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Effect of Longwall Mining on Ground Permeability and Subsurface Drainage

by B. N. Whittaker, R. N. Singh, and C. J. Neate,
Department of Mining Engineering,
University of Nottingham,
Nottingham, United Kingdom

SUMMARY

The paper briefly reviews mining subsidence characteristics associated with longwall mining and discusses the implications of subsidence on surface and subsurface drainage pattern changes. Both surface subsidence and subsurface subsidence aspects are discussed. Investigations are described into ground permeability changes between the surface and the mining horizon. Instrumentation and investigation techniques to study ground permeability changes are described and the results of United Kingdom studies presented and discussed.

LONGWALL MINING SUBSIDENCE

Longwall extraction involving caving of the roof strata is the prevalent underground method in European Coalfields. The caving of the roof strata behind the longwall extraction produces controlled subsidence of the ground between the mining horizon and the surface. The amount of subsidence occurring at the surface can be predicted from knowledge of the principal mining dimensions namely depth below surface, width of longwall and extracted seam height together with knowledge of the geological conditions. The prediction method used in British Coalfields is based on an empirical design procedure established over several years from precise levelling observations in different mining conditions covering a depth range of 100 to 1000 metres below the surface (1). It applies entirely to longwall mining type of extractions and allows accurate predictions to be made of anticipated subsidence both in extent and amplitude in addition to the calculation of surface ground strain and tilt. An example of the general characteristics of a surface subsidence trough above a longwall mining extraction is shown in Figure 1.

The creation of a subsidence trough at the surface can itself introduce a change in surface drainage pattern especially for thick extractions at relatively shallow depths. Rib pillars are frequently left between successive longwall extractions in order to reduce surface subsidence and the magnitude of surface ground strains. The method of using pre-designed ratios of width of longwall to width of rib pillar between faces has been employed over many years with considerable success in European Coalfields as a means of controlling subsidence in areas where surface drainage is critical, for example under low-lying agricultural land close to a major tidal river, and under major inland water courses such as rivers and canals.

LONGWALL SUBSIDENCE AND SUBSURFACE DRAINAGE ASPECTS

If the surface ground strains, especially in the tensile zone, are sufficiently high and the surface rocks brittle then cracking and opening of fissures can occur which can affect surface and subsurface drainage patterns. It is generally thought that the depth below surface of such subsidence cracks which have a direct connection with the surface, is limited in extent and does not affect major surface water bodies such as the sea or large lakes but small ponds have been known to be drained by such subsidence cracks opening at the

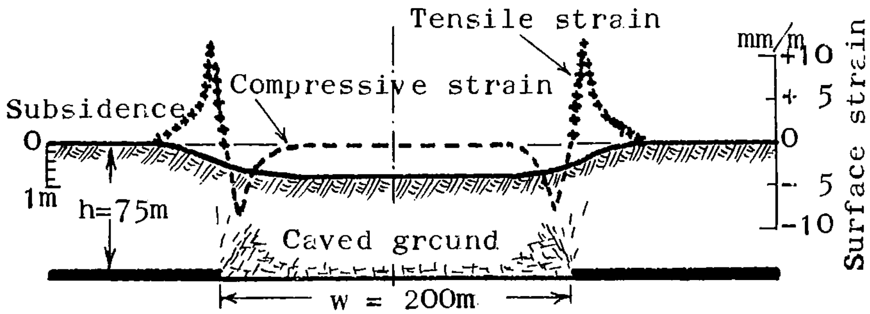

Figure 1. General characteristics of subsidence trough and surface ground strain due to longwall mining of coal seam in shallow conditions. (The subsidence parameters have been calculated using the National Coal Board Subsidence Engineer's Handbook method).

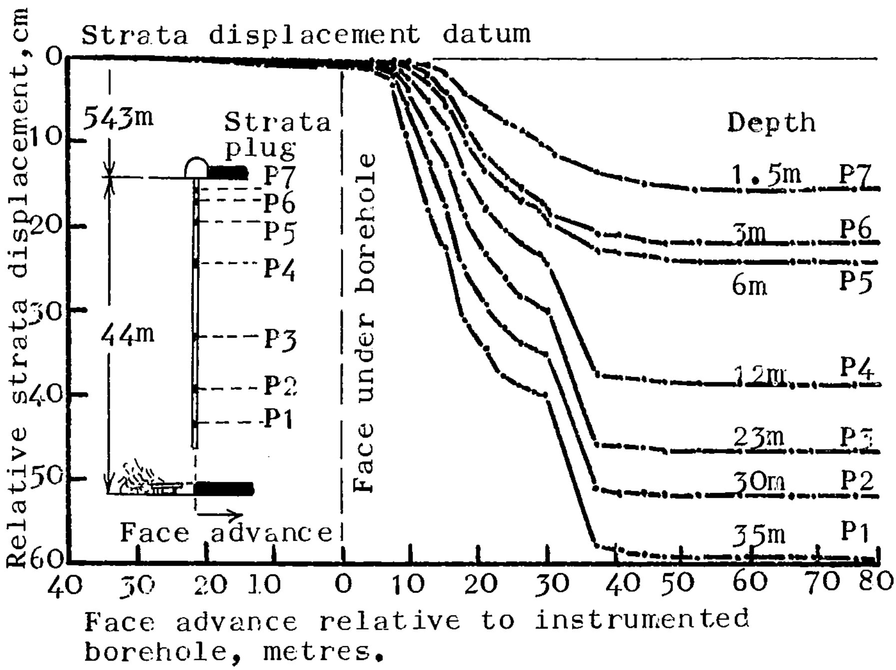

Figure 2. Development of inter-strata displacements in an instrumented borehole located in the path of an approaching longwall extraction. (The illustration has been taken from King, Whittaker and Batchelor (1972)).

pond's base although this greatly depends upon the type of geological formations. The likelihood of cracks appearing at the surface greatly decreases with deeper workings since the ground strain effects are more widely spread with a significant reduction in their magnitude.

The caving process of the roof beds behind the longwall extraction creates a zone of broken strata which in time becomes consolidated. Consequently the zone of broken strata immediately behind the longwall face is one which is likely to encourage flow of water towards the working horizon, providing an aquifer (or other source of water) is within the zone of influence. This is vitally important to the safe working and success of all underground mining operations. The present investigation has been directed towards examining the zone of influence of mining operations on changes in ground permeability and potential subsurface drainage pattern changes.

