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MINE INUNDATIONS

by

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ABSTRACT

The paper describes the types of inundations affecting underground mining operations together with their safety, operational, and stability implications. A critical analysis has highlighted three major causes of inundations. These have been classified as event controlled, accidental or spontaneous. The event controlled inundations are associated with the development of fracture zones around a longwall working and followed by main and periodic roof falls in caved mine workings, particularly in coal mines. An approximate theory to predict the event of main and periodic roof falls in the goaf behind the long wall face is given. These types of inundations have been illustrated with several case histories.

INTRODUCTION

Mining below the groundwater table causes seepage of water into mine workings and presents a variety of mining, rock mechanics, operational and economic problems. The structural stability of mining excavations in a rock mass is dependent upon rock-water interaction in the following manners:-

- o Introduction of uplift pressure on the floor rocks.
- o Development of hydrodynamic pressures in the rock mass.
- o Reduction of rock mass shear strength due to the development of pore pressure.
- o Saturation of tensional cracks and development of cleft water pressure.
- o Disintegrating action of water on argillaceous or shaley rocks.
- o Solubility of saline rocks in the presence of water, (Hofer 1979).

A catastrophic inflow of water into a mine further complicates the problem by endangering the safety of men, machinery and mine workings.

This paper examines the causes of inundations into mine workings and considers in detail the mechanism of event controlled inundations in longwall mining. The paper presents a reassessment of various incidences of mine water inflow on the basis of a new hypothesis.

CAUSES OF MINE INUNDATIONS

The classification of mine inundations is necessary in order to understand the cause of sudden inflow and hence provide remedial measures to control such incidents. A critical review of various inundations has enabled the author to identify the following three categories of inundations. The first two types, are mining induced, whilst the third is a natural phenomenon.

(i) Event Controlled Inundation:- This type of inundation is associated with caved mine workings which are followed by main and periodic falls in the roof strata. The inflow rate of the water is suddenly increased from a background level to a peak rate within a short span of time. The flow rate is then exponentially reduced to the background level. These types of mine inrushes are governed by the following factors:-

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

(ii) Accidental Inundation:- This is the major cause of concern to the mining industry which may take place due to the following reasons:-

- Accidental connection of present workings or boreholes to old water-logged mine workings.
- Accidental connection to unstable fluidized strata or natural bodies of water.
- Sudden and unprecedented inflow of surface water to mine workings, (Davis and Baird, 1977).

The accidental inundations can be attributed to a sudden connection of current workings to water-logged old mine workings or unprecidented inflow of surface water to the underground mine. There is an increasing need to control these inundations through rigorous scientific monitoring. In the past, several borehole survey techniques of identifying the presence of old water logged workings in the vicinity of the current mining operations have been used. A technique involving the interpretation of mine water chemical analysis has also been developed for the detecting the onset of inundation.

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

- o Presence of a large quantity of water.
- o Development of high hydraulic pressures, sufficient to overcome pressure losses due to flow through the protective barrier or structural discontinuities. For example, in the coal mining district of Dorog (Hungary), 409 water inrushes have taken place since the beginning of century, out of which, 95% have been caused by flow through a fault within the protective barriers, Schmeider (1978).
- o Thickness of the protective barrier.
- o Development of a fracture zone within the barrier
- o State of high stress within the barrier.

The spontaneous inrushes are often preceded by the following warnings, (Sammaraco, 1982):-

(i) Changes in groundwater flow and pressure regime.
(ii) Changes in gas flow patterns.
(iii) Outburst of gas.

Therefore, continuous monitoring of one of the following parameters in the mine aquifer system may help in forecasting such dangerous inflows.

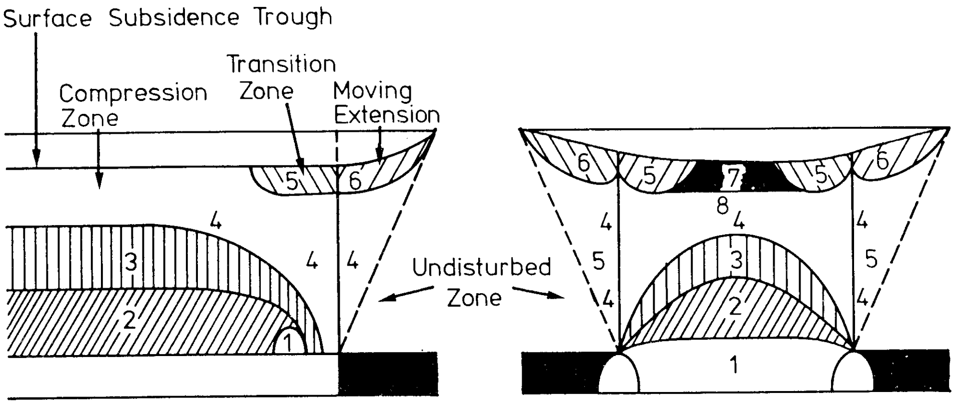
- o Increase in the piezometric head of water.
- o Increase in the intensity of gas or water inflows.
- o Variation in the gas percentage or ratio of gases. Sammaraco (1982, 1986).

DEVELOPMENT OF FRACTURE ZONES AROUND CAVED MINE WORKINGS

Figure 1 shows a generalized pattern of fracture zone developments above caved mine workings. Immediately above the mining horizon, there is a caving zone extending upwards 3-5 times the extracted seam height. The increase in the permeability of rock in this zone is 40-80 times that of the intact rock permeability and it gradually reduces as the consolidation within the goaf takes place. Immediately above the caving zone is a zone of fractured strata, which detaches itself from the main body of the superincumbent caving rock mass. Various authors have attempted to predict the height of this zone above the mining horizon as shown in figure 2. Three major factors govern the height of a fracture zone; the brittleness of the strata, the thickness and the width of extraction. It has been observed that in strong, brittle strata the height of the fracture zone is higher than in weak rock masses. A general formula to estimate the extent of the relaxation zone is given by $56xt^{1/2}$ m, which gives the height of relaxed zone with a factor of safety. The effective thicknesses of barriers for the protection undersea workings are shown in figure 2. Farmer (1980), based on his observations in the undersea collieries in the Durham coalfield. This work suggests the prediction of the fracture zone by the following empirical relationship:-

h = 0.75 W + 5
where, W = width of extraction
h = height of fracture zone

However, the author proposes that any empirical relationship to predict height of fracture zone should take into account the thickness of extraction, width of extraction, the nature of the rock mass and the ratio of primitive strata stresses in the lower part of the fracture zone is characterized by the development of bed separation cavities. In this zone, the horizontal conductivity of the strata is greatly increased and provides a storage for large quantities of water. It can be shown that a bed separation cavity of 25 mm x 60 m x 90 m stores 135,000 l of water.



1- Caving zone
2- Bed separation zone
3- Vertical relaxation zone
4- Shear and horizontal compression
5- Horizontal compression zone
6- Horizontal extension zone
7- Vertical compression zone
8- Vertical and horizontal compression zone

Fig 1 - Zone of destressed strata above caved mine workings.

