

OPTIMIZATION OF LONGWALL PANEL LOCATION WITH REGARDS TO THE GRADIENT OF COAL SEAMS

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Abstract The paper begins by outlining the role and importance of coal as a source of energy and in the steel industry. It briefly describes the longwall method of working together with the conventional machinery used in the method. A mathematical model is then proposed that shows the relationship between the gradient of the coal seam, that of the face and the entries to the panel. Determination of a model that mathematically shows the economically best location for the longwall panel with regards to the seam gradient is the core section of the paper which is accomplished by introducing an objective function and devising its component models. The model is then subjected to sensitivity analysis. The results can assist the mining engineer in determining the most economic location for the longwall panels.

Key Words Coal, Longwall, Face, Steep Seam Panel, Face Direction

چکیده مقاله حاضر ابتدا به نقش و اهمیت زغال سنگ به عنوان یک منبع مهم انرژی اشاره نموده بطور خلاصه روش جبهه کار طولانی و ماشین آلات مورد استفاده در آن را توضیح می دهد. سپس یک مدل ریاضی ارائه شده که رابطه بین شیب حقیقی خط جبهه کار، تونل های دسترسی دو طرف آن و شیب کلی لایه زغال سنگ را نشان می دهد. قسمت اصلی مقاله ارائه یک مدل ریاضی است که با استفاده از آن می توان اقتصادی ترین محل قرارگیری یک پهنه نمونه جبهه کار طولانی را بدست آورد. این مدل با استفاده از تعریف یک تابع هدف و محاسبه اجزای تشکیل دهنده آن با استفاده از اعداد حقیقی بدست آمده است. نتایج این تحقیق را می توان در طراحی های استخراجی لایه های زغال سنگ بکار برد.

1. INTRODUCTION

Energy is considered to be one of the most important factors contributing to economic growth. Despite short-term fluctuations and geographical variations regarding the global demand for energy, coal has been a primary source of energy for centuries and its total world output has always had an increasing trend. The increase in total production has been brought about, more than anything else, by the application of more efficient methods and machinery. Longwall method is relatively new in many countries. It has always been predominant in the U.K coal mining industry but its full potentials as regards

production levels, mechanizability and productivity were realized by the American coal mining industry and others, in the latter part of the twentieth century. It is now the most widely used underground coal mining method in many parts of the world.

Access is gained to the coal seam by shafts or inclined drifts, or a suitable combination of both. The seam is then divided into rectangular panels. These panels are developed with respect to seam thickness, gradient and depth; characteristics of roof, floor and the surrounding strata, presence and the extent of faults and other discontinuities, seam gas content, etc. A typical coalface is composed of a coalface and two parallel entries (Figure 1).

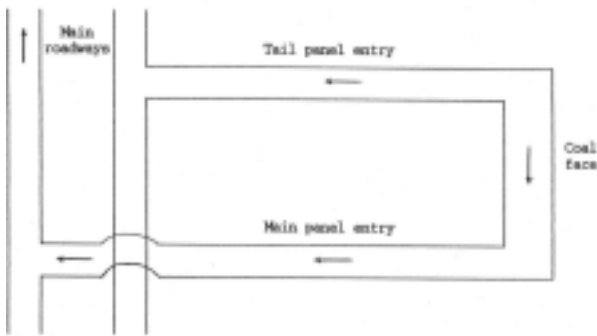


Figure 1. A typical longwall panel.

Each of these sections has certain duties to perform:

1. The coalface is conventionally equipped with a number of powered supports or hydraulic props; one or more cutter/loaders, such as shearer loader, plough, etc; and a type of armored flexible conveyor (AFC) for transporting the coal from the face to the main entry.
2. The main entry is the roadway through which coal is transported out of the panel area, by means of a usually fixed belt conveyor to the trunk roadway.
3. The tail entry could be considered as a store for electrical, control and ancillary equipment as well as means of providing through ventilation.

Coal seams of 3.5m thick with the gradient of 0-45° could be considered suitable for longwall mining, although continuity of the seam and the nature and characteristics of its roof and floor can have important bearing on the application of the method.

Longwall panels of 700-1500m long and 100-250m wide are now most common. Coal from these panels is won either by advancing or retreating system of working (Figure 2).

