The graphical analysis referred to above and many others also in use give reasonable transmissibility assessment. The use of computer based mathematical solutions however provide a more detailed analysis for formation evaluation.

Drill stem tests were developed for deep cased borehole testing but have been in use for mine hydrological testing for some 20 years, mainly for shaft investigations. The system has some limitations particularly for near surface high permeable zones where flow times can be very short, and by reason of the small volume of test in complex conditions. Also specialist services are needed to carry out the tests.

Pump Packer Tests

This is an adaption of the drill stem test method developed for relatively shallow groundwater testing at high flow rates [19] and has special application in mine shaft centre test borehole investigations. A down-the-hole test unit developed by a shaft sinking contractor [20] uses single or double staddle packers inflated by compressed air from the surface and pressure transducters monitor the test section and provide digital and chart readout at surface. A main feature of the test equipment is a submersible pump coupled to the drill stem and housed below static water level in the upper section of the borehole. The 10 kW pump is 140 mm diameter with a maximum delivery of 3 litres per second against 250 m head. A full test programme for shaft investigations may take 1 to 2 months to complete.

The test procedure is conventional with pumping at constant rate for drawdown, followed by pressure recovery measurement against time from stopping the pump. The system allows for greater inflow rates and longer test duration in permeable zones than drill stem testing and thereby induces a larger test area and a better analysis of ground conditions.

Formation values are calculated for each test zone by semi-log plot of the recovery data using the non-equilibrium formulae, as for drill stem testing [15,17].

Injection Tests

These tests are not normally used for hydrological testing in mine investigations but have an application in ground treatment investigations for fracture and rock matrix properties. Injection tests are best carried out through a packer system. Care is needed in interpreting the results as problems can occur from back flushing due to movement of fine grained material within the rock matrix resulting in erroneous readings.

Flow Meter Tests

A flow profile during pumping over the depth of an open hole can be measured by an in-hole flow meter. Indications of relative permeability can be assessed by measuring the change in total flow rate, as the flow meter is raised from base to top of borehole or test section, while pumping at a constant rate is in progress. The flow meter is instrumented to provide a surface read-out of velocity. The system is not normally sufficiently accurate for formation evaluation for mineshaft or mine design.

Piezometers

Casing should be left in a selected number of boreholes for observation of seasonal changes in piezometric levels and to determine flow direction.

GEOTECHNICAL ASPECTS

General

Geotechnical information is an essential base for hydrogeological prediction in mine and mineshaft design. The testing technology cannot be an exact science as rock mass is a complex and non-isotropic material so that all geotechnical investigations retain an aspect of uncertainty which should be quantified. Geotechnical engineering depends primarily on good sampling and data collection which together are the most expensive part of investigations, often however, more emphasis is given to the analytical end of the work and good sampling procedure given a lower priority to the detriment of the value of prediction data.

Drilling

Shaft test boreholes should be fully cored at 90% minimum core recovery, except in unconsolidated ground and if possible, triple-tube split inner core barrels should be used; a typical core diameter is 75 mm. In general exploration for structure and coal quality determinations boreholes are usually open holed to the mining horizon and core drilled only through the mining horizon, that is from about 50 metres above the top seam to 20 metres below the bottom seam, all holes being petrophysically logged. Except in small test programmes about 1 in 20 boreholes should be fully cored to provide indexation for petrophysics logging. Mineral sample cores should achieve 95% minimum core recovery, it being noted that in stratified deposits the core loss of thin sterile bands within the deposit has potentially more quality implications than loss of mineral core. Core recovered for quality purposes should also be logged for hydrogeological purposes.

Core Handling

A systematic procedure for core handling is needed for sampling control. Cores, laid out in core boxes should be colour photographed and logged within 24 hours of recovery or if this is not possible the cores should be sealed in plastic sleeves or "Cling" film for future sampling. Reasonable core shed facilities are needed with lighting and water for core examination and racked storage.

On Site Sampling

During drilling, information should be logged on, mud viscosity, mud loss, or gain, rate of drilling, run number and depth, water levels etc.

Following geological logging the core should be geotechnically logged and then samples removed and wrapped for laboratory testing. Site logging should record; total core recovery, solid core recovery, rock quality designation (RQD), fracture index, discontinuity type and infilling, point load test values. Subsidiary laboratory tests which may be required include slaking tests, moisture content and clay liquid and plastic limits.

