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A review of recent in-situ stress measurements in United Kingdom Coal Measures strata

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ABSTRACT: The in-situ stress regime is recognised by United Kingdom coal mine operators as a significant design parameter related to efficient mine design. The results obtained from recent overcore stress measurements undertaken in Coal Measures strata are analysed and presented. A relationship has been deduced which relates the maximum horizontal stress to the depth and to the elastic properties of the rock. This relationship is considered more suitable for estimating the maximum horizontal stress magnitude in Coal Measures strata than existing methods based solely on the depth of cover. This study also indicates that all in-situ stress determinations in sedimentary strata should be quoted with the elastic properties of the test horizons.

1. INTRODUCTION

It is now recognised that the stability of underground excavations in Coal Measures strata is significantly influenced by the in-situ stress regime. In recent years a large number of in-situ stress measurements have been undertaken in Coal Measures strata within the United Kingdom. This occurred as a response to a change in support strategy within the coal mining industry from standing steel framework support to rockbolt support. An understanding of the in-situ stress field is now considered by the coal producers of the United Kingdom to be a parameter directly relevant to mine design (Altounyan et al., 1997).

Assessing the in-situ stress regime at a particular site without a stress measurement can be difficult and often many assumptions are made. Whilst stress directions and the magnitude of the vertical stress can be estimated from data banks, such as that held by the World Stress Map Project, and the depth of cover, estimation of the magnitude of the horizontal stresses presents significant problems. In the past, it has often been the case that a relationship between the horizontal stress and the depth below the surface has been sought. The normal practice has been to relate either the ratio k ($k = \sigma_{H,h}/\sigma_V$ or $\sigma_{Hav.}/\sigma_V$) to depth or the maximum or minimum horizontal stress to depth by some linear function, Hoek & Brown (1980), Rummel et al. (1986), Pine et al. (1990), Stephansson (1993) and Sugawara (1993). Relationships of this form have often resulted in a general trend with depth but with considerable scatter especially at shallow depths. Only in rock types which have fairly consistent elastic properties does a reasonable depth-horizontal stress relationship exist. In rock formations which are interbedded and hence have potentially variable elastic properties, such as sedimentary basins, horizontal stress relationships based on depth are far less precise, Bigby et al. (1992). In Coal Measures strata horizontal stress profiles based on depth have indicated a poor relationship and it has been necessary to undertake stress measurements to describe the state of stress. A relationship which would take account of the variable elastic properties of interbedded Coal Measures strata and give a reasonable estimate of the maximum horizontal stress magnitude would therefore be advantageous in the initial design stages.

2. IN-SITU STRESS MEASUREMENTS IN COAL MEASURES STRATA USING CSIRO HI CELLS

Over the past six years a series of underground stress measurements have been undertaken in UK coal mines by overcoring CSIRO Hollow Inclusion (HI) cells. The programme provided design data for mine layout and tunnel support. Despite the weak rock which generally surrounds most productive British coal seams over 80 successful overcores have been completed at 22 mine sites. Of these, 26 stress measurements at 16 mine sites represent what is considered to be virgin or near virgin conditions.

The location of the stress measurement sites ranged from the Longannet Complex, near Alloa in Scotland to Lyn Mine in South Wales, some 600 km apart. The deepest site was at Hem Heath Colliery at 1060 m and the shallowest was at Lyn Mine at a depth of 90 m. Details of the measurement sites are summarised in Table 1.

In undertaking the measurements a conscious effort was made to measure the stress at a point in excess of twice the average roadway width from the edge of the opening. This was assumed sufficient to reduce the influence of the opening on the stress to a satisfactory level.

In all cases, the tests were undertaken at a distance greater than 1.5 times the roadway width from the edge of the excavation with the exception of Lyn Mine in South Wales, which occurred at approximately one roadway width. The depth of cover at this site was only 90 m and the visible deformation was minimal suggesting that the extent of influence of the opening on the stress may be less than would otherwise be the case. Although the test was closer to the mine opening than desired it provided the only data at this shallow depth and has been included in the data set for analysis.