CHARACTERISTICS OF SUBSIDENCE IN PROXIMITY OF EXTRACTION HORIZON

Figure 2 shows the development of inter-strata displacements in the immediate roof beds overlying a longwall face 587 metres below the surface (2). The instrumented borehole was drilled vertically downwards from a horizon 44 metres above the longwall which was to subsequently undermine the borehole and had seven strain wires P1 to P7 anchored at the depths shown in Figure 2. The borehole was located centrally within the path of the approaching 200 metres wide longwall extraction. The strata displacements are relative to a datum at the borehole mouth, that is a horizon 44 metres above the longwall extraction. The most important feature of the results shown in Figure 2 is the zone of major strata movement recorded between 10 to 40 metres behind the longwall face. Also of importance is the progressive decrease in the amplitude of relative vertical strata displacements from the mining horizon. The results also show a progressive change in consolidation from the working horizon. It was viewed important to investigate the influence of such subsidence on

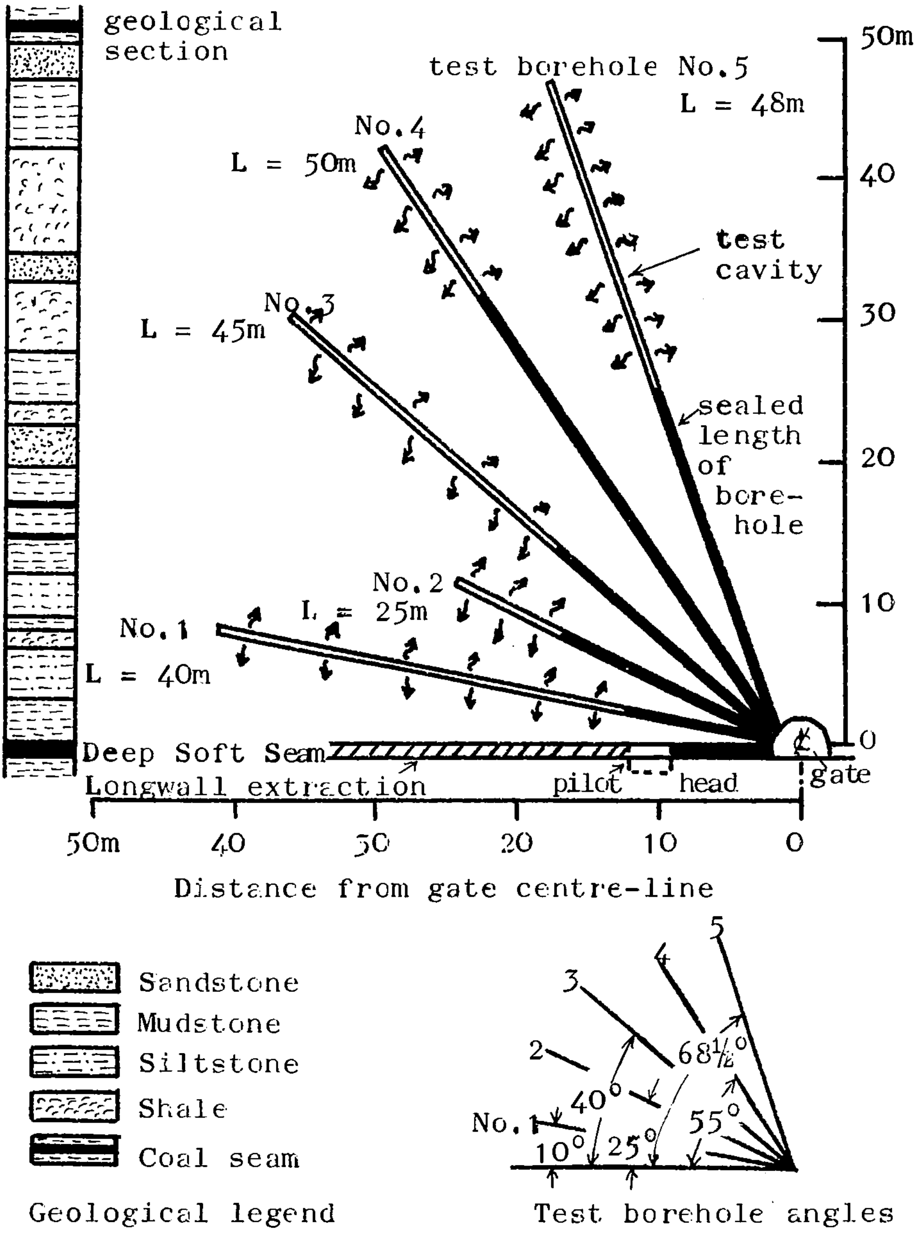

Figure 3. Illustrating positions of test boreholes at experimental site in Deep Soft Seam, East Midlands Coalfield and their location in relation to the Longwall extraction.

changes in permeability of the strata within this zone close to the working longwall face.

RESEARCH OBJECTIVES

The main objective of this work was to investigate the zones of increased permeability resulting from undermining by a longwall extraction. Within this investigation also came the need to establish the base permeability of the rock types overlying the longwall extraction and to ascertain the change in permeability resulting from progressive undermining. It was firstly required to design a scheme of instrumentation which permitted these changes to be investigated. Having established the investigation technique it was a major aim to study how the subsidence resulting from longwall mining affected the strata permeability.

Two major sites were selected for the study. The first permitted the strata permeability change to be investigated in close proximity to the mining horizon, whilst the second concentrated on permeability changes arising close to the surface and well within the critical area of extraction.

STRATA PERMEABILITY CHANGES IN PROXIMITY OF THE LONGWALL FACE

The site chosen for the investigation was in the East Midlands Coalfield, in the Deep Soft Seam. The retreating longwall face was 220 metres long and had an extracted seam height of 0.81metre whilst the depth below surface was 628 metres.

Figure 3 shows the general location of the test boreholes in relation to S34's face. The gate from which the boreholes were drilled had been formed previously for the extraction of S32's longwall advancing face, immediately to the right of S 34's, see Figures 3 and 4. A small pillar of coal was left between the gate and the pilot heading as shown in Figure 4.

