Fault reactivation, an example of environmental impacts of groundwater rising on urban area due to previous mining activities

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ABSTRACT: Groundwater rising phenomena have been reported in many circumstances, and the mechanism of rising groundwater varies according to hydrological and hydrogeological conditions. Groundwater rising can cause various geohazards which can have serious impact on environment as well as society. Fault reactivation is one such geohazard example associated with rising groundwater. The case in the Durham Coalfield is one of the cases where many recent fissurings can be found and are considered to be the result of fault reactivation accompanied with rising groundwater after cessation of coal mining over the region.

The aim of this research is to estimate past and present hydrogeological condition in the Durham Coalfield enabling the evaluation of the influence of rising groundwater phenomenon on the urban and rural environment.

Hence, in this research, the hydrogeological condition of the Durham Coalfield is evaluated. The past and present condition is discussed with the available groundwater data, and the future trend has been simulated, by a numerical hydrogeological model using a 3-D groundwater code MODFLOW. The result of hydrogeological model for past, present and future conditions show that general groundwater level in the Durham Coalfield has been rising for the last a few decades. The discussion of this research shows that groundwater rising can cause pore water pressure to increase, resulting in reducing shear strength of pre-existing fault, which has been shown by some case histories. In addition it is found that some fault directions enables slippage and some faults have experienced fault reactivation. Therefore it is concluded that this reduction in fault strength caused by change in hydrogeological condition of the Durham Coalfield enables a pre-existing fault to be reactivated when they exist in a direction of slip with respect to present regional stress direction.

1 INTRODUCTION

Groundwater levels can change due to the variation of inflow into and outflow from a groundwater body. The change in groundwater regime can influence the ground mass in various ways.

The research presented in this paper focused on the rising groundwater phenomena in the Durham Coalfield, England. Rising groundwater is considered to result from partial cessation of dewatering in former coal mine workings. At the same time, fissuring has been reported over the region for the last a few decades. Donnelly (2006) represented 12 cases of fault reactivation in the Durham and Northumberland Coalfield which date back to the 1960's, while reviewing coal mining induced fault reactivation in U.K. Wingham (2000) introduced several cases of open fissures which occurred at some places in the Durham Coalfield such as Quarrington Hill. Young and Culshaw, (2001), and Young and Lawrence (2001) reported fissuring and related ground movement on the Houghton-le-Spring area in the Durham Coalfield. Some fault reactivations of the cases presented above are considered to have been induced directly by coal mining activities, while other cases are unlikely to be to have directly resulted from the coal exploitation, as those mine workings had been closed too early to result in any further recent fissurings. Thus the research presented in this paper will evaluate the relationship between rising groundwater and fissuring in the Durham Coalfield.

The research presented here has reviewed physical setting of the Durham Coalfield, and general mechanism of groundwater level rising from which its impact on the environment has been suggested. The hydrogeological model of the Durham Coalfield was created in order to evaluate the hydrogeological change over the region. In addition, the created numerical model, hydrogeological conditions have been evaluated under scenario when the present pumping scheme is ceased, this representing the worst case future scenario. Finally as the result of groundwater level rising, the mechanism of fault reactivation will be discussed, based on the worst case scenario of a complete cessation of pumping across the Durham Coalfield as well as on a present hydrogeological condition.

2 DURHAM COALFIELD

2.1 *Physical setting*

The Durham Coalfield is located in the North-eastern side of England, which is bounded by the North Sea to the East and by the Pennine to the West. The River Tyne flows and makes an approximate northern boundary of the region. The River Wear flows through the Durham Coalfield (Figure 1).

Generally western parts consist of higher area and the topography is slightly inclined to the east making river flow to the east.

Geology mainly consists of the Permian Rocks and the Carboniferous Rock (Figure 2). The Pre-Carboniferous strata exist beneath the Carboniferous Rocks but do not outcrop over the Durham Coalfield. The Permian Rocks overlying the Carboniferous Rocks unconformably.

