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THE EFFECT OF TEST CAVITY GEOLOGY ON THE IN SITU PERMEABILITY OF COAL MEASURES STRATA ASSOCIATED WITH LONGWALL MINING

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ABSTRACT

Longwall mining results in induced ground strains which cause in situ permeability changes in the surrounding strata. A review is made of the two methods most commonly used to measure in situ permeability changes, namely 'pumping out' and 'pumping in' tests, along with the advantages and disadvantages of their use in Coal Measures strata. A detailed examination is then made of the effects of test cavity geology on the induced in situ permeability changes monitored at five investigation sites in Great Britain.

INTRODUCTION

Longwall mining results in a redistribution of stresses, which in turn causes a change in the natural in situ permeability regime of the surrounding strata. A variety of techniques have been used in an attempt to understand the nature of the observed changes and these vary in approach from mathematical modelling to the empirical method of selectively analyzing field data.

The empirical technique was adopted by an established research group six years ago (1, 2, 3, 4, 5), whereby field data was collected over a variety of British mining sites and analyzed with a view to establishing a unified approach similar to that achieved by the National Coal Board for the prediction of mining subsidence (6). In a previous paper (7), the authors re-examined the original data and presented the results in a unified form, thus allowing observed permeability changes to be related directly to specific areas of strata occurring around the longwall panel: ahead of the face line, the face end and the ribside pillar.

The object of this paper is to examine the relationship between the induced permeability changes and the geological horizons in which the original test cavities were located.

DETERMINATION OF IN SITU STRATA PERMEABILITY

Originally, analytical techniques were developed to determine the properties of an isotropic, homogeneous aquifer, which exhibited Darcian flow conditions. Subsequently, further techniques were involved which allowed for a variety of simplified aquifer conditions and boundary effects to be taken into account, although a Darcian flow regime was still assumed. An examination of field data reveals the flaw in this hypothesis, since aquifer formations seldom exhibit Darcian conditions and except in extremely localized areas exhibit considerable lithological and structural anisotropy. However, non-Darcian techniques are extremely complex and usually involve the substitution of arbitrary values into 'undefined' parameters. A compromise must therefore be reached between the use of semi-applicable Darcian techniques and the complex non-Darcian equations.

Two main techniques are employed for the field determination of aquifer parameters, both of which assume Darcian conditions:

1. Pumping Out Tests
2. Pumping In Tests

Each method has its relative advantages and disadvantages depending upon the type of test strata.

The British Coal Measures constitute a series of interbedded sandstone, siltstone, mudstone, seatearch/coal sequences which exhibit a relatively low permeability regime. However, each strata sequence exhibits a combination of intergranular and fracture/fissure permeability components.

It is therefore intended to briefly examine the applicability of each technique to Coal Measures strata, before examining in more detail the relationship between observed permeability changes and the test cavity geology.

'PUMPING OUT' TESTS IN COAL MEASURES STRATA

The parameters of any aquifer system with an abundant supply of in situ water can be determined by 'pumping out' techniques. The technique involves test pumping a well, monitoring the resultant drawdown and/or recovery and then subjecting the data to a variety of curve fitting or semi-analytical techniques (8, 9).

When analyzing the data, it is normally assumed that either Darcian or near Darcian conditions exist in strata surrounding the well. However, Coal Measures strata particularly in areas of mining activity usually exhibit a marked degree of fracture/fissure permeability in the flow regime. It is therefore necessary to question the validity of such techniques in Coal Measures strata or for that matter in any conditions where a marked fracture fissure permeability exists.

An analysis of 76 wells and boreholes sunk in the limestone/carbonate formations of the Silurian/Devonian of Ohio, U. S. A. (10) revealed that when the data was analyzed using standard methods (8, 9), the pumping out technique was valid, although the results needed to be interpreted with care. However, it was necessary to assume that the aquifer permeability was predominently fracture/fissure and that the fissure networks were connected on an areal basis. Similarly, although minor inconsistencies did occur, realistic transmissivity and permeability values could be obtained, especially on a regional basis. In another case (11), a detailed examination of constant rate tests in an ultra-mafic orebody in India, revealed that parameters could be reliably obtained using existing techniques in an aquifer with a predominant fracture/fissure permeability regime.

