International Journal of Mine Water, 4 (1983) 35 - 56
Printed in Granada, Spain

DESIGN CONSIDERATIONS FOR MINE WORKINGS UNDER ACCUMULATIONS OF WATER

R N Singh* and A S Atkins**

* Department of Mining Engineering, University of Nottingham University Park, Nottingham NG7 2RD UK

** Department of Mining Engineering, North Staffordshire Polytechnic, College Road, Stoke on Trent, Staffordshire, UK

ABSTRACT

The study outlines the effects of surface and underground subsidence patterns on the spatial distribution of in-situ permeability and its effects on groundwater inflow. The behaviour of strata surrounding a longwall face where limited knowledge exists has been outlined. The effects of mining subsidence on the surface flow pattern have been described with the remedial solutions. The mechanism of formation of sinkholes in certain chemical rockmass has been described. Factors affecting mine water inflow have been described in detail with the aid of a simplified conceptual model and case studies. Practical examples of undersea workings and those under a large accumulation of water are given, both in the United Kingdom and worldwide.

INTRODUCTION

Mining under accumulations of water include workings under sea, lakes, esturaries, rivers, streams, ponds, underground aquifers, abandoned mine workings and unconsolidated surface deposits liable to liquifaction. In order to maximize the percentage extraction (52 percent in UK) it is important that for future mining under bodies of water, attention should be given to the detailed design of such workings [1]. An economical assessment should be made for providing protective pillars, consequently sterilizing reserves, versus cost of pumping inflow water during the entire life of a mine. It is imperative that damage to life and appreciable loss of property is not compromised.

EFFECTS OF MINING ON IN-SITU PERMEABILITY CHANGES AND GROUNDWATER INFLOW

The underground mining modifies surface and underground flow pattern which may affect groundwater hydrology and mining operations in one of the following ways:

(i) mining subsidence changing the surface flow pattern and water table;

(ii) under certain conditions, promote formation of sink holes; and
(iii) cause serious water inflow problems to a mine.

Surface Subsidence Pattern

Underground mining causes redistribution of strata stresses resulting in underground and surface subsidence. Fig. 1 shows components of ground movements at the surface as a consequence of total extraction. Three distinct zones of subsidence are apparent which are as follows [2]

(i) zone of full subsidence;
(ii) zone of compression; and
(iii) zone of elongation

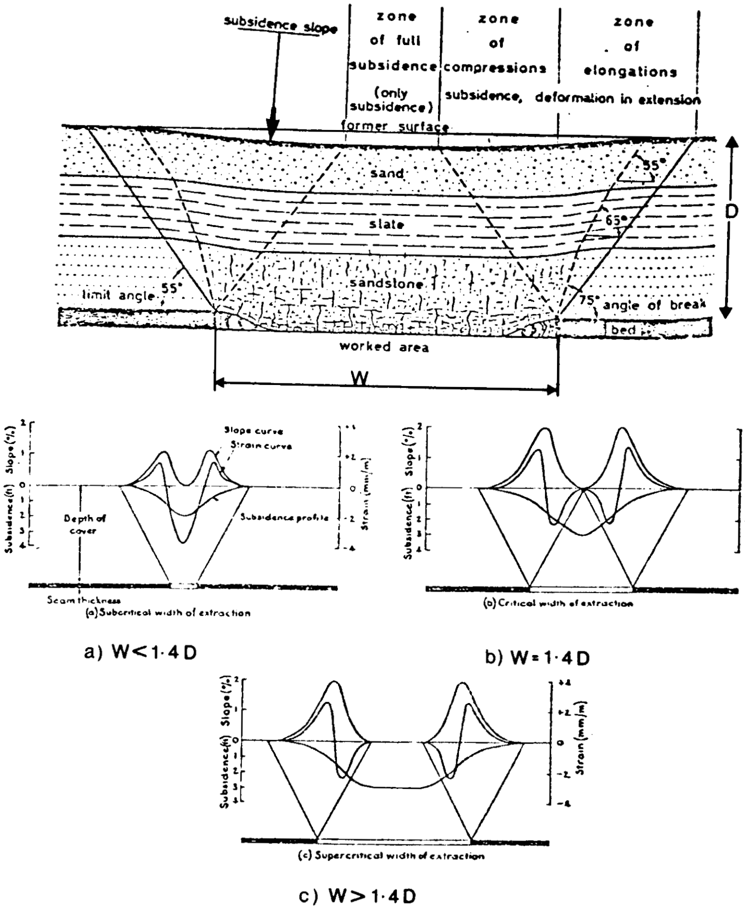


Fig. 1 Component of ground movement at the surface due to total extraction

With reference to Fig. 1 the zone of full subsidence develops when the width of extraction exceeds 1.4D and is characterized by only vertical displacement of ground surface. The zone of elongation is bounded by a line vertically above the panel edge and the limiting angle intersecting the surface (UK average value 55^{o}). This zone is characterized by development of horizontal tensile strains inducing surface fractures, which are known to extend up to 15 metres in depth. The zone of compression which lies between the zone of subsidence and the zone of elongation is characterized by horizontal compressive strains and reduction in water inflow.

Underground Subsidence Pattern

Fig. 2 shows a schematic presentation of underground subsidence associated with mining which is characterized in three distinct zones as follows:

(i) zone of vertical compression;
(ii) zone of vertical extension;
(iii) zone of incomplete convergence.

The zone of vertical extension lies immediately above the central zone of extraction and is caused by caving of waste as a consequence of extraction and is the result of volume expansion from caving. The vertical subsidence at the surface (in the zone of full subsidence Fig. 1) is less than the height of extraction (surface subsidence ranges between 40-90% of seam extraction). At the centre of extraction, the floor heave is more pronounced and tapers towards the edge of extraction. At this point the vertical closure is minimum because of contraint provided by the pillar edge.