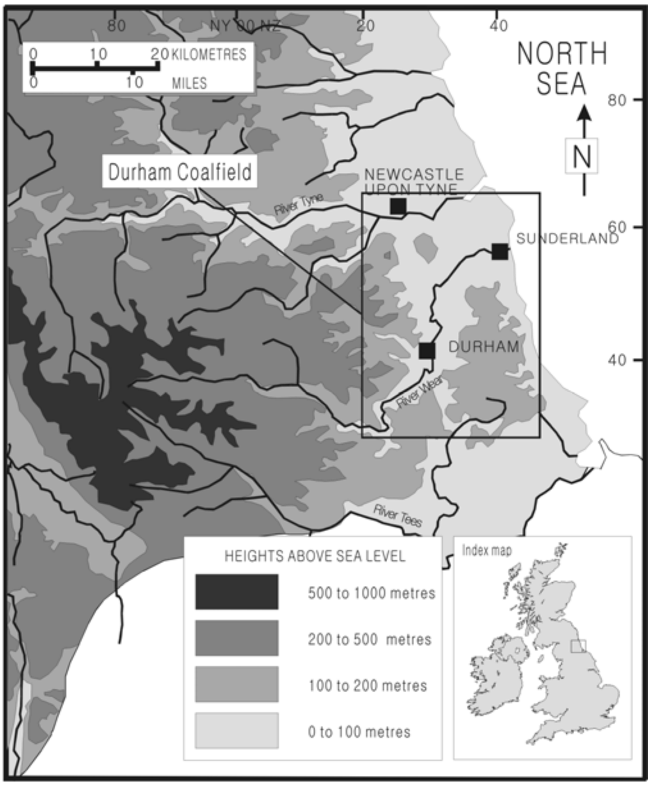

Figure 1. Geographical settings of the Durham Coalfield (after Taylor et al., 1971)

2.2 *Fissuring and fault reactivation*

In the Durham Coalfield, fissuring and related ground movements have been reported (Wingham, 2000; Donnelly, 2000; Young and Culshaw, 2001; Young and Lawrence, 2001; Donnelly, 2006). One example of such fissures and holes found near Quarrington Hill, County Durham (Figure 3) is over 2 metres deep with a diameter of around 1 metre, representing a threat to the local communities over the region.

Young (2003) reported fissuring causing cracking of the A690 road near Houghton-le-Spring in the Durham Coalfield, which needed immediate repairs to be undertaken by the local authority in April 2000 and again in June 2003. Cracks appeared on the A690 road surface, fissures were found on the west cutting of the A690 and top of hill on both side of the road were almost at the same line (Young and Culshaw, 2001).

In the Durham Coalfield collieries the use of deep mining methods ceased by 1993 (Yu, 2006), which makes it unlikely that those recent fissurings are directly influenced by coal mining (i.e. ground expression of mining subsidence or mine induced fault reactivation). It may be that fissuring has only been recently noticed and the causal mechanism dates from earlier activity and is directly related to mining activity. However, Yu (2006) after evaluating this considered that a more likely mechanism was due to groundwater induced fault reactivation (see discussion in Section 5.1). It should be noted that in the area of Quarrington Hill, the colliery was closed in 1983 (Wingham, 2000), and in Houghton-le-Spring area, Houghton Colliery was abandoned in 1981(Young and Culshaw, 2001). Thus groundwater induced movement seemed a more likely explanation.