A section of the roof strata above S34's face is shown in Figure 3 and this consists mainly of

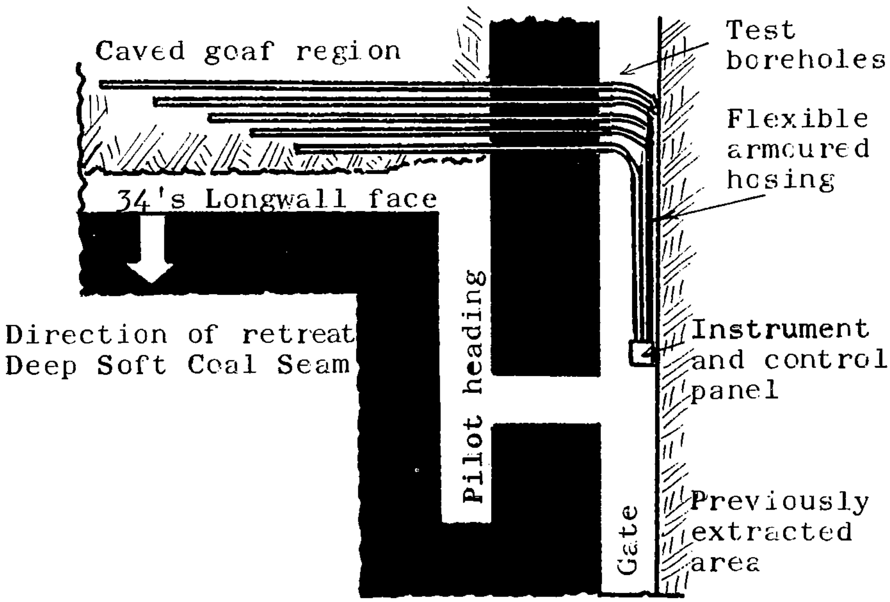

Figure 4. Showing location of test boreholes and instrumentation/test panel

shale, siltstone, mudstone and sandstone within the 50 metres above the Deep Soft Coal Seam. Figure 3 also shows the positioning of the test boreholes and their respective lengths.

The test boreholes were drilled 60 millimetres diameter. The first borehole was completed when the face was still 55 metres from the borehole plane. The five boreholes were drilled in the same vertical plane. Each test cavity was formed by pumping cement grout into the borehole mouth; cement was pumped against an increasing head until cement began to return via a 19 millimetre diameter breather tube. A second tube had also been placed in position leading to 3 metres beyond the end of the breather tube and was to be used later for pressure testing of the test cavity. A flexible seal was positioned between the end of the breather tube and the test cavity to prevent any tendency for cement grout to continue filling the borehole beyond the end of the breather tube.

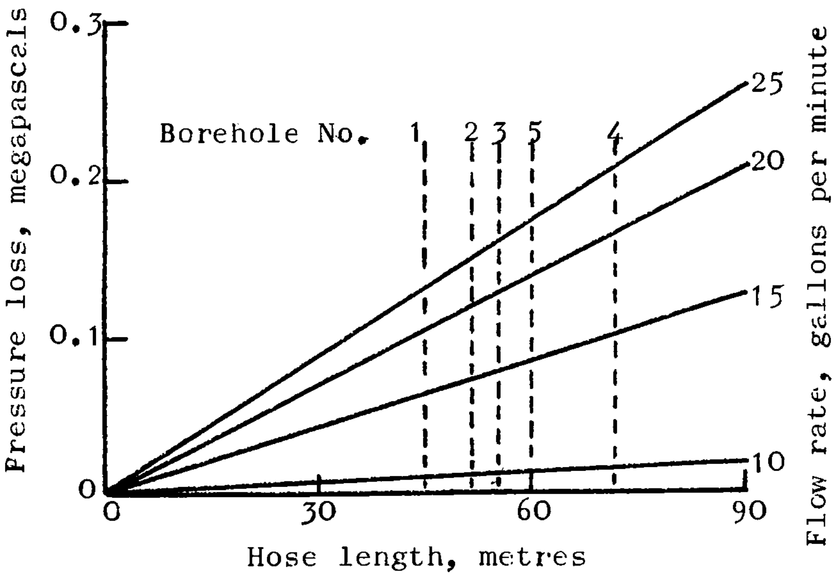

Figure 5. Correction for pressure loss in connecting hosing (Deep Soft test station)

Figure 4 shows a general layout of the test boreholes in relation to the face-end. Flexible armoured hosing connected each borehole mouth to the instrumentation panel which was conveniently located for access some distance outbye of the face line.

STRATA PERMEABILITY TESTING PROCEDURE

Each borehole was pressure tested using water when the face was at different positions in relation to test boreholes. The pressure testing equipment consisted of an assembly similar to that shown in Figure 12. The inlet water pressure was 6.3 megapascals and this was reduced by an in-line reducing valve. Due account was taken of the pressure loss resulting from hydraulic connections and Figure 5 shows the nonogram for this correction for a given flow rate and length

