CHAPTER FIVE

SUPPORT LOAD REQUIREMENTS ON LONGWALL FACES
SUPPORT LOAD REQUIREMENTS ON LONGWALL FACES

5.1 Introduction

The Mining Research Establishment having been requested by Her Majesty's Inspectors of Mines to compare the stability of roofs supported by props and bars (with strip packs) with that of roofs supported by the then new powered supports (with total caving), the author spent a number of years studying strata behaviour on longwall faces. The concept of mean load density as a means of comparing face support systems was postulated [3], and was later developed to show that a certain minimum mean load density was required to give face stability [4]. This work was later extended by Shepherd, Ashwin and others [52] [53] [54], but no attempt was made to assess how the load should be distributed between the front and the back legs; nor was any consideration given to the problems of inclined seams. The present distribution of load between the front and back legs of the modern powered support has been based on good mining sense tempered with a certain amount of trial and error. In general, when the roof is weak, adequate support near the face is essential, but when the roof is strong the bulk of the thrust is required along the waste edge. In inclined seams, effort has gone into making the supports stable when used on a slope, but little thought has been given to any possible change in requirements.

In theory, the ideal load can be obtained by gradually reducing the support thrust until roof instability occurs, but such a practice could be both dangerous and expensive, and has therefore not been adopted. In the early days of the investigation carried out by the Mining Research Establishment
this condition was achieved adventitiously on a few occasions [4]. Although the results obtained were sufficient to postulate a minimum mean load density, they gave no indication of the required distribution of load between the front and back legs, nor how the loads should be varied for extreme conditions.

It has therefore been necessary to adopt a more hypothetical approach to the problem of ideal support requirements — to make assumptions about the amount and shape of the roof which must be supported, to calculate the support thrusts required to keep such a shape in stable equilibrium, and to compare the deductions with the small amount of factual knowledge available. Only then can the hypothesis be accepted as a basis for support design.

5.2 Behaviour of Strata Around Faces

To fully appreciate the support requirements on a longwall face, the condition and behaviour of the strata surrounding the face must be thoroughly understood. Consideration will be restricted to a longwall face which is regularly turning over, having already been subjected to its first weight. In general, the roof can be divided into two zones, the lower roof, which caves in the waste, and the upper roof, which, although it may develop fractures, remains continuous and gradually lowers, compressing the caved material below it. A cross-section of a typical face is shown in Figure 34.

If we consider the stress at seam level, the first increase is detectable about 100 m ahead of the face. The stress gradually rises, until a few metres in front of the face it reaches a peak of about four times cover load. At this point the coal or
FIGURE 34. CROSS-SECTION OF TYPICAL LONGWALL FACE
immediate roof begins to fail, and the stress falls off rapidly. Across the working area the stress is only that supplied by the supports. Behind the supports the lower roof caves, and the stress rises gradually as the upper roof settles down on the caved material. Provided the area of extraction is sufficiently large, eventual cover load will again be reached.

At the abutment peak, where the strata fails, the roof begins to slope. Consequently it will be at an angle over the working area. This slope of the upper roof strata gives rise to a minimum rate of convergence with respect to distance from the face, observable across the working area. As the rocks all the way to the surface are involved in this movement, the relatively small thrust capable of being exerted by even the strongest supports can have only a small effect on this convergence rate. A high support thrust will reduce the expansion of the yield zone which forms above the face, and reduce slippage between the beds, but too high a thrust can cause failure of the rock near the waste edge, especially in the weak roofs which frequently occur in British mining conditions. Too low a support value, however, causes bed separation in the lower roof, and convergence above the minimum rate will then occur. Behind the face the slope gradually levels off as the roof settles down on the caved material. These changes of slope produce bending concave down over the working area, leading to compression in the lower surfaces of the upper roof, and concave up over the waste, inducing tensions. In the latter case, support is now given to the upper roof by the caved waste material, and its stability will be maintained.

- 111 -
In the course of the investigation into roof behaviour by the Mining Research Establishment, well over one hundred convergence results from Britain, France and Germany were examined. It was concluded that the minimum convergence rate can be approximated by

\[ \text{conv.} = 10 M + 30 \text{ mm/m} \]  \hspace{1cm} (5.2.1)

where \( M \) is the height of seam extracted in metres. Subsequent work has shown that high support resistance or strong strata in the roof can reduce this figure, but not to any great extent, and that the formula can still be accepted as the 'norm' for the average face. This convergence rate is indicative of an angle of slope between roof and floor of \( 2^\circ \) to \( 3^\circ \), depending on the height of seam extraction. This is illustrated in Figure 34. Although conventionally shown as a bending of the roof strata only, this angle will also include the floor lift bound to occur as a consequence of the removal of the cover load from the floor strata.

Equation 5.2.1 implies that the convergence rate is independent of depth. This is only approximately true. An analysis of early British results [4] (reproduced in Figure 35) indicated a decrease in convergence with depth. This has been confirmed by work in France [55] which suggests that the convergence rate is proportional to \( H^{-1} \). Such a curve has been added to Figure 35. This decrease in convergence with depth cannot continue indefinitely. Eventually the stage is reached when the increasing abutment load ahead of the face will produce major failure of the floor, causing excessive
FIGURE 35. EFFECT OF DEPTH ON CONVERGENCE RATE
floor lift near the face. There is evidence that, as depths increase, this is already occurring in some of the softer British floors.

The convergence does not necessarily occur immediately the face is advanced, but may be stored as 'potential convergence', which gradually manifests itself with time. This explains the steady increase in convergence with time found on many faces, an increase which sometimes takes days to disappear. Any major disturbance of the roof, however, will allow rapid release of some of this potential convergence, a fact which probably explains the convergence which occurs when props and bars are withdrawn or powered supports are advanced.

The presence of a massive rigid stratum in the roof can influence the pattern of closure. Instead of bending evenly in the neighbourhood of the face, the massive beds break in sections, producing irregularities in the convergence rate. A period of negligible convergence will suddenly be terminated by a major lowering of the roof, referred to as 'a weighting', which is caused by a fracturing of the massive bed ahead of the face. On occasion, this can be accompanied by a shockwave, bursting the coal on the face and disturbing the supports. The average rate of convergence over a period of weeks, however, will still approximate to the minimum convergence rate referred to above.

Massive rigid strata overlying shallow depths of mining are particularly difficult to control. The periodic breaks which form may extend to the surface, causing excessively high loads on the supports and making longwall extraction almost impossible.
Such conditions come within the sphere of Hard Rock Mechanics, and will not be discussed here.

5.3 Concept of the Roof Block

The minimum required support thrust cannot be obtained by merely measuring the thrust supplied by the supports on the face. As these are acting against an irresistible minimum convergence, the greater the capacity of the support, the greater will be the thrust engendered. What one requires to know is the minimum thrust needed to prevent the onset of instability in the roof, manifested by an increase in convergence.

Consider the forces required to hold in place that mass of rock which would be released if the supports were to be removed. For this purpose the roof is deemed to be divided into two zones, the lower roof, which caves in the waste, and the upper roof which, although it may develop fractures, remains continuous over the waste. The horizontal stresses originally present in ground help maintain the stability of the upper roof, any joints or breaks being closed by the compressional forces. This effect is augmented over the working area by the concave-down curvature of the roof, which adds to the compression on the lower surface of the upper roof. The lower roof is not continuous, and has a free face along the caving line. The horizontal compressional forces will be absent, and the lower roof must thus rely for stability on the supports. Should the supports be removed, the lower roof will collapse and the caving line will move forward to the face. The upper roof, however, will still remain intact, and hence only the lower roof need be considered when assessing the minimum required support thrust.
If the roof is unbroken over the working area, the supports will not have to take the full weight of the lower roof, which will possess a certain degree of inherent stability as a cantilever projecting out from the face, and also, possibly, because there will be adhesion between the beds of the lower roof and the beds of the upper roof. However, should there be a simultaneous face break and a parting between the upper and lower roof beds, the full weight of the lower roof will be thrown on to the supports. Although not necessarily a common occurrence, the possibility of this happening exists on every face. It is this extreme condition which will be considered.