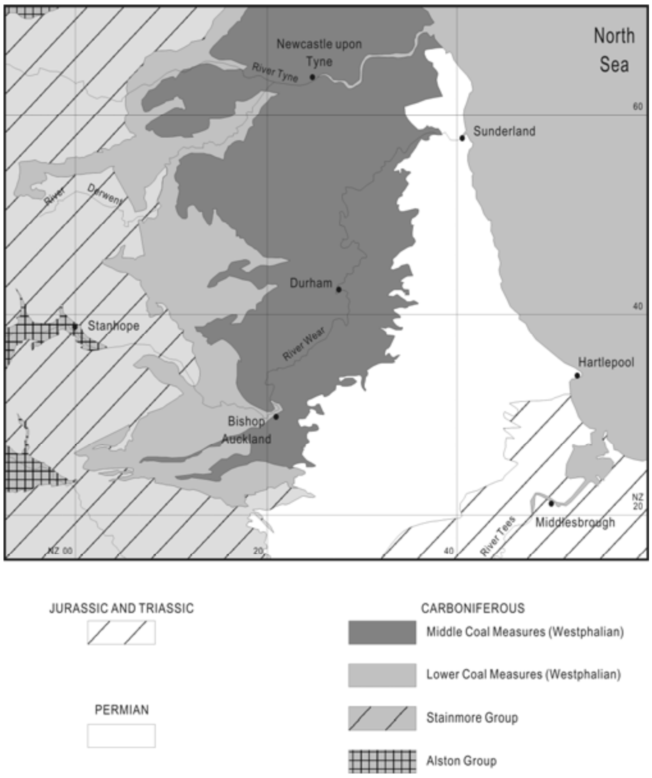

Figure 2. Geological map of the Durham Coalfield (Yu, 2006)

3 GROUNDWATER RISING AND ITS IMPACT

It has been reported that in various regions groundwater level is rising for a number of reasons. Yu (2006) reviewed the possible sources of groundwater level change including change in precipitation, river level change, sea level change, urbanisation, agricultural activities, and mining activities. With respect to the Durham Coalfield, it is concluded that mining activities mostly influenced the change in groundwater regime over the region (Yu, 2006).

The Durham Coalfield was one of the most famous coalfields in England, whose history of the coal exploitation dates back to medieval times. During coal mining, the groundwater level was lowered in order to make the coal work accessible. However after closing coal mining in the Durham Coalfield, the dewatering scheme was changed, causing an alteration in the groundwater level over the region. Younger (1995) and Yu (2006) showed groundwater level changes over the research area.

Figure 3. Depression shown on the surface in the Durham Coalfield

Groundwater rising phenomena can cause some serious impact on the local communities over the regions, such as landslides, ground subsidence, seismicity, gas emission, impact on structures, and salinisation (Yu, 2006). It is suggested that seismicity or fault reactivation and gas emission are main key geohazard occurrences influenced by changes in groundwater level in the Durham Coalfield (Yu, 2006).

4 HYDROGEOLOGICAL CONDITONS OF THE DURHAM COALFIELD

Hydrogeological setting of the Durham Coalfield has been reviewed from late 1980's to the future case of a full cessation of dewatering (the worst scenario) based on measured groundwater level data and numerical simulation.

4.1 *Past and present conditions*

Yu (2006) showed the groundwater levels have changed from 1995 to 2004. However, it was difficult to acquire reasonable data sets on groundwater levels before 1995 since the data sets available do not cover the whole area. This can lead to an unreliable hydrogeological model of the Durham Coalfield. The most detailed data for groundwater levels before 1995 has been presented by Harrison et al. (1989). Figure 4 shows the groundwater level change between late 1980's and 2004. Figure 4 indicates groundwater level in the areas around Sunderland and Seaham change drastically for this period, showing a change of a few hundred metres.

The reason why those two areas experienced the severe change in groundwater level is related to the relatively late closure (early 1990's) of collieries under operation around those areas and their associated deep groundwater control necessity.