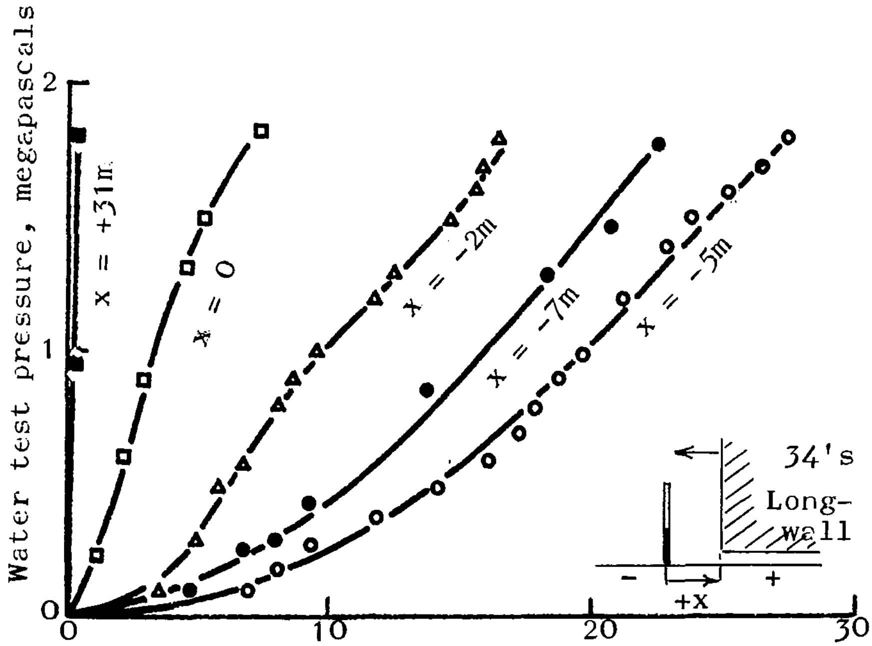

Figure 6. Borehole No.3 flow characteristics

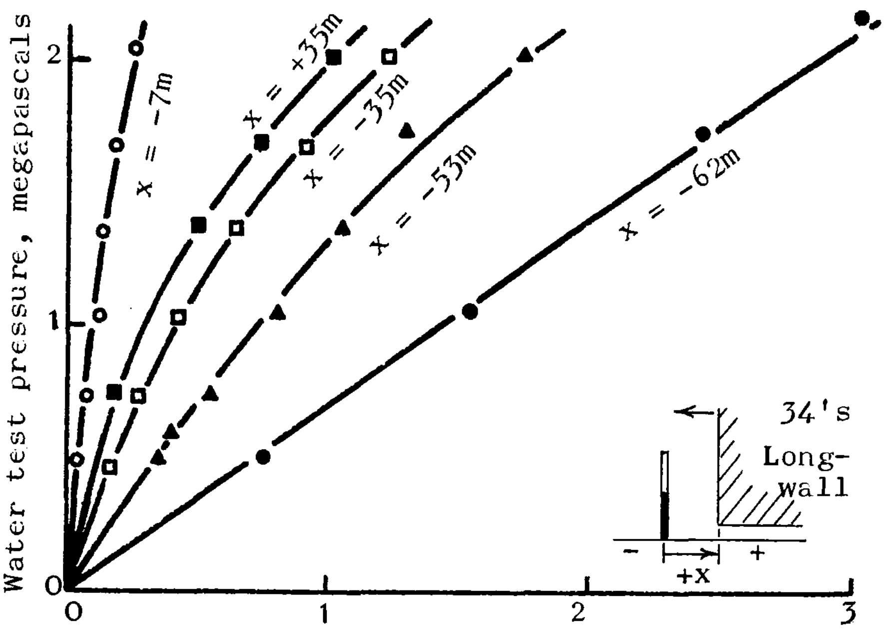

Figure 7. Borehole No.5 flow characteristics.

of hose. Static head was also corrected for by using the vertical height to the central position of the test cavity.

The test procedure involved observing the flow rate for increments of testing pressure usually up to 2 - 3 megapascals. Two flow meters were incorporated in the circuitry, one reading up to 100 litres per minute and the other up to to 20 litres per minute. Testing firstly involved attaining equilibrium saturation within each test cavity by allowing flow under maximum pressure for at least 15 minutes and thereafter flow as observed at up to about 12 different test pressure levels within the testing pressure range given above. The flow rate was observed when steady state flow was established during each test and usually took less than 2 - 3 minutes. Testing all five boreholes usually took about 3 hours.

TEST RESULTS IN PROXIMITY TO MINING HORIZON

Figures 6 and 7 show typical test results for two of the boreholes tested at different positions of longwall face advance. The results presented in Figure 6 show the flow characteristics before the ground was undermined together with test data showing the effect of undermining. The flow characteristics indicate the formation of widening cracks along the test cavity as the longwall face gradually undermined the test section. Figure 7 shows a test section which was only slightly affected by undermining; these results indicate that the ground became more impermeable before moving to a phase of increased permeability some distance after undermining. Comparing the results given in Figures 6 and 7, it is inferred that the ground associated with borehole No.3 became significantly affected by caving whilst the test section of borehole No.5 was virtually intact during undermining. The pressure-flow curve variation was due to opening and closing of minor fissures/cracks.

The degree of variation in flow in two of the test boreholes is clearly illustrated in Figures 8 and 9 which show flow rate plotted against longwall face position. In the case of Figure 8

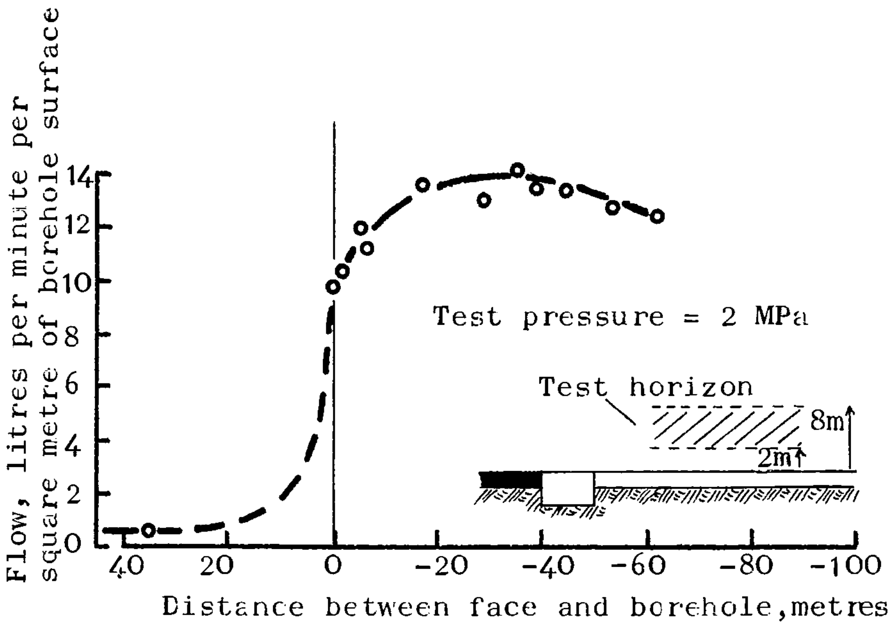

Figure 8. Relationship between flow characteristics of borehole No. 1 and face position

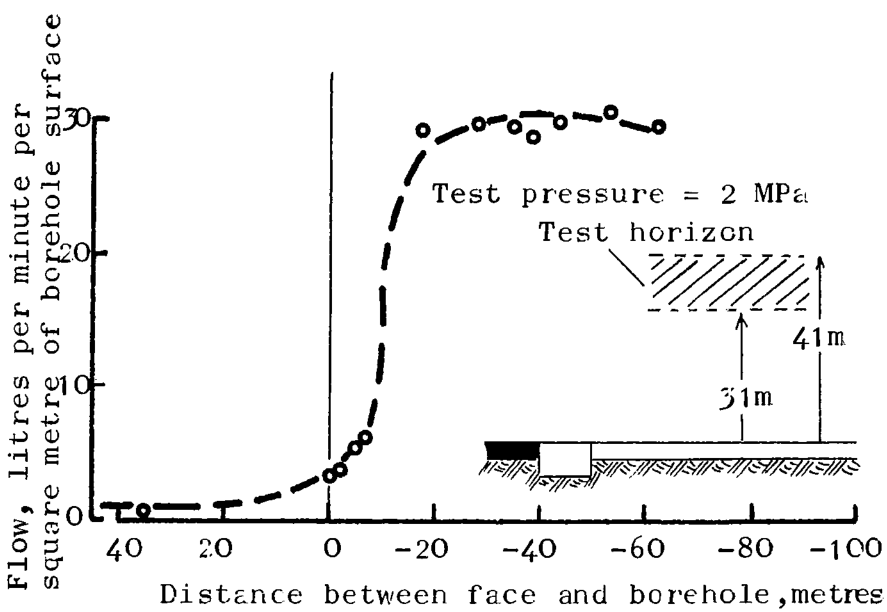

Figure 9. Relationship between flow characteristics of borehole No. 4 and face position

which shows the test horizon covering a band 2 to 8 metres above the seam, the results show that the strata were significantly affected immediately after undermining. In the case of Figure 9 which represents data from a test horizon covering 31 to 41 metres above the longwall extraction, the strata were not greatly affected until about 15 metres after undermining. In the latter case, a bed of sandstone and appreciable thickness of shale formed the strata test horizon and it appears that the sandstone behaviour during undermining may have accounted for the relatively high flow rate after undermining.