Immediately above the fracture zone, is a region of compression where the hydraulic conductivity of the rock is greatly reduced. This zone is also known as an aquiclude zone. In between the fracture and compression zones, a transition zone characterized by tensile and shear failures exists and may be associated with micro-seismic activities.

Immediately above this zone a vertical compression zone is formed which extends to within 15 m from the surface. On the surface, depending upon the width of extraction, typical tensile, compression and subsidence zones develop. In weak coal measures rock, the surface subsidence zone progresses up to 15m below surface. The compressional zone

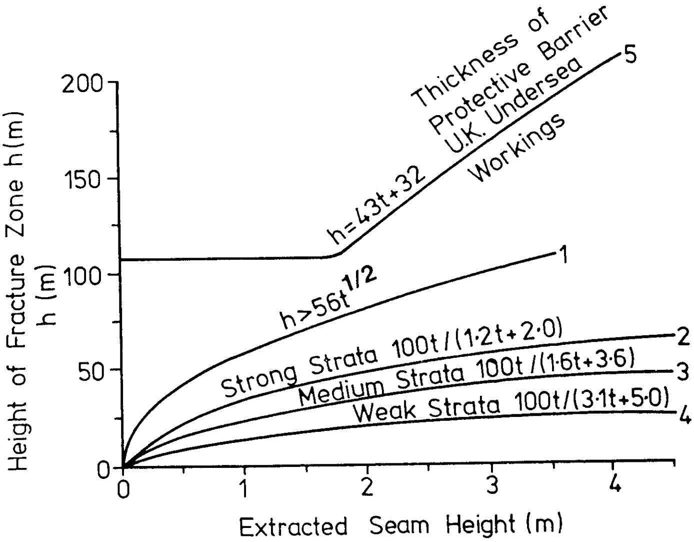


Figure 2 - Height of fracture zone (h) above a longwall face for various thicknesses of extraction, t (m).

inbetween mine workings and the surface trough acts as a protective barrier against water danger under favourable lithological conditions as in this zone beds flex without creating a linked vertical fracture pattern. However, if hard and brittle strata of considerable thickness is present near the surface, the subsidence cracks and fissures developed in the surface extention zone may propagate down to much greater depths.

WATER PROBLEMS ASSOCIATED WITH CAVED MINE WORKINGS

The water inflow to caved mine workings mainly depends upon the interaction of the following mining, hydrogeological and structural factors:-

(i) Development and location of fracture zones around mine workings:- The bed separation zones provide a major reservoir for storing and transmitting water. The in situ permeability and storage coefficent of bed separation cavities are considerably higher (several orders of magnitude) than the intact rock mass. Depending upon the width of extraction, depth of working and thickness of extraction a relaxed zone develops around the mining extraction. The method and extent of workings beneath an accumulation of surface water or an aquifer is controlled by the following factors, (Singh and Atkins, 1982):-

(a) sufficient thickness of barrier
(b) sufficient thickness of carboniferous materials within the barrier
(c) the thickness of extraction, and width of extraction in relation to depth should be such that the tensile strain induced at the aquifer bed or at the bottom of surface accumulation should not exceed 6 to 10 mm/m.
(d) in shallow workings, partial extraction systems should be designed in order to limit the tensile strains.

The maximum tensile strain at the bottom of a surface accumulation of water or disturbance at the bed of an underground aquifer can be estimated by the following equation:-

$$\varepsilon = S/D = C \times 0.9t/D$$

Where ε surface tensile strain (mm/m)
S maximum surface subsidence (m)
= 0.9 x extracted seam height t, (m)
D depth below surface m.
C disturbance factor at the bottom of the aquifer.

Figure 3a shows the relationship between the width of workings/ depth ratio and disturbance factor for coal measures rock. It can be shown that for a 200 m extraction at depth 300 m below an aquifer with a total extraction of 1.0 m, the disturbance factor is 0.71 and maximum strain is 2.13 mm/m.

Tension cracks as a consequence of longwall extraction may develop at the surface at the zone of horizontal tensile stress concentration over rib abutment pillars, as shown in Table 1. However, surface fractures with large apertures have continuity up to 15 m from the surface, and they do not provide continuity to the mine workings from a surface accumulation of water.

(ii) Hydrogeology and lithology of the intervening strata:- Major aquifers form underground water reservoirs which will transmit water to the bed separation cavities through the intervening beds by fracture permeability, intergranular permeability and structural discontinuities. Alternative beds of clay, mudstone, shale, and schist etc. form aquicludes, acting as protective barriers. That is because the horizontal

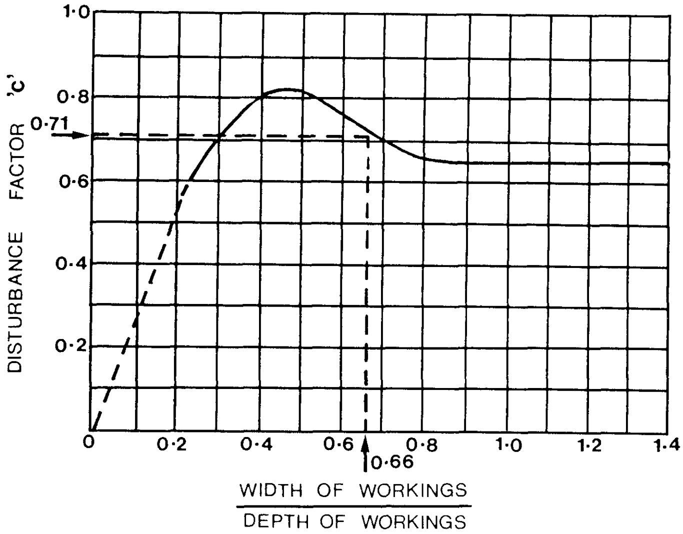


Figure 3 (a) – Disturbance factor for various ratios of width of working and depth, (Watson 1980)

Table 1. Tension fractures observed in the the Nottingham Coalfield (after Orchard, 1969).

Seam depth (m)	Other seams worked (m) +above -below	Tensile strain (mm/m)	Location of fissure	Nature of fissure
620	-	4.0	Parallel to ribside 165 m outside	25 mm wide fracture
115	-	5.5(Est)	Parallel to and over the face	10 mm wide fractures
320	-66	2.2	Over face	25 mm crack
220	+25	4.8	Parallel to and over 3 coincident ribsides	50 mm fracture
137	+7 -15 -30	4.9(Est)	Parallel to 4 coincident ribs, 46 m outside rib	50-300 mm wide fractures 45 m min depth
155	+30	4.1(Est)	Parallel to and 45 m	220 m long,
485	-	2.0	Parallel to and 90 m in front of face	90 m long, 25 mm wide

movement in such beds due to bending tend to close pre-existing vertical cracks. Konstantinowicz (1974) has observed that in bedded aquicludes a thickness of strata eight times the extracted seam height provides an adequate thickness of protective layer. The residual inflow in such cases can be easily dealt with by pumping. In massive monolithic rock masses comprising sandstone or limestone the natural joints can further extend due to mining extraction, and a protective barrier of the thickness 15 times extracted seam height is not often adequate to prevent inflow.