One of the attractions of the longwall method is its applicability in seams with higher gradients. Since all the developments are driven within the coal seam, the gradient of the face and that of the entries change with changes in the location of the panel. The total cost of winning the coal in the panel also changes accordingly and it is the intention of this paper to find the optimum gradient for the face and hence that for the entries, so that the total

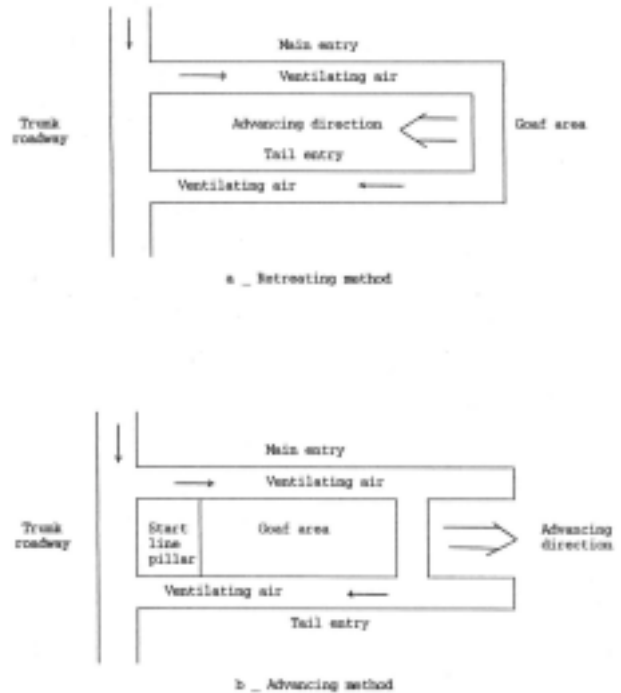


Figure 2. Longwall advancing and retreating.

cost will be at minimum.

2. RELATIONSHIP BETWEEN THE GRADIENT OF THE FACE, ENTRIES AND THE COAL SEAM

A typical face with two entries (single entry) is assumed. The face line is also assumed to be perpendicular to the direction of the entries and therefore any rotation of the panel within the seam increases the gradient of one, while decreasing that of the other. For example, if the panel is rotated in a way that face gradient is decreased, then the gradient of the entries increases; and ultimately the face is level (zero gradient) when the gradient of the entries is equal to the seam full dip. The maximum dip for each of these is therefore equal to the seam full dip and the minimum is zero. To obtain a relationship between these, a part of the coal seam, such as “abcd” plane (Figure 3) is considered.

The two lines “eg” and “eh” show the gradients of the face and of the entries respectively. These

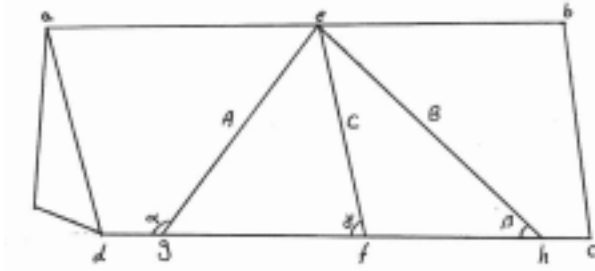


Figure 3. Coal seam “abcd”, face and entries’ lines.

two lines are within the “abcd” plane and are perpendicular to each other. They also form gradients of “ α ” and “ β ” respectively, with the horizontal plane. Using the drawing in fig 3, the length of the three lines “eg”, “eh” and “ef” can be defined as follows:

$$eg = A = \frac{1}{\sin \alpha} \quad (1)$$

$$eh = B = \frac{1}{\sin \beta} \quad (2)$$

$$ef = C = \frac{1}{\sin \gamma} \quad (3)$$

On the other hand, the angle at “h” is common between triangles “egh” and “feh” and the two angles “geh” and “efg” are equal (both 90°). The two triangles “egh” and “efh” are therefore similar and hence:

$$\frac{C}{A} = \frac{fh}{B} = \frac{B}{gh} \quad (4)$$

Or

$$gh = D = \frac{BA}{C} \quad (5)$$

Also in triangle “egh” we have:

$$A^2 + B^2 = D^2 \quad (6)$$

Combining the two Relations 5 and 6, it is concluded

that:

$$A^2 + B^2 = \left(\frac{BA}{C}\right)^2 \quad (7)$$

Or

$$\frac{1}{B^2} + \frac{1}{A^2} = \frac{1}{C^2} \quad (8)$$

If the values of A, B and C are now substituted in this equation, we will have:

$$\sin^2 \alpha + \sin^2 \beta = \sin^2 \gamma \quad (9)$$

This equation shows the relationship between the gradient of the coalface (α), that of the two parallel entries (β) and the seam full dip (γ).