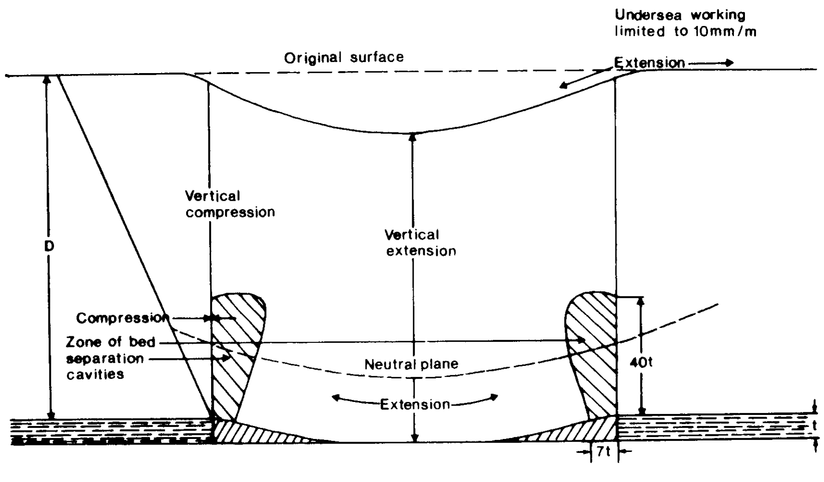


Fig. 2 Schematic Depiction of Stress Zones in Underground Mining

As a consequence a vertical compression zone develops directly above the pillar edge and extends to the surface. At the mining horizon, in between the pillar edge and the central caved zone, there is a zone of incomplete convergence characterized by a compacting goaf. Directly above this zone of incomplete convergence there must be a transition zone between compression and tension zones. The precise location and extent of this zone requires further investigation. However, evidence from a study of water problems associated with working close to the base of Trias shows that immediately behind the longwall face there is a tension zone 8 to 10 metres wide which extends upwards to a height of 40t [3]. This tension zone contains a large volume of bed separation cavities capable of storing large quantities of water.

Idealized Model of In-situ Permeability Changes around a Total Extraction Mining Layout

Fig. 3 is a generalized presentation of in-situ permeability changes around a longwall panel. Three distinct zones of marked permeability changes are outlined [4].

(i) Fracture zone - extending up to 30t to 58t (t is the thickness of the seam) above the seam horizon. A caved zone extending upto 3t to 5t above the extraction horizon.

(ii) Aquiclude zone - is characterized by constrained strata with no appreciable changes in strata permeability. This zone extends from 30t to (D - 15 metres) above the extraction horizon (D is overburden height)

(iii) Zone of surface cracking - 15 metres depth from the surface.

As a result of coal extraction, the immediate strata above the mined area caves into the void. This induces disturbance in the strata within the zone of influence of the extracted region. A study of the permeability changes in the roof above the rib pillar towards the centre of the panel indicated a pronounced change in permeability (60-80 times intact permeability) as a consequence of mining, this is illustrated in Fig. 3 [5]. The disturbance at the surface manifests itself as subsidence and/or surface cracks, depending on the depth to seam thickness ratio, and other factors. As regards underground disturbance, it is known that the strata constituting the immediate roof areas caves into the void, and the layers above the caved zone are subjected to compressive and tensile stresses. The tensile strain in the vertical direction generally gives rise to bed separation, whereas, in the horizontal direction it tends to open up joints in the rock formations.

Fig. 3 indicates areas of unknown permeability changes above the longwall extraction which are affected by the extent and orientation of crack formations, individual bed thickness, rockmass flow characteristics and lithology.

MINING SUBSIDENCE CHANGING THE SURFACE FLOW PATTERN AND WATER TABLE

The effects of ground movement due to subsidence often changes hydrological conditions as follows:

(i) Development of fractures due to mining subsidence in brittle rockmass causing water infiltration to mine workings and localized lowering of the water table with ecological and environmental consequences.

(ii) Subsidence effect on a thick plastic bed rock may be in the form of a deep subsidence trough without development of water conducting fracture, causing outcroping of water table and consequently, surface ponding [6].

Fig.4 shows the effects of mining subsidence on surface hydrology together with the remedial measures.

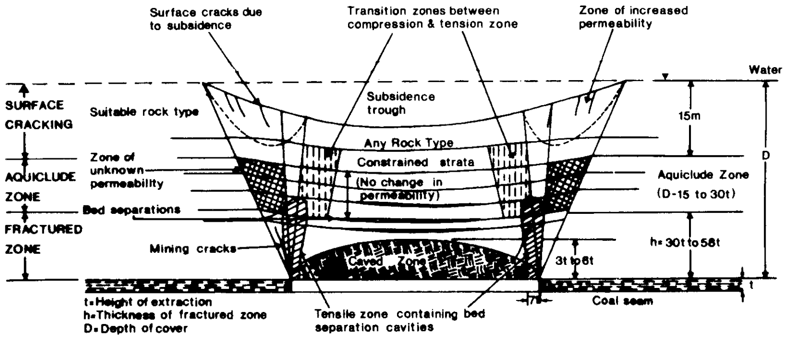


Fig.3. Generalized Depiction of Strata Behaviour with Total Extraction Mining (after Singh and Kendorski, and modified by authors)

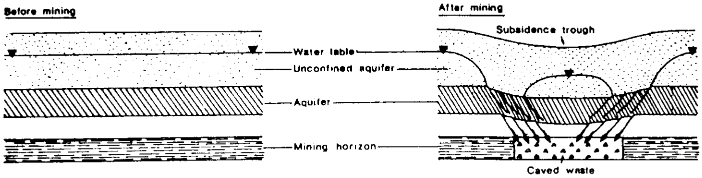
FORMATION OF SINKHOLES

Mining beneath fissured limestone or dolomites can result in the modification of groundwater inflow pattern to the mining horizon causing the enlargement of the existing fissures and caving into the existing caverns. This can result in the formation of sinkholes extending to the surface as illustrated by Fig.5.

MINE WATER INFLOW CAUSED BY WORKINGS UNDER ACCUMULATION OF WATER

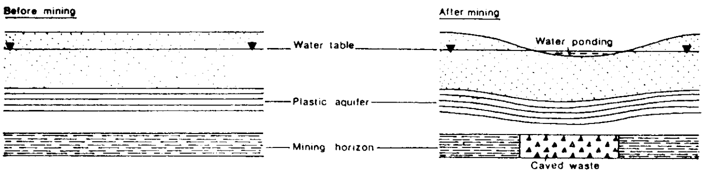
The mine water inflow variables can be represented by a simplified model shown in Fig.6 which indicates three distinct regimes: water, protective layer and the mining horizon. The factors which affect the design of mine workings under accumulations of water can be summarised as follows:

(a) - Solid Stratum



Infiltration of Groundwater Resulting from Mining Subsidence (schematic cross section)

(b) - Thick Plastic Aquifer



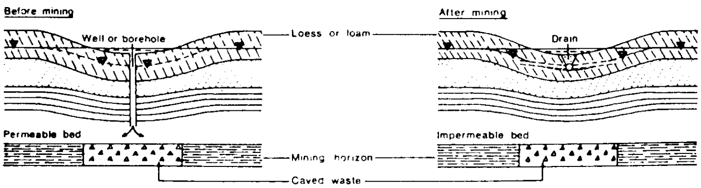
Outcropping of the Groundwater in a Subsidence Trough (schematic cross section)

Remedial Measures

Subsidence trough may cause water table to pond and may be aggrevated by surface water resulting from rainfall or melting snow.