The measurement procedure generally conformed to ISRM suggestions and the HI cell manufacturer's handbook (ISRM, 1987; Mindata, 1986). Data reduction and analysis was performed using in-house software based upon the Duncan, Fama and Pender isotropic solution (Duncan et al., 1980).

In any stress measurement there are several sources of both random and systematic errors, only a few of which are quantifiable. Useful discussions of the problems and errors in in-situ stress measurements using HI cells can be found in papers by Pine, Tunbridge and Kwakwa (1983) and Price Jones and Simms (1984).

3. ANALYSIS OF HI OVERCORE STRESS MEASUREMENT RESULTS

The results of the stress determinations are presented in terms of the magnitude, bearing and dip of the principal stresses in Table 1. These measurements confirm that an anisotropic stress regime prevails in the UK Coal Measures.

If the principal stresses are resolved to give the stresses in the horizontal plane, the orientation of the maximum horizontal stress can be plotted on a rosette. The resulting plot is shown in Figure 1. The length of

TABLE 1 - DATA ON VIRGIN STRESS MEASUREMENTS IN UNITED KINGDOM

Colliery	Depth	Tunnel Size	Test borehole			Principal Stresses									Rock Type	Elastic Modulus	Poisson's Ratio	Measure of Elastic Property
			Bearing	Dip	Depth Into Rib	Sigma 1	Bearing	Dip	Sigma 2	Bearing	Dip	Sigma 3	Bearing	Dip				
	(m)	(m)	(deg)	(deg)	(m)	(MPa)	(deg)	(deg)	(MPa)	(deg)	(deg)	(MPa)	(deg)	(deg)		(GPa)		
N Selby	987	4.9x3.7 arched	4	-18	7.7	25.7	18	69	18.8	162	17	12.1	256	12	Sandy Siltstone	21	0.44	Biaxial
Wistow	440	4.5x3.0 rect	100	-45	7.5	17.3	267	-28	15.7	140	-49	7.9	13	-28	Siltstone	22.2	0.4	Biaxial
Bolsover	660	4.9x3.7 arched	154	-28	10.05	19.8	309	0	18.9	300	88	12.1	39	0	Siltstone	25.4	0.4	Biaxial
	660				11.06	21.5	308	9	18.3	119	81	10.8	38	-1	Siltstone	30	0.35	Assumed
Coventry	825	4.9x3.7 arched	3	-26	7.92	27.8	325	-18	24.5	206	-56	15.4	65	-28	Silty Sandstone	30	0.44	Biaxial
Lea Hall	810	4.9x3.7 arched	326	-39	7.65	20.6	58	-71	14.1	182	-11	6.5	275	-15	Sandstone	15.4	0.36	Biaxial
	810				8.25	19.6	78	-78	11.9	103	-5	6.4	284	-11	Muddy Silts	16	0.4	Assumed
Asfordby	495	5.0x3.0 rect	12	-33	7.37	44.6	321	-12	12.8	263	69	5.2	47	18	Sandstone	66	0.2	Biaxial
	495				7.86	43.7	324	-14	13.5	159	-76	4.3	55	-4	Sandstone	53	0.3	Biaxial
Welbeck	800	4.9x3.7 arched	135	-8	8.18	24.3	85	63	11.7	181	3	8.3	273	26	Siltstone	18.3	0.22	Biaxial
	800				8.92	22.4	5	-68	12.2	186	-22	7.9	276	1	Siltstone	18.6	0.15	Biaxial
	800				9.52	26.1	72	75	12.4	211	12	8.3	303	10	Siltstone	17.5	0.31	Biaxial
Prince of Wales	450	4.5x2.7 arched	236	-15	10.96	12.3	335	48	11.4	158	42	6.3	67	1	Silty Muds	16.1	0.34	Biaxial
Thoresby	780	4.9x3.0 arched	154	-33	9.05	22.1	335	87	16.8	120	2	12.1	30	-2	Interbedded Sand/silts	21.5	0.4	Biaxial
	780				10.7	21.4	297	73	16.1	111	17	10.0	21	-2		25.4	0.24	Biaxial
Longannet Aberdona	430	4.9x3.7 arched	272	-31.5	9.1	11.1	76	-73	9.7	174	-2	4.1	85	16	Mudstone	12	0.3	Biaxial
	430				10.3	11.6	351	-47	10.3	155	-41	6.7	72	8	Mudstone	12	0.3	Assumed
Longannet Solsgirth	292	4.5x2.8 rect	92	-30	9	8.8	338	14	7.8	213	67	6.9	73	18	Mudstone	12.8	0.39	Biaxial
	292				10.1	9	7	37	7.7	138	41	3.4	74	-27	Mudstone	21	0.22	Assumed
Harworth	960	4.5x2.8 rect	191	-42	9.8	29.2	7	-65	23.7	145	-19	11.7	61	15	siltstone	25.5	0.4	Biaxial
Maltby	974	4.9x3.0 rect	257	-7	9.48	25	346	75	16.2	182	14	6.8	271	-4	Siltstone/ sandstone	28.2	0.26	Biaxial
	974				>9.60	25.6	85	-77	17.29	163	3	6.46	72	13		29.4	0.26	Biaxial
Hem Heath	1060	4.8x3.6 rect	n/a	n/a	10.7	29.8	320	-64	23.8	356	22	20.2	260	14	Siltstone/ sandstone	32.7	0.34	Biaxial
Littleton	560	5.0x3.0 rect	n/a	n/a	7.4	15.6	135	83	10.3	327	7	6.9	236	1	Sandstone	13.9	0.36	Biaxial
Lyn Mine	90	7.0x1.2 rect	210	-25	6.33	9.39	327	1	2.8	238	-41	1.98	56	-49	Sandstone	17.3	0.32	Biaxial
Pentral/ clwydau	400	4.8x3.6	325	-36	10.7	15.2	285	63	8.8	252	-23	7.3	348	-13	Siltstone	17.6	0.39	Lab tests

