THE APPLICATION OF COMPUTER BASED NUMERICAL TECHNIQUES TO THE PROBLEMS OF GROUNDWATER REBOUND IN MINING AREAS

Gareth M. Swift [1]; David J. Reddish [2] and M. Lewis

University of Nottingham, School of Chemical, Environmental and Mining
University Park
Nottingham, NG7 2RD, United Kingdom
Phone: + 44 115 9514073, Fax: + 44 115 9514115

[1] e-mail: Gareth.swift@nottingham.ac.uk
[2] e-mail: david.reddish@nottingham.ac.uk

ABSTRACT

The closure of deep coal mines and their subsequent abandonment has been a prevailing feature of the last few decades, throughout some of Europe's largest coalfields. The environmental problems associated with mine abandonment have been widely documented; prevalent amongst these are the implications of groundwater recharge caused by switching off the water pumps in many of these deep mines. For the environment, the most significant recharge related problem documented to date has been the pollution of surface water courses.

This paper documents current research being undertaken at the University of Nottingham pertaining to the environmental implications of groundwater rebound, and details a potentially more intrusive aspect of groundwater recharge, that of shallow mine stability. Ongoing analysis of a number of mine sites throughout the United Kingdom has highlighted the applicability of state of the art computer based numerical modelling techniques to the problems associated with groundwater flooding previously abandoned shallow mineworkings, which have for many years been kept free of water through pumping.

Research has been directed at quantifying the effects of saturation on the laboratory strength and stiffness characteristics of coal measure rocks, with the objective of relating this to the behavioural characteristics of the rock mass. The application of a 2-dimensional finite difference numerical modelling method to the stability problems caused by groundwater recharge is being investigated and the results of this ongoing analysis are documented. Visualisation of the recharge phenomena as intersection with mine horizons takes place can be carried out using the powerful VULCAN software. The application of this software to a case study site is outlined and the results to date are presented.

INTRODUCTION

Many of Europe's coal seams lie at a depth that places .em beneath the natural water table. As the strata associated with these coal seams, especially the Carboniferous rocks in the United Kingdom (UK), are generally of a low permeability, it is possible to work these seams by controlling the groundwater through routine pumping at mine level. Regular pumping may result in a depression in the potentiometric surface, or the water table throughout a mining district, and in general can dewater the strata between the surface and the working mine. Upon abandonment water levels will slowly recover as workings flood, this maybe anticipated to take anything from a few years to up to 25 years, and is dependent upon factors such as water make, mine environment, mining depth and permeability of the intervening strata, as well as the increased permeability of the rock mass directly affected by mining. (Smith and Colls, 1996; Sherwood and Younger, 1994; Younger, 1993).

A quantitative and qualitative analysis of a number of mine sites throughout the UK has produced a significant amount of data relating to the nature and quantity of typical mine discharges. Many of these sites represent situations where the mine has flooded and subsequently reached a dynamic equilibrium with the local hydrogeological regime. These case studies have provided an insight into the mine recharge phenomena. Initial hydrological analysis of these sites has been satisfactorily undertaken using established numerical formulae in the form of Darcy's equations, relating mine inflow to the recorded outflow. This research has been supplemented by laboratory and field based experimental analyses of the effects of water, specifically pore pressure development, on the strength and stiffness characteristics of UK coal measure strata, with the intention of quantifying the effects of groundwater on the rock mass. Numerical analysis is considered to be the next stage in the research process, based on our conceptual understanding of the recharge phenomena, and upon the conclusions drawn from the intact rock tests. The final stage is validation.

A further case study site has been provided in the form of the Woolley complex, located North of Barnsley, West Yorkshire. This study has facilitated an in depth analysis of the behaviour of water throughout an underground mining district, and has also provided the opportunity to examine treatment options for the receiving water course.

In the past, much work within the Geotechnics Group has been directed at rock mechanics problems associated with active underground mine working. These two projects present a recent trend in an alternative direction, specifically towards the environmental implications of mine abandonment in the form of pollution prevention and remediation and surface stability aspects in the form of subsidence. The following sections will outline this current research, highlighting its relative importance in light of the recent changes in the UK coal mining industry.