The results show that the maximum effect of undermining on change in ground permeability occurred between the face line and 40 metres behind, and there is a progressive upward movement of change in permeability behind the face line. The test results also generally indicate opening and closing of cracks and bed separation cavities during the undermining phase. After 40 metres behind the face line there is an indication of increasing consolidation of the strata taking place. The results and discussion here are in general agreement with the strata displacement results given in Figure 2.

STRATA PERMEABILITY CHANGES CLOSE TO THE SURFACE AND ABOVE LONGWALL EXTRACTION

The site selected for this part of the investigation was located in the Yorkshire Coalfield in the Swallow Wood Seam at Wentworth where the coal seam is 2.1 metres thick and 54 metres below the surface.

Figure 10 shows the position of the instrumented borehole in relation to the approaching longwall extraction (190 metres long) at the time the borehole was drilled.

The instrumented borehole was 96 millimetres diameter and drilled 42.7 metres deep. This depth was judged to give an adequate thickness of strata between the base of the hole and the underlying Swallow Wood Coal Seam (at 54 metres) which

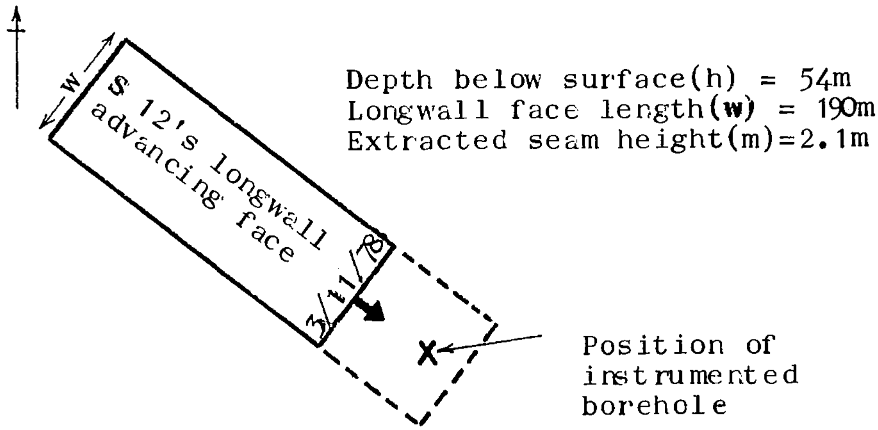

Figure 10. Location of instrumented borehole in relation to longwall face position (Wentworth site)

was to be undermined by S12's longwall face. A section of the strata at the borehole is given in Figure 13 and as can be seen the beds are mainly Coal Measures formation types which are well known for their relatively high impervious properties. The thickness of cover between the borehole base and the Swallow Wood Coal Seam was further increased by the 1.4 metre thickness of cement grout seal used at the base of the borehole to secure the first strain wire.

Figure 11 shows the instrumented borehole used at the Wentworth Test Site. Four permanent resin seals were located as shown. The seal was formed by firstly lowering a fairly tight-fitting multi-deck platform of fibre/foam discs secured to a steel framework, and thereafter Celtite-Selfix M100 resinous injection grout pumped to rest on the upper surface of this flexible temporary seal. The general procedure involved firmly securing the flexible temporary seal in position at the desired depth by clamping the 19 millimetre diameter plastic tubes (for subsequent testing) at the surface rig. Each temporary flexible seal was located in position by special insertion rods which were uncoupled from the seal prior to pumping the M100 grout onto the temporary seal. The grout produced a seal which was about 3 metres in length and