Laboratory Testing

Laboratory sample should be at least three times core diameter in length. At least three samples should be taken for each lithological rock type. Samples selected should be wrapped in aluminium foil, dipped in wax and placed in a tube and encapsulated in wax. An alternative is the use of cold mixed polyurethane foam.

A comprehensive laboratory test programme is required and should include strength and porosity tests, an indication of magnitude of testing being that some 600 analyses can be required for a shaft test borehole programme alone. A number of low temperature tests are also needed for ground treatment evaluation. This can present problems in preparing laboratory samples and special procedures are necessary [21] together with dry ice or low temperature freezing facilities. In a coal project a test programme will include methane emission, spontaneous combustion and coal washing tests plus coal and ask chemistry.

Groundwater quality tests are required for each main groundwater horizon, usually 5 litre samples suffice but care is needed that the samples are not contaminated by drilling fluid.

Calculation of Mine Inflow

The three main areas of inflow to be considered in a new deep mine project are :

- seepage from adjacent aquifers
- localised inflows along faults and major fissures
- changes in permeability and storage from caving and subsidence due to mining

At the pre-development level of investigation, general seepage, excluding local inflows, are modelled at order of magnitude level by considering the mining area as equivalent to a large well encompassing the workings and penetrating the mining horizon. The Theim equilibrium formula for steady state flow from a confined aquifer to a large diameter well is used to predict water inflow. In two known instances the method under-estimated the actual mine drainage quantities and prudence is needed in the use of this assessment for drainage design.

Under isotropic conditions for constant drawdown conditions a reduction in inflow should occur with time [22] but this effect is likely to be masked by vertical leakage and mine expansion.

The degree of hydraulic conductivity along major faults should be tested during exploration by inclined drilling and/or pump testing if necessary. Inflow may be calculated as flow to a vertical planar cut (the fault). The water hazard from the intersection of major faults is from sudden water/mud inrush rather than potential long term flow and protection pillars or advance probe drilling from the mining face is necessary.

Seam extraction creates strata movement through to surface which can be lowered by up to 80/90% of seam thickness. Extraction increases permeability and investigations on the effect of longwall mining on ground permeability and subsurface drainage have been carried out at the University of Nottingham [22] where further investigations on deep mine drainage are currently in progress [23].

A groundwater hazard plan must be compiled for mining control by integrating the mining proposals with hydrogeological conditions. The indices include data on groundwater, surface water, major faults, hydrostatic pressure, plus old mine workings, boreholes etc.

Undisturbed hydrostatic pressures can be reasonably estimated from the mining depth below piezometric surface. As an underground mine develops the hydrostatic pressure approaches atmospheric as water drains to mine openings. Following seam extraction, floor heave could occur from an aquifer overlain by a relatively impermeable aquitard, where the weight of superincumbent strata is less than the hydrostatic pressure of the aquifer. Mining would however be restricted or pre-drainage carried out should aquifer create such a hazard.

Special mining systems may be required to suit the hydrogeological conditions determined by investigations. When mining under water or water bearing beds total extraction may be necessary to allow uniform subsidence and minimum strain effects. In this case remnant pillars between extraction panels would create stress concentrations, fracturing of the rock mass and communication with overlying water. An opposite could be that only partial extraction can be permitted to minimise subsidence effects or that stowing which may be uneconomic is needed to minimise subsidence.

Surface Subsidence

A consequence of mining is the effect of subsidence on the surface water regime. Soil drainage and near surface cracks and fissures are affected by the subsidence wave, though such effects need not always be detrimental, particularly for hard sub-pan soils. A further feature in low lying areas can be the creation of potential areas of flooding requiring significant expenditure for control purposes.

Water Pollution

Water contamination through mining depends on a number of factors including, type of mineralisation, residence time and others and should be evaluated as an important environmental factor.

An important objective of any hydrological study must be to determine water management aspects for mining and processing. A mine can be a large user of water but with good management pollution effects should be minimal. Arid regions present special problems in both abstraction and return of water and water quality.

CONCLUSIONS

In the past less than order of magnitude estimates of water inflow into deep mines have been common. Precise estimates are not possible but by the use of the hydrological tests summarised combined with the semi-quantitative methods described in the paper much better approximations can be made. Because the information used concerns several disciplines and is obtained from a number of different sources, e.g. exploration drilling, geotechnical drilling, meteorological and stream gauging stations, contractors, etc., and because each individual input is inadequate for providing an estimate; it is essential that a member of the mine project team acts as a focal point for assessing the extent of any water hazard.

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