POST ABANDONMENT ENVIRONMENTAL IMPACT OF MINE WATER

The environmental impact of mine water discharges following the abandonment of an underground mine, has become an increasingly emotive topic since the onset of widespread closure of UK coal mines. Abandoned mine workings are a source of poor water quality in specific areas of England and Wales. In many cases, this situation has been a longstanding one, but with the continued abandonment of mines, the situation will deteriorate still further. The Coal Authority is currently giving a high priority to preventing polluting mine waters from recently abandoned coal mines reaching sensitive water courses, as well as dealing with pollution that has already occurred from long abandoned mines (Anon, 1999). In many cases the history and extent of mining is such that neither the hydraulic conditions, nor the chemical nature of the water can be predicted once mining ceases.

Surface and underground mining can disrupt natural groundwater flow patterns, and may expose rocks containing iron pyrite to oxygenated water. This can result in the production of acid mine drainage (AMD), which can lead to surface and groundwater contamination. Following mine closure, pumping is either reduced or stopped thus allowing the local water table to rebound. This rebound may eventually reach the surface where either a spring will form or seepage through the ground or the bed of a river or stream will occur. Surface discharges may also occur from shafts or old adits if a head difference is experienced. Where the water emerges it may well be clear as the underground water is low in oxygen (O_2) and the iron is in solution. However, as this water is exposed to air, the iron rapidly oxidises from the ferrous to the ferric form and precipitates out as a visually intrusive orange deposit, known as ochre. In shallow mines or within adits, this cycle may be repeated continually as groundwater levels fluctuate. In deeper mines connections may be made with aquifers, possibly resulting in contamination. The principal problems in terms of the constituents of the water, may be summarised as follows: suspended solids; iron compounds; dissolved salts; ammonia; O_2 demand; and acidity (Buchanan and Brenkley, 1994). Control of AMD can be categorised into 3 groups (Dey, 1997).

- Primary controls – AMD is prevented from forming by methods eliminating one or more of the primary factors
- Secondary controls – AMD generation is restricted by the control of air, water or both, and
- Tertiary control – AMD generation is allowed, but the contaminated waters are collected and treated by various methods.

The Woolley colliery, located in Yorkshire, ceased production in 1991. A pumping station was developed at the site to control the level of underground mine water over approximately 100 km of linked, abandoned collieries to prevent the inevitable discharge of potentially contaminated mine water effluent from many ancient drainage adits (Laine, 1999). Initially, 15 separate pumping stations were utilised to control groundwater levels during operations at individual sites, however, it was determined that levels could be more efficiently controlled by allowing the mine water to travel under gravitational flow along pre-existing underground tunnels to a single pumping site at Woolley.

Discharge from the site is to the River Dearne, after the mine water is passed through a series of water treatment processes, initially at a rate of 40 litres per second, but increased to over 200 litres per second once pumping was centralised, hence extensions to the existing treatment facilities were necessary. Treatment methods utilised at the site are shown schematically in Figure 1. These include cascades where the polluting waters are aerated to allow oxidation of the ferrous iron by atmospheric oxygen; primary settlement ponds to reduce the concentration of suspended solids, which have now been improved; secondary earth ponds, with a positive filtration system utilising two fabric filters to remove the fine suspended solids within the effluent; and finally a wetland facility has been developed to achieve long term removal of the fine suspended solids, and also to reduce the concentration of ammonia in the mine water through the installation of a gravel substrate in the wetland. This ensures that the plants within the wetland cannot get nutrients from external sources, and instead can only get them from the ammonia in the water. A facet of this research is to determine the future strategy for dealing with polluted mine waters, specifically for this site.