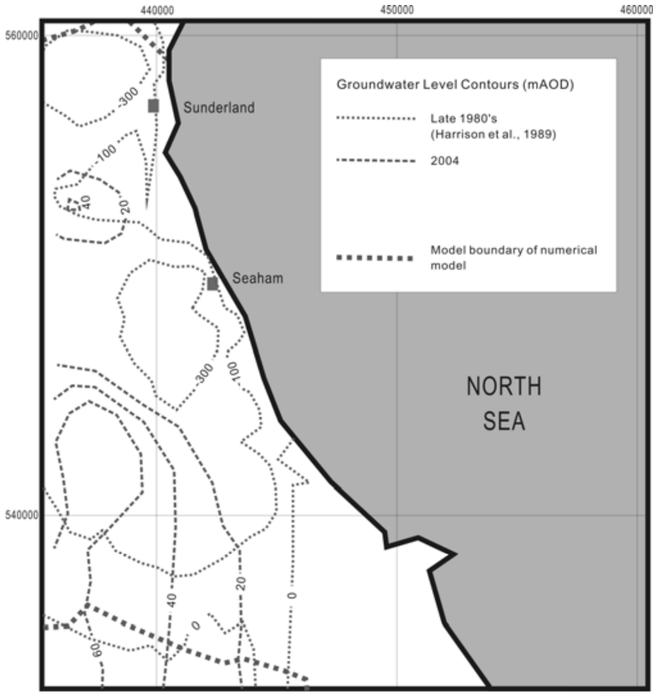

Figure 4. Comparison of groundwater levels of the 1980's by Harrison et al. (1989) and 2004 (Yu, 2006)

4.2 *Future conditions*

In order to simulate a worst case scenario where all present operating pumping stations in the Durham Coalfield have stopped, a numerical model has been created. The model has been created using MODFLOW, a code for three dimensional groundwater flow using finite difference method, which was developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988).

Figure 5 shows groundwater level change after stopping dewatering in the Durham Coalfield (after steady state conditions have been achieved). Figure 5 indicates that it is unlikely to expect a dramatic groundwater level change, but still further level rising can be expected to some extend, partially in the Seaham area.

5 DISCUSSION: FAULT REACTVATION

Groundwater level has been changed for the last a few decades and is expected to change in the future if the present dewatering scheme is ceased. In the following section the relation between groundwater level rising and fissuring found in the Durham Coalfield.

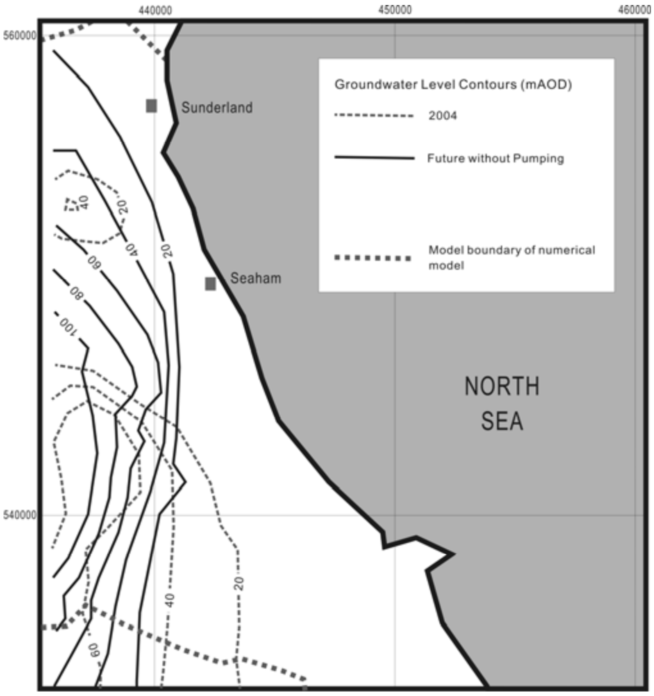

Figure 5. Comparison of groundwater levels of 2004 and worst case scenario where no pumping is under operation (Yu, 2006)

5.1 *Conventional approaches to evaluate fault reactivation mechanisms*

The mechanisms of the fissuring in Quarrington Hill, County Durham, Wigham (2000) suggests that the spatial variations in coal extraction rates due to existence of fault around coal seams caused differential subsidence over the area leading to fissuring on the surface. Donnelly (2006) reviewed several fault reactivation cases induced by coal mining.

However, considering the time the colliery in Quarrington Hill closed, which was in the early 1980's, and the depth of the seams which were around 500 metres, it is unlikely that mining subsidence is still progressing. Whittaker and Reddish (1989) suggested that even in the case of deep mines with depth of around 450 metres, the subsidence process is expected to be completed in 5 years.