Adopting these concepts, the supports will be required to hold up a freed block of strata, as is illustrated in Figure 36. The angle \( \alpha \) is the average angle of caving in the waste. This angle will depend on the geology of the lower roof. If the immediate roof contains a number of strong beds, \( \alpha \) will be small, as the successive beds will overhang in the waste; if the immediate roof is weak, \( \alpha \) will be large, and, in the case of a very weak roof, may approach 90\(^{\circ}\). If the supports are removed, it is not unreasonable to assume that the caving line will move forward to the face, but with the angle \( \alpha \) unaltered.

The height of caving in the waste, \( c \), will be governed by the bulking factor, \( B \), which is the ratio of the density of the unbroken strata to the density of the fragmented material, and represents the expansion of the strata brought about by fragmentation. An analysis by Kenny [56] suggests a value of \( B = 1.5 \), a value independently accepted in Germany [57]. As \( c = \frac{M}{B-1} \), where \( M \) is the height of extraction, this gives \( c = 2M \).
(a) Weight forward of support thrust

(b) Weight to rear of support thrust

**FIGURE 36. CONCEPT OF ROOF BLOCK AND FORCES INVOLVED (LEVEL SEAMS)**
It is recognised that the bulking factor could be lower than 1.5, especially as regards stronger strata which tend to cave as slabs, but it is intended here to adapt $B = 1.5$, with the proviso that, should it give incorrect values of support resistance when applied to field results, it will be revised.

In a hypothetical approach to such a concept as that of a freed roof block, certain compensating factors can come into play. Although strong strata may give lower values of $B$, and hence higher values for $c$, they may also exhibit cantilever strength along the face line, and the two factors will tend to cancel each other out.

The base of the roof block, $l$, will be taken as the supported width, i.e., the distance from the face line to the rear of the roof canopy or bar. With strong massive roofs, the strata may overhang in the waste, and this may have to be taken into account when designing supports specifically for this type of strata. With weak roofs, where the caving angle is large, caving along the rear of the canopies is the more severe, as will be shown later.

The size of the roof block requiring support has thus been established in terms of the caving angle $\alpha$, the height of the seam extracted $H$, and the supported width $l$. The remaining dimension, the thickness of the block, can be taken as the support spacing along the face, $s$.

The roof block considered need not be a solid unit. It could be bedded, jointed, or otherwise fractured. It is the purpose of the canopy to hold the broken pieces together and
to prevent them falling out; it is the purpose of the thrust supplied by the legs to hold the canopy in place, and of the base to distribute this thrust onto the floor. It should be noted that any pressure capsule incorporated in the canopy in order to increase tip load is an internal force within the canopy, and, although it may affect the load distribution between the front and back legs before yield, it does not influence the size or position of the support thrust when all the legs are at setting load or at yield load.

5.4 Equilibrium of Forces, Level Seams

The roof block will be acted on by three sets of external forces, as shown in Figure 36. These are:

(1) The body weight \(W\)

This may be taken as a single vertical force acting through the centre of gravity of the block.

\[
W = c \cdot g \gamma = 2M \cdot g \gamma \quad \ldots (5.4.1)
\]

where \(\gamma\) is the average density or body weight of the lower roof. If a reference point \(A\) is taken on the face line, then this force will act at a distance \(w\) from \(A\) where

\[
w = \frac{1}{2}(r + c \cdot \cot \alpha) = \frac{1}{2} r + M \cdot \cot \alpha \quad \ldots (5.4.2)
\]

(2) The support resistance \(P\)

This will be the combined vertical thrust of all the legs. It will act at a distance \(p\) from \(A\), where \(p\) depends on the distribution of load between the legs, on the geometry of the support, and on the prop-free-front distance.
(3) The reaction $R$

Unless $P$ is in line with $W$, a reaction $R$ will develop on top of the roof block to counteract the turning moment. As $W$ and $P$ are both vertical, $R$ will also be vertical. For $P$ to be a minimum, $R$ should be right at the edge, but, as the edge may crumble, it is better to consider it acting some distance in. The reaction $R$ lies on the same side of $W$ as $P$, and, if $P$ increases above its minimum for stability, $R$ will increase, but it will move closer to the line of $W$. Assume $R$ acts at the distance $r$ from the reference point $A$.

For equilibrium of the roof block, two conditions must be met:

(a) total upward force = total downward force
   \[ \text{ie } P = W + R; \quad \text{...(5.4.3)} \]

(b) moments about any point, say $A$, must equal zero
   \[ \text{ie } Pp = Ww + Rr. \quad \text{...(5.4.4)} \]

Eliminating $R$ from these two Equations gives

\[ P = \frac{W - w}{r - p^*} \quad \text{...(5.4.5)} \]

Alternatively, moments may be taken about $R$, giving the same result.
As \( P = W + R \), \( P \) must be greater than \( W \), other than when \( P \) is below the centre of gravity, when it need only equal \( W \). The further \( P \) lies away from below the centre of gravity of the roof block, the greater \( P \) must be made. In order better to illustrate this, imagine for one moment the holding up of a slab to the ceiling. If the centre of pressure is below the centre of gravity, the slab can be held with the minimum of force. If the centre of pressure moves away from below the centre of gravity, the upward force required increases considerably, and becomes impossibly large as the edge is approached. The same consideration applies to the roof block. This need to increase \( P \) as the support thrust moves closer to the waste edge has been a major source of misunderstanding among some of those who are involved in the design of supports.
5.5 Minimum Load Required on Front and Back Legs

P will be the resultant thrust of all the legs of the support unit. In general, the individual thrusts of the front legs will be equal, as will the individual thrusts of the back legs. Thus it is convenient to divide P into two parallel forces, F and B, where F is the sum of the thrusts on the front leg or legs and B is the sum of the thrusts on the back legs. These can be taken as acting at distances f and b from the face, values which for any particular installation will be known.

For F and B to be statically equal to P, then

\[ F + B = P \]

and \[ Ff + Bb = Pp \]

These can be substituted in Equations 5.4.3 and 5.4.4 above, giving

\[ F + B = W + R \]

\[ Ff + Bb = Rr + Ww \]

F + B will be a minimum when R is a minimum. If w lies between f and b, R can be made zero by putting

\[ R = 0 \]

\[ Ff + Bb = Ww \]

\[ F + B = W - f + B = W - f \]

\[ F = \frac{b-w}{b-f} \quad B = \frac{w-f}{b-f} \]  \hspace{1cm} (5.5.1)

If w is less than f, then R will be a minimum when

\[ F = \frac{r-w}{r-f} \quad B = 0 \]  \hspace{1cm} (5.5.2)

where r is as large as possible. If w is greater than b, the minimum condition will be achieved by putting

\[ F = 0; \quad B = \frac{w-r}{b-r} \]  \hspace{1cm} (5.5.3)

where r is as small as possible. These latter two conditions
are shown in Figures 36a and 36b respectively.

If the supports are efficient and well set, then, on a face which is turning over regularly, the natural convergence will soon build up load after setting. To prevent excessive convergence and to keep the face safe, even if bed separation is followed by a face break, the yield loads of the supports should be at least those calculated from Equations 5.5.1, 5.5.2 or 5.5.3, as appropriate.

To obtain some idea of the yield loads involved, calculations have been made. In these calculations use has been made of representative figures for the values normally known to exist in given situations. A survey of popular support units indicates that average values for $f$ and $b$, the distances of the front and back supports from the face, are $f = k - 1.6$ m and $b = k - 0.5$ m. Before the cut, the face width $k$ is about 3.0 m, after the cut about 3.6 m; if a 1.2 m cut is considered, this will increase $k$ to 4.2 m. These three values for $k$ have therefore been considered. Five values for the mean caving angle have been taken, viz $90^\circ$, $75^\circ$, $60^\circ$, $45^\circ$ and $30^\circ$. These can be very roughly interpreted as very weak roof, weak roof, medium roof, strong roof and very strong roof. Three heights of extraction have also been considered, viz $M = 1$ m, $M = 2$ m and $M = 3$ m.

Concerning the values of $r$, although the absolute limits of the reaction are the front and back corners of the block, it was thought to be unwise to take these extremes. In a weak rock the corner may crumble under load; in a strong rock the
angle of the wedge is fairly acute. The limits for \( r \) have therefore been taken as 0.5 m away from the corners, giving

\[ r = 2w - 0.5\text{ m for } w < f, \quad r = 0.5\text{ m for } w > b. \]

It only remains to take the density (or, more correctly, the body force) \( = 0.028 \text{ MN/m}^3 \), the caving height \( c = 2 \text{ M} \), and to assume a support spacing \( s = 1 \text{ m} \). This allows the typical values for yield load shown in Table 5 to be calculated. In Table 6 are shown the computed mean load densities. The figures have been quoted to two places of decimals, and, as 1 MN = 100 tons approximately, by ignoring the decimal point, the values of \( F \) and \( B \) can be read in imperial tons.