As the mine water inflow takes place mainly through a fracture flow regime, some of the authors have placed secondary importance to the rock lithological characteristics, (Garrity 1983). However the competence of the immediate seam roof, especially 20 - 30 metres of overlying strata, play an important role in the determining the severity of the inundation.

(iii) Thickness of Overlying Strata:- Thickness of the overlying strata plays an important role in the incidence of mine water inflow to longwall workings. When the thickness of the barrier between the coal seam and the unconfined aquifer exceeds 50 metres, little or no water is encountered in the workings except where tensional zones from previous workings have induced breaks. However, in the Selby Coalfields, despite of the thickness of 89 metres of coal measures strata between the coal seam and a major aquifer a major inflow of 115 l/sec occured. In the Northumberland Coalfield, the longwall mining operations appear to experience inflows in excess of 20 l/sec where cover to sea bed thickness was around 140 metres. In the Durham Coalfield, however, mining operations under carboniferous cover of between 100 m and 150 m show an incidence of major inflows of approximately 15%, increasing to 100% at about 80 m cover. Approximately, 10% of workings with a cover of 250 metres to the base of the Permian experience flow rates of 4 l/sec, but the incidence increases rapidly at 80 metres cover. In the Western Area of British Coal, a barrier of 60 metres is usually adequate between the coal seam and the unconformity below the Permian aquifers. Thus, the maximum requirement of 60 metres cover between the mine workings and aquifer is not adequate.

(iv) Geological Structures:- The vertical propagation of water from an aquifer or surface source of water to the bed separation cavities, can take place through the rock mass by intergranular permeation and flow through joints and faults. These permeabilities of rock masses are considerably mobilized due to mining by caving methods. The differences between the permeabilities of intact rock and that of the jointed rock masses with joint spacing of one metre are formulated in Table 2.

Various research workers have studied the problems of mine workings under the hazard of water (Orchard 1975, Aston and Whittaker 1985, Neate and Whittaker 1979, Garrity 1983, Singh and Atkins 1982). Intrusive dykes are often heavily associated with major inflows of water, eg. Westoe Colliery where an exploration borehole penetrating a dyke has yielded water at the rate of 90 l/sec.

Table 2 - Permeability of Intact Rock and Rock Mass, (after Louis)

Rock Type	Permeability Coefficient	Joint with more than one m spacing		
		Joint Width mm	Permeability m/s	Ratio
Limestone	$0.36\text{-}23.0 \times 10^{-15}$	0.1	0.7×10^{-6}	2.0×10^{9}
Sandstone	$0.24\text{-}6.0 \times 10^{-13}$	0.4	0.5×10^{-4}	2.0×10^{9}
Sandstone	$0.21\text{-}2.0 \times 10^{-13}$	0.7	2.5×10^{-4}	1.0×10^{8}
Granite	$0.50\text{-}2.0 \times 10^{-12}$	1.0	0.7×10^{-4}	1.5×10^{8}
Schist	$0.76\text{-}1.60 \times 10^{-12}$	2.0	0.6×10^{-2}	0.9×10^{10}
Limestone	$0.07\text{-}12.0 \times 10^{-10}$	4.0	4.0×10^{-1}	0.75×10^{9}
Dolomite	$0.05\text{-}12.0 \times 10^{-12}$	6.0	1.6×10^{-1}	30.0×10^{11}

Garrity (1983) has examined the effects of geological features like faults, swellies, areas of strata flexing, presence of lenticular sandstone, monoclinal structures, aquiferous formations within the coal measures, incrops of sandstone to Permian beds, jointing and faulting and therefore, a detailed presentation is not presented here.

(v) Main and Periodic Falls in Roof:-The main and periodic roof falls associated with the caving system of mining, result in creating water channels between the bed separation zone and current mine workings. The flow pattern of such inundations are shown in figure 3 (b).

In the soft coal measures rock, the "insitu" strength of rock is considerably lower than that evaluated in the laboratory and the primitive stress away from the excavation is assumed mainly hydrostatic. Under these circumstances the caving of roof bed behind a longwall face is quite regular. The broken rock mass in the caving zone consolidates easily, thus the extent of the relaxation zone is comparatively small.

However, in the presence of hard massive beds where rock mass strength is considerably higher, the virgin horizontal stresses in the rock mass may be high and stress field may not be hydrostatic. Under these conditions the onset of subsidence is delayed and the width of the subsidence trough is considerably less than the width of extraction, especially at shallow depth.

Main Roof Falls

The span of main and periodic roof falls behind a longwall face in the presence of a massive roof bed has been calculated by using simple

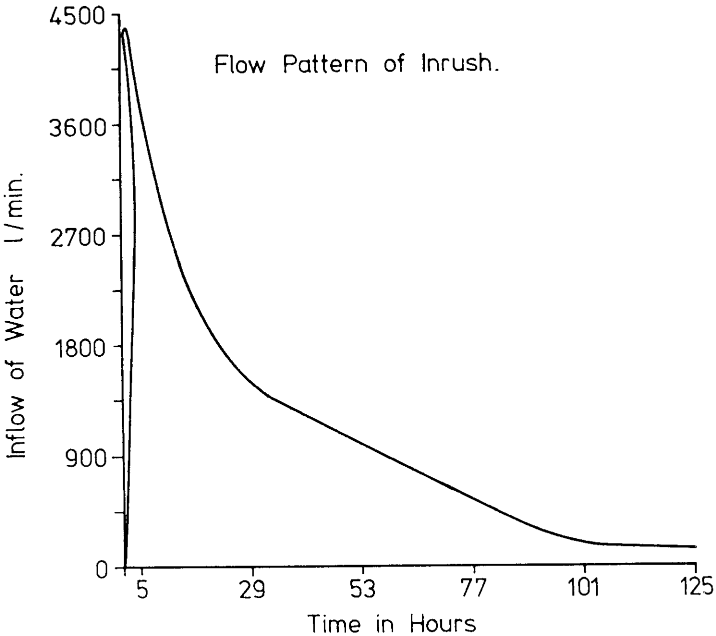


Figure 3 (b). Flow Pattern of Event Controlled Inundations, (Pugh 1981)

beam theory, (Wilson 1986). A massive roof bed bridging over a longwall excavation can be considered as a beam clamped at sides and loaded by the superincumbet strata, (Figure 4). The vertical strata pressure acting on