Hence it is considered that the fissuring, which has been reported in the Durham Coalfield for the last several years, is not the result of mining subsidence directly. Rather than, it is considered to be influenced by the rising groundwater phenomena caused by cessation of dewatering for coal extraction.

5.2 *Pore water pressure*

The increase in pore water pressure can reduce strength of a fault shear plane, leading to a fault reactivation.

Ingebritsen and Sanford (1998) show that injection of liquid can induce seismicity. Liquid was injected at northeast of Denver, Colorado, U.S. and an unexpected earthquake was generated. After that, Raleigh et al. (1976) evaluated the influence of fluid injection on triggering of earthquakes under controllable fluid pressure at Rangely, Colorado. Figure 6 shows the relationship between fluid injection and earthquakes. Their research presented a good relationship between liquid injection that cause pore water pressure and fault reactivation, which can be used to evaluate the influence of pore water pressure on fault reactivation.

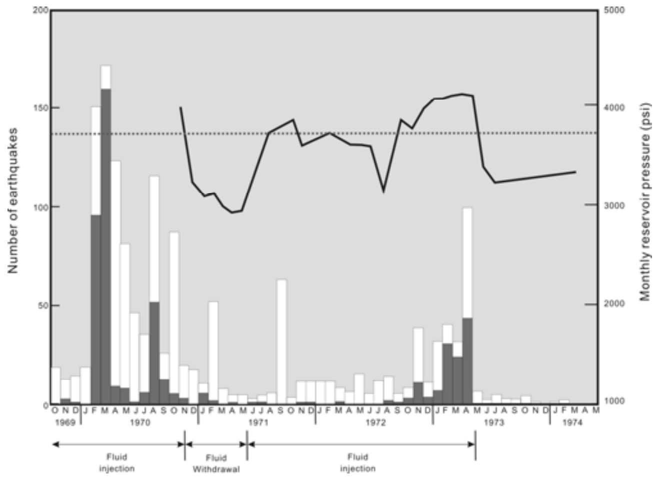

Figure 6. Frequency of earthquakes at Rangely. Gray bars indicate earthquakes within 1 km of experimental well. The white area indicates all others. Pressure history in a well is shown by the solid line and predicted critical pressure is shown by the dashed line (Raleigh at et., 1976).

5.3 *Fault reactivation occurrence in the Durham Coalfield*

Considering pore water pressure has increased as groundwater level is rising, the fault is considered to be reactivated in the Durham Coalfield. Some faults lie in a direction which can make fault reactivation easier.

An example of fault under this condition is the fault of Houghton-le-Spring. Yu (2006) suggested that the direction of the fault in Houghton-le-Spring is in the correct direction to fault slip especially when considering the orientation of the regional maximum stress suggested by Donnelly and Rees (2001) and by Bott and Bott (2004). Figure 7 illustrates the relationship between the direction of the maximum principal stress (Bott and Bott, 2004) and the orientation of the fault in Houghton-le-Spring proposed by Young and Culshaw (2001).

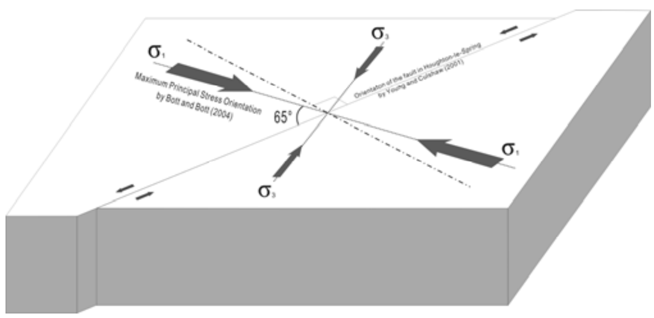

Figure 7. Diagram of the maximum principal stress direction (Bott and Bott, 2004) and the orientation of the fault in Houghton-le-Spring (Young and Culshaw, 2001) showing vulnerability of fault reactivation (Yu, 2006)