Obviously, greater thicknesses and greater widths of extraction require greater support loads, but variation in the caving angle does play an important part. At high angles of caving, the load is thrown on the front legs; at low angles of caving the load is thrown on the back legs. This conforms to the known facts. When the caving angle is low, its effect overshadows that of increasing face width, and the thrust required from the supports then remains almost constant for a given seam thickness.

The early underground work by KRE [4] indicated that the minimum load density for seams in the range 0.7 m to 1.7 m should be about 0.05 MPa. Further investigations [52] [53] did not result in any change to this figure, but Ashwin et al [54] concluded that it should be increased proportionally with the height of extraction. The mean load density figures deduced in Table 6 are in line with these experimental figures and are
TABLE 5

Minimum Values for F and B in Level Seams

(assuming $c = 2M$, $f = \lambda - 1.6$ m, $b = \lambda - 0.5$ m, $r$ acts 0.5 m from the relevant corner, rock density = 0.025 MN/m$^3$, support spacing along face = 1 m).

<table>
<thead>
<tr>
<th>M</th>
<th>$\alpha$</th>
<th>$\lambda = 3.0$ m</th>
<th>$\lambda = 3.6$ m</th>
<th>$\lambda = 4.2$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>deg</td>
<td>F</td>
<td>B</td>
<td>F</td>
</tr>
<tr>
<td>1</td>
<td>90</td>
<td>0.14</td>
<td>0.01</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>0.10</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.06</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0.27</td>
<td>0.03</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>0.13</td>
<td>0.17</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0</td>
<td>0.32</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0</td>
<td>0.45</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>0.67</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>0.41</td>
<td>0.04</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>0.08</td>
<td>0.37</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0</td>
<td>0.61</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>0</td>
<td>0.90</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>0</td>
<td>1.39</td>
<td>0</td>
</tr>
<tr>
<td>m</td>
<td>α</td>
<td>Mean Load Density (UK nomenclature)</td>
<td>Mean Load Density (German nomenclature)</td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>------------------------------------</td>
<td>----------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda = 3.0 , \text{m}$</td>
<td>$\lambda = 3.6 , \text{m}$</td>
<td>$\lambda = 4.2 , \text{m}$</td>
</tr>
<tr>
<td>90</td>
<td>deg</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>75</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>5 M</td>
</tr>
<tr>
<td>60</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>5 M</td>
</tr>
<tr>
<td>45</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>5 M</td>
</tr>
<tr>
<td>30</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
<td>7 M</td>
</tr>
<tr>
<td>90</td>
<td>0.10</td>
<td>0.12</td>
<td>0.14</td>
<td>5 M</td>
</tr>
<tr>
<td>75</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>5 M</td>
</tr>
<tr>
<td>60</td>
<td>0.11</td>
<td>0.10</td>
<td>0.10</td>
<td>6 M</td>
</tr>
<tr>
<td>45</td>
<td>0.15</td>
<td>0.13</td>
<td>0.11</td>
<td>8 M</td>
</tr>
<tr>
<td>30</td>
<td>0.22</td>
<td>0.18</td>
<td>0.16</td>
<td>11 M</td>
</tr>
<tr>
<td>90</td>
<td>0.15</td>
<td>0.18</td>
<td>0.22</td>
<td>5 M</td>
</tr>
<tr>
<td>75</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>5 M</td>
</tr>
<tr>
<td>60</td>
<td>0.20</td>
<td>0.17</td>
<td>0.16</td>
<td>7 M</td>
</tr>
<tr>
<td>45</td>
<td>0.30</td>
<td>0.25</td>
<td>0.22</td>
<td>10 M</td>
</tr>
<tr>
<td>30</td>
<td>0.46</td>
<td>0.38</td>
<td>0.32</td>
<td>16 M</td>
</tr>
</tbody>
</table>

Note: As resistance of support may be required entirely on front legs or on back legs, to be universally applicable its design should be based on a figure equal to twice the minimum mean load density.
given both in British nomenclature (MPa) and in German nomenclature (Np/m² expressed in terms of the height of extraction M metres). German engineers have in the past used a figure of 8 Np/m² in their design of supports, but for general application they are now increasing this figure to 15 Np/m². Thus the mean load density values deduced in Table 6 are in line with those obtained experimentally. The described method of approach might thus by confidently applied to special conditions in which past experience cannot be used as a guide.

5.6 Application to Wider than Normal Prop-free-fronts

Since the introduction of prop-free-front systems, Her Majesty's Inspectors of Mines have restricted the distance from the face to the first row of props to a limit of about 2 m. This limit is gradually being relaxed, and more and more faces are being granted exemptions to operate prop-free-fronts in excess of 2 m. When the weight of the roof block to be supported lies to the waste side of the support thrust, no problems arise, since the extra roof weight forward of the thrust helps to balance the forces involved. When the caving angle is steep, however, as is frequently the case with weak roofs, the roof weight lies to the face side of the thrust, and an increase in prop-free-front distance tends to increase the instability. This condition will be examined in further detail.

The roof weight W will be the furthest forward when the caving angle \( \alpha = 90^\circ \). If the reaction R is adjudged to act at the very edge of the block, as shown in Figure 37a, and if the lower roof has a weight per unit length of \( \Delta \), then taking movements about B

- 127 -
FIGURE 37. DIMENSIONS AND POSITION OF THRUST FOR TYPICAL POWERED SUPPORTS
\[ P \cdot (\ell - p) = W \cdot \ell = \Delta \cdot \frac{P}{\Delta} \]

\[ \frac{P}{\Delta} = \frac{\frac{\ell}{p}}{\frac{\ell}{p} - 1} \]

The relationship between the dimensionless quantities \( \frac{P}{\Delta} \) and \( \frac{\ell}{p} \) is shown in Figure 38.

In order to allow free access of men through the typical powered support unit, the distance between the front row and the back row of legs is usually about 1.1 m (see Figure 37). The rear overhang of the canopy is, on average, about 0.5 m, and the maximum distance from the front leg to the face is fixed at 2 m. The position of the support thrust \( P \) will depend on the type of support used. If the legs give an equal thrust \( T \) then \( p \) will vary from 2.55 m to 2.88 m, depending on the number of legs (as shown in Figure 37b). Assuming caving occurs at the rear of the canopy, the ratio \( \frac{\ell}{p} \) will vary from \( \frac{3.6}{2.55} = 1.25 \) to \( \frac{3.6}{2.88} = 1.41 \). These values are indicated in Figure 38.

If the roof in the waste holds up for a short distance, then \( \ell \), and hence \( \frac{\ell}{p} \), will increase; the required minimum value of \( P \) for stability will decrease until \( \frac{\ell}{p} = 2 \), i.e. until the centre of gravity of the roof block comes above the support thrust. Thereafter, \( P \) will rise, and, by taking moments about \( A \) (through which \( R \) now acts), this increase can be shown to follow the law

\[ \frac{P}{\Delta} = \frac{\ell^2}{p} \]

This rise is also shown in Figure 38, but the value of \( \frac{\ell}{p} \) must increase to 2.2 before \( P \) exceeds the value appropriate for \( \frac{\ell}{p} = 1.41 \).
FIGURE 38. VARIATION OF SUPPORT LOAD WITH RATIO $\frac{g}{p}$
(VERTICAL CAVING)
Hence, if the roof weight is forward of the support thrust, the worst condition for stability will occur when the roof caves vertically along the line of the rear of the canopies. In such a situation, the four-leg unit gives greater stability than does either the five-leg or the six-leg unit.

This general approach can be used to assess whether or not it is safe to increase the prop-free-front distance beyond 2 m, in order to permit the taking of a wider than normal web. The initial wide web trials at Holditch Colliery are an example of calculating the limits of an existing support installation. The face in question was supported by 6 x 240 Gullick conventional powered supports (40 tonne per leg) at a spacing of 1.22 m; the caving angle was steep and close to the rear of the canopies; for the purpose of the calculation it was assumed that at the rear of the canopies the angle was 90°. What was proposed was the introduction of a 1 m web, giving a total l of 4.33 m before the supports were advanced. The maximum safe height of extraction h was required.