Theoretically, the pumping out test can be used to evaluate the aquifer parameters of Coal Measures strata (10, 11). However, the aquifers are usually small with finite quantities of water contained in low yielding formations and insufficient water is usually present to undertake prolonged pumping. Similarly, the technique usually requires the installation of a submersible pump in the borehole. Test boreholes must therefore be of sufficient diameter to allow the insertion of a pump and stable enough to prevent subsequent damage. This latter aspect is particularly important if permeability changes are to be monitored in the dynamic conditions which exist around an advancing longwall. Finally, since the technique can only be used in boreholes oriented vertically downwards, the technique has limited application to underground mining conditions.

'PUMPING IN' TESTS IN COAL MEASURES STRATA

When a strata type is encountered which has either insufficient yield for pumping out tests or a low permeability, then an alternative monitoring technique can be used whereby water is pumped in. A comprehensive discussion and analysis of pumping in techniques for the determination of permeability is given elsewhere (12, 13).

Pumping in techniques can be readily adapted for monitoring aquifer parameters in low permeability formations, such as the Coal Measures. The technique is not restricted to use in stable ground conditions and can be used in boreholes of any desired orientation, providing a suitable packer arrangement is designed and installed. However, as with all techniques, certain inherent problems do exist. Test cavities within the borehole must be located so as to minimize boundary effects between one or more strata types. This is particularly important in Coal Measures strata and a detailed knowledge of the site geology is essential before installation of the test equipment. Also the assumption that Darcian conditions exist around the test cavity is necessary for the development of workable equations. However, accurate permeability values can be obtained with a high degree of confidence and the collection of a series of values at a static site will usually provide a base value against which later dynamic values can be compared.

TEST CAVITY GEOLOGY VS PERMEABILITY

A full description and discussion of the five test sites examined is beyond the scope of this paper and has already been adequately covered elsewhere (1, 2, 3, 4, 5). Similarly, those areas in which permeabliity changes occur around a longwall panel and their relation to subsidence profile formation have also been discussed elsewhere (4, 5, 7).

The spatial location of each test site in relation to the longwall panel as well as the sequence of test cavities in each borehole is given in Figure 1. Table 1 lists the test cavity geology and dimensions at each site and was derived by either direct examination of core samples or the extrapolation of geological data from nearby logged boreholes.

Examination of Table 1 reveals that the test cavities can be divided into one of four geological types:

1. Sandstone
2. Sandstone, Mudstone and Coal
3. Composite Sequences
4. Coal

In order to obtain a meaningful data set, all the re-assessed data (5, 7) was arranged into a series of arbitrary face positions. A comparison of the various geological cavity types and their permeability values can therefore be undertaken.

SANDSTONE TEST CAVITIES

Table 2 gives tabulated mean permeability values for Lynemouth Borehole No. 1 cavities 1 and 5 (1.1 and 1.5), Borehole No. 2 cavities 1 and 5

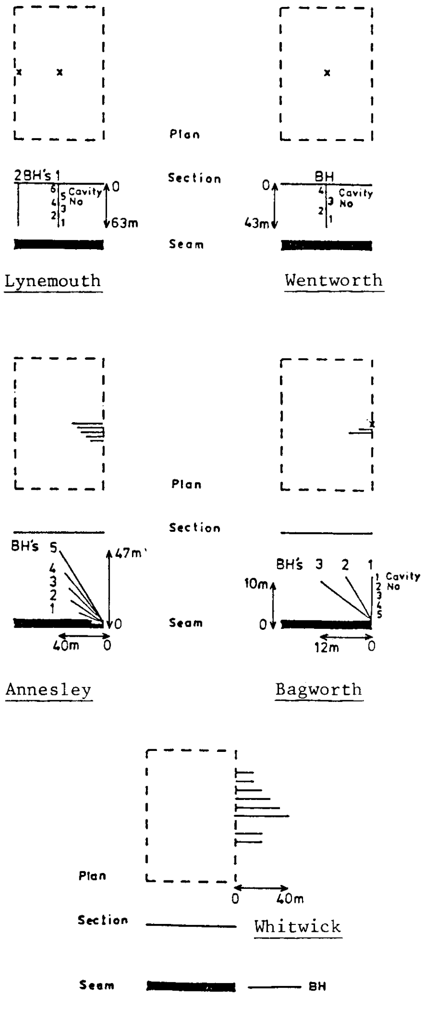

Figure 1 - Spatial Position of the Test Sites in Relation to the Extraction Panel