(c) - Ponding water discharged by absorbing well or borehole into suitable rock formation.

(d) - Ponding water discharged by drains.



Remedial measure is to sink absorbing well or borehole into suitable receiving rock formation to drain surface water. The well drainage can also be assisted by mole or french drains.

In this case because underlying strata is impermeable de-watering techniques using a well is unsuitable. Remedial measures is to use absorbing drains and discharge into suitable water course.

Fig. 4 The Effects of Mining Subsidence on Surface Hydrology together with Remedial Measures

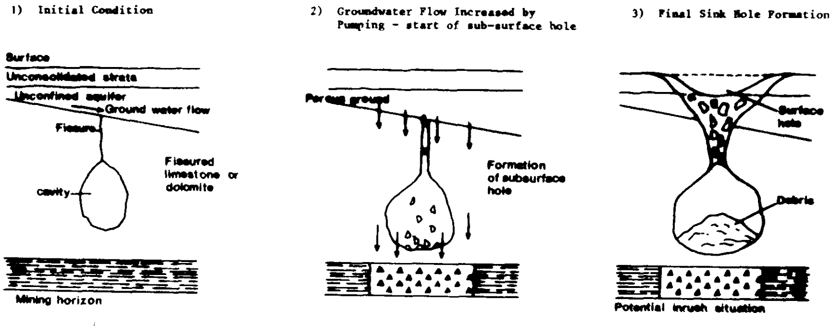


Fig. 5 Formation of Sinkholes in Limestones and Dolomites

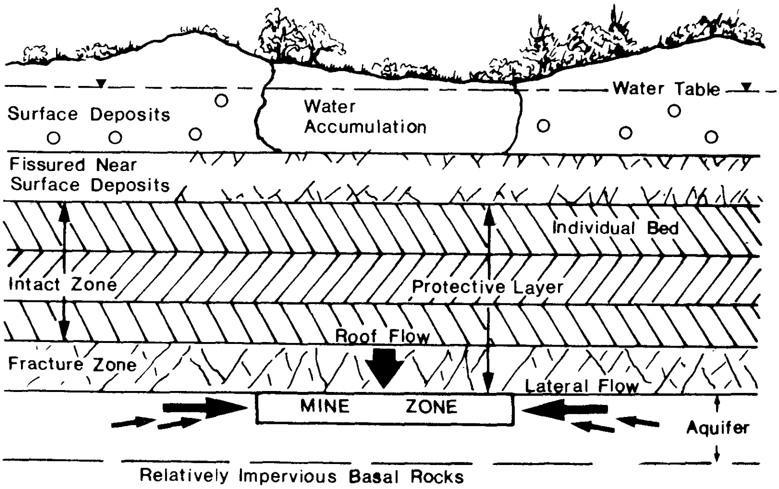


Fig. 6 Simplified scheme of Flow to a Mine through a Protective Layer

1. size of bodies of water
2. nature of intervening strata
3. structural discontinuities and geological features
4. mode of stress distribution < caved waste
   induced fracture on rib pillar
5. thickness of intervening strata
6. water pressure.

Size of bodies of water - water accumulation and the inrush potential

(i) In this context, water bodies can be divided into three categories depending upon the potential intensity of an inrush and summarised as follows:

- o catastrophic - which may pose threat of destruction in the mine, should there be an inrush. It includes oceans, large lakes, rivers underground aquifers, solution cavities, bed separation cavities, underground abandoned mine workings and unconsolidated surface deposit liable to liquifaction.

- o Major - those with major potential danger would include lakes streams and aquifers which might present a danger to both life and property if adequate design considerations are not specified during the mine planning stage.

- o Minor - finite bodies of water with a volume considerably smaller than the mine volume which can offer a limited potential for mine damage in the case of an inrush.

For an inrush to occur it is necessary that the following conditions are simultaneously satisfied:

- a large accumulation of water or fluid;
- a presence of low resistance route from the accumulation to the mine workings;
- the hydraulic pressure should exceed the threshold pressure to cause inrush.

(ii) Types of Reservoirs Providing Inrush Potential

Aquifers - in some formations such as sandstones large quantities of water can be stored. In most cases, if the aquifer is breached, through mining activities, the inflow will significantly increase to the mine but it is usually not instantaneous. This can create pumping problems which may become permanent if the aquifer becomes recharged.

Abandoned or Disused Workings - old goaves can provide a highly permeable storage area for a large accumulation of water. This water is capable of being released instantaneously, thus providing potential catastrophic danger of an inrush. Water logged shafts, boreholes or saturated fissures connected to flooded workings may provide further danger because of an increase in hydraulic head. Hydraulic fills as used in metalliferrous mining may also become fluidized and aggrevate the situation. The existance of unchartered old workings are also potential sources of danger.

Old goaves contain contaminated water which can be chemically analysed to ascertain the origin of the mine water.

Water storage capacity of abandoned underground workings can be calculated as follows [7] :

Quantity of water stored in an old abandoned working is given by:

$Q_w = C\ A\ M\ \mathrm{Sec}\ \alpha\ (m^3)$

where

A = plan area of the old workings (extracted m^2)
M = thickness of extraction (m)
α = inclination of the seam
C = coefficient of compaction of a goaf - (C = 0.125 for total longwall extraction for a 1.8 m extraction (UK values))
Q_w = quantity of water (m^3)

Table 1 - C Values for different types of mining systems

	Type of Workings	C
1	Short wall	0.438
2	Longwall total extraction	$0.485^{e\ -0.00205\ M}$
3	Sand filled goaves	$0.275^{e\ -0.0147\ p}$
		p = strata pressures

Solution cavities - Solution cavities are formed in certain formations like dolomites or limestone when the water percolating through them is slightly acidic and capable of dissolving rock. Consequently, large interconnected caverns are formed which are capable of releasing water rapidly. Fig. 7 illustrates West Driefontein Mine, S. Africa in which solution cavities connected by fissures intercepted the mine working causing a catastrophic inrush [8].