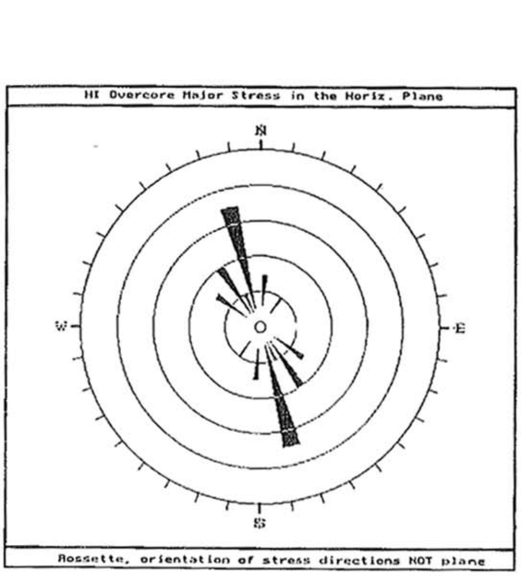

Figure 1 - Rosette indicating orientation of the major stress in the horizontal plane

a sector on the rosette indicates an increasing frequency of the maximum horizontal stress orientation in that direction. The most frequent orientation of the maximum stress resolved into the horizontal plane is between 340 and 350 degrees.

Comparison of the in-situ stress orientation in the United Kingdom with those of other parts of western Europe suggests that the NW-SE maximum horizontal stress direction is dominant over much of this area and originates from plate tectonic forces associated with the northerly to north westerly collision of the African and Eurasian plates and the south easterly push of the North Atlantic spreading ridge (Evans, 1987).

Based on the measured data, an analysis has been conducted on the magnitude of the stress components. In all cases the stresses have been resolved into the vertical and maximum and minimum horizontal normal components for ease of analysis.