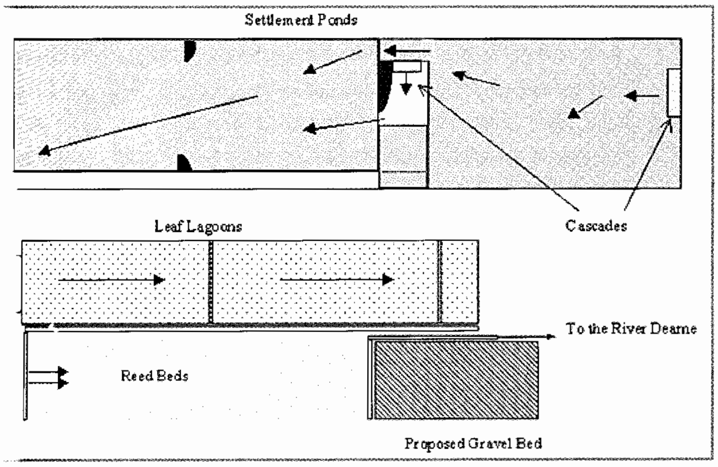

Figure 1. Schematic of the treatment processes at Wolley Colliery.

Research is being directed at studying the hydrogeological regime and environmental impact of the mine water discharge following the closure of the Woolley colliery and the surrounding connected collieries. This work is concentrated on the questions arising as to the impact of the current discharge upon the local environment, and how the current situation compares to that prior to closure in terms of quantity and quality of flow. The aim of this phase of the project is to propose viable options which could be applied in the future, through the development of a flow model of the underground network, to other mining regions where data and information is less abundant. The primary objective is to improve the understanding of the outflow behaviour, and use this knowledge to determine the most appropriate environmental treatment strategy for mine abandonment.

In order to improve this understanding, it is first necessary to be able to accurately visualise the complex system under examination. The commercially available 3-dimensional modelling package, Vulcan, is being used as a powerful visualisation tool to accurately represent the complex, interconnected multi-seam, multi-colliery situation apparent at Woolley. This allows visualisation of the entire area at Woolley, and therefore provides a better understanding of the spatial relationship and the possible behaviour of the mine water under investigation. Figure 1 presents a schematic of the treatment processes utilised at Woolley, while Figure 2 shows a cross section of the mine complex including the Woolley pumping station. Figure 3 shows a 3-dimensional model of the area under investigation, showing the spatial relationship between the worked seams and the surface.

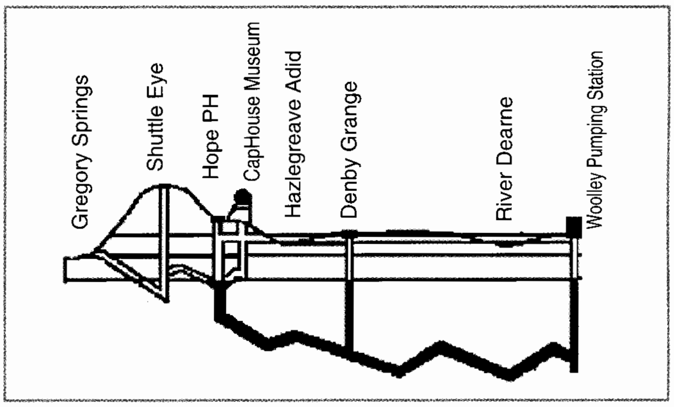

Figure 2. Cross section of the Wolley mine complex.

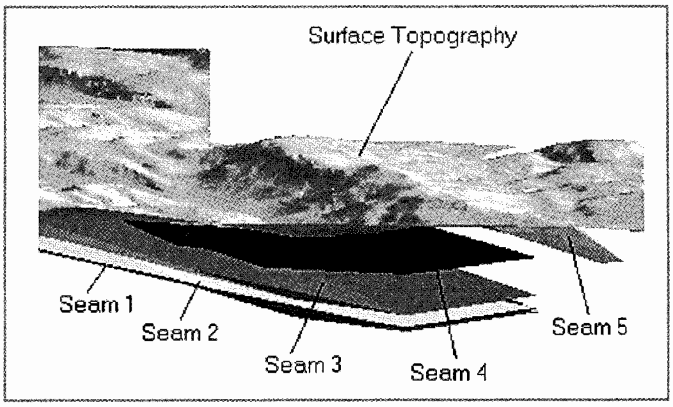

Figure 3. 3-dimensional model of the Wolley area.