Bed separation cavities - In the Coal Measures, particularly below an unconformity at the base of Trias, tensional zones are developed above the margin of the longwall panels [3]. These tensional zones are characterised by a series of beams of uniform thickness of sandstone or coal, where bed separation cavities are developed and strata permeability is greatly increased. These cavities are capable of storing sizeable quantities of water if recharged by an aquifer. The mechanism which causes the water held in bed separation cavities to be suddenly released is not known but could be attributed to a combination of factors such as minor faults, increased joints developments or facies changes in roof strata [9].

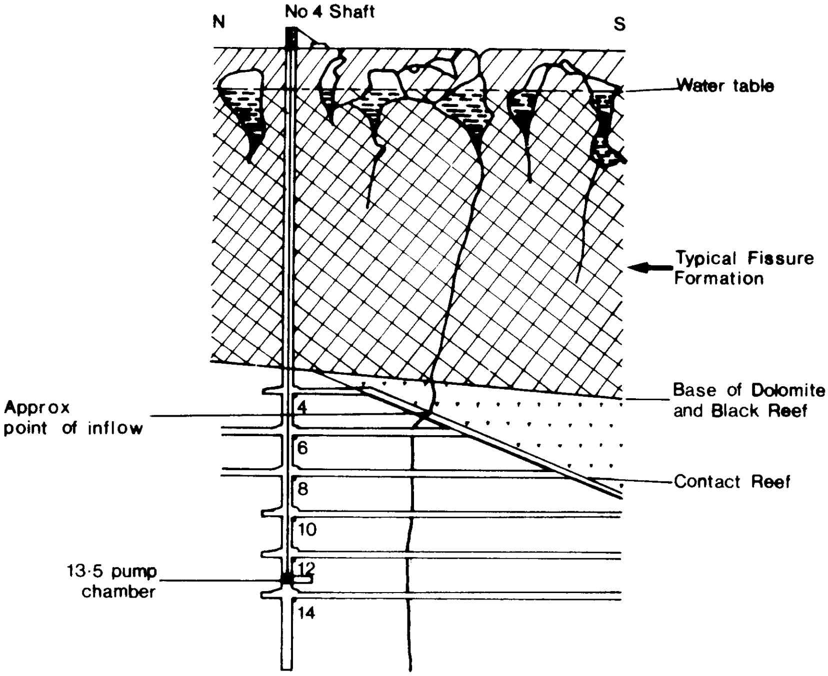


Fig. 7 Section Showing Solution Cavities and Fissure Formation at West Driefontein Mine, S. Africa (after Cousens and Garrett 1969) [8]

Surface accumulation - This includes sea, oceans, lakes, rivers, unconsolidated deposits liable to liquifaction and tailing dumps. In the Mufulira mine in Zambia, subsidence effects from mine workings resulted in an inundation of the mine by the liquifacted tailings [10]

Nature of the Intervening Strata

Rockmass lithology has a significant influence on the design thickness of the protective layer between the water accumulation and mine workings. In general, coal measures strata consist of successive beds of sandstone, coal, mudstone, siltstone, shales and seatearth.

In *intact state* the sandstone and coal beds may formulate aquifers, capable of storing and transmitting water. However, mudstones, shales and seatearths are relatively impervious to water flow and therefore, form *aquiclude*. These beds of adequate thickness should, therefore, be included while designing a protective layer.

Coal Measures rock including shale, mudstone and seatearths, when intercepted either by *natural cracks and fissures* or *induced mining*, fractures can transmit and store large volumes of water. However, the fractured coal measures, particularly coal, shale, mudstone and seatearth can be consolidated under high differential stress and can virtually prevent water inflow. Rockmass lithology also plays an important role in controlling or promoting the formation of bed separation cavities which can store large quantities of water [3].

A thick strong massive sandstone bed presents considerable difficulty in the formation of roof beams and consequently prevents the development of bed separation planes.

A weak or thinly bedded rock may easily form bed separation cavities, thus storing large quantities of water.

Thus, rockmass lithology, thickness of carboniferrous cover, thickness of total cover and in particular percentage of sandstone in the vicinity of mine workings within a limiting height of 45 m are thought to be significant contributing factors controlling mine water inflow.

Structural Discontinuities and Geological Features

The incidence of water through a protective layer has often been associated with strata discontinuities and other geological features such as faults and dykes. In coal measures, joints are universally present and have a highly variable geometrical orientation and spatial distribution, depending on the type of rock, thickness of beds, geological age, depth, geological stresses and stress history. In coal mining few new cracks are formed due to the mining operations, most of the subsidence occurs by movements along pre-existing joints and cracks. A minimum of 35×15^{-6} m opening is required for water to transmit through the joints. The joints may have rough, interlocking or slickensided surfaces or they may be coated with filling materials, thus altering their flow characteristics [4].

Characteristics of joints in sedimentary rocks are:

- spacing often depends on lithology, bed thickness and rock mass strength. In coal measures spacing of 0.3 to 1 m is common.
- Joints in shale are inconspicuous but shales may develop closely spaced joints near the surface.
- In alternating sandstone-shale sequences, joints are generally better developed in the sandstones and may be confined to it.

Igneous dykes often intercept rock formations associated with heavily watered horizons or water saturated cavities and consequently, feeders of water may be encountered if the mining operations are carried out in their close proximity [9].

Small faults having throws ranging up to 1m very rarely present water problems. However, when water is encountered, the water make tends to be greatest in the vicinity of any fault. Increased water danger is apparent where mine workings approach or encounter faults parallel to the faceline, faults which hade over workings, faults of increasing throw and large faults where strata disruption and dislocation is greatest.

In the UK water problems in the undersea workings have been more pronounced in the vicinity of the geological features such as swalley banks, areas of rapidly increasing dip, monoclinal structures, lenticular sandstones, incrop to the Permian or major sandstone aquifers and massive aquiferous roof sandstones [9].