Test Site	Test Cavity No. 1	Test Cavity No. 2	Test Cavity No. 3	Test Cavity No. 4	Test Cavity No. 5	Test Cavity No. 6
Lynemouth No. 1 B'H	Sandstone 6.10*	Sandstone 4.57 Coal 0.38 Mudstone 1.52	Sandstone 4.57 Mudstone 1.52 Coal 0.23	Sandstone 4.57 Mudstone 1.52 Coal 0.68	Sandstone 6.10	Sandstone 7.62 Mudstone 3.05 Coal 0.53
Lynemouth No. 2 B'H	Sandstone 6.10	Sandstone 4.57 Mudstone 1.52 Coal 0.23	Sandstone 4.57 Mudstone 1.52 Coal 0.46	Sandstone 4.57 Mudstone 1.52 Coal 0.38	Sandstone 6.10	Sandstone 7.62 Mudstone 3.05 Coal 0.38
Wentworth	No Permeability readings Composite Geology	Mudstone Sandstone Siltstone	Mudstone Siltstone Coal 0.79	Sandstone	-	-
Annesley	Mudstone Shale Siltstone Mudstone	Siltstone Mudstone Shale	Shale Mudstone Shale Sandstone Mudstone Coal Mudstone Coal Mudstone	Shale Sandstone Shale	Mudstone Shale Sandstone Shale Mudstone	-
Bagworth No. 1 B'H	Siltstone	Sandstone Ironstone Siltstone	Siltstone	Siltstone Mudstone	Mudstone	-
No. 2 B'H	Siltstone	Sandstone Ironstone Siltstone	Siltstone	Siltstone Mudstone	Mudstone	-
No. 3 B'H	Ironstone Siltstone	Siltstone	Siltstone Mudstone	Mudstone	Mudstone Ironstone	-
Whitwick	All cavities in Coal Ribside Pillar					

* All lengths in metres

Table 1 - Dimensions and Geology of the Test Cavities

	LYNEMOUTH				WENTWORTH
	B'H1		BH2		
Face Position (m)	1	5	1	5	4
+ 100	N/A	3.1	13.6	0.6	-
70 - 100	5.7	69.1	5.6	2.3	-
30 - 70	7.6	67.4	11.8	5.7	1.0
10 - 30	4.8	40.7	5.5	9.5	11.9
0 - 10	2.7	24.4	11.8	9.4	5.7
20 - 0	-	-	-	-	-
50 - 20	-	-	-	-	20.4
First 4 Days	4.4	6.4	9.2	9.1	-
After 4 Days	8.3	72.9	23.7	13.1	28.3

All permeability values are x 10^{-6} cms^{-1}

Table 2 - Permeability Values for the Lynemouth and Wentworth Sandstone Cavities

	LYNEMOUTH								WENTWORTH
	B'H1				B'H2				
Face Position (m)	2	3	4	6	2	3	4	6	3
+ 100	4.5	12.1	8.0	4.0	4.0	9.3	5.2	5.9	-
70 - 100	12.0	40.1	42.0	19.1	1.4	5.3	6.8	9.8	-
30 - 70	29.9	35.2	51.2	18.5	6.7	5.4	22.3	29.5	0.2
10 - 30	35.4	25.7	16.3	18.7	11.7	15.6	14.2	16.0	0.1
0 - 10	48.0	36.0	7.5	16.6	8.2	7.4	14.4	18.8	0.9
20 - 0	-	-	-	-	-	-	-	-	-
50 - 20	-	-	-	-	-	-	-	-	4.2
First 4 Days	25.2	30.2	3.1	7.2	10.4	11.1	37.9	12.4	-
After 4 Days	28.8	46.1	23.5	10.2	17.3	19.7	38.7	14.3	2.3
Coal seam thickness (m)	0.38	0.23	0.38	0.53	0.23	0.23	0.38	0.15	0.79

All permeability values are x 10^{-6} cms^{-1}

Table 3 - Permeability Values for the Lynemouth and Wentworth Sandstone, Mudstone and Coal Seam Cavities

(2.1 and 2.5) and the Wentworth No. 4 cavity.

Geologically, it appears as though the cavity 1 and cavity 5 sandstone horizons intersect both the No. 1 and No. 2 boreholes. In the cavity 1 sandstone it appears that slightly greater permeability values are experienced in the No. 2 rather than the No. 1 borehole, while in the cavity 5 sandstone the permeability values are greater in the No. 1 rather than the No. 2 borehole. It is difficult to explain the observed values purely in terms of tensile strain associated with subsidence profile formation and it is possible that geological or test cavity factors may have affected the results. A more detailed discussion of geological and test cavity factors is given in a subsequent section.