The relationship between the measured vertical stress and depth below the surface is shown in Figure 2. This confirms the accepted theory that vertical stress is related to depth. Where γ is the unit weight (MN/m^3) of the overburden and z is the depth (m).

$$\sigma_v = \gamma . z \qquad \text{(MPa)} \qquad (1)$$

A regression indicates that the gradient of the line is 0.025 MN/m^3 (the unit weight) with an R^2 correlation coefficient of 0.95. If the line is forced through the origin the value of the unit weight increases slightly to 0.027 MN/m^3 with an $R^2 = 0.94$. The results of the

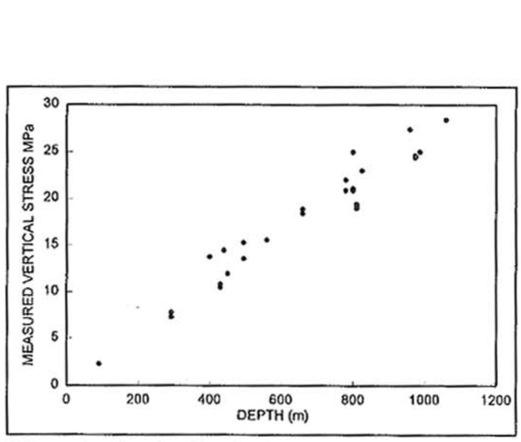

Figure 2 - Graph of vertical stress against depth.

regression analysis are consistent with that expected from theory and other published data.

The relationship between the horizontal stress and depth is shown in Figure 3. It can be seen that a strong correlation with depth does not occur with either horizontal stress component. In both cases there is a general increase in the horizontal stress with depth, but there is considerable spread. Two tests indicate exceptionally high values of maximum horizontal stress. These were both undertaken at Asfordby Mine in a thin very stiff (53 - 56 GPa) sandstone bed.

The ratio of maximum to minimum horizontal stress has been plotted with respect to depth in Figure 4. With the exception of three tests, the ratio is fairly consistent with depth. If these three tests are not included in a statistical analysis the mean H_{max}/h_{min} ratio is 1.68 with a sample standard deviation of 0.35. It is not clear why the three anomalous ratios are much higher than the other test values and further investigation is required.

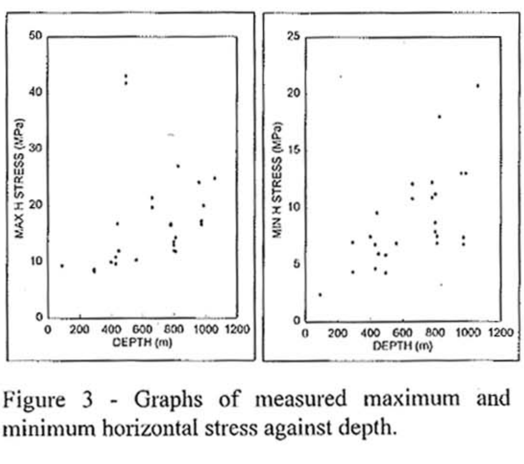

Figure 3 - Graphs of measured maximum and minimum horizontal stress against depth.

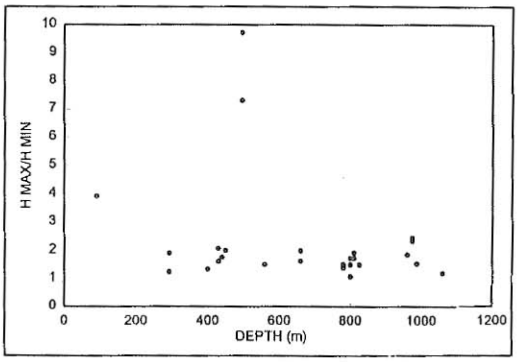

Figure 4 - Ratio of maximum to minimum horizontal stress against depth.

Variations in the in-situ stress observed from earlier underground overcoring work have been shown to be related to formation stiffness (Bigby et al., 1992). Since this initial work further stress measurements have been undertaken which confirm the relationship between horizontal stress and rock stiffness. The graph of maximum horizontal stress against elastic modulus (E) which is shown in Figure 5 indicates a strong correlation between these quantities.