Modes of Stress Distribution

(a) Caved Waste

The natural stress field in the strata is mainly due to the overlying rocks, though some areas have reported active geological horizontal stress. The creation of a void in the strata by underground mining produces a disturbance in the natural stress field. The effect of the stress change results in strata deformation which, depending on the dimensions of the excavation, can extend it to the surface causing it to subside.

The effect of high strata pressure on the consolidation of caved roof strata in Coal Measures (indicated in Fig. 3) and its effects on the permeability can be illustrated by a laboratory experiment shown in Fig. 8. The diagram illustrates a significant reduction in flow rate with increasing stress, for example the flow rate decreased from 22 l/m to 4 l/m for an increase in deviatoric stress of 5 MPa. At a deviatoric stress of 50-60 MPa, the caved material resulted in the compaction of the Coal Measures rock, virtually eliminating the water flow.

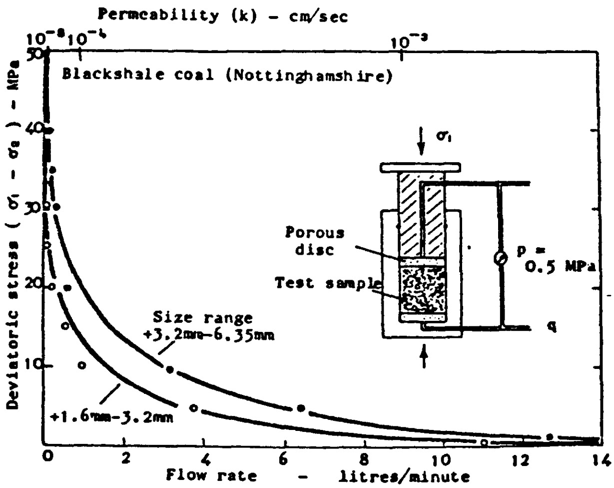


Fig 8 Effect of Stress on Flow Rate Through Broken Coal (after Whittaker and Singh 1978)[11]

The implication of this result is that in the caved consolidated waste under confining stress the permeability will decrease depending upon the level of deviatoric stress. If it was possible to increase the deviatoric stress to 50-60 MPa, theoretically, the inflow to the mining panel could be virtually eliminated.

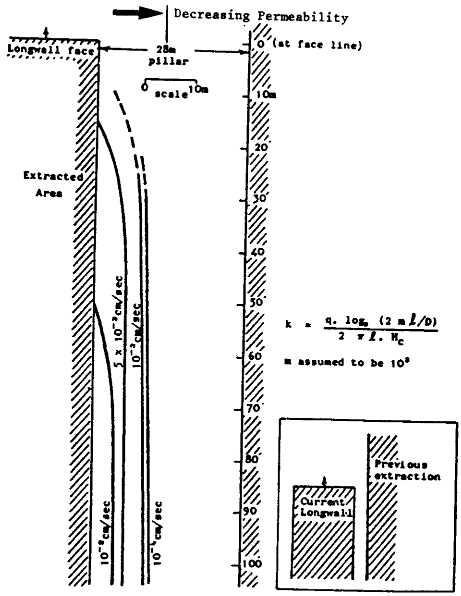


Fig. 9 Rib Pillar Permeability Values from Borehole Tests (after Whittaker and Singh 1978)[11]

(b) Induced fracture zones in rib pillars

The effect of high strata pressure loading on barrier pillars is to produce fracture zones especially associated with the edges. Figure 9 shows a generalised representation of the location of the main fracture zones in a rib pillar. Field evidence indicates that the fracture zones start developing virtually in line with the longwall extraction. Fractures continue do develop for some distance behind the longwall face and equilibrium is ultimately reached at a distance depending upon depth, thickness of extraction, width of pillar, strength properties of the coal seam and width of longwall. Clearly the presence of these induced fractures will increase the permeability of the coal pillar and consequently reduce its ability to contain water.

Fig. 10 shows the development of increased permeability at the pillar edges. In certain cases the permeability of pillar edges can be as high as 1.5 m/sec whereas the permeability of the pillar core is of the order of 2 x 10^{-1} m/sec.

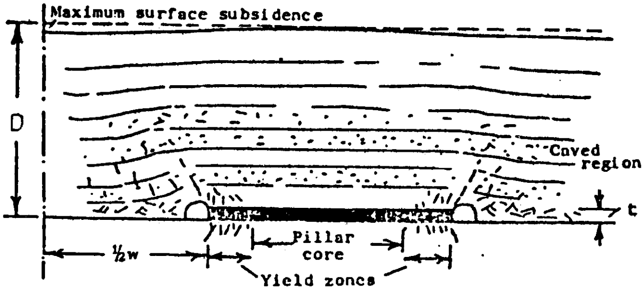


Fig 10 Generalised Representation of Main Fracture Zones Associated with Longwall Mining Rib Pillar (after Whittaker and Singh 1978) [11]

In the situation of water flow in the caved waste through the barrier pillar, an increase in hydraulic pressure would result in opening of the fissure systems within the pillar resulting in increase in permeability.

In certain circumstances, it is beneficial to induce stress on the rib pillar to crush the core, thus reducing the strata permeability, which would otherwise increase because of opening of fissures. This is particularly pertinent to undersea workings where induced stresses on the protective layer can cause sealing of water flow. Experimental evidence also indicates that the sealant properties of coal measures mudstones, shales and sealants are more pronounced than coal, and the significance is stipulated by the recommendations to maintain 60m of carboniferrous strata above a longwall panel when working under the sea or aquifer.

In the design of a barrier pillar, adequate allowance should be made for the following factors:

- stress on the pillar;
- additional pillar thickness to allow for increase in rockmass permeability;
- additional allowance to account for increase in hydraulic pressure;
- additional allowance for undermining.

Thickness of Interventing Strata

(a) Working in the same seam - Fig. 9 shows a coal barrier between an abandoned panel or a coal mine in the existing workings. The thickness of coal barrier can be calculated by the following empirical formula:

$$W = \frac{1}{10} \text{ depth of cover} + \frac{2}{3} \text{ maximum head of water in metres.}$$

(b) Working under accumulation of water in an inland situation

In the United Kingdom the thickness of intervening strata between the mining horizon and inland accumulations of water is governed by the Mines (Precautions Against Inrushes) Regulation 1979 [12], which specify the following minimum barrier, unless an alternative method of work has been approved by the Inspectorate.