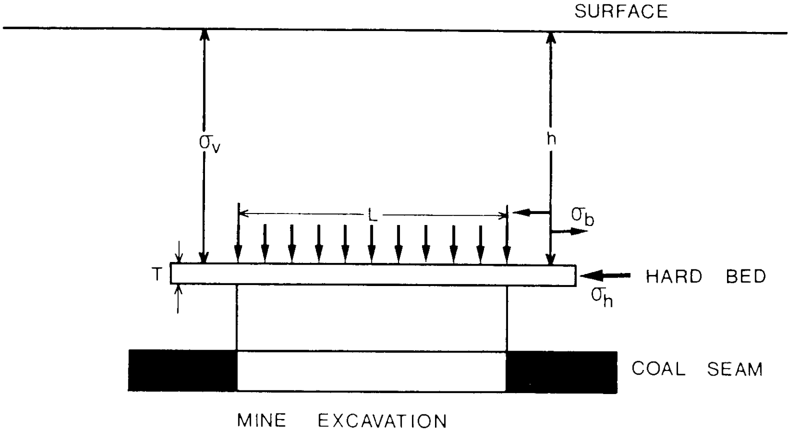


Figure 4. Theory of a Massive Bed Bridging over and Excavation.

the beam is given by the $\gamma.h.$ and the corresponding horizontal pressure by $m.\gamma.h$, where m is the ratio of virgin horizontal stress to vertical stress, γ is strata density and h being the depth of strata supported. It can be shown that the component of horizontal stress acting at the ends of the beam is given by the following equation:-

$$\sigma_b = 1/2.\gamma.h.L^2/T^2 \qquad (1)$$

where

γ = average strata density, MN/m^3
h = height of strata being supported, m.
L = span of the beam, m.
T = thickness of the massive beds.

At a shallow depth the failure of beam will be in tensile mode (Wilson 1986) when the critical stress equals the tensile strength of the massive bed. Under these conditions the failure of spanning beam will be queit, remote from the excavation. It can be shown:-

$$\sigma_t = \sigma_h - \sigma_b$$

$$= m.\gamma.h - 1/2.\gamma.h.L^2/T^2$$

$$\text{or } L = T\sqrt{2(\sigma_t + m.\gamma.h)/\gamma.h} \qquad (2)$$

where

σ_t = tensile strength of the beam
γ = average strata density
σ_h = virgin horizontal stress
m = ratio of horizontal to vertical stress

At a deep level, the failure mode will be compressional as characterized by abrupt failure in the close proximity of the face line. For compressional failure to occur the critical stress should be equal to the uniaxial compressive strength of the rock (σ_c). Thus,

$$\sigma_c = \sigma_h + \sigma_b$$

$$= m.\gamma.h + 1/2.\gamma.h.L^2/T^2$$

or

$$L = T\sqrt{2(\sigma_c - m.\gamma.h)/\gamma.h} \qquad (3)$$

The critical depth at which tensile failure mode changes to compressional failure is given by the following equation:-

$$H = (\sigma_c - \sigma_t)/2.m.\gamma$$

where σ_c = uniaxial compressive strength of the beam
σ_t = uniaxial tensile strength

In the presence of an aquifer above the longwall face, the rock mass will be saturated, and hydraulic pressure will act on the beam. The equation 2 has to be modified as follows:-

For tensile failure mode:-

$$L = T\sqrt{2(\sigma_t + m.\gamma.h)/(\gamma.h + \gamma'.h')} \quad (4)$$

For compressional mode of failure

$$L = T\sqrt{2(\sigma_t - m.\gamma.h)/(\gamma.h + \gamma'.h')} \quad (5)$$

where

γ' = density of water
h' = hydraulic head of water in the aquifer, m.

The above equations provide a simple means of estimating the roof span before first main roof fall.

Periodic Roof Fall:- Following the major first fall, the roof strata will lose its horizontal constraints and will act as a cantilever. The critical stress at the tensile mode of failure is given by the following equation:-

$$\sigma_t = 3.\gamma.h.L^2/T^2$$

$$L = T\sqrt{\sigma_t/\gamma.h} \quad (6)$$

Equation 6 permits estimation of the span of periodic falls in tensile failure mode.

CASE EXAMPLES RELATED TO EVENT CONTROLLED INUNDATIONS ASSOCIATED WITH THE CAVING SYSTEM OF MINING

This section discusses various case histories dealing with inundations associated with the caving system of mining initiated by the interaction of mining geometry, sub-surface and surface subsidence patterns and the hydrogeology of the intervening strata. Mining geometry may affect the sub-surface subsidence pattern in such a way that the zone of compression may be entirely absent, thus creating a significant danger from sub-surface water to underground workings. Some case histories involving unprecedented inflow situations are described in this section.

Case Study 1- Wide Face at a Shallow Depth:-

The site under consideration was situated in the North Derbyshire Coalfield where coal seams dip West to East with Permian rocks overlying unconformably over the Coal Measures on the east of the take. The coal seams have been extensively faulted with faults outcropping at the surface as well as incropping underground. A number of coal mines operate in the area exploiting some 15 coal seams. The face concerned was mined in the Clay Cross Soft seam at a depth of some 80 m below the surface, extracting a 240 m wide face in a 2 m thick coal seam. The estimated height of the fractured zone above the coal seam was 79 m ($56t^{1/2}$ m) and the surface strain was 14.6 mm/m, thus the relaxed zone around the longwall excavation is linked to the surface, providing a recharge area at the surface and bed separation cavities acting as a major reservoir. The immediate roof strata formulates a beam of fine grained siltstone with an average thickness of 17 m, uniaxial compressive strength of 50 MN/m^2 and uniaxial tensile strength of 17 MN/m^2. It can be shown that the main roof fall will take place at a span of 65 m. Similarly it can be shown that periodic roof falls will take place at span of 24 m. Inundations of water were coincident with the main and periodic roof falls and consequently, workings were constantly wet.

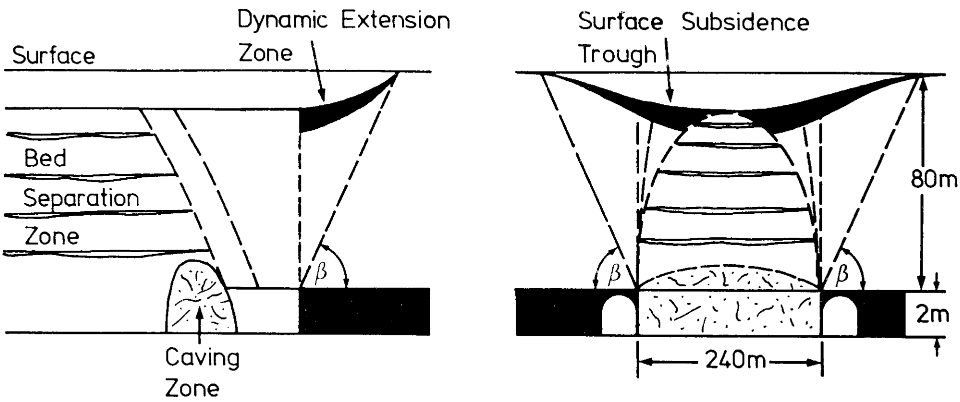


Figure 5. Wide Face at Shallow Depth.