For the maximum horizontal stress a regression analysis gives :

$$\sigma_H = 0.782E - 0.98 \quad \text{(MPa)} \qquad (2)$$

$R^2 = 0.898$ and the standard error in the y estimate = 2.95 MPa.

A graph of k ($k = \sigma_{Hav.}/\sigma_V$) against the depth is shown in Figure 6. The results from the overcore stress measurements are consistent with those presented by Hoek and Brown (1980) and reside towards the lower

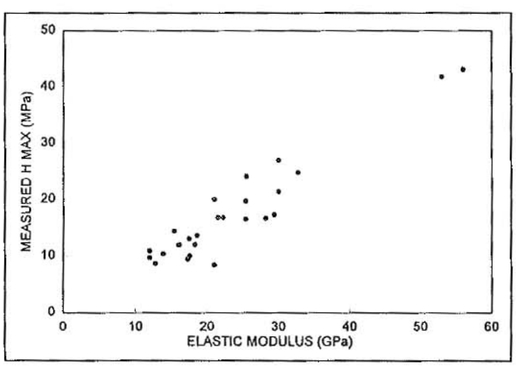

Figure 5 - Graph of maximum horizontal stress against elastic modulus.

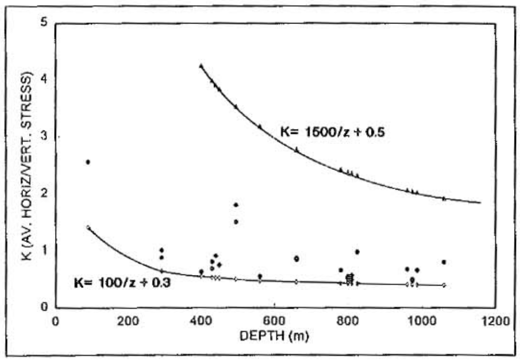

Figure 6 - Graph of k ($k = \sigma_{Hav.}/\sigma_V$) against depth.

bound for k as defined by Hoek and Brown and shown in Figure 6.

In summary, the above stress measurement results indicate that:

a. an anisotropic stress regime prevails within the UK Coal Measures.
b. the vertical stress is related to depth of burial with a mean unit weight of the overburden of approximately 0.027 MN/m^3.
c. there is a strong correlation between the maximum horizontal stress and the elastic modulus.
d. there is a general increase in the horizontal stress with depth of burial.

4. ESTIMATE OF MAXIMUM HORIZONTAL STRESS MAGNITUDE

The above analysis indicates that the maximum horizontal stress component is related to both the depth below the surface and the formation stiffness. In the following analysis a relationship has been investigated based upon two components. One is due to the depth of burial and the other which is termed the "tectonic component".

With regard to the depth of burial, using an elastic analysis, the induced horizontal stress of confined sedimentary strata is related to the vertical stress ($\sigma_v = \sigma_z = \gamma.z$) and the Poisson's ratio (ν) by the formula:

$$\sigma_x = \sigma_y = \gamma.z.(\nu/1-\nu) \qquad (3)$$

This implies a constant induced stress in the horizontal plane at a given depth, irrespective of direction.

With regard to the tectonic component, a correlation

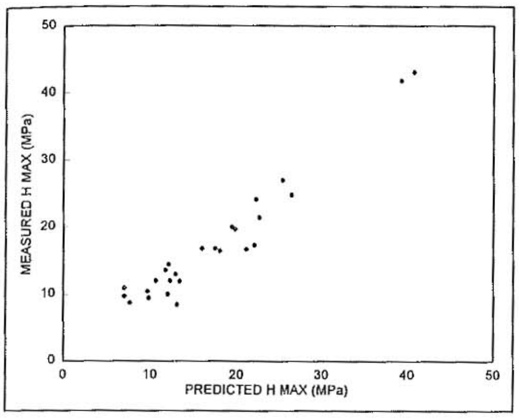

Figure 7 - Graph of measured against predicted maximum horizontal stress.