(i) 45 m (measured in any plane) of the surface
- o any rock or stratum containing water or likely to contain water
- o any peat, moss, sand gravel, silt or other material that flows or is likely to flow when wet
- o any disused workings not being disused mine workings, or

(ii) 37 metres (measured in any plane) of any disused mine working.

(c) Undersea Workings or Major Aquifer

Prior to 1968 the various British coalfield working undersea reserves had their own individual rules based largely on Crown lease conditions which had applied at the time when the leases were administered by the Coal Commission. There were anomalies, however, in the arrangements and it was decided to standardize the rules and issue new instructions. Code of working practice 'Working under the Sea' Pl/1968/8 (revised 1971) and the Mines (Precautions against Inrushes) regulation 1979 to cover the whole country [13].

These recommendations were based on the following criteria:

- o past experience
- o subsidence considerations and experience of fractures from known strains;
- o a contingency to allow for incomplete knowledge of factors.

(i) Longwall Extraction

Requires a minimum cover between the top of the seam and the sea bed of 105 m and minimum thickness of 60 m of carboniferrous strata above the top of the seam. Tensile strain at the sea bed shall not exceed 10 mm/m in both first and successive seam workings.

Fig. 11 indicates the minimum depth of cover versus extracted seam height (aggregated height) for a single or multiple seam extraction.

(ii) Room and Pillar Extraction

This shall not be carried out when the cover to the sea bed is less than 60 m and where the thickness of carboniferrous strata is less than 45 m. The size of the pillar must not be less than 0.1 depth plus the thickness of seam if over 2 m. Depth for this purpose must include half depth of sea water.

$$1 = \frac{(D + d/2)}{10} + t \qquad t => 2 \text{ m}$$

for soft floor case where floor is known to become plastic when wet to an extent that the stability of the pillars may be affected.

$$1 = \frac{(D + d/2)}{6}$$

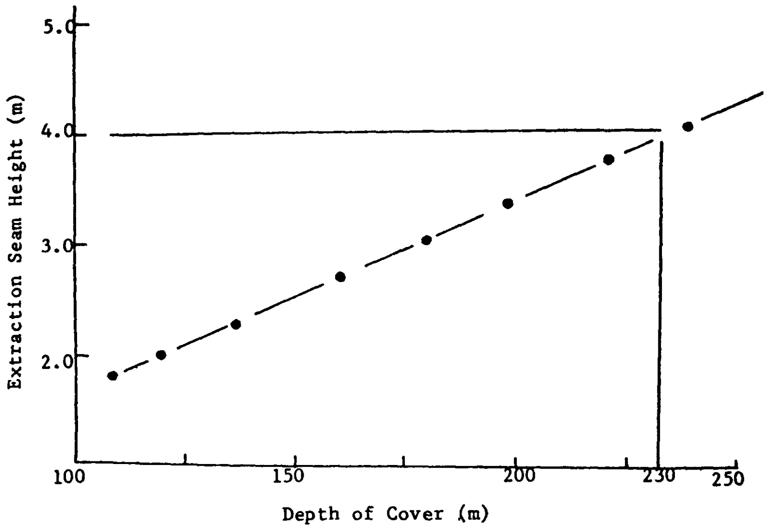


Fig. 11 Working under sea or major aquifer Minimun Depth of cover vs extracted seam ht (Total Extraction Layout)

Pillar extraction

Where pillar and stall working is adopted including the extraction of pillars then the limitations as regards the minimum thickness of cover and the maximum tensile strain as defined for longwall extraction shall apply. The development plans of the mine are required to show sea bed levels, thickness and nature of sea bed deposits, the levels of the top and bottom of all aquifers which could transmit large quantities of water - faults, outcrops etc.

Fig. 12 indicates a method for a design of room and pillar working for a design of undersea operation. For example, if the thickness of extraction is 3 m and the selected bord size is 4.9 m at a cover of 150 m, the size of pillar required is 19.7 m (say 20 m).

Fig. 13 illustrates a comparison of codes of practice between the UK and USA regarding undersea workings [14].

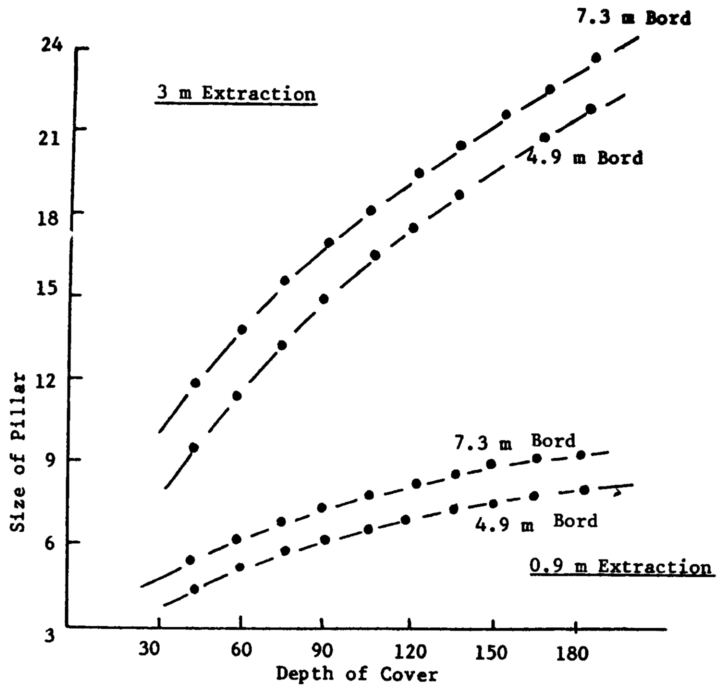


Fig. 12 Design of room and pillar working for undersea working

PRACTICAL EXAMPLES OF WORKINGS UNDERSEA AND LARGE ACCUMULATION OF WATER

United Kingdom

In the North East Area a total of ten mines have workable undersea reserves producing 8 Mt/yr. Output comes from medium to large capacity mines producing 1450-5000 tonnes/day. At undersea pits 70 percent of total output comes from longwall faces and the remainder from mechanised room and pillar mining. Room and pillar mining is practiced at Hardon Ellington and Lynemouth. Room and pillar is practised only where there is cover limit to the sea bed or where full extraction layout is in close proximity to an aquifer which would cause large quantities of water to enter the mine. Longwall face length ranges from 120 m to 250 m except at Blackhall where average face length is 64 m. Retreat faces give best individual results and produce 22 percent of undersea output. In the future it is intended to increase the number of retreat faces and decrease the total number of faces [15, 16].