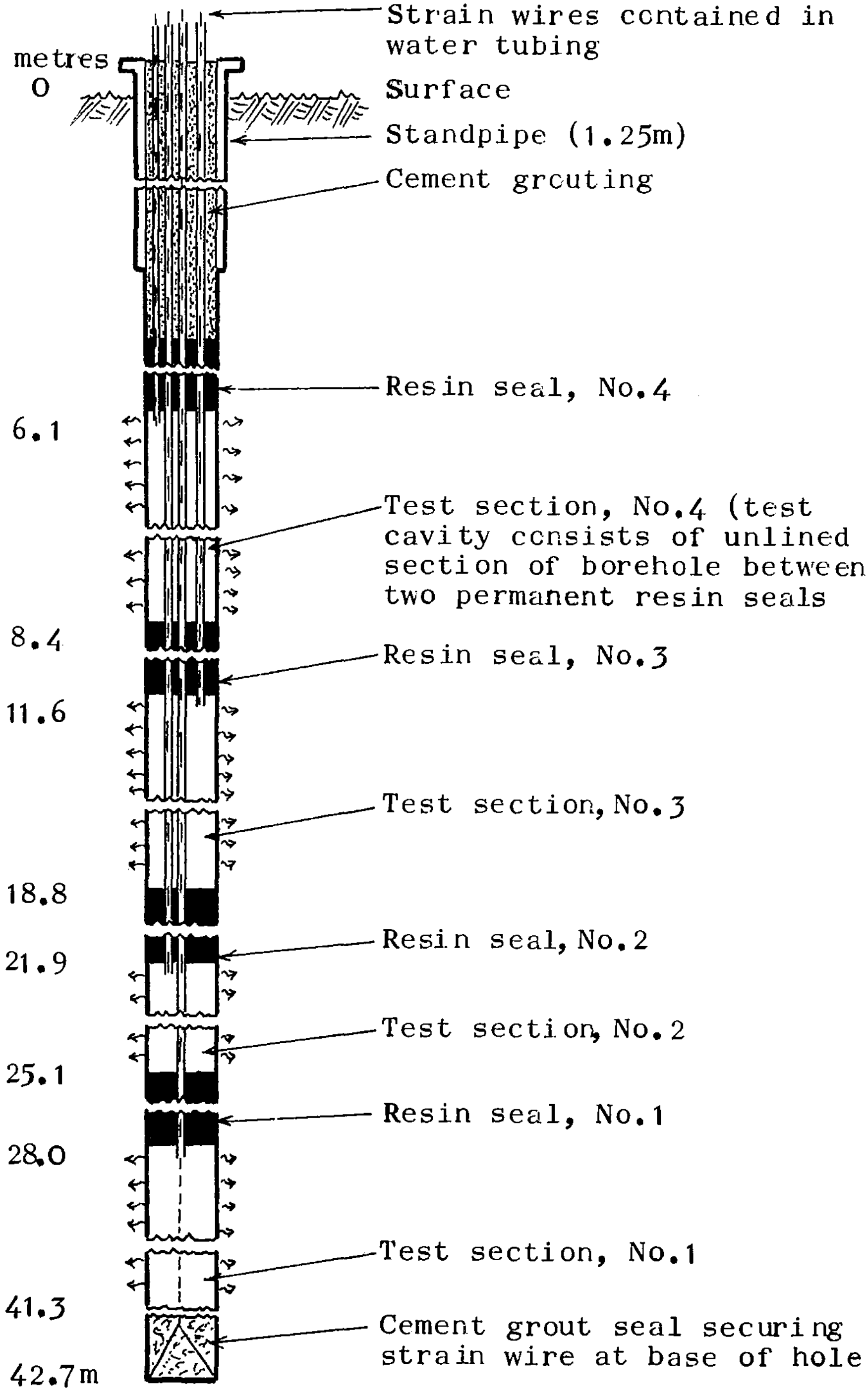

Figure 11. Wentworth instrumented borehole

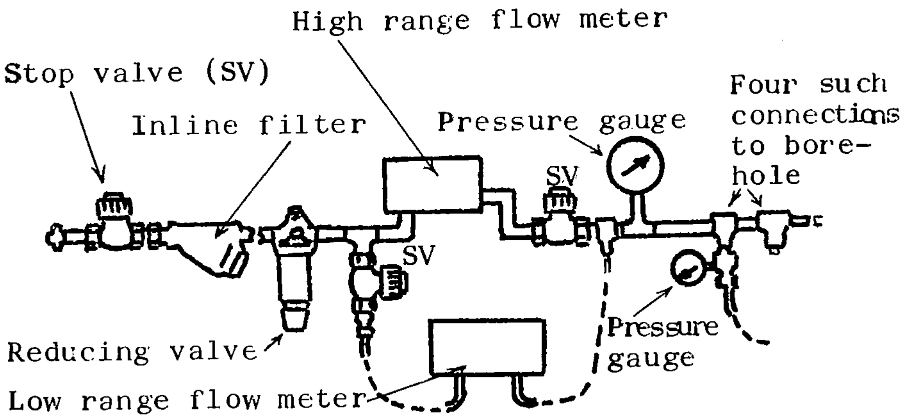

Figure 12. General hydraulic circuitry used at Wentworth instrumented borehole

proved effective in sealing different sections of a borehole which contained an increasing number of plastic tubes and was to be subsequently affected by undermining. Mechanical seals were judged to be inadequate for such geotechnical and mining conditions. Each seal was established as a separate operation and the resinous grout allowed to cure (about 2 - 3 hours) before the next seal operation was carried out. This method of providing a borehole with several sealed sections has been successfully applied in boreholes down to a depth of 70 metres and where six seals have been installed in a 100 millimetre diameter unlined hole. Strain wires were secured to the base of each resinous grout seal, and brought to the surface via the water pressure testing tube. Resin seal No.1 plastic testing tube contained two strain wires, one connecting to the base of the seal and the other to the base of the hole. The upper section of the borehole was grouted to a depth of 6.1 metres to test section cavity No.4. Each strain wire was tensioned and observations made of displacement with an extensometer.

The testing arrangement is shown in Figure 12. A rotameter was used to measure low flow rates up to 1 litre per minute. A constant test pressure of 2 bars (at the borehole mouth) was used throughout the testing programme.

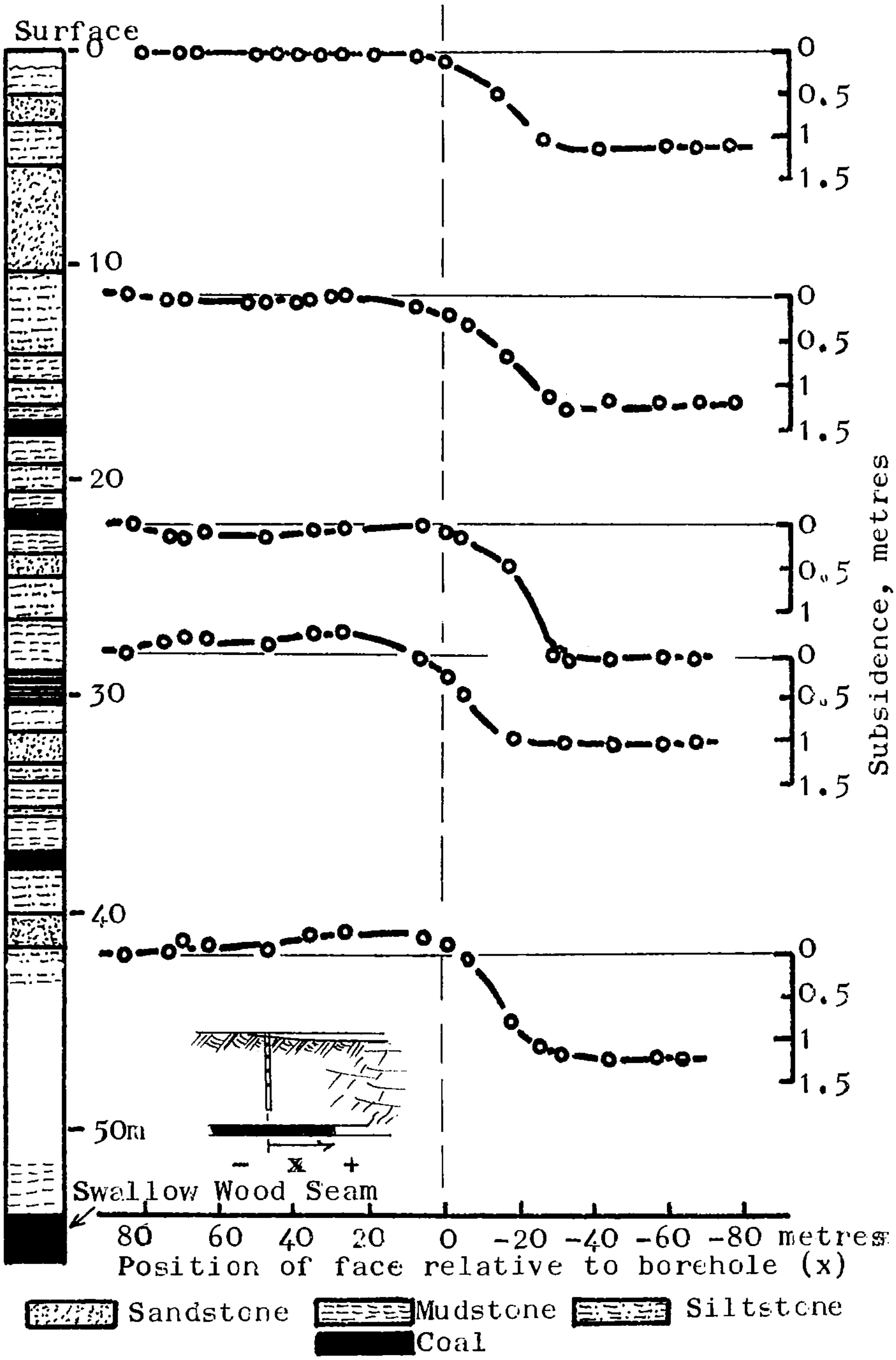

Figure 13. Surface subsidence and sub-surface subsidence characteristics, Wentworth borehole