The shear stress on the shear plane of the fault can be expressed as

$$Shear\ Stress = \frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\theta - \mu'\left[\frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3)\cos 2\theta\right] \quad (0^\circ \le \theta \le 90^\circ) \qquad (1)$$

where σ_1 and σ_3 are the maximum principal and the minimum principal stress respectively, μ' is apparent coefficient of friction, and θ is the difference between the maximum principal stress direction and the orientation of the fault in Houghton-le-Spring, which is 65 degree as shown in Figure 7.

Regarding the values of the maximum and minimum principal stress, as those values are not available, the maximum principal stress is estimated to be 10.5 MPa and the minimum is -0.2 MPa based on the data near Clawthorpe, Cumbria, England by Becker and Paladini (1992), which enables Equation 1 to be written as:

$$Shear\ Stress = \frac{1}{2}(10.5 + 0.2)\sin 2\theta - \mu'\left[\frac{1}{2}(10.5 - 0.2) - \frac{1}{2}(10.5 + 0.2)\cos 2\theta\right] \qquad (2)$$

Equation 2 indicates the changes of fault condition according to the changes in apparent coefficient of friction as pore water pressure changes, as well as difference of the direction of the maximum principal stress and the fault orientation, which is drawn in Figure 8.

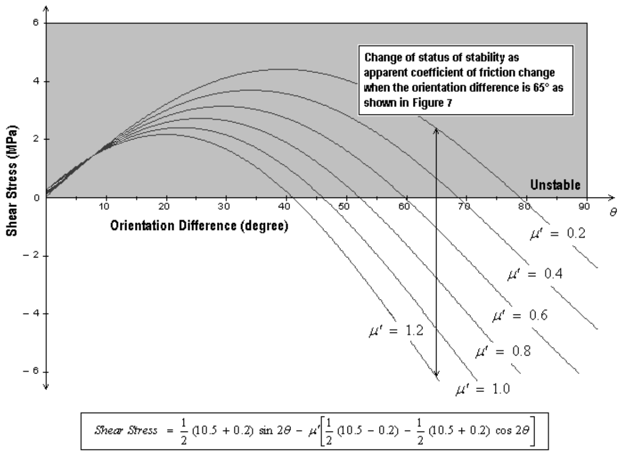

Figure 8. Diagram showing the changes in shear stress at the fault in Houghton-le-Spring as apparent coefficient of friction of the fault plane changes from 0.2 to 1.2 and difference between the maximum principal stress direction and the orientation of the fault in Houghton-le-Spring varies. The diagram indicates that as the values of apparent coefficient decrease, condition of the fault becomes unstable (Yu, 2006).

As shown in Figure 8, as groundwater level is rising, pore water pressure changes are expected, resulting in decrease of apparent coefficient of friction. As the difference of the direction of the maximum principal stress and the fault orientation is 65 degree, the condition of the fault is assumed to change along the vertical line crossing 65 degree on the x-axis (Figure 8). Hence apparent coefficient of friction is estimated to be between 0.4 and 0.6 based on the fault in Houghton-le-Spring being in an unstable condition.

In the case of modelling a fault in central California, Reasenberg and Simpson (1992) assumed the apparent coefficient of friction of the fault is 0.2, while Harris and Simpson (1992) assumed that the apparent coefficient of friction is 0.8 when pore fluid drains and the pore water pressure re-equilibrated with time. Therefore it seems that the range of apparent coefficient of friction suggested from Figure 8 lies within the range by Reasenberg and Simpson (1992) and Harris and Simpson (1992).

However, Figure 8 does not seem to imply that any other faults whose orientations are less 65 degree are necessarily under unstable condition since it is likely that the value of apparent coefficient of friction can vary depending upon each specific condition of fault such as water distribution, spatial variation of groundwater level and roughness of fracture. Hence Figure 8 is assumed to be only applicable to the case of the fault in Houghton-le-Spring.