STABILITY IMPLICATIONS OF GROUNDWATER RECHARGE IN ABANDONED MINE WORKINGS

The implications of groundwater recharge are not only related to the perceived environmental problems, but also include the potential stability issues related to the flooding of old, shallow, abandoned mine workings. This aspect of the research has followed a number of inter-related paths. The first has been the collection of flow data from up to 30 mine sites located throughout the UK. This has produced a significant amount of quantitative and qualitative data relating to the nature and quantity of typical mine discharges. Many of these sites represent situations where the mine has flooded and subsequently reached a dynamic equilibrium with the local hydrogeological regime. Three of these sites were examined in greater detail through the collection of mine abandonment plans, detailed geological maps, and topographical maps of the surface area. This desk study was combined with a detailed investigation of the site of the discharge. Initially, geological cross sections were drawn, followed by a basic hydrological analysis utilising Darcy derived equations for well flow in a confined or an unconfined aquifer. Where necessary, more complex mine inflow analysis can be undertaken by calculating the degree and depth of fracturing within the strata overlying the mine, in the case of longwall mines, as this cracking will cause an increase in the effective hydraulic conductivity of the overlying strata. As Darcy's analysis requires a rock mass permeability to be assigned, this is clearly an important consideration. Ultimately these case studies have provided an insight into the mine recharge phenomena, but have in no way attempted to quantify either the rate of recharge, nor the impact of the groundwater on the mechanical properties of the rock mass surrounding the abandoned workings. Figure 4 shows the recorded discharge from one of these sites over a 12 month period, and Figure 5 illustrates a conceptual hydrological model of one of the mine discharge sites.

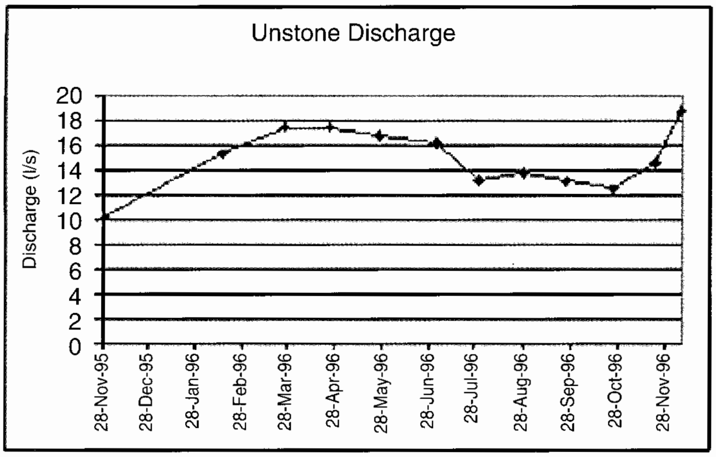

Figure 4. Mine discharge over a 12 month period.

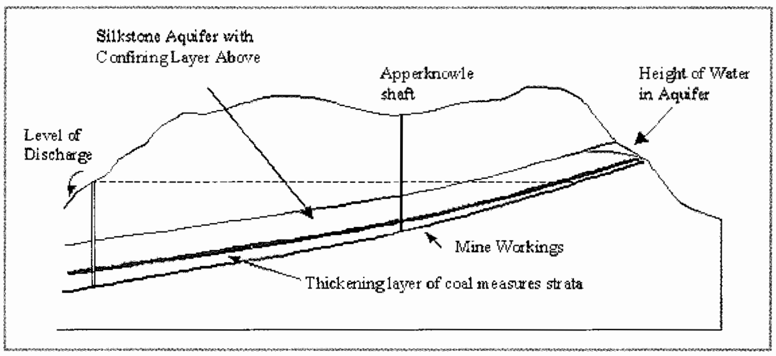

Figure 5. Conceptual hydrological model of the Unstone mine.