Observed permeability fluctuations in the cavity 1 sandstone at Lynemouth varied between 2.7×10^{-6} cm $^{-1}$ and 1.4×10^{-5} cm $^{-1}$, while those in the cavity 5 sandstone varied between 6.0×10^{-7} cm $^{-1}$ and 7.3×10^{-5} cm $^{-1}$ for the same range of face positions. A comparison of the Lynemouth and Wentworth sandstone cavities reveals similar permeability changes within the magnitude of 10^{-6} to 10^{-5} cm $^{-1}$ over the same distance of face advance.

SANDSTONE - MUDSTONE - COAL CAVITIES

Detailed logging of the Lynemouth and Wentworth boreholes provided a unique opportunity to examine permeability changes associated with test cavities intersected by coal seams. In each case, but with the exception of Lynemouth No. 6 and Wentworth No. 3, the mean cavity length was 6 m. The Lynemouth No.'s 2, 3 and 4 cavities have typical geological sequences with up to 4.5 m of sandstone and 1.3 m of mudstone, in which are contained coal seams of variable thickness up to a maximum of 0.6 m. Table 3 lists mean permeability values for each test cavity over a range of face positions along with the thickness of coal occurring in each cavity.

Initially, it was thought that the presence of a coal seam within a test cavity might effect the magnitude of the recorded permeability values.

Similarly, the greater the coal seam thickness then the greater the change. However, a careful examination of the results reveals no indication of this trend. In the Wentworth No. 3 cavity the recorded permeability values are lower than any recorded in similar Lynemouth cavities, even though it is intersected by a thicker coal section: 0.79 m at Wentworth compared with a maximum of 0.53 m at Lynemouth.

A direct comparison of the Wentworth and Lynemouth cavities reveals a permeability range of 10^{-7} to 4.2×10^{-6} cm $^{-1}$ compared with 4.5×10^{-6} to 4.8×10^{-5} cm $^{-1}$ over the same distance of face advance.

COMPOSITE CAVITIES

The composite test cavities constitute those which intersect more than one identifiable strata type. In the case of the remaining Wentworth, Annesley and Bagworth boreholes, the test section usually comprised a highly interbedded sequence of mudstones, siltstones, sandstones and seatearth/coals. In each case, the composite cavities exhibited lower permeability values, 10^{-7} to 10^{-6} cm $^{-1}$, than those seen in either the sandstone or sandstone-mudstone-coal cavities over the same range of face advance.

COAL CAVITIES

Figure 2 shows iso-line permeability values for a ribside coal pillar (1). The permeability at any point within the pillar appears to be governed by the face proximity to the test site.

Permeability values of greater than 10^{-2} cm $^{-1}$ are recorded in the pillar section closest the working panel (less than 5 m from the roadway). Further into the pillar, 5-10 m depth, permeability values of between 10^{-2} and 10^{-4} cm $^{-1}$ are recorded which continue to decrease with increased distance towards the pillar core. The results suggest that fracture/fissure zones (or permeability) associated with stress relief around the working panel are less well developed within the pillar core.

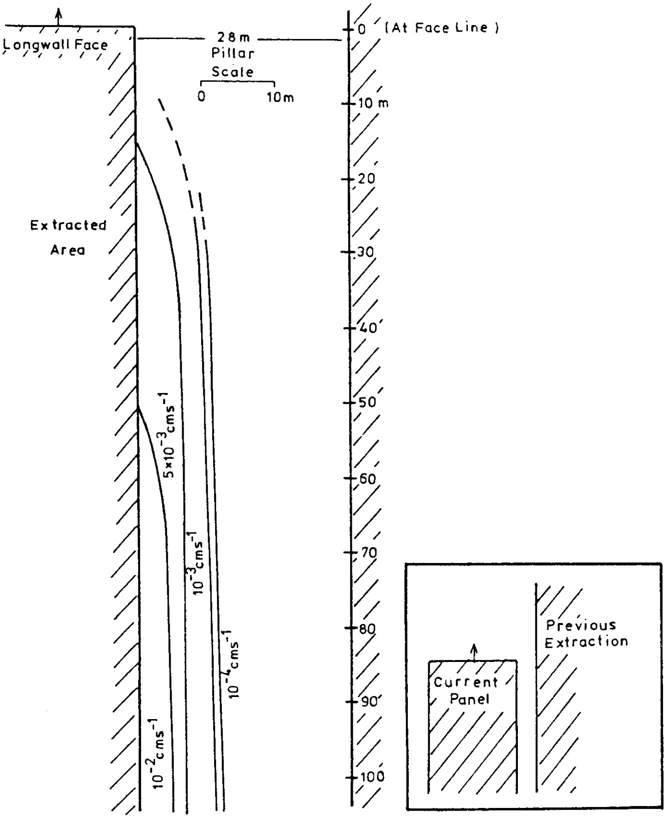

Figure 2 - Iso-line Permeability Values for a Ribside Coal Pillar, Whitwick Colliery (after Whittaker and Singh (1))

DISCUSSION OF RESULTS

The greatest permeability values and fluctuations occurred in the ribside coal pillar. Progressively smaller values and fluctuations are then seen in the sandstone-mudstone-coal, sandstone and composite cavities. The question therefore arises, how can the permeability changes be related to the geology of the test cavity unit.