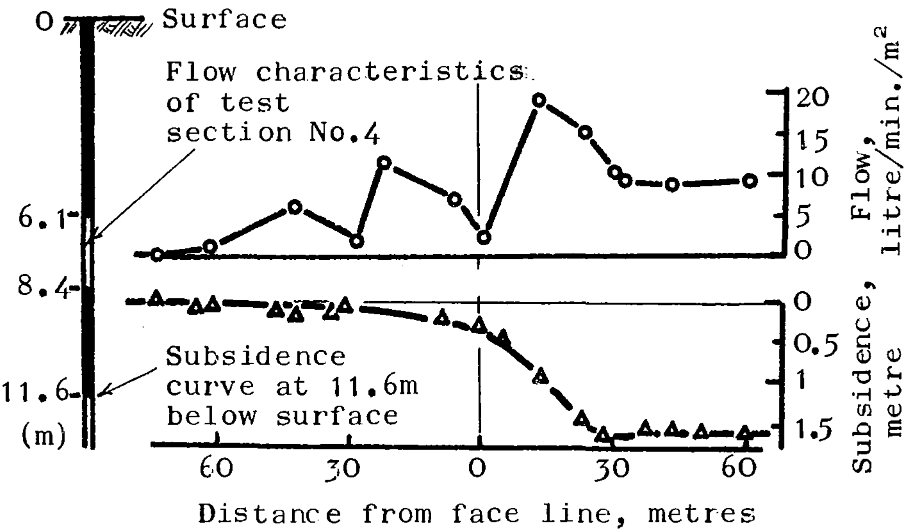

Figure 14. Flow characteristics of test section No.4 in relation to sub-surface subsidence arising from undermining, Wentworth instrumented borehole

Surface levelling was carried out to determine the progressive subsidence of the borehole mouth and also the seal positions within the borehole since strain readings relative to the borehole mouth were observed also.

TEST RESULTS IN PROXIMITY TO SURFACE

The surface subsidence curve for the borehole is shown plotted in Figure 13 together with the subsurface subsidence curves as determined using the strain wires. Some uplift of the strata ahead of the face line was recorded at the lower horizons. Subsidence showed a more marked change at the lower horizons as depicted by the more distinct step characteristic of the subsidence profile.

Figure 14 shows test results for the uppermost test section (No.4) and it demonstrates that discernible change in the flow characteristic was taking place at some 50-60 metres ahead of the face line and this increased in marked steps implying opening and closing of near-surface cracks/fissures. The flow curve settled to a consistent value at about 35 - 40 metres behind the face line.

The testing condition has been assumed to be equivalent to a constant head test and the following equations have been used for determination of in situ permeability of the strata. These equations represent Horslev's approach (3) and they have been discussed elsewhere (4) and (5) regarding application to estimation of in situ permeability of bedded and jointed rock structures.

$$k = \frac{q}{F.\ Hc} \qquad \ldots\ldots\ (1)$$

$$F = \frac{2\ \pi\ \ell}{\log_e(2\ m\ \ell/D)} \qquad \ldots\ldots\ (2)$$

combining (1) and (2)

$$k = \frac{q.\ \log_e(2\ m\ \ell/D)}{2\ \pi\ \ell.\ Hc} \qquad \ldots\ldots\ (3)$$

Where,
k = coefficient of permeability normal to hole
kp = coefficient of permeability parallel to hole
q = flow rate
F = shape factor of test cavity ($\ell > 4D$)
Hc = constant pressure head of water applied during test (above any original ground water value)
ℓ = length of test cavity
D = borehole diameter in test cavity
m = $(k/kp)^{0.5}$

The authors have adopted a value of $k/kp = 10^6$, this being consistent with an earlier paper by the present authors (5) and has been discussed in detail previously.

Values of in situ permeability have been determined using these equations and a detailed presentation of the results is given in Figure 15 which shows the ratio of subsequent permeability/base permeability plotted against longwall face position. These results indicate that the upper ten metres of the strata section (which contained a bed of sandstone, see Figure 13) experienced the