(i) Longwall System

Ellington - 1.1 Mt/yr, 1700 men, OMS - 3.8 t, average depth below sea 130 m. Average face to shaft distance is 9.1 km. Water pumped at the rate of 2.8×10^6 m^3/yr. Longwall face nil, room and pillar district 19, development by Dosco dintheader and continuous miner.

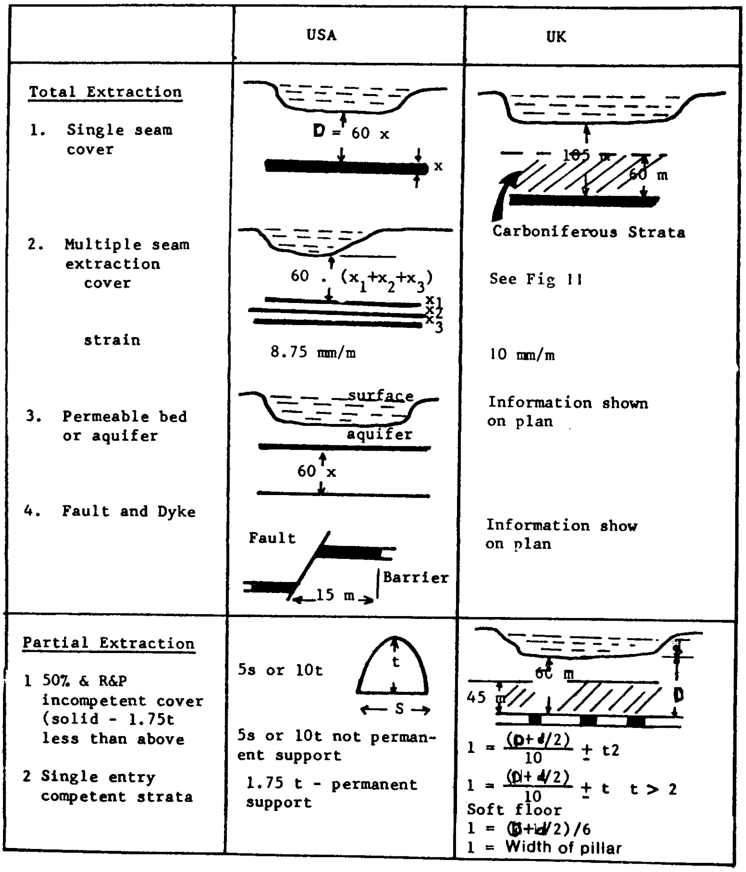


Fig. 13 Code of Practice for Under sea Working

Lynemouth - 0.9 Mt/yr, 1900 men, OMS - 2.4 t, average depth below sea 125 m. Average face to shaft distance 7.8 km. Water pumped at the rate of 4.0 x 10^6 m^3/yr. Three longwall faces and seven room and pillar districts, development by Dosco dintheader, roadheader and continuous miner.

Dawdon - 1.1 Mt/yr, 2300 men, OMS 2.7 t. Average depth below sea 410 m. Average face to shaft distance 3.8 km. Water pumped at the rate of 0.3 x 10^6 m^3/yr. Five longwall faces, development by Dosco dintheader, Dosco roadheader, continuous miner, drill, fire and machine loading.

Blackhall - 0.3 Mt/yr, 1300 men, OMS 1.1 t. Average depth below sea 390 m. Average face to shaft distance 8.3 km. Water pumped at the rate of 5.5 x 10^6 m^3/yr. Four longwall faces, development by Dosco dintheader, drill and fire and hand loading.

(ii) Room and Pillar Systems

Hardon - This colliery was previously worked by longwall methods, however, the limit of cover to water bearing strata decreased, increasing the quantity of water make. Longwall mining was abandoned for less productive room and pillar mining systems which reduced the heavy feeder of water but the output reduced considerably. Attempts to work 55 m longwall faces gave good production but after 140 m of retreat and the occurence of 76 l/s (1000 gpm) of water feeder the face stopped.

Ellington and Lynemouth - Two thick seams are worked by room and pillar mining and this complex is the largest undersea operation in the world.

World Wide Applications

Total coal extraction under the sea is being practised successfully in many parts of the world, including Eastern Canada, Japan, Chile, Taiwan and the Soviet Union. Total extraction has also been taking place beneath rivers in Duisberg Harbour, (W Germany), River Tyne England, Lougher River Estuary [4] and under stored water in large dams near Sydney, Australia [17].

Canada - Coal has been mined in Cape Breton Island, Nova Scotia under the ocean floor since 1720 [18]. The present overall production is 2.8 million tonnes per year. Four major coal seams are mined from the existing 3 mines; Bonnar Seam (3 m), Hub seam (2.7 m), Harbor seam (2.1 - 4.2 m) and Phalen seam (1.5 - 2.1 m). Total extraction is permitted when the depth of cover is 97 m per metre of coal extracted. The cover should include shales and other impervious beds to water.

No. 6 Mine - Work Harbor Seam, manpower 1200, OMS 4 t, annual production 0.9 m tonnes from two advancing longwall faces. Depth below ocean 756 m. Average distance of workings from the shaft is 10 km. Face length 212 m equipped with shield supports and double ended ranging drum shearer (225 kw). Development by Dosco Roadheader or alternatively drilling and blasting and loading with Eimco loader.

Lingan - Produces 1.4 Mt/yr from 3 advancing faces, 212 m long at a mining depth of 485 m. OMS 6.3 tonnes. Development work is done with Dosco Mk II roadheaders.

Prince - Working Hub seam, some 4.2 kms from the portal, 163 m below sea level. The present production level is 2000 t/day from a retreating longwall face equipped with 300 tonnes, 4 legged chock shield and double ended ranging drum shearer. Development is by Dosco Dintheader and Lee Norse continuous miners. Manpower 400, OMS 4.4 tonnes.