<u>Case Study 2</u>- Shallow Caving Workings:-

The site concerned was situated in a shallow drift mine in the North Derbyshire Coalfield. The longwall face concerned was worked in Clowne Seam, having an extraction width of 275 m, thickness 1 m at a depth of 120 m. The immediate roof of the coal seam was a sandstone with conglomerate with a uniaxial compressive strength of 64.6 MPa and tensile strength 9.9 MPa. Immediately above this bed was a fine grained sandstone with uniaxial compressive strength of 71 MPa and tensile strength of 10.7

MPa. Near the surface, alluvial soil and rock was underlain by a thick, jointed sandstone bed. It can be shown that the estimated surface strains was 4.9 mm/m. The cracks and fissures due to subsidence in the surface extension zone linked to the jointed sandstone bed which was in turn linked to the bed separation cavities. It can be shown that if the immediate roof beam was 17 m thick, the estimated span of first fall was 45 m and span of secondary or periodic roof falls were 19 m. The main cause of inundation was surface water entering the rockmass through the cracks in the surface extension zone and vertical joints recharging the bed separation cavities.

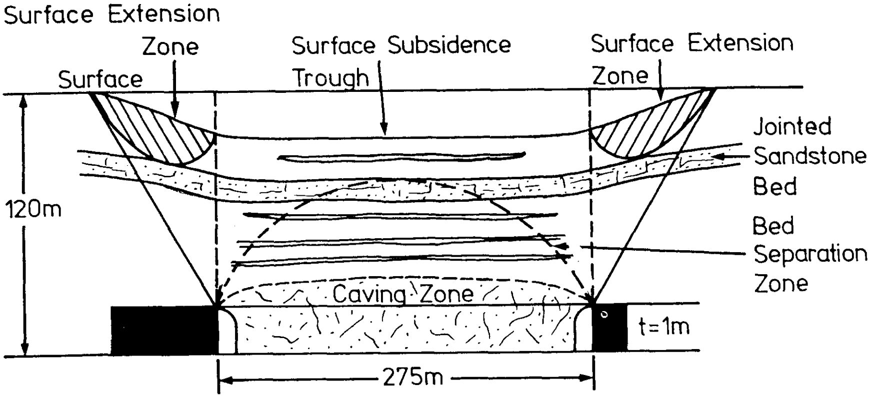


Figure 6. Shallow Caving Workings.
(Surface Water Inflow Through an Extension Zone, Jointed Sandstone Bed and Bed Separation Zone.)

<u>Case Study 3</u>- **Water Problems Associated with Workings in the Vicinity of the Base of Trias:-**

Here water danger occured due to the relaxed zone encroaching into a saturated zone below an unconfined aquifer under high hydraulic pressure. The mine concerned was situated in the South Staffordshire Coalfield where the coal measures underlie Triassic rocks unconformably. The Trias here consist of the basal Coal Measures beds, overlain by the Bunter Pebble Beds which forms major aquifers characterised by high permeability and storage coefficients. The coal measures strata underlie the Bunter Sandstone, are highly saturated upto a depth of 60 m below the unconformity; so much so mining within this zone is fraught with water dangers. In the mining area the coal measures dip 1 in 2 forming a steep western limb of an anticline which was partially eroded, Figure 7(a). Consequently, most of the upper coal seams are incropping into the base of Trias, thus acting as minor aquifers. The coal seam concerned was 2.2 m in

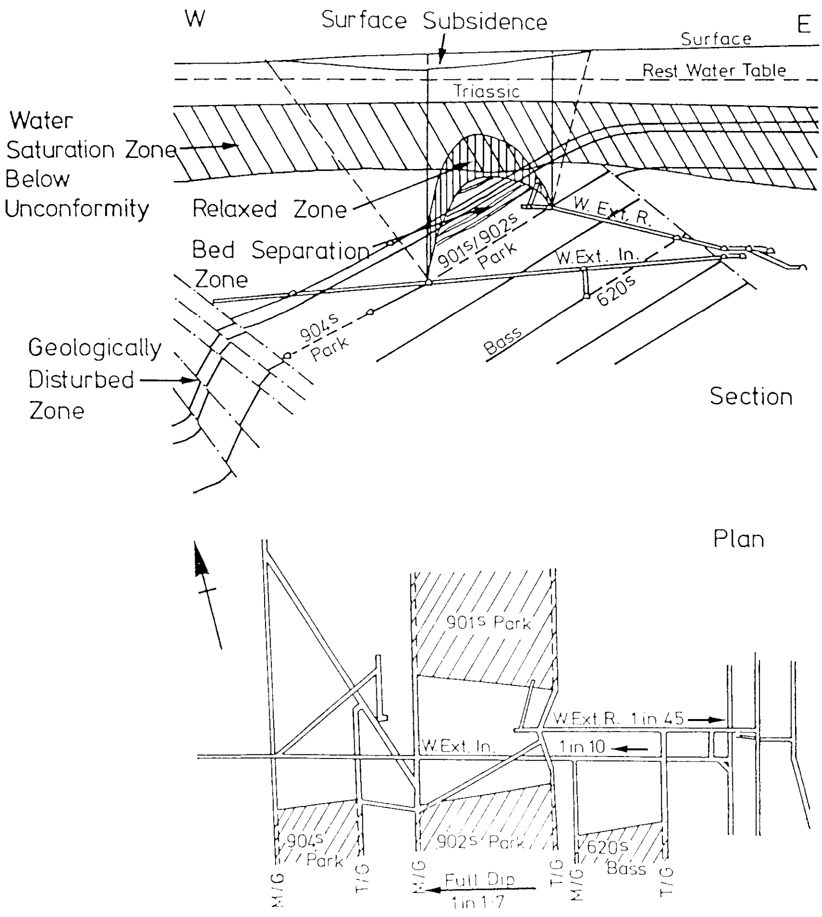


Figure 7. Water Problem of Steep Longwall Face Working Under a Saturation Zone Below Triassic.

thickness of which 1.83 m was worked by longwall advancing method. The face was developed in full dip 1 in 1.7 and had advanced to 680 m when it met with a 3 m fault, Figure 7(b). The face was subsequently redeveloped on the inbye side of the fault and had advanced 120 m, when the main fall occured and the base inflow rate of 1.5 l/s was established. At a further advance of 80 m a major inrush of water occured in the maingate of the face with a flow rate of 75 l/s which gradually reduced to the base rate over in next four days. It is significant to note that the inrush of water occured when the face were stationary and could be attributed to a combination of factors as follows:-

a) Depth below surface and depth below the base of Trias
b) Face geometry including thickness and width of extraction and depth of workings.
c) Existance of saturated coal measures strata including sandstone coal and siltstone within 45 to 50 m of the mining horizon.
d) Development of bed separation cavities within 15 to 30 m above the coal seam, intersecting saturated strata. Thus providing a reservoir of water in the close proximity of the workings.
e) Connection by the main and periodic roof falls, face breaks, natural joints and faults to the water-logged bed separation cavities providing a path for the water to reach current workings.
f) The presence of aquiclude beds like mudstone and shale etc especially in caved conditions and under high compressive loads providing a water barrier.
g) A study by Whitworth (1982) in the Western Area of British Coal, has shown that the bed separation cavities develop within 100 m of the longwall working horizon containing more than 55 % of hard strata. Observations have indicated that these beams tend to have standard thicknesses of 15 to 19 m ± 2.5 m depending upon the thickness of the extraction bed separation cavities develop forming tensile zones of very high horizontal permeability.