In such a case it is easiest to refer all distances to the rear of the canopy. If the thrust per leg is T, and if the four rear legs give a thrust at b and the two front legs a thrust at f from the rear of the canopy, then, by taking moments about the reaction R, assumed to act at a distance r from the rear of the roof block, we obtain

\[ 4T (h-r) + 2T (f-r) = W (w-r) \]

ie \[ 2T (f-2b-3r) = \gamma s l \]

\[ M = \frac{T(f+2b-3r)}{\gamma s l (\frac{3}{2} l - r)} \]
For the case in question:

\[ T = 40 \text{ tonnes} \]
\[ f = 1.77 \text{ m} \]
\[ b = 0.58 \text{ m} \]
\[ r = 0.61 \text{ m} \text{ (i.e. about 2 ft)} \]
\[ \gamma = 2.54 \text{ tonnes/m}^3 \]
\[ s = 1.22 \text{ m} \]
\[ \lambda = 4.33 \text{ m} \]

the height of extraction \( M = 2.1 \text{ m} \).

In the event, the height of extraction was reduced to 2 m.

Measurements before and after the change-over showed that excellent roof conditions had been maintained. The front legs, however, were now coming up to yield, which they had not done previously; measurements of change of roof slope showed that with the wide web the roof in advance of the front row of legs tended to dip down towards the face, particularly at the time of cutting. This was taken to indicate that, as predicted, the roof was close to the limit beyond which difficulty might have been experienced. Quite a number of faces in the Midlands have now been successfully worked with wide webs, a requirement being that, before exemption is granted for the wider than normal prop-free-front, the stability according to the above method of calculation is checked.

5.7 Possible Equation to Replace the 2 m Prop-free-front Limit

The prop-free-front system of mining requires that the resultant thrust of the supports must lie some distance back from the face line. Although the support canopy can prevent loose roof from falling out near the face, it cannot, in itself,
bring the resultant thrust closer to the face line.

With conventional supports, the magnitude and position of the resultant thrust can be fixed approximately by stipulating the yield pressure and the distance between the face line and the front row of legs, i.e. the prop-free-front distance, as shown in the previous Section. With shield supports this is not the case. The legs need no longer go to the canopy; the legs are frequently inclined; these factors, and the type and position of the hinge linking the canopy to the base, all enter into the calculation of the resultant thrust from the support. An alternative to the prop-free-front distance in controlling the position of the resultant thrust is therefore required.

Limitations to the distances are particularly important when controlling weak roofs. In such a situation, the weight of the roof block will lie forward of the support thrust, and therefore the most severe condition will be vertical caving at the rear of the canopy. If the reaction is assumed to occur at the rear of the roof block, and moments are taken about the rear of the canopy, then

\[ P \cdot p = W \cdot \frac{1}{3} l \]
\[ \gamma = 2W \cdot \frac{1}{3} l \cdot \frac{1}{3} l \]

\[ M = P \cdot p \cdot \frac{1}{s} \cdot \frac{1}{\gamma} \]

If a factor of safety of 2 on the yield load is now introduced, to take account of the extra roof weight which must be sustained when the supports are advanced, and further account is taken of the possibility that the reaction is not at the very
end of the roof block, and that there are probable leaks in
some of the hydraulic circuits, then the Equation may be rewritten
\[ M^2 \gamma = K, \]  \hspace{1cm} \ldots (5.7.1)

where \( K = 20 \frac{PP}{s} \), a constant for any particular support type,
\( M \) = height of extraction (m),
\( \gamma \) = maximum distance, face to rear of canopy (m),
\( P \) = total vertical thrust of the support at yield (MN),
\( p \) = distance of this thrust from the rear of the canopy (m),
\( s \) = support spacing along the face (m),
and \( \gamma \), the average density of the lower roof, is taken
as 0.025 MN/m\(^3\).

The term 'support characteristic' is proposed for \( K \), the units of
which are m\(^3\).

Confirmation of Equation 5.7.1 was sought by comparing
current practice in the use of existing conventional powered
supports. Details of a representative set of current supports,
including the 'support characteristic' \( K = 20 \frac{PP}{s} \), are shown in
Table 7. Using the relevant 'support characteristic', \( M \) was
plotted against \( \gamma \) for each support type, as shown by the full
lines in Figures 39a to 39l. To obtain the equivalent prop-free-
front distances, a second (dotted) curve was drawn. This was
done by offsetting the original curve by the distance from the
rear of the canopy to the front leg (the distance \( d \) in Table 7).
Despite the fact that the maximum working height of a support is
usually governed by the stability of its base, there is a
remarkably close correlation between the prop-free-front at the
<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>p</th>
<th>s</th>
<th>K</th>
<th>d</th>
<th>M(max)</th>
<th>M(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gullick 6/240</td>
<td>2.44</td>
<td>0.98</td>
<td>1.2</td>
<td>39.9</td>
<td>1.78</td>
<td>2.65</td>
<td>1.45</td>
</tr>
<tr>
<td>Gullick 6/240</td>
<td>2.44</td>
<td>1.24</td>
<td>1.2</td>
<td>50.4</td>
<td>2.03</td>
<td>2.65</td>
<td>1.45</td>
</tr>
<tr>
<td>(ext rear cant)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gullick 6/210</td>
<td>2.13</td>
<td>0.97</td>
<td>1.2</td>
<td>34.4</td>
<td>1.88</td>
<td>2.31</td>
<td>0.63</td>
</tr>
<tr>
<td>Gullick 5/200</td>
<td>2.03</td>
<td>0.82</td>
<td>1.2</td>
<td>27.7</td>
<td>1.78</td>
<td>2.19</td>
<td>0.74</td>
</tr>
<tr>
<td>Gullick 5/200</td>
<td>2.03</td>
<td>1.08</td>
<td>1.2</td>
<td>36.5</td>
<td>2.03</td>
<td>2.19</td>
<td>0.74</td>
</tr>
<tr>
<td>(ext rear cant)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gullick 4/250</td>
<td>2.54</td>
<td>1.11</td>
<td>1.2</td>
<td>47.0</td>
<td>1.86</td>
<td>3.16</td>
<td>1.49</td>
</tr>
<tr>
<td>Mk III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gullick 5/150</td>
<td>1.53</td>
<td>0.82</td>
<td>1.1</td>
<td>22.8</td>
<td>1.83</td>
<td>2.30</td>
<td>0.67</td>
</tr>
<tr>
<td>Rb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dowty 6/240</td>
<td>2.44</td>
<td>0.99</td>
<td>1.2</td>
<td>40.3</td>
<td>1.78</td>
<td>2.44</td>
<td>1.03</td>
</tr>
<tr>
<td>Dowty 5/150</td>
<td>1.53</td>
<td>0.70</td>
<td>1.1</td>
<td>19.5</td>
<td>1.65</td>
<td>1.27</td>
<td>0.45</td>
</tr>
<tr>
<td>ART</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dowty 6/180</td>
<td>1.83</td>
<td>0.86</td>
<td>1.2</td>
<td>26.2</td>
<td>1.65</td>
<td>1.59</td>
<td>0.44</td>
</tr>
<tr>
<td>ART</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dowty 4/250</td>
<td>2.54</td>
<td>0.86</td>
<td>1.2</td>
<td>36.4</td>
<td>1.47</td>
<td>3.27</td>
<td>1.29</td>
</tr>
<tr>
<td>Dowty 5/200</td>
<td>2.03</td>
<td>0.86</td>
<td>1.2</td>
<td>29.1</td>
<td>1.78</td>
<td>1.98</td>
<td>0.81</td>
</tr>
</tbody>
</table>

![Diagram showing the relationship between P, p, d, and M.](image)
maximum permitted working height, calculated by Equation 5.7.1, and the 2 m prop-free-front distance. The only exception to this is the Gullick Dobson 5/150 RB (Figure 39g), which appears to have a rather high permitted working height for a 150 ton support. Hence the adoption of Equation 5.7.1 would not greatly influence the current use of powered supports at their maximum permitted working height, and would allow extension of the prop-free-front distance when the height of extraction is reduced. The Equation is also applicable to shield supports.