All Coal Measures strata exhibits a variable lithology both sequentially and spatially, which is intersected by either micro or macro level discontinuities. A test cavity therefore exhibits three dimensional anisotropy based on variable lithology, each sequence of which exerts a combination of intergranular and fracture permeability, Figure 3.

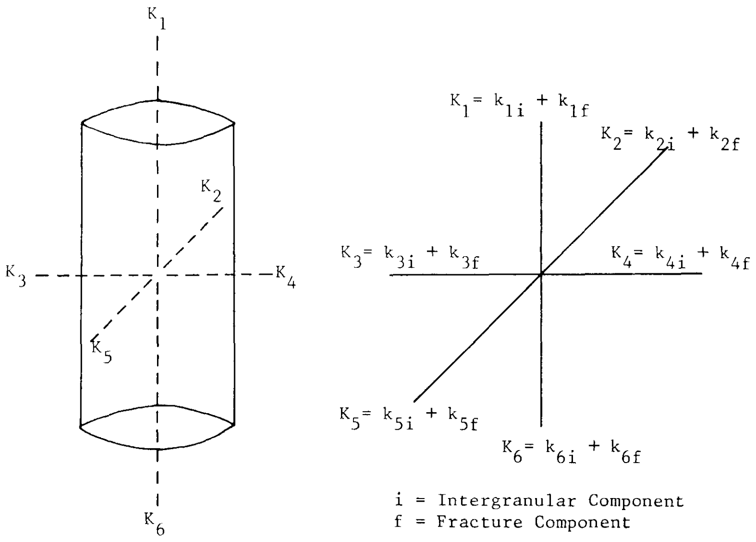

Figure 3 - Test Cavity Exhibiting Three-Dimensional Anisotropic Permeability

If a test cavity is subjected to dynamic conditions, such as increasing face proximity, a change will occur in the relationship between intergranular and fracture permeability. For example, a sandstone cavity under static conditions will exhibit a much greater proportion of intergranular rather than fracture permeability provided that it is not intersected by significant discontinuity systems. However, once influenced by induced stresses due to mining, separation begins to occur along planes of inherent weakness and the fracture component of the permeability regime begins to increase. This model can now be related to the sandstone and sandstone-mudstone-coal cavities and used to explain the increasing, though fluctuating permeability values seen with increased face proximity and the marked increase apparent once the face line has passed the site.

Low permeability values seen in the composite cavities are primarily due to the presence of mudstones, siltstones, and shales all of which have very low permeability regimes unless fractured. Under normal conditions these cavities normally exhibit either aquitard or aquiclude properties, although the proposed model derived in Figure 3 can also be applied.

Some of the mudstone, siltstone and shale sequences can contain small quantities of clay minerals, which upon becoming wet swell. This in turn can produce a self-sealing effect in the test cavity and reduce the overall in situ permeability, unless either washing out occurs or sufficient induced stress is exerted to rupture the seal. It is therefore possible for the silting up or washing out of strata around a test cavity to alter the natural in situ permeability of the monitored horizon.

Similarly, errors can occur, whereby cement seepage from the sealing plug section of the test cavity, if such seals are used, can cause a whole host of possibilities ranging from the partial to complete blockage of the test cavity, as in the Wentworth No. 1 cavity. A partial cement shell could form around the test cavity wall, which initially would be impermeable, although still sufficiently weak to be broken by the stresses induced by mining. Cement from a seal section could also penetrate the strata surrounding a test cavity via natural fracture/fissure networks, thereby reducing the inherent strata permeability.

CONCLUSION

Ground strains induced by longwall mining can be linked to changes in strata permeability. However, the magnitude of the induced permeability changes appear to be significantly effected by the geology of the horizon in which the test cavity is located. The presence of coal seams within the test section does not appear to effect the magnitude of the recorded permeability values. Finally, 'pumping in' techniques appear very adaptable for measuring permeability changes in Coal Measures strata or any geological horizon exhibiting low permeability values or containing low yields of water.

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