Case Study 4- Working Below a Major Aquifer in East Yorkshire, in a 80 % Brittle Type of Coal Measures Strata:-

The carboniferous strata in the East Yorkshire Coalfield consists of fairly strong brittle shale and sandstone and are devoid of the presence of aquicludes. This is overlain by 5 m of weakly consolidated sands and a 65 m thick massive limestone bed. Rest of the cover consists of 200 m of mixed strata. The base of limestone bed and unconsolidated sands form a major confined aquifer with hydraulic pressures equivalent to the depth below surface. The extracted seam thickness was 2.44 m and initial width of extraction was 138 m, Figure 8. The initial extraction width was selected so that mining should not cause damage to the major

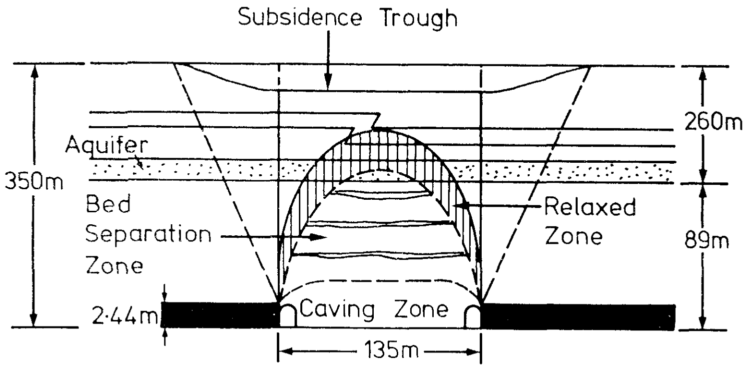


Figure 8. Bed Separation Zone Linked to a Major Aquifer.

magnesian limestone bed. Taking the thickness of limestone bed as 65 m, tensile strength as 10 MPa, compressive strength as 80 MPa and average depth of limestone is 230 m, it can be shown that the bridging span of limestone bed will be in the order of 175 m. Initial face widths were selected as 138 m. The calculations show that a 138 m wide extraction for the given mining geometry will create an estimated strain of 17 mm/m at the base of the aquifer. The estimated height of the fracture zone was 90 m. Thus the bed separation zone would provide a hydraulic link between the major aquifer and mine workings. At this site the first major fall took place when the face was advanced 113 m when some 250,000 m^3 of water inundated the mine workings with a flow rate of 115 l/sec which was eventually reduced to 53 l/sec after 19 days. During the periodic weighting the inflow again increased for a short period followed by slow reduction in flow rate to the base level.

A second retreat face was also started with a different orientation again with sudden inflow. The mining layout was subsequently modified to a single entry longwall retreat layout with a face length of 45 m, figure 9. The average weekly output for the single entry face was 7500 t/week. The performances of two single entry faces are presented in table 3, (Bonnell 1986). It can be seen that the productivity of single unit faces is superior to the area average. Figure 9 shows the details of single entry longwall face.

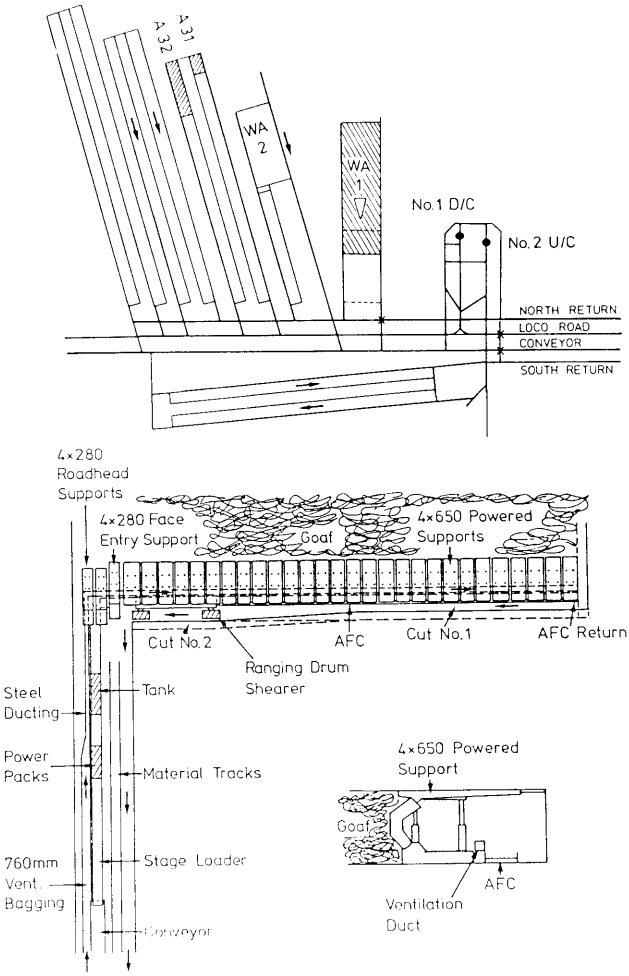


Figure 9. Layout of a Single Entry Face for Working Under a Major Aquifer.

Table 3. Productivity Trend by Single Entry Faces

Face	No. Weeks	Tonnes	Face		Area	
			DOF	OMS	DOF	OMS
A31	15	92299	1419	74		
A32	18	121000	1552	80	1128	18.06
BEST		12000	2406	162		19.03

OMS Output per man shift
DOF Daily output per face

Case Study 5- Bed Separation Zone Linked to Jointed Limestone Bed Outcropping Certain Distance Away:-

There have been several incidents of mine water inflow in longwall workings in the High Main Seams, under the Permo-Triassic aquifer in the East Midlands Coalfield. The High Main Seam occurs towards the top of Middle Coal Measures with a cover to the overlying Permo-Triassic rock of 90 to 130 metres. Three major sandstone beds occur above the coal seams within the coal measures and form three aquifers referred to as Upper, Middle and Lower aquifers. The water problem occured in two districts, worked parallel to each other and separated by a 4 m fault, hading over the maingate of the first face. The face concerned was 255 metres wide extraction thickness 1.3 m, depth 170 m and cover to Permian 100 m. The