3. OPTIMISATION OF PANEL LOCATION WITH RESPECT TO DIP

The intention here is to find the optimum location of the longwall panel, that is, where the total cost of the development and coal extraction in the typical panel is minimum. For this purpose, the objective function C_T is defined as follows:

$$C_T = C_1 + C_2 + C_3 + n(C_4 + C_5) + C_6 + C_7 \quad (10)$$

Where:

- C_T is the total cost of exploitation of the panel,
- C_1 is the costs associated with the face supports,
- C_2 is the shearer loader costs,
- C_3 is the AFC costs,
- C_4 is the total support costs of the two entries,
- C_5 is the cost of driving the two entries,
- C_6 is coal transportation cost in the main entry,
- C_7 is all other panel costs, such as ventilation, lighting, drainage, communication etc,
- n is the number of entries serving the panel, which will be equal to 2 in a single entry system.

Individual models will therefore have to be devised for C_1 - C_7 in order to evaluate C_T , the total cost of the panel. For this purpose, a typical panel is

considered with most common parameters. Since, amongst all external variables, the gradient is of interest here, at this stage, all other parameters are assumed constant.

4. ASSUMPTIONS

- 1) Panel type: single entry, retreat face
- 2) Seam thickness: 2 meters
- 3) Seam full dip: 40°
- 4) Panel dimensions: 1200m × 200m
- 5) Powered supports capacity: 240-450 tons
- 6) Coal cutting is carried out by one shearer loader, DERDS, 250-500 KW
- 7) Coal transport is carried out by AFC, width 762mm
- 8) Both roof and floor are sandstone or some other competent material
- 9) Three 8 hour shifts are performed per day
- 10) Steel frame support system is used throughout the entries
- 11) Coal transport in the main entry is carried out by 800mm wide belt conveyor.

5. POWERED SUPPORTS COST

As the gradient of the face varies, the magnitude of the load exerted upon the roof changes and with that the capacity of powered supports will have to be different. This in turn makes powered supports costs vary with the face gradient.

To determine the magnitude of the force exerted on the roof, Wilson formula has been used [1]. This states:

$$F = \gamma H \left(\frac{\sin \alpha}{\tan \psi} + \cos \delta \right) \quad (11)$$

Where:

- F is the average density of the load exerted on the face (ton/m²).
- γ is specific gravity of the immediate roof (tons/m³).
- H is thickness of the immediate roof (m).
- α is the face gradient (degrees).
- δ is the seam full dip (degrees).

- ψ is the angle of friction between the immediate roof and the main roof.

The roof material is assumed to be sandstone, therefore:

$$\gamma = 2700(\text{tons/m}^3) \quad \delta = 40^\circ \quad \tan \psi = 0.4$$

Hence the magnitude of the load is calculated by:

$$F = 1.32 \times 10^{-3} \left(\frac{\sin \alpha}{0.4} + 0.766 \right) \quad (\text{tons/m}^2) \quad (12)$$

On the other hand, we have the following formula for designing powered supports for such a face [2]:

$$P_{sa} = \frac{F.W}{102 \cdot le} \quad P_{sn} = \eta \cdot P_{sa} \quad P_{yn} = \lambda P_{sn}$$

$$P_y = 102 P_{yn} \cdot le \cdot s \quad (13)$$

Where:

- W is the width of the immediate roof (m)
- le is the length of the canopy (m)
- P_{sa} is the active static stress on the support (MPa)
- P_{sn} is the nominal static stress (MPa)
- P_{yn} is the nominal yield stress (MPa)
- η is the correction coefficient, which is equal to 1.25
- λ is a constant equal to 1.25
- S is the center distance between powered support sets
- P_y is the capacity of powered supports (tons)

Since it is assumed that the powered supports used are of the shield type, it can be deduced that W=5.6m and le=3.5m.