Australia - Mining is being undertaken both by bord and pillar method and panel and pillar mining under the stored water of Sydney Basin, Lake Macquarie, Tuggerah Lakes and the Pacific Ocean. Near Sydney, Australia Bord and pillar mining is permissible at a depth in excess of 60 m, with bords of a maximum width 5.5 m and pillars of minimum 15 times the height of extraction or 1/10 depth of cover, whichever is greater, provided the cover includes 60 m Coal Measures

In case of partial extraction of coal by panel and pillar method the permissible size of panel is not less than 1/3 depth of cover and pillar sizes are of a length coextensive with that of the panel extracted and of a width not less than 1/5 of depth of cover or 15 times the height of extraction which ever is the greater [17]

Wongawilli - The Bulli and Wongawilli seams are extracted by longwall caving over super critical area under stored water of 5 ft dam in Sydney. The area of increased permeability extends 138 m above the workings (h/d = 29). The total thickness of coal mined was 1.8 m + 3 m = 4.8 m, at a depth of 276 m with h/d ratio 57.7. The coal seams are overlaid by at least 60% of low permeability sandstone [19].

Kamira - Panel workings were carried out under stored water at Sydney in 1976 with a panel width of 122 m (sub-critical width). A total of 4.8 m thickness of coal was extracted at a depth of 275 m. The total surface subsidence was 2 m.

Japan - In Japan coal is being mined under sea by longwall extraction in a 4.2 m thick seam at a depth of 330 m below the sea bed. Coal mine safety regulations required the drilling of holes in advance of mining [19].

Chile - Longwall mining was practised at Lota near Concepcion where 3 coal seams were mined. The minimum permissible thickness of cover for longwall extraction is 140 m although mining is carried out at a considerable depth. Special regulations exist to provide safety barriers against faults and in mine boundaries [19].

The main conclusion of the above review, is that where coal seams occur under sea beds the coal can be totally mined subject to certain limitations. The main limitations on workings are thickness of intervening strata, nature of intervening beds (minimum thickness of carboniferous beds) the presence of geological structures, and height/width ratio of extraction resulting in limited surface strain (10 mm/m).

CONCLUSIONS

The information concerning underground subsidence and its effects on in-situ permeability is uncertain in some specific areas, particularly the tensile zone ahead of mining and also in the transition zone between the elongation and compression zones. A large number of factors affect the design of mine workings and thickness of barriers between the mining horizon and the accumulation of water. At present it is not possible to incorporate all the factors in the design of a protective layer. Consequently, reliance is usually placed on a semi-empirical approach and guidelines for the design thickness of the protective layer based on previous experience.

ACKNOWLEDGEMENTS

The authors wish to record their thanks to Mr P Proudlove for assistance with the illustrations. The authors are also grateful to Lynette Atkins for her patience in reading the manuscript.

REFERENCES

1. National Coal Board, Recovery of Reserves, NCB Mining Department 1978 p4

2. NCB 'The Subsidence Engineers Handbook', National Coal Board Publication, Production Dept., Hobart House, London 1975

3. Whitworth K R 'Induced Changes in Permeability of Coal Measures Strata as an Indicator of the Mechanics of Rock Deformation above a Longwall Coal Face' Symposium on Strata Mechanics, University of Newcastle upon Tyne, 5-7 April 1982, pp 18-24

4. Singh MM and Kendorski FS (1981) 'Strata Disturbance Prediction for Mining Beneath Surface Water and Waste Impoundments' Proc 1st Conf. on Ground Control in Mining, West Virginia University, Morgantown, USA, USA WV, July 1981, pp 76-89, (1981).

5. Whittaker, BN, Singh RN and Neate CJ ' Effects of Longwall Mining on Ground Permeability and Subsurface Drainage' Mine Drainage Proc. of the 1st International Mine Drainage Symposium Denver, Colorado, May 1979, pp 161-183

6. Wohlrab B 'Effects of Mining Subsidence on the Ground Water and Remedial Measures' pp 502-511

7. Rogoz M 'Water Capacity of Abandoned Workings in U/G Coal Mines' Sympsoium on Water in Mining and Underground Works, SIAMOS, 1978, Granada, Spain Vol 2, pp 1291-1302 (1978)

8. Cousens RRM and Garrett WS 'The Flooding at West Driefontein Mine, South Africa', 9th Commonwealth Mining and Metallurgical Congress, 1969, paper no. 36, p 5

9. Garritty P 'Water Percolation into fully caved Longwall faces' Symposium on Strata Mechanics, University of Newcastle upon Tyne, 5-7 April 1982, pp 25-29

10. Sandy ID, Piesold, DDA, Fleischer VC and Forbes PJ 'Failure and Subsequent Stabilization of No. 3 dump at Mufulira Mine', Transaction A, of the Institute of Mining and Metallurgy, Vol 85, 1972, pp 144

11. Whittaker BN and Singh RN 'Design Aspects of Barrier pillars against water logged workings in Coal Mining Operations Symposium of Water in Mining and Underground Works, SIAMOS 1978, Granada, Spain Vol 1, pp 675-692 (1978)

12. Coal Mines Regulations, Precautions Against Inrushes - 1979 regulation - UK

13. NCB 'Working Under the Sea' Production Dept. Instruction PI/1968/' - 1971

14. Babcock CO and Hocker VE 'Results of Research to Develop Guide Lines for Mining Near Surface and Underground Bodies of Water' Department of Interior, Bumines K 8741, 17 p (1977)

15. Watson HF 'Undersea Coal Mining in North East England' 10th World Mining Congress, Istanbul, Turkey, Sept. 1979, Vol 3, paper 3, pp 1-20

16. Neate CJ and Whittaker BN 'Influence of Proximity of Longwall Mining on Strata Permeability and Ground Water' Proc 20th Symp. in Rock Mechanics, Austin, Texas, 1979, pp 217-224

17. Williamson WH 'Hydrogeological Aspects of Coal Mining Under Stored Waters near Sydney, Australia' Proc. Symp. on water in mining and u/g works, Granada, Spain, 1978, pp 309-328

18. Maclean AR 'Mining under the ocean floor is a way of life in the coalfields of Nova Scotia' World Coal, 1982, pp 70-73

19. Kapp WA and Williams RC 'Extraction of Coal In Sydney Basin from Beneath Large Bodies of Water' A I Min. and Metallurgy, Newcastle, May-June 1972 pp 77-87