In addition, considering further groundwater level rising as shown in Figure 5, further fissuring could be expected as it is expected that pore water pressure will increase. But as groundwater level change is not as drastic as it has been, severe fault reactivation is not anticipated.

6 CONCLUSION

Fissuring found in the Durham Coalfield is considered not to be the result of subsidence, since the subsidence in the Durham Coalfield seems to be completed. Hence rising groundwater caused by cessation of coal mining resulted in the stress pattern in the Durham Coalfield, which reduce the strength of the fault leading to fault reactivation over the region.

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REFERENCE

Becker A. and Paladini, S., 1992. Intra-plate stresses in Europe and plate-driving mechanisms. Annales Tectonicae, 6, 2, 173-192.

Bott, M.H.P. and Bott, J.D.J, 2004. The Cenozoic uplift and earthquake belt of mainland Britain as a response to an underlying hot, low-density upper mantle. Journal of the Geological Society, London, 161, 19-29.

Donnelly, L.J. and Rees, J.G., 2001. Tectonic and mining induced fault reactivation around Barlaston on the Midlands Microcration, North Staffordshire, UK. Quarterly Journal of Engineering Geology and Hydrogeology, 34, 195-214.

Donnelly, L.J., 2000. Reactivation of geological faults during mining subsidence from 1859 to 2000 and beyond. Transactions of the Institution of Mining and Metallurgy (Section A: Mining technology), 109, A179-A190.

Donnelly, L.J., 2006. A review of coal mining induced fault reactivation in Great Britain. Quarterly Journal of Engineering Geology and Hydrogeology, 39, 1, 5-50.
Harrison, R., Scott, W.B., and Smith, T., 1989. A note on the distribution, levels and temperatures of minewaters in the Northumberland and Durham coalfield. Quarterly Journal of Engineering Geology, 22, 355-358.
Harris, R.A. and Simpson, R.W., 1992. Changes in static stress on southern California faults after the 1992 Landers earthquake. Nature, 360, 19, 251-254.
Ingebritsen, S.E. and Sanford, W.E., 1998. Groundwater in Geologic Process. Cambridge University Press, 341p.
McDonald, M. G. and Harbaugh, A. W., 1988. A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the United States Geological Survey, Book 6, Chapter A1, 586 p.
Raleigh, C. B., Healy, J. H., and Bredehoeft, J. D., 1976, An Experiment in Earthquake Control at Rangely, Colorado. Science, New Series, 191, 4233, 1230-1237.
Reasenberg, P.A. and Simpson, R.W., 1992. Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake. Science, 255, 1687-1690.
Taylor, B.J., Burgess, I.C., Land, D.H, Mills, D.A.C., Smith, D.B. and Warren, P.T., 1971, British Regional Geology: Northern England, Institute of Geological Sciences. 125p.
Whittaker, B.N. and Reddish, D.J., 1989. Subsidence: Occurrence, Prediction and Control. Elsevier, 528p.
Wigham, D., 2000. Occurrence of mining-induced open fissures and shear walls in the Permian Limestones of County Durham. Transactions of the Institution of Mining and Metallurgy (Section A: Mining technology), 109, A172-178.
Young, B. and Culshaw, M.G., 2001. Fissuring and related ground movements in the Magnesian Limestone and Coal Measures of the Houghton-le-Spring area, City of Sunderland. British Geological Survey Technical Report WA/01/04.
Young, B. and Lawrence, D.J.D., 2001. Recent fissuring in the Magnesian Limestone at Houghton-le-Spring, City of Sunderland. British Geological Survey Research Report, RR/02/03, 22p.
Younger, P.L., 1995. Hydrogeology. In: Johnson, G.A.L. (ed.), Robson's geology of North East England, Transactions of the Natural History Society of Northumbria, the Natural History Society of Northumbria, 353-359.
Yu, M.H., 2006. Geohazards associated with rising groundwater in urban areas affected by former coal mining. PhD thesis, Birmingham University, 246p.