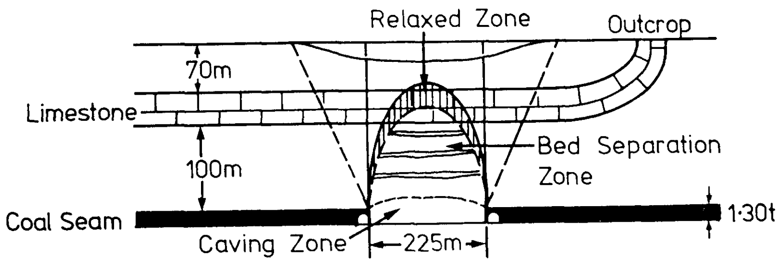


Figure 10. Bed Separation Zone Linked to a Jointed Limestone Bed Outcropping a Certain Distance Away.

estimated disturbance at the base of Permo-Triassic limestone was 7.6 mm/m. Interpretation of the chemical analyses of water indicated that, the water was derived from more than one source and may be related to the coal measures aquifers together with contamination and dilution from Permian limestone and surface water as shown by presence of nitrates. The height of the border zone above the coal seam is estimated as 62.7 m. It is considered that the Permian Limestone bed overlying the High Main Seam outcrops a certain distance away and provides a recharge area for the Permian aquifer. Vertical joints and fissures in the Permian permits saturation of the Coal Measures aquifers below the unconformity. Thus, a combination of surface, Permian and coal measure water finds its way to the working horizon through bed separation cavities.

Case Study 6-Development Workings Driven Within Surface Extension Zone of Previous Workings:-

There are several examples where shallow drifts driven from surface to a coal seam being driven through hard strata encounters 2 - 4 cm wide

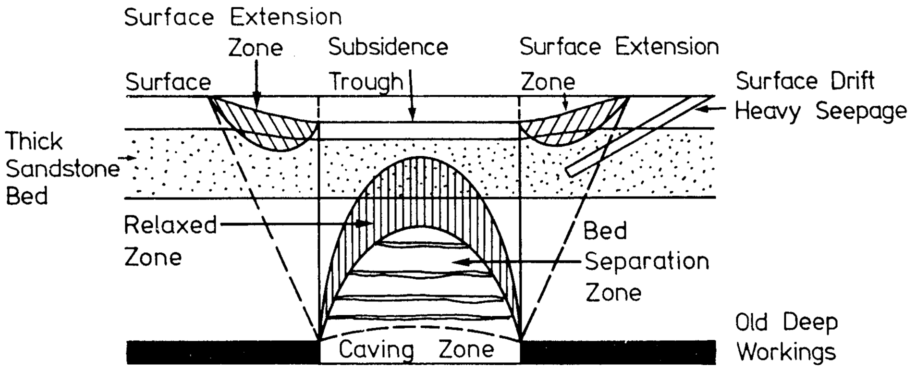


Figure 11. Shallow Headings Passing Through Hard Strata Connected to Surface Extension Zone.

cracks with heavy feeders of water, (Pocock 1982 p 719). Thick sandstone beds situated near the surface permit the cracks to develop within the surface extension zone due to presence of deep underground workings and propagate to a deeper horizon, developing major fissure systems. Surface water can enter within the surface extension zone through the cracks within the massive brittle sandstone beds. Figure 12 shows that the relaxed zone due to the presence of deep mine workings intersecting with a thick massive sandstone bed which in turn is linked to the surface extension zone. This developed a flow pattern between the surface and deep mine workings. A surface cross-measure drift driven through thick sandstone beds containing upto 60 % hard beds intersected 20 - 30 mm wide cracks at depth of 80 m and 100 m respectively causing serious inflows of water. The inflow of water, therefore, can be attributed to the interaction of mining geometry, and the surface subsidence modified by lithology as characterised by the presence of hard strata.

<u>Case Study 7</u>- Under Sea Workings in North East of the England

Under sea coal mining in the North East of England is associated with pumping of large quantities of water, 8 tonnes of water being pumped for every tonne of coal extracted. For many years the mine workings have concentrated in the deeper and better quality coal seams. The major water problems in these workings are associated with workings below the base of the water bearing Permian strata where a static water head of 230 m prevails. The Permian in this area consists generally of a basal yellow unconsolidated sandstone up to 30 m thickness, overlain by jointed dolomitic limestone. The basal sandstone is characterised by high porosity and permeability with the overlying limestone being highly jointed. Thus, Permian beds are capable of holding and transmitting large quantities of water. However, the strata some 2 km outbye under the sea contains a thick evaporite sequence some 40 m above the limestone, which acts as aquiclude. The coal seams are gently dipping east with a gradient between 1 in 25 and 1 in 90. Although the intensity of faults is low due to combination of faulting and the natural dip of the coal measures may result in reducing the thickness of coal measures cover over the workable seams. Moreover, some of the upper coal seams may incrop at the base of the Permian. The mine workings are therefore designed in such a way that a minimum thickness of the protective barrier between the coal seam and the base of the Permian was designed by graph 5 in figure 2. The mining method is selected in such a way that the disruptive effect in the overlying strata due to the development of subsidence is minimised.

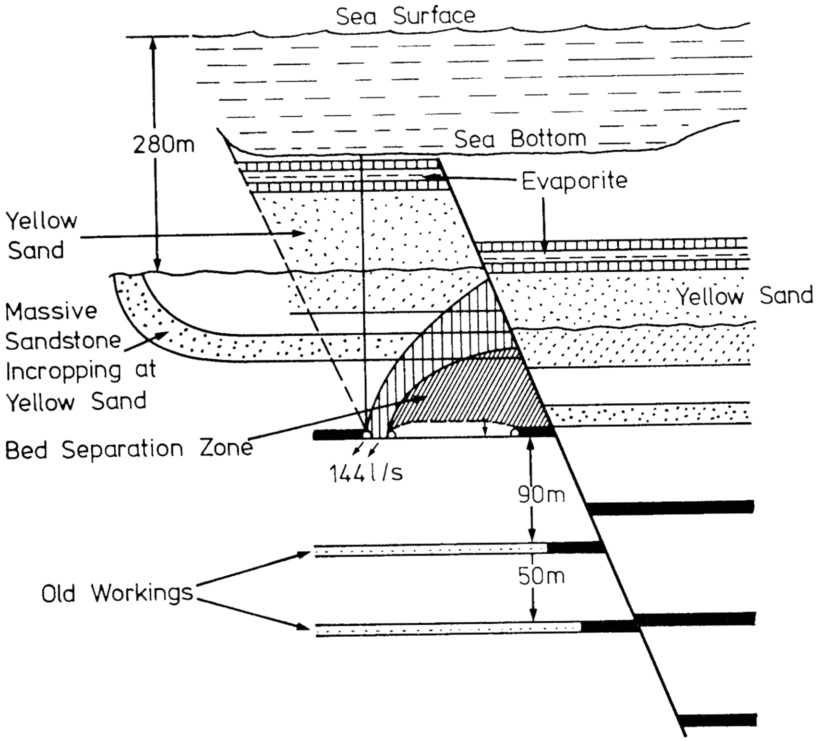


Figure 12. Under Sea Workings in Hard Stara in Faulted Zone.