Equation 5.7.1 implies, however, that, at the minimum support height, a major extension (of up to 5 m or more) would occur in the allowable prop-free-front distance. In the event, this latter value would be severely restricted by the difficulty of designing a suitable canopy. If a linear stress distribution is assumed above the canopy, this restricts its useful length to 3 x p. Any additional length would act as a screen rather than as an active support. If the maximum supported width \( \lambda \) was restricted, say to 4 x p, + 0.5 m unsupported roof, this would effectively restrict the maximum prop-free-front distance to 3.5 m or less (depending on the value of \( p \)).

To summarize, the existing prop-free-front limitation of 2 m could be replaced by a 'support characteristic' unique to each type of support. When the support is installed underground, the product of the height of extraction and the square of the total supported width should at no time exceed the 'support characteristic', subject to an upper limitation on the supported width of, say, 4 p + 0.5 m.
FIGURE 39. APPLICATION OF FORMULA TO REPLACE PRESENT PROP-FREE-FRONT DISTANCE LIMITATION
c. Gullick Dobson 6/210

d. Gullick Dobson 4/250 Mk III

FIGURE 39 (CONTINUED)
e. Gullick Dobson 5/200

f. Gullick Dobson 5/200 (Ext. rear cantilever)

FIGURE 39 (CONTINUED)

- 139 -
g. Gullick Dobson 5/150 RB.

h. Dowty 5/150 Art.

FIGURE 39 (CONTINUED)

j. Dowty 5/200

FIGURE 39 (CONTINUED)

- 141 -
FIGURE 39 (CONTINUED)
- 142 -
5.8 Equilibrium of Forces, Inclined Seams

(a) Derivation of equations

The stability of a freed roof block is again considered, by a method similar to that postulated in the level seam condition. A further variable, the seam inclination, must now be introduced, and consideration must also be given to the possibility of the roof sliding sideways.

Figure 40a shows the cross-section of a face rising at an inclination \( \delta \). As before, the roof block will be acted on by three sets of external forces, each capable of representation by a single resultant force. These are:

(i) the body weight \( W \), taken as a single vertical force acting at the centre of the block and distance \( w \) from the face line;

(ii) the combined support resistance \( P \), acting at a distance \( p \) from the face line. (As conventional supports in general are not designed to take side thrusts on their canopies, any contribution from the rigidity of leg mountings has been ignored. If account has to be taken of a forward hade of the legs, it can be done by inclining \( P \) to the roof. This is a relatively simple matter if the analysis is done graphically. For the purpose of the present calculation, \( P \) has been assumed to act normal to the plane of the roof);

(iii) A reaction \( R \) between the freed block and the remaining mass of the roof, acting at a distance \( r \) from the face line.
(On this occasion \( R \) cannot be zero, because, owing to the inclination of the seam and \( P \) being taken normal to the roof,
(a) Position of forces

(b) Corresponding force diagram

To prevent bodily movement:
\[ R \sin \theta = W \sin \delta \]
and
\[ P = W \cos \delta + R \cos \theta \]

To prevent rotation:
moments about \( A \)
\[ Px (r-p) = W \cos \delta \times (r-w) + W\sin \delta \times \frac{r}{2} \]

(c) Required equilibrium of force components

FIGURE 40. CONCEPT OF ROOF BLOCK AND FORCES INVOLVED
(INCLINED SEAMS)
P cannot act along the same line as W.)

The magnitudes and directions of these forces may be represented as vectors in a force triangle (see Figure 40b). For the block to be in equilibrium under the action of these forces, two basic conditions must be met:

(a) the force triangle shown in Figure 40b must form a closed figure;

(b) the projected lines of the forces indicated in Figure 40a must meet in a point.

In addition, if R is inclined to the roof strata, its transference to the block relies on friction between the upper and the lower roof. Therefore, if $\delta$, the angle which R makes to the normal, is greater than the angle of friction $\phi$, stability will be lost and the block will slip sideways.

These conditions of equilibrium can be used as a means of calculating the required value of P in terms of the other variables. In the force triangle (Figure 40b), $\delta$ is the angle of inclination of the seam and $\theta$ is the angle which the reaction R makes with the normal to the roof. Using the properties of a triangle,

$$\frac{W}{\sin \theta} = \frac{P}{\sin (180^\circ - \delta - \theta)} = \frac{P}{\sin \delta \cos \theta + \cos \delta \sin \theta}$$

Hence,$P = W \left( \frac{\sin \delta}{\tan \theta} + \cos \delta \right)$  

...(5.8.1)

Should the value of R be needed, it can be found from the relationship
\[ R = \sqrt{(W^2 + P^2 - 2WP \cos\delta)}. \]

Referring again to Figure 40a, if the three forces are to meet in a point, then

\[ \frac{C}{2} = (r - p) \cot\delta - (p - w) \cot\delta. \]

Substituting the value for \( \cot\delta \) obtainable from Equation 5.8.1, and rearranging the equation, gives

\[ P = W \frac{\frac{C}{2} \sin\delta + (r - w) \cos\delta}{(r - p)}. \]

As before, the distances \( r \) and \( p \) are limited by the boundaries of the block and the positions of the front and the back legs.

(b) Significance of the equations

The implications of Equations 5.8.1 and 5.8.2 can be more clearly appreciated if the forces \( P, W \) and \( R \) are resolved into rectangular components. This has been done in Figure 40c.

The roof block will not tend to move bodily downhill provided

\[ R \sin\delta \geq W \sin\delta. \]

The roof block will not tend to move bodily in a direction at right angles to this provided

\[ P \geq W \cos\delta + R \cos\delta. \]

Taking the condition when the block is just about to move bodily, we have

\[ R \sin\delta = W \sin\delta \]

and \( P = W \cos\delta + R \cos\delta. \)
Eliminating $R$ from these two equations we obtain

$$P = W \left( \frac{\sin \phi}{\tan \theta} + \cos \phi \right).$$

Hence Equation 5.8.1 represents the condition which must be met in order to prevent a tendency for the block to move bodily in any direction. However, it may still tend to rotate, and it can be shown, by taking moments about any point, that Equation 5.8.2 is the additional requirement to be met in order to prevent a tendency to rotate.

To prevent the block sliding out, the conditions of Equation 5.8.1 must be met at all times, even when the supports are first set. This equation can thus be used to calculate the minimum setting load. Should the block merely rotate in either direction, this will cause movement against the force $P$; because of the rising 'support characteristic', the value of $P$ will increase until further rotation is prevented — provided the yield load has not been exceeded. Thus Equation 5.8.2 can be used to deduce the required yield load. Even during rotation, the laws of friction will apply, preventing the block sliding out. Although undesirable, such a rotation will not necessarily create a hazard.

5.9 Minimum Setting and Yield Loads: Inclined Seams

(a) Minimum setting load

In order to give stability, as indicated above, the angle $\theta$ must be less than the angle of friction $\phi$. The limiting condition for safety is therefore

$$P = W \left( \frac{\sin \phi}{\tan \theta} + \cos \phi \right).$$

...(5.9.1)
where $P$ is the minimum setting load per support,
$W$ is the weight of the lower roof associated with
each support,
$\delta$ is the angle of inclination of the seam, and
$\phi$ is the angle of rock friction between the roof layers.

This equation is independent of $p$, $r$, $w$ and $a$; it depends
only on the magnitudes and the directions of the forces.

$P$ does not increase indefinitely with increase of $\delta$. It can
be shown that it reaches a maximum of $P = \frac{W}{\sin \phi}$ when
$\delta = 90^\circ - \phi$,
"when R is at right angles to W in the force triangle, and then
drops off to $P = \frac{W}{\tan \phi}$ when the seam is vertical.

Concerning the value of $\phi$, there has been little information
published on the angle of friction between beds. A survey of
available literature, supported by more extensive data on the
angle of internal friction, indicates that a value of $\tan \phi = 0.4$
"(ie $\phi = 22^\circ$) is an acceptable minimum standard.