The second area of research exploited, is that pertaining to the effects of water on the geomechanical properties of intact rock. Laboratory and field based experimental work has been undertaken in order to quantify the effect water saturation may have on rock integrity. There are essentially two facets to this. The first is the direct effect of water on rock integrity, which invariably relates to the mineralogy and the structure of the rock under examination, and physico-chemical reactions with the groundwater. The second is the mechanical effect of pore water pressure building up within the rock mass under a hydraulic head. These have been examined through novel and standard laboratory test procedures.

Laboratory tests

A number of tests have been carried out on UK coal measure rocks to examine the effects of varying the moisture content within the rock, on it's mechanical behaviour. These tests have included uniaxial compressive tests (UCS), tensile tests (UTS), triaxial tests and Young's modulus (E). The moisture content was varied within the samples using largely chemical techniques. Work undertaken by Oldham (Oldman, 1985) identified a number of chemical solutions of inorganic salts which, in a suitably controlled environment, could control the atmospheric relative humidity, and hence control the moisture content of the rock samples. When the rock samples had attained the required moisture content, they were tested to ISRM standards, either in uniaxial compression or in tension. To determine the Young's modulus at varying moisture contents, strain gauges were attached to the intact samples, and the UCS test was carried out.

In order to determine the triaxial behaviour of the sample under varying moisture contents, a modified Hoek cell was developed. This triaxial cell is shown schematically in Figure 6. The cell allows water under pressure to be forced into the rock sample contained within the rubber membrane of the apparatus, thereby allowing pore pressures to increase within the sample. The pore pressure within the rock could therefore be determined by the pressure valve on a gas cylinder, thus allowing samples to be triaxially tested under varying pore pressure to establish the extent to which this factor affects the overall rock strength. Terzaghi (1943) showed that in soils the pore water pressure will act against the applied stress, thereby affecting the strength envelope. This effect can be seen in Figure 7. It was hoped that this experiment would determine whether this law of effective stress could be established for rock materials. Figure 8 illustrates the shape of the resultant strength against pore pressure curve from such tests. This shows that there is in general, a decrease in rock strength from the dry to the saturated state, but as pore pressures develop within the material, the strength increases accordingly. However, tests show that this strength increase only occurs at lower pore pressures.

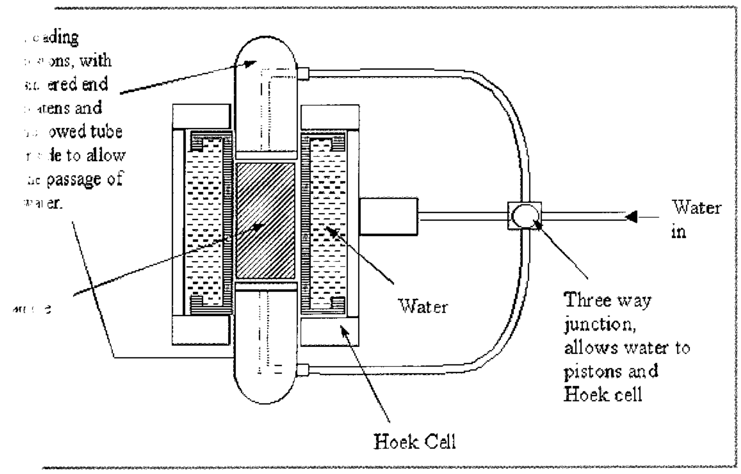

Figure 6. Modified triaxial cell.