has already been found linking the maximum horizontal stress to the elastic modulus of the rock. The tectonic component of the maximum horizontal stress is considered to be the product of the elastic modulus of the rock formation and a coefficient which can be thought of as a "tectonic strain". In the initial analysis a constant is also included in the tectonic component since a constant was evident in the relationship between maximum horizontal stress and elastic modulus. The approach brings together the above components in the following form:

$$\sigma_H = a_1.z.(\nu/1\text{-}\nu) + a_2.E + a_3 \quad \text{(MPa)} \qquad (4)$$

where a_1 is a coefficient which includes the unit weight of the rock and therefore has units of MN/m^3, a_2 is a measure of tectonic strain and a_3 is a constant with the units of stress (MPa).

A multiple correlation analysis has been undertaken using the stress measurement data to generate values for the coefficients a_1, a_2, and the constant a_3 which allow a "best fit" estimation of the dependant variable σ_H. Using all the data in Table 1:

$$\sigma_H = 0.0092.z.(\nu/1\text{-}\nu) + 0.779.E - 3.998 \qquad (5)$$

The statistics generated in the regression analysis give $R^2 = 0.94$ and the standard error in the y estimate (σ_H) = 2.39 MPa. This equation has been used to calculate a predicted value for the maximum horizontal stress for each site from the depth and the elastic properties of the test horizon. A graph of measured against predicted maximum horizontal stress is shown in Figure 7.

Table 2 Multiple Correlation Results for Maximum Horizontal Stress.

mines analysed	a_1	a_2	a_3	R^2	std. err. in σ_H est. MPa
all UK	0.0092	0.779	-3.998	0.936	2.39
all UK	0.0049	0.688	0	0.912	2.72
English	0.0090	0.803	-4.566	0.947	2.17
English	0.0038	0.716	0	0.93	2.45

The above graph and statistics indicate that a good correlation exists between the measured and predicted stress magnitudes.

Additional multiple correlation analyses have been conducted without the constant a_3 and using only data for English mines which, due to their relative geographical proximity, are more likely to be part of the same regional stress environment. The results are summarised in Table 2.

The regression data indicates that the fit of the model improves when only English Mines are considered and although improved correlation does occur when the constant a_3 is included in the analysis, the effect of removing the constant (i.e. $a_3 = 0$) from the model is not significant.

A similar analysis was been conducted for the minimum horizontal stress using a model of similar form. The degree of correlation of this model with measured data was not as good as that obtained with the maximum horizontal stress model.

A sensitivity analysis indicates that the model is most sensitive to changes in the elastic modulus of the rock, with the depth and Poisson's ratio having only a marginal overall effect. This would indicate that the tectonic component is the major driving force in the development of the horizontal in-situ stress field.

5. CONCLUSIONS

Based on recent virgin in-situ stress measurement results obtained by overcoring in the United Kingdom Coal Measures, it is possible to make the following conclusions:

a. The results confirm that an anisotropic stress regime prevails in the UK Coal Measures.

b. The trend of the maximum horizontal stress component is NNW - SSE with anomalies related to structural features.

c. With the exception of three anomalous values, the ratio of maximum to minimum horizontal stress remains fairly consistent with depth giving a mean ratio of 1.68. The reasons for the exceptional values are unclear and further investigation is required.

d. The vertical stress is related to the depth of burial and the unit weight of the overburden. From this data the unit weight of the overburden has been found to be 0.027 MN/m^3.

e. The relationship of k ($k = \sigma_{Hav.}/\sigma_V$) with depth for the measured in-situ stress data is consistent with that found by Hoek and Brown (1980). In addition, a strong relationship has been confirmed between maximum horizontal stress and the elastic modulus of the rock.

f. A formula has been developed to estimate the maximum horizontal stress that occurs within the Coal Measures strata of the United Kingdom. The relationship relates the maximum horizontal stress to the depth, the elastic modulus and Poisson's ratio of the rock formation.

g. In sedimentary strata the magnitude of the horizontal stress should always be quoted with the elastic properties of the test horizon and the method of elastic property determination.

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