An alternative means of expressing the setting load force
is to represent it as the mean load per unit area of roof. If $S$
is this mean setting load density, $s$ the support spacing, and $\gamma$
the density of rock, then, from Equation 5.9.1,

$$S = s c = \frac{s}{(\tan \phi + \cos \phi)}$$

".$$

$$s = \gamma (\frac{\sin \phi}{\tan \phi + \cos \phi})$$

$$S = c \gamma (\frac{\sin \phi}{\tan \phi + \cos \phi})$$

$$= \frac{W}{20} (\frac{\sin \delta}{0.4 + \cos \delta}) \text{ MPa}$$

$$\text{MPa}$$

$taking \gamma = \frac{1}{40} \text{ MN/m}^3$, $\tan \phi = 0.4$ and $c = 2$ M.
A graph of Equation 5.9.2 is shown in Figure 41. As a guide, a scale has been included on the right of the Figure. This indicates the setting load per support for a 1½ m thick extraction, 3 m wide face with supports at 1 m intervals. Also shown, for comparison, is the value of mean setting load density recommended by the German Inspectorate [58], a value based on a similar equation independently derived by Jacobi [57].

In Figure 40a the cross-section of a face advancing to the rise is shown. If a face break and a roof parting co-exist for any considerable distance, and if the setting load is insufficient, a substantial length of the roof is liable to slide back into the waste. For only a small section of the roof to slide, breaks free of pressure have to be present normal to the face. If a fault cuts the face line, the associated broken ground could represent a hazard in this respect. Normally, the block would slide back only until it comes into contact with the caved material in the waste. However, if the dip exceeds about 30°, it is possible for the caved material to slide down the dip and be missing from the area immediately behind the section of face in question. This is especially true early in the life of the face, when caving has not been everywhere established.

Figure 42 shows a cross-section along the length of an inclined face. Equations 5.8.1, 5.9.1 and 5.9.2 apply equally for components in this direction; they also apply equally for blocks of roof extending over a number of supports. Provided the roof remains continuous in this direction, little trouble should be experienced, as each block of roof will be supported by the one below it. Should one portion of the roof be removed,
FIGURE 41. VARIATION OF REQUIRED SETTING LOAD WITH INCLINATION OF SEAM
Figure 42. Cross-section along inclined face

\[ P = W \left( \frac{\sin \delta}{\tan \phi} + \cos \delta \right) \]

\[ 5P = 5W \left( \frac{\sin \delta}{\tan \phi} + \cos \delta \right) \]

\[ \text{i.e. } P = W \left( \frac{\sin \delta}{\tan \phi} + \cos \delta \right) \]
however, by slipping back into the waste or by falling out in any other way, the whole up-dip section is in jeopardy, unless the support load is sufficient to clamp the lower roof in place. If the face has components of inclination both in the direction of advance and along the face, it is the full inclination (ie the true dip) which should be used in checking the roof stability.

Thus, when working inclined seams, it is recommended that consideration be given to increasing the minimum setting load of the supports, such that the total thrust per unit area of supported roof is that given by Equation 5.9.2.

(b) Minimum yield load

The support yield loads required to prevent rotation of a freed roof block may be calculated by the use of Equation 5.8.2, but the limits imposed on $r$ and $p$, together with the necessity to keep $\tan \phi$ less than $\tan \phi$, present difficulties in its use. A clearer approach is to use a graphical solution with the formulae used only to obtain a subsequent, more precise, value, if the latter should be required.

Examples of graphical solutions are provided in Figure 43. A cross-section of the face and supposed roof block is shown on the left, drawn to scale. The direction of the weight $W$ is drawn vertically through the centre of gravity of the block, and the direction of the combined support load $P$ is drawn normal to the roof, between the limits imposed by the positions of the front and back legs ($f$ and $b$). $R$ may then be drawn through the intersection of $P$ and $W$, keeping it within 0.5 m of the end of the block, and making an angle $\phi$ ($= 22^\circ$) or less with the normal
(a) Approach of R to rear edge of block as limit

(b) Position of P anywhere between f and b possible

(c) Approach of R to front edge of block as limit

FIGURE 43. EXAMPLES OF GRAPHICAL ANALYSES OF FORCES ON INCLINED FACES
to the roof. The force triangle on the right can now be drawn, and the magnitudes of R and P determined. P may then be further divided into the loads on the front and the back legs, F and B, by substitution in the formulae

\[
F = P \frac{b - P}{b - f}, \quad B = P \frac{P - f}{b - f}.
\]

P will be a minimum when \( \theta \) is made as large as possible, subject to it not exceeding \( \phi = 220^\circ \). In Figure 43a the overriding limitation is the approach of R to the rear edge of the block, and, even when \( p = f \), the angle \( \theta \) can only be made \( 19^\circ \).

In Figure 43b, \( p \) may lie anywhere between \( f \) and \( b \) without altering the value of \( P \), the position of \( R \) moving across the top of the block as the position of \( P \) alters. Figure 43c shows the approach of \( R \) to the front edge of the block as the overriding limit. In practice, although a parting along the bedding plane may be smooth, a fracture at a shallow angle across the bedding plane is probably stepped. Hence the angle which \( R \) makes with the front face of the block in Figure 43c is assumed to be acceptable. If this were not the case, this particular block would be incapable of being supported by thrust on its under-side.

This graphical method, checked by calculation, was used to compute the values of \( F \) and \( B \) given in Table 8, which has been limited to three values of the caving angle \( \alpha \) and to a single face width of 3.6 m (i.e., after an average web width has been cut, but before the supports are moved forward). Where there has been a choice of position for \( p \) between \( f \) and \( b \), the value to give a relationship of 1 to 2 between \( F \) and \( B \) has been chosen, i.e., a
### TABLE 8
Minimum Values for F and B in Inclined Seams

(assuming \( l = 3.6 \) m, \( c = 2 \) m, \( f = l - 1.6 \) m, \( b = l - 0.5 \) m, 
\( r \) acts 0.5 m from the relevant corner, rock density = 0.025 MN/m³, 
support spacing along face = 1 m)

<table>
<thead>
<tr>
<th>( \alpha ) deg</th>
<th>( \delta ) deg</th>
<th>( M = 1 ) m</th>
<th>( M = 2 ) m</th>
<th>( M = 3 ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( F ) MN</td>
<td>( B ) MN</td>
<td>( F ) MN</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.21</td>
<td>0</td>
<td>0.43</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0.24</td>
<td>0.02</td>
<td>0.53</td>
</tr>
<tr>
<td>90</td>
<td>20</td>
<td>0.26</td>
<td>0.07</td>
<td>0.62</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.27</td>
<td>0.11</td>
<td>0.69</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>0.27</td>
<td>0.16</td>
<td>0.75</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>0.12</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.09</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>0.11</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>0.13</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>0.14</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>0</td>
<td>30</td>
<td>0</td>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.09</td>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>0.11</td>
<td>0.21</td>
<td>0</td>
</tr>
</tbody>
</table>
six leg support has been assumed. The present generation of powered supports will cover most of the cases considered, with the exception of the 90° caving angle in the thicker seams. Here much greater thrust will be required from the front legs, and, as r and b are alike in this situation, little or no advantage can be gained from increasing the thrust provided by the back legs.

5.10 Application to the Roof Fall at Seafield Colliery

In 1973 an extensive fall of roof took place on the D22 face at Seafield Colliery [59]. Figure 44 shows a plan of the up-dip end of the face just before the fall. The face had advanced only 6 m, and the first weight had not yet taken place. A minor fault crossed the face in the neighbourhood of chock 91, and a crack was reported in the roof 9 m from either side of chock 128. The machine was at rest, at chock 114, but had not completed its cut, and the chocks between 114 and 91 were still standing back. Difficulty had been experienced in advancing chock 91 because of a broken bolt in the advance mechanism. The support had been reset where it stood, but the back legs had not been pressurised because the roof had fallen out over the rear part of the canopy. The height of extraction was 1.5 m; the supported width before the cut was 3.2 m and after the cut 3.8 m; the support spacing was about 1 m.

A few hours before the fall, roof breaks were seen to be developing close to, and parallel with, the face; the waste behind the supports began to break down, most noticeably in the vicinity of supports 90 to 104. The fall occurred from and including chocks 91 to 154, and, according to one eye-witness,
'the whole roof slid down the hill, taking the chocks and almost everything with it'. The fall was 2 m to 2.4 m high, and subsequent inspection revealed a well-defined polished parting in the roof.