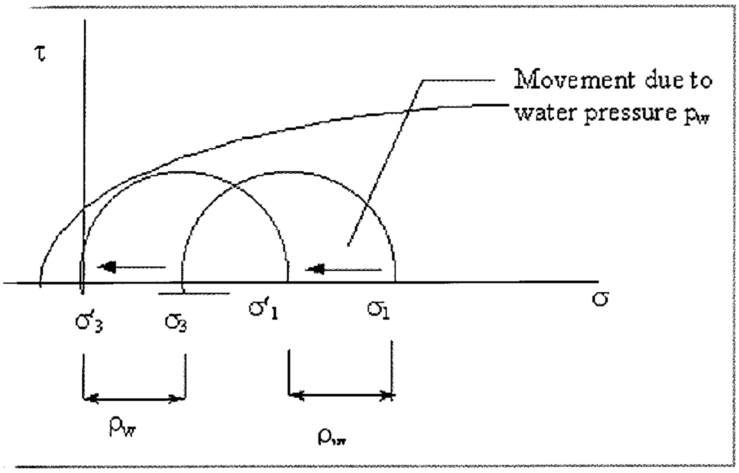

Figure 7. Effect of pore pressure on the strength envelope.

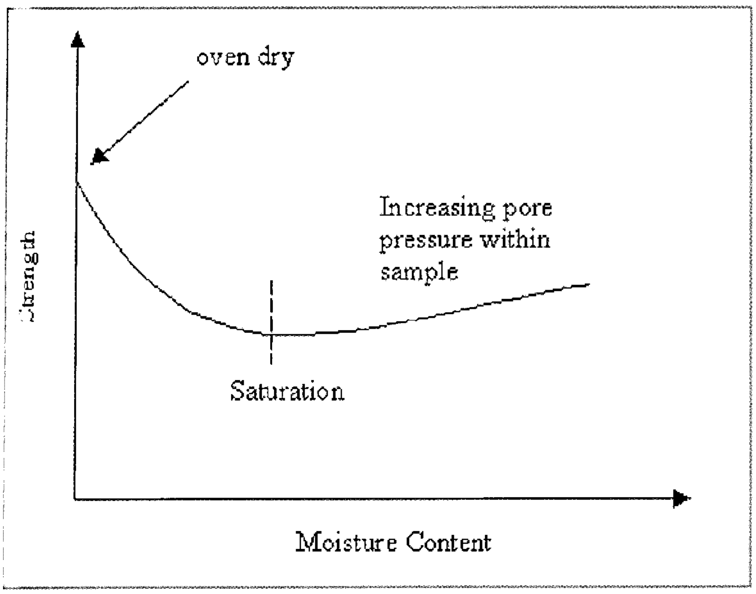

Figure 8. Typical strength against pore pressure curve for coal measure sandstone.

Field based experimental work

The time dependent affect of water on the weatherability of a particular material can be determined using the Slake Durability Index (ID_2). This test was modified to establish whether the increased acidity apparent within mine water discharges would have an increased effect on the durability of rock. An equivalent slake durability index could be determined from a field based procedure supplemented with laboratory analysis. The procedure simply comprised of placing standard weight rock samples in small jars, these were placed behind a dam structure placed in a mine discharge stream, and samples were taken, sieved (>2mm fraction), dried and weighed after 1, 24 and 68 hours' exposure to the mine effluent. A control was established in the laboratory with samples of the same rock tested in distilled water, and the results compared after the same periods of exposure.

The final facet of the research is related to the development of a suitable modelling strategy to determine the overall impact of groundwater recharge on the stability of abandoned mines. Work thus far has attempted to determine possible modifications to standard stability formulae, in order to provide a simple quantification of the implications of pore water pressure on the strength and stability of the rock mass. However, these are considered to be too simplistic in their approach. The alternative to such techniques involve complex numerical modelling strategies. However, the numerical modelling at this stage can only be based upon a conceptual understanding of the problem under investigation, as very little data exists at present pertaining to the actual physical effects of groundwater recharge within any mine. The proposed models are being developed using the 2-dimensional finite difference modelling package, FLAC (Fast Lagrangian Analysis of Continua) (Itasca, 1995). With this specific problem it has been shown that changes in pore pressure within a rock mass will result in changes in the effective stress, this in turn will effect the response of the solid. In many practical situations, this strong interdependence between the mechanical behaviour and the hydraulic behaviour of the rock mass requires coupled solutions to be formulated. Two forms of coupling may be encountered, these are explicit and implicit. The first requires two separate models with data being transferred between them, whilst the latter formulation is such that displacements and pressures are calculated concurrently during iterations. FLAC uses this latter approach thereby producing a fully coupled model. This stage of the project is still in it's development phase, however the next paragraph will outline the modelling methodology used.