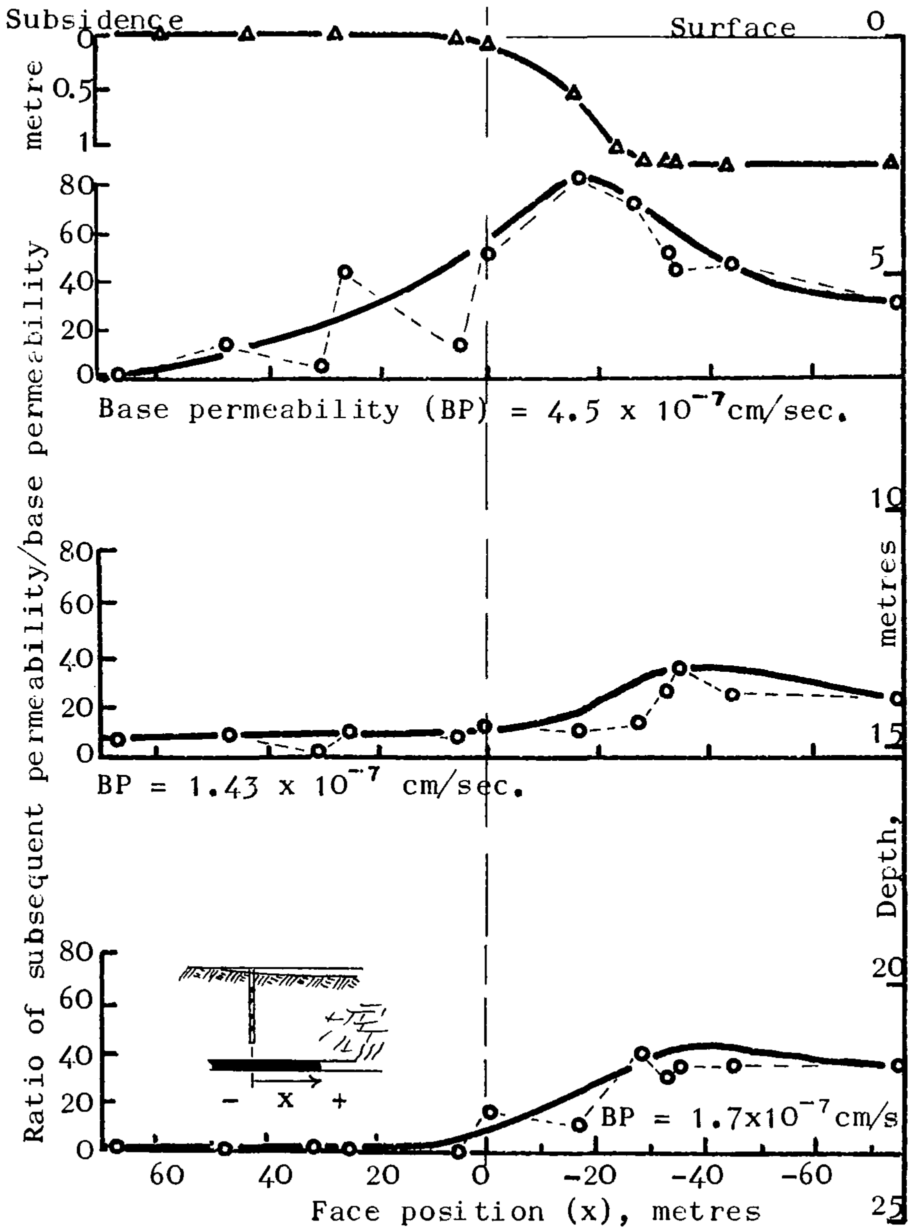

Figure 15. Illustrating comparison of change in ground permeability of strata overlying a longwall extraction (Wentworth instrumented borehole)

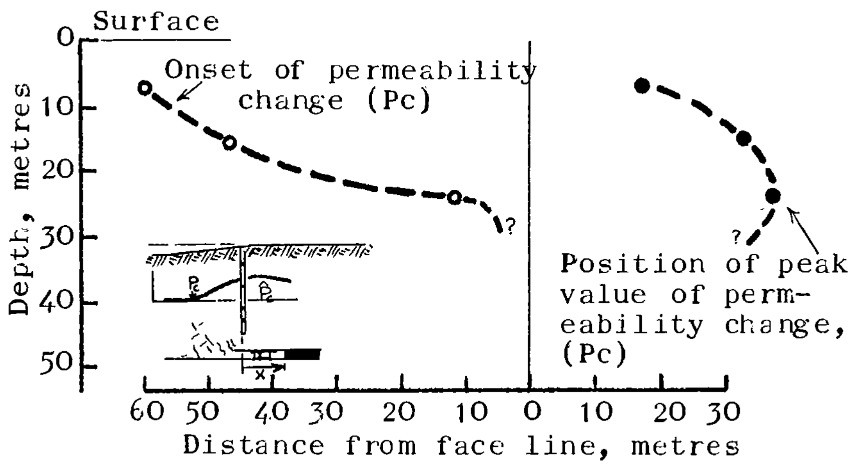

Figure 16. Position of onset and peak value of permeability change of strata overlying a longwall extraction due to undermining

greatest change in permeability. It is considered that the main factor responsible for this feature is the close proximity with the surface even though sandstone was present which would have also contributed to this degree of change. All the test curves indicate a tendency towards decreased change in permeability after 35 - 40 metres behind the face line.

Figure 16 has been plotted using data from Figure 15 and it indicates that onset of permeability change occurs significantly ahead of the face line with the upper test horizon when compared with the lower test horizons. A similar trend is indicated with the position of the peak value of permeability change.

GENERAL DISCUSSION OF RESULTS

The testing procedure and equipment described in the paper proved satisfactory for investigating ground permeability changes resulting from longwall mining operations. The instrumentation scheme was sufficiently sensitive to monitor small changes in permeability. The results permit the onset of permeability change arising from mining

Table No. I

In situ strata permeability data

Site	Test section	Test section position, metres	Strata type	In situ permeability (k) centimetres per second Base value	Maximum value
Deep Soft	1	2-8*	M Slt Sh	1.5×10^{-4}	1.4×10^{-3}
Deep Soft	2	8-11*	Slt M	1.1×10^{-5}	1.5×10^{-3}
Deep Soft	3	13-29*	M C Sh	1.4×10^{-4}	4.5×10^{-4}
Deep Soft	4	30-41*	Sh M Sd	5.7×10^{-6}	1.3×10^{-3}
Deep Soft	5	25-45*	M Sh Sd	5.2×10^{-6}	4.9×10^{-5}
Wentworth	1	28-41**	C M Sd Slt	1.0×10^{-9}	NA
Wentworth	2	22-25**	C M Sd Slt	1.7×10^{-7}	2.1×10^{-6}
Wentworth	3	12-19**	Slt M C	1.4×10^{-7}	6.6×10^{-6}
Wentworth	4	6-8½**	Sd	4.5×10^{-7}	2.3×10^{-5}

* measured vertically above coal seam; ** measured below surface
C = coal, M = mudstone, Sh = shale, Slt = siltstone, Sd = sandstone
NA = not available

proximity to be readily evaluated. Values of in situ permeability have been calculated for the experimental sites described in the paper, and Table I presents the base and maximum values of coefficient of permeability (k) for each of the test horizons studied.

In the case of the Deep Soft Coal Seam Experimental Site the ground was found to have a discernible degree of permeability before being disturbed by current longwall mining, see Table I. This is probably due to previous mining. The effect of current mining operations was to produce appreciable change in ground permeability especially in the test zones near to the mining horizon.

The strata tested can be described as virtually impermeable before undermining in the case of the Wentworth Site, but after undermining change in ground permeability was sufficient to promote minor flow in the case of the upper horizon but the lower horizons were not so affected. The presence of impervious beds within the strata sequence plays a major role in such mining situations.

CONCLUSIONS

1. The instrumentation and testing procedure proved successful for studying ground permeability change resulting from undermining by a longwall extraction.

2. The main zone of appreciable change in in situ permeability was found to lie between the face line and 40 metres behind the face.

3. Appreciable in situ permeability change was observed to occur up to 40 metres above the extraction horizon.

4. Changes in ground flow properties of the strata were found to be of a stepped characteristic and this is thought to be due to opening and closing of cracks and separations.

5. Significant change in ground permeability

was observed close to the surface above a long-wall extraction in shallow mining conditions.

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