Equation 5.8.1 gives the required thrust per support to prevent slippage on a roof parting, should it occur at a height of 2M above the seam roof. Assuming a minimum value of \( \tan \beta = 0.4 \) at this level, the minimum thrust to ensure stability would be

\[
P = 2M \times L \times S \times \gamma \left( \frac{\sin \beta}{\tan \beta} + \cos \beta \right)
\]

\[
= 0.29 \left( \frac{0.63}{0.4} + 0.77 \right)
\]

\[
= 0.67 \text{ MN}
\]

The actual setting pressure available at the time was equivalent only to 0.25 MN per support. The face had not advanced sufficiently for appreciable face convergence to occur. Hence only the setting pressure of the supports was available, even after some time had elapsed following the cut.

The actual slippage took place on a bedding plane 2.2 m above the seam roof, i.e. less thrust was required to prevent movement than at the full 2M (3 m) above. In addition, the coefficient of friction might have been higher than 0.4. The required angle of friction to prevent movement can be found by transposing Equation 5.8.1 to the form

\[
\tan \gamma = \frac{\sin \beta}{\frac{P}{W} - \cos \beta}
\]
and the roof weight \( W \) to a height of \( 2.2 \, \text{m} = 0.21 \, \text{MN}, \)
\[
\tan \theta = \frac{0.63}{0.25 - 0.77} = 1.5
\]

Representative values for the coefficient of friction are, for shale 0.5, for coal 0.75 and for sandstone 1.0. The figure for \( \tan \theta \) is well above any of these. Therefore, the support thrust at setting (and for some time after, because of lack of convergence) would have been insufficient to prevent slippage of a roof block, if the block was freed by a natural roof parting, by a face break, by caving in the waste and by a roof fault. All of these factors were present simultaneously in the neighbourhood of chock 91. Once the roof at chock 91 had been lost, the roof up-dip along the face would have been in jeopardy. Hence, the sliding of the roof would tend to have propagated up-dip for as far as the roof parting and the weakness along the face line existed. The reported facts confirm this analysis.

5.11 Shield Supports

(a) Calculation of \( P \) and \( p \)

When dealing with shield supports, problems arise in calculating the resultant thrust \( P \) and its position \( p \). Shield supports can be divided into four main types. These are illustrated in Figure 45.

The 2-leg simple caliper shield is relatively easy to calculate, as the thrust \( P \) must act through the upper canopy hinge point, as shown in Figure 45a. Taking moments about \( H, \)
FIGURE 45. VARIOUS TYPES OF SHIELD SUPPORT
\[ p \cos \lambda \cdot (m + n) = B \cos \psi \cdot n \]

\[ B = p \frac{(m + n) \cos \lambda}{n \cos \psi} \]

The angle \( \lambda \) will vary with the coefficient of friction between the canopy and the roof, and both \( \lambda \) and \( \psi \) will vary with the height of extraction.

Because of the sloping legs and the lemniscate mechanism, the exact solution of the forces concerned with the other types of shield is difficult. Computer programs are available, and a semi-graphical solution is given in Appendix 1.

(b) Distribution of Load on Canopy and Base

With 2-leg shield supports, it is possible to have the thrust \( P \) well forward. As the floor load will be equal to \( P \) and will act along the same line, this can produce severe loading on the toe of the base. This is particularly the case when there is little lateral movement between the roof and the floor, and when a horizontal load is not generated on the canopy, causing \( P \) to act vertically.

Providing a linear distribution of load is assumed, the manner of distribution on the canopy and the base can be estimated. One method of estimation is provided in Appendix 2. The possible stress distribution for the various types of shield support is illustrated by the dotted lines in Figure 45. Equal loads in the legs have been assumed, and a nominal coefficient of friction of 0.2 has been taken between the support and the strata. The resultant load passes through the centre of pressure, its position and direction being shown by the chain.
lines. The more even distribution of floor loading by the use of four legs is also clearly illustrated. In the case of the chock shield the higher stress is to the rear, a fact which will greatly ease the problems of advancing should floor penetration occur.

(c) Roof Stability with Shield Supports

When shield supports are used, the thrust $P$ can no longer be deemed always to act normal to the roof. Lateral movement between roof and floor can generate a component of $P$ which will tend to hold the roof block into the corner. This can have significant effect on the stability. A complete re-analysis of the forces involved has therefore been carried out, but has been limited to the condition of vertical caving. The effect of friction between the roof block and the remaining roof has also been taken into account.

The forces involved in the stability of the portion of roof liable to move are shown in Figure 46a. Insufficient support thrust will cause anti-clockwise rotation of the block. If the roof break in line with the face is irregular, such rotation will cause the block to move back as the face crack opens. Contact will probably continue at A and B, and frictional forces will come into play, as shown.

Consider unit length of face, and let the frictional forces be $Q$ and $S$ at A and B respectively, with the angle of friction $\phi$ assumed to be the same at both points. $W$ is the weight of the roof block and $P$ the support thrust. The other nomenclature is as shown in Figure 46a.
a. Forces involved

b. Resolution of forces

c. Nomenclature of support distances

FIGURE 46. ANALYSIS OF ROOF STABILITY WITH SHIELD SUPPORTS
These forces can be resolved into components along and normal to the direction of the bedding, as shown in Figure 46b. This allows three equations to be set up, and the three unknowns $S$, $Q$ and $P$ to be deduced.

Equating forces at right angles to bedding

$$P \cos \beta + S \sin \phi = W \cos \phi + Q \cos \phi \quad \ldots \text{(5.11.1)}$$

Equating forces in direction of bedding

$$P \sin \beta + Q \sin \phi = W \sin \phi + S \cos \phi \quad \ldots \text{(5.11.2)}$$

Taking moments about $A$

$$p \cdot P \cos \beta + c \cdot P \sin \beta + \ell \cdot S \sin \phi$$

$$= w' \cdot W \cos \phi + \frac{c}{2} \cdot W \sin \phi \quad \ldots \text{(5.11.3)}$$

Eliminating $Q$ and $S$ from Equations 5.11.1, 5.11.2 and 5.11.3 gives

5.11.3 gives

$$P \left\{ (p \cos \beta + c \sin \beta) (1-\tan^2 \phi) + \ell \tan \phi \right\}$$

$$= W \left\{ (w' \cos \phi + \frac{c}{2} \sin \phi)$$

$$\left(1-\tan^2 \phi \right) + \ell \tan \phi \right\} \left(\sin \phi + \cos \phi \cdot \tan \phi \right) \} \quad \ldots \text{(5.11.4)}$$

If the geometry of the face and of the supports is as shown in Figure 46c, then $\ell = f + a + p - d$ where $f$ is the prop-free-front distance and $d = 0$ when the supports are standing back.

For vertical caving $w' = \frac{c}{2}$, and under normal caving conditions $c = 2 W$. The roof weight

$$W = \text{weight per unit length of face}$$

$$= \text{density} \times c \times \ell$$

$$= 0.025 \times 2 \, M \times (f + a + p - d) \, MN$$

where all distances are quoted in metres.
In the previous analysis a safety consideration was
introduced, by assuming the reaction \( R \) to act 0.5 m from the
corner. In the present analysis it has been found easier to
introduce a safety consideration by the direct introduction of
a factor of safety \( F \). By making the above substitutions in
Equation 5.11.4, the following general relationship is
established

\[
P = 0.05 M \times F \frac{(\frac{1}{2} \cos \delta + M \sin \delta)(1 - \lambda^2) + \mu \lambda (\mu \cos \delta + \sin \delta)}{(p \cos \delta + 2 M \sin \delta)(1 - \lambda^2) + \mu \lambda (\mu \cos \delta + \sin \delta)} \quad \cdots (5.11.5)
\]

where \( P \) = the required support thrust (MN per m length of face),

\( M \) = height of extraction (m),

\( l \) = face width (m) = \((f + a + b - d)\), as defined in

Figure 46c,

\( F \) = factor of safety,

\( \delta \) = angle of rise in direction of face advance,

\( \mu \) = \( \tan \delta \) = coefficient of friction, rock on rock,

\( p \) = distance of resultant support thrust from rear of
canopy (m),

\( \delta \) = angle of support thrust to the normal to the roof.

In the case of lateral roof movement with shield supports, \( \tan \delta \)
is the coefficient of friction between roof and support canopy.

As an aid to subsequent calculations, Equation 5.11.5 has
been programmed on the NCB Cannock computer.