The main objective of the numerical modelling is to determine the influence of pore pressure on the stress distribution around an underground mine, with a view to assessing the implications for short and long-term stability. Initially simple mine geometry's will be simulated, with increasing complexity, as a greater understanding of the actual mechanics of the problem is gained. Initial input parameters have been taken from past work carried out at the University of Nottingham, on the strength of coal measure rocks. These will be systematically reduced to reflect in situ conditions.

FUTURE WORK

Future work within the School in these areas, will include the development of a conceptual model illustrating the implications of groundwater recharge on mine stability, and how this problem may be simulated using numerical models through the application of the modelling techniques determined to actual case study data, when such data becomes available.

Intact rock samples have been comprehensively tested, however the results gathered to date have only a limited use when attempting to characterise the rock mass itself, as no account is given of the effect of pore pressures on structural discontinuities, such as bedding planes, cleat etc. Classification schemes attempt to quantify the detrimental effects of water in joints, but only in terms of joint fill material. They do not take any account of the longer term physico-chemical effects of water on certain coal measure strata, such as mudstone's, nor do they consider the implications of pore pressure development, not only across the joints or weakness planes, but also within the rock matrix itself. Classification schemes have in general been developed in accordance with the needs of active mining and therefore do not recognise the importance of saturation on rock behaviour. In abandoned mineworkings the rocks surrounding a mine will in extreme circumstances change from dry to saturated conditions. Further work needs to be developed in this area.

Complete visualisation of the recharge phenomena will be provided by the Woolley project, and it is hoped that this will yield useful information that can be applied to other mining areas where information is less abundant.

CONCLUSIONS

Recent research has looked in detail at the effect of water on the geomechanical properties of rocks, with a view to quantifying the impact of groundwater recharge on abandoned mine stability. The capabilities of FLAC in terms of modelling the recharge phenomena is being fully assessed, and a conceptual model is under development. Visualisation of a mine under recharge has been undertaken utilising the commercially available VULCAN package. This will lead to a greater understanding of the hydrology of abandoned mines. Numerical analysis of the hydrology of abandoned mines has been documented, but is considered to be simplistic in comparison to modern computer based approaches, as it only considers the steady state condition, whereas a transient approach is considered to be more appropriate.

REFERENCES

Anon., 1999. UK's Coal Authority is to give priority to the prevention of mine water pollution. Coal International, 247, (1), 6.

Buchanan, D.J. and D. Brenkley, 1994. Green coal mining. In: Issues in Environmental Science and Technology: Mining and its Environmental Impact, Royal Society of Chemistry, 71-95.

Dey, B.M., 1997. The Origins and Control of AMD. PhD Thesis, University of Wales, Cardiff.

Itasca, 1995. Fast Lagrangian Analysis of Continua (FLAC). Version 3.3, Vol. 1-4, Itasca Consulting Group, Minnesota, USA.

Laine, D.M. 1999. The treatment of pumped minewater at Woolley colliery. Coal International, May, 109-111.

Sherwood, J.M. and P.L. Younger, 1994. Modelling groundwater rebound after coalfield closure: an example from County Durham, UK. In: Proceedings of the 5th International Mine Water Congress, Nottingham, 2, 769-777.

Smith, J.A. and J.J. Colls, 1996. Groundwater rebound in the Leicestershire coalfield. Journal of the Institution of Water and Environmental Management, 10, (4), 280-287.

Terzaghi, K., 1943 Theoretical Soil Mechanics. Wiley, New York.

Oldham, R.H., 1985 The Influence of Water on the Long Term Strength Properties of Coal Measures Rocks Associated with Mining Excavations. PhD Thesis, University of Nottingham.

Younger, P.L., 1993 Possible environmental impact of the closure of two collieries in County Durham. Journal of the Institution of Water and Environmental Management, 7, 521-531.