- **Aquifer with High Hydraulic Head.**
- **Massive Sandstone Incropping within 60 m. of the Major Aquifer.**
- **Old Workings Below (90 - 140 m.) The Present Workings.**
- **Fault Hading over the Coal Face.**

A longwall face in the area was 190 m wide extracting a 2 m thick coal seam which had advanced 210 m from the face starting line. It met with a feeder of water with a inflow rate 900 - 1250 l/min from the roof strata. At this position the thickness of the cover at the base of Permian was 76 m. The seam was immediately overlain by a thick sandstone and another 15 m thick coarse grained, jointed coal measures sandstone the base of which was 60 m above the High Main Seam, incrop to the base of Permian above the face. Around 60 % of the cover above the coal seam to the Permian consists of hard sandstone or siltstone. The uniaxial compressive strength was 80 MPa and uniaxial tensile strength of 10 MPa. The span of the coarse grained sandstone bed was calculated as 30 m. It can be shown that the fracture zone above the High Main Coal Seams will extend 79 m above the coal seam thus encroaching into the Permian. Thus, Permian water will pass relatively easily through the sandstone beds down to the fracture zones in the coal measures to the High Main workings. The estimated strains at the base of Permian will be in the order of 15.4 mm/m. The span of the main fall will be 23 m and that of the periodic falls is 17 m. Thus water contained in the bed separation cavities will easily find its way to the mine workings.

In order to minimize water inflows a partial extraction layout of 65 m wide face with 50 m barrier pillar at a cover to Permian of 90 m was adopted to reduce the strain at the base of Permian to 14 mm/m. A water inflow of 1.1 l/sec was recorded with reducing cover to 85 m at another location a larger quantity of water 12.5 l/sec was encountered. At a reduced cover of 76 m, the face width was reduced to 40 m but this increase the estimated strain at base of permian to 19 mm/ m and a inflow rate of 53 l/sec was encountered. Under these conditions the inflow rate can be related to the disturbance at the base of Permian.

In the same area, a 60 metres wide longwall retreat face with around 82 metres vertical cover to the Permian was started some 10 metres from the 90 metres down-throw fault zone which haded back over the face. After about 90 metres retreat a major feeder of water with the estimated inflow rate of 114 l/sec was encountered. The estimated strain rate at the base of Permian was 14.2 mm/m. It is indicated that the tensional zone at a consequence of longwall the retreat mining has affected the fault plane and allowed the inflow of Permian water at the face, figure 12.

Case Study 8-Deep Seated Under the Sea Workings Below a Coal Measures Aquifer:-

A longwall face 203 metres wide, extracting a 1.42 metres thick seam, 310 metres below the sea and 116 metres under the Permian strata. The hydrostatic head of water in the Permian was some 220 metres. The face worked its planned life of 550 metres, even though on four occasions of main and periodic falls in the goaf were accompanied by water inflows of 75 l/sec. The estimated strains at the base of Permian was 7.2 mm/m. A chemical analysis of water confirmed the origin of water was from Coal Measures rather than Permian origin. A series of water drainage boreholes

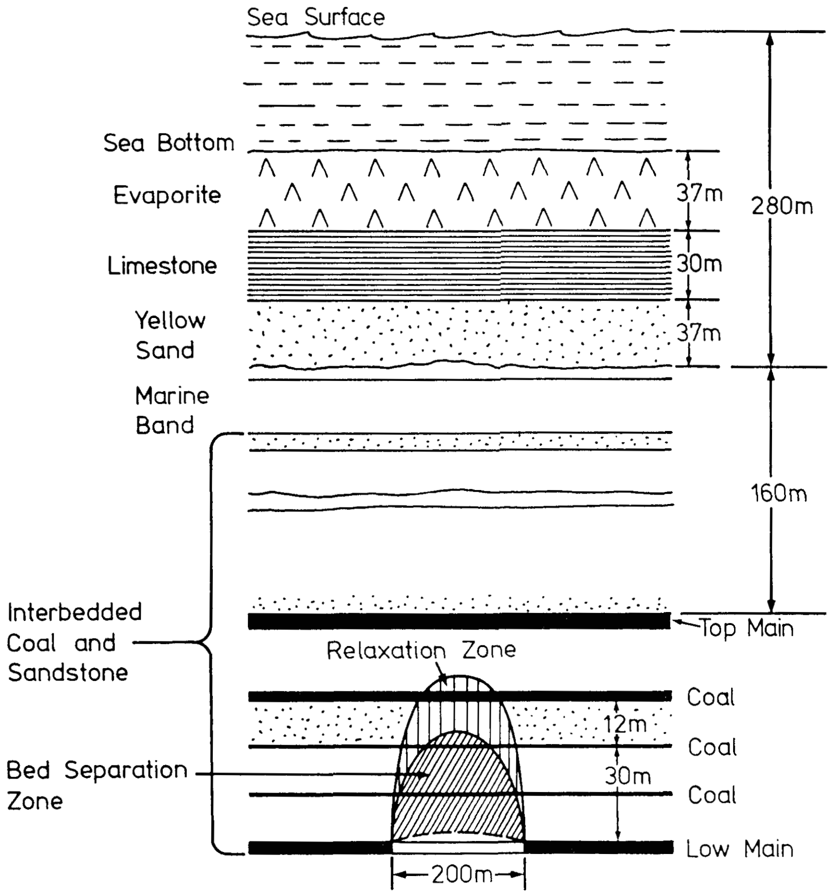


Figure 13. Under Sea Working at Great Depth.

drilled at 65 metres apart and intersected bed separation cavities at a height of 36 metres. The water here was encountered from the zone of bed separation cavities some 30 metres above the Low Main Seam in the vicinity of Yard Seam, where water at hydrostatic pressure has been occasionally encountered. Because of the presence of mudstones above the Yard Seam, it is thought that the water originates in a sandstone bed some 60 metres above the Coal Seam.

CONCLUSIONS:-

The entry of water into longwall mine workings is governed by a combination of complex factors and can be related to the formation of bed separation and relaxed zones around the caved excavation. The extent of bed separation and relaxed zones around the mine workings depends upon the width of working depth below the aquifer, thickness of extraction and presence of brittle strata above the longwall extraction. Hydrogeology of the intervening strata, the presence of the surface or underground source of water, thickness of the intervening strata together with its permeability characteristics are important factors to recharge the bed separation cavities. The thickness and strength of roof beds immediately above the coal seams, depth of workings and the ratio of horizontal to vertical virgin stress control the span of the major and periodic roof falls in the goaf which permit bed separation cavities to drain, thus results in mine inundation.

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