The value of \( P \) has lower limits, below which it should not
be taken. The resultant of \( S \) and \( Q \) will be \( R \) passing through
the intersection of \( P \) and \( W \) (see Section 5.8). If \( R \) is
inclined over the waste, \( S \cos \phi \) will be negative, and, to
prevent it sliding back, the block will rely solely on friction.
The previously obtained limit of $P$ derived in Section 5.9 will apply,

$$P = W \left( \frac{\sin \theta}{\tan \delta} + \cos \theta \right) \text{ where } \tan \theta < 0.4 \quad \ldots (5.11.6)$$

If $R$ is inclined over the face, as could be the case with a shield support, this is equivalent to the roof block being pushed forward bodily, and there will be no such limit to the value of $\theta$. However, another limiting condition will apply.

Figure 47 analyses the stability of forces $W$, $P$ and $R$ where they intersect above the top of the roof block. The reaction $R$ has been divided into $R \cos \delta$ and $R \sin \delta$, acting at $A$ and $B$ respectively. If the points of application of $P$ and $W$ get closer, or the angle between them gets greater, they may intersect below the top surface of the block. The formula calculates the case of $R$ passing through this intersection and through the point $A$; $R$ would then be a force on the front face of the block with an upward slope. A frictional component would be required on the interface $BC$, with the possibility of some part of the roof going into tension. This can be avoided by imposing a lower limit on $P$, such as to keep the reaction $R$ normal to the front face of the block. This condition is shown in Figure 48.

The angles of the vector diagram in Figure 48 are easily deduced in terms of the friction angle $\beta$ and the face rise $\delta$. From the properties of a triangle, if $R$ is normal to the face of the roof block, then
FIGURE 47. STABILITY ANALYSIS WITH FORCES INTERSECTING ABOVE TOP OF ROOF BLOCK
FIGURE 48. STABILITY ANALYSIS WITH FORCES INTERSECTING BELOW TOP OF ROOF BLOCK
\[
\frac{P}{\sin (90^\circ + \beta)} = \frac{W}{\sin (90^\circ - \beta)}
\]

\[\therefore \quad P = \frac{W \cos \beta}{\cos \beta} \quad \ldots (5.11.7)\]

This represents a lower limit below which \( P \) should not be taken when the roof block is being pushed forward.

5.12 Application to Shield Supports at Daw Mill Colliery

The faces in the NW district of the Warwickshire Thick Seam at Daw Mill Colliery are equipped with Dowty 4 x 250 conventional-type powered supports, operating at a height of extraction of 3.2 m, a prop-free-front distance of 2.0 m, and advancing to a rise of 1 in 10. To increase the take of coal and allow the use of a wider conveyor, a greater height of extraction and an extension to the prop-free-front distance was required. As the Dowty 4 x 250 chocks appeared to be working at their limit, it was proposed that this be accomplished by installing a Dowty 4 x 300 chock shield system. Before granting an exemption for the wider than normal prop-free-front distance, HM Inspector of Mines requested a theoretical analysis of the roof stability.

(a) Required Setting Load

In the case of the setting load, any downward movement of the roof would bring about a rise in support thrust as a result of the compression of the fluid in the legs. Premature roof movement could weaken the roof along the face line, but this would not endanger life; hence a factor of safety of unity was considered tolerable.
Movement of the roof will be possible only if the friction is overcome. The coefficient of friction will vary with the type of strata. As the upper roof is frequently of weak mudstone, a conservative value of 0.4 has been taken for $\mu$. The setting load has been considered normal to the roof, hence $\beta = 0$.

When set, the supports will be in the forward position, and hence the distance from the face to the rear of the canopy will be reduced by one web width. The Dowty 4 x 250 tonne Chock and the Dowty 4 x 300 tonne Chock Shield have similar leg spacings, and in both cases $a = 0.71 \, \text{m}$, $p = 1.00 \, \text{m}$, and $d = 0.6 \, \text{m}$. These values were inserted in Equation 5.11.5 and Figure 49 was produced. This shows the recommended setting loads based on the above considerations, plotted against prop-free-distance for various heights of extraction.

Both the support types have nominal setting loads of 113 tonnes per support, but the chocks have a spacing of 1.2 m, whilst the shields have a spacing of 1.5 m. Hence the thrust per metre of face length for the chocks is 0.92 MN and for the chock shields 0.74 MN. These have been indicated on Figure 49. The setting pressure of the present 4 x 250 chocks is seen to be adequate for the current height of extraction of 3.2 m and the current prop-free-front distance of 2.0 m. If the prop-free-front distance is increased to 2.5 m, then the setting load of either support type should be increased to 1.02 MN/m; if the height of extraction is subsequently raised to 3.6 m, the setting load should be further increased to 1.16 MN/m. These correspond to 156 tonnes and 177 tonnes in
the case of the shield support, ie 52% and 59% of the yield load.

(b) Required Yield Load

In the case of the yield load, the support thrust no longer has a rising characteristic to oppose any movement. Therefore, for the sake of safety, the most adverse condition should be considered. If the roof break at the face is plane, no backward movement is required to drop the block. Consequently, no frictional forces will be developed. This can be programmed into Equation 5.11.5 by putting $\mu = 0$. Moreover, the supports may at the time be standing back; hence $d = 0$. A factor of safety of 1.5 has also been adopted.

If lateral roof movement occurs, the flexible seatings of the frame-type of chocks will not oppose movement. Hence $\beta$ will remain approximately zero, provided the movement is not excessive. By inserting the requisite values into Equation 5.11.5, Figure 50 was produced. A yield load of 250 tonnes per chock on a 1.2 m spacing corresponds to 2.04 MN/m, and this has also been added. The present 4 x 250 chock is adequate for a prop-free-front distance of 2.0 m and a height of extraction of 3.2 m, but, if the 50% safety factor is to be maintained, this represents the limit of the support when operating up a rise of 1 in 10.

The 4 x 300 chock shield will offer resistance to lateral roof movement, and, provided such movement occurs, $\tan \beta$ will not be zero. The supports are designed for a $\tan \beta = 0.3$, but, because of the presence of a weak shale in the roof, it was considered prudent to adopt a value $\tan \beta = 0.2$. The additional insertion of this value into Equation 5.11.5 allowed
FIGURE 50. RECOMMENDED YIELD LOADS, DAW MILL
4 x 250 CHOCK
Figure 51 to be drawn. The change of slope is a consequence of the reaching of the limiting condition imposed by Equation 5.11.7. The yield load of the chock shields gives an equivalent of 196 MN per m length of face. This also has been indicated.

Figure 52 represents the condition where no relative lateral roof movement is present. If the factor of safety of 1.5 is to be maintained for such conditions, the prop-free-front distance of 2 m cannot be extended or the height of extraction of 3.2 m raised. However, if the factor of safety is taken as unity, there is still a fair degree of scope for extending the prop-free-front distance and/or the height of extraction, as is indicated by the dotted lines. If, when supports are installed, relative lateral roof movement is assumed, but in fact not present, the dotted lines on Figure 52 represent the limits which can be 'absorbed' by the factor of safety.

(c) Recommendation

The theoretical analysis indicates that the Dowty 4 x 250 chocks have reached the limits of their safe working capacity. The installation of Dowty 4 x 300 chock shields should allow the prop-free-front distance and the working height to be extended, provided that the existing setting load is increased to 60% of the yield load and that there exists a lateral roof movement to be resisted.

Measurements carried out at Daw Mill Colliery indicated that lateral movement of roof and floor was in fact present. Despite this, it was further recommended that the prop-free-front distance should not exceed
FIGURE 51. RECOMMENDED YIELD LOADS, DAW MILL
4 x 300 SHIELD. COEFFICIENT OF FRICTION 0.2
FIGURE 52. RECOMMENDED YIELD LOADS, DAW MILL
4 x 300 SHIELD
NO RELATIVE LATERAL ROOF MOVEMENT
2.8 m at a height of extraction of 3.4 m
2.7 m at a height of extraction of 3.5 m
2.6 m at a height of extraction of 3.6 m,
since at these values lack of lateral roof movement would
completely 'absorb' the factory of safety. This condition
could arise immediately after the face is started away.

With the help of these theoretical calculations, Daw Mill
was granted an exemption to work a 3.55 m height of extraction
with a 2.40 m wide prop-free-front distance. The Dowty 4 x 300
Chock Shields were subsequently installed, and, at the time
of writing (February 1980), the face is producing over
1600 tonnes/day, with excellent roof conditions.