Therefore:

$$P_y = 102 \times 3.24 \times 10^{-5} \left(\frac{\sin \alpha}{0.4} + 0.766 \right) \times 3.5 \times s \quad (14)$$

Now if the capacity of one set of powered support is known, for example 250 tons and if the face length is 200m, we have [3]:

$$N = \frac{200}{S} = 94 \left(\frac{\sin \alpha}{0.4} + 0.766 \right) \quad (15)$$

Where N is the theoretical number of 250 tons

powered support sets.

In this way the numbers of powered support sets are calculated. We now assume that the useful economic life of a powered support set allows the set to be used on six consecutive panels and also that the whole length of the roof is covered by powered supports. Also considering the price range of US\$ 18,480 for supporting each meter of the face length in the case of 6-leg 240 tons sets to US\$ 33,280 in the case of 4-leg 450 tons sets, we can deduce [4]:

$$C1 = 1.02 [5983.542 + 587927.324 (\alpha)] \quad (16)$$

Where:

- C1 is the total powered support cost in US Dollars
- α is the face gradient in radians

This relation holds for $22^\circ \leq \alpha \leq 40^\circ$ and if $\alpha \leq 22^\circ$ then its value is assumed to be equal to 22° .

6. CUTTING/LOADING COSTS

For the seam assumed to be 2m thick here, it is considered that one Double Ended Ranging Drum Shearer (DERDS) unit is suitable and its total costs will be:

Total cutting/loading costs = Capital cost + Operational costs

The price of one unit of such shearer loader is assumed to be US\$ 1,200,000 and that during its economic life; it should be able to serve six panels. The capital cost of such shearer loader is therefore US\$200,000 per year. The total power cost of the shearer loader can be calculated from:

$$\text{Total power } P_t = (P1 + 340) + P2 \quad (17)$$

Where:

- P1 is the power consumption when cutting (down the slope)
- P2 is the power consumption when flitting (up the slope)
- 340 is the power used to rotate the drums, which is constant

We now expand P1 and P2 and the power consumption is analyzed with regard to its normal

and horizontal components. Also the weight of a DERDS unit is assumed to be 20 tons and its cutting and flitting speed are assumed to be 4.7 and 14.1 meters per minute respectively. We then have [4]:

$$P1 = 26.72 \cos \alpha + 0.314 \sin \alpha + 238 \text{ (KWh)} \quad (18)$$

P1 is the power consumption when the shearer loader is running, i.e. either cutting or flitting. Combining this relation with that for the total number of cuts, we have:

$$P = n \cdot \frac{\text{s.f}}{\eta} p_1 \quad (19)$$

Where:

- n is the total number of cuts in a panel, assumed to be 1,437
- s.f is the safety factor, assumed to be 1.2
- η is the technical efficiency of shearer loaders, taken to be 0.8

We therefore have:

$$C = 200,000 + 68.976 (26.72 \cos \alpha + 0.314 \sin \alpha + 238) \quad (20)$$

In this model, the angle α is measured in terms of degrees and C measures the total power cost. Adding the miscellaneous power costs, cost of idle periods etc, we have [4]:

$$C2 = [(1 + 0.0005(\alpha)) [200,000 + 68.976 (26.72 \cos \alpha + 0.314 \sin \alpha + 238)] \text{ US\$} \quad (21)$$

7. COAL TRANSPORT COSTS AT THE FACE

When the face gradient varies, the power required to transport coal along the face also varies. With this variation, the cost of coal transport increases with the gradient of the face line. To calculate the AFC power consumption, the forces against motion of the AFC are analyzed.

$$F_s = W_s \cdot L (\cos \alpha \cdot \mu_s + \sin \alpha) \quad \text{Empty} \quad (22)$$

$$F_c = W_s.L(\cos \alpha.\mu_s + \sin \alpha) + W_c.L(\cos \alpha.\mu_s - \sin \alpha)$$

Full

$$(23)$$

Where:

- F_s is the force required to move the empty AFC up the slope
- F_c is the force required to move the full AFC down the slope
- W_s is weight of unit length of the AFC (kg)
- W_c is weight of the coal loaded on unit length of the AFC (kg)
- μ_s is the AFC friction coefficient
- μ_c is the loaded AFC friction coefficient
- L is length of the AFC (m)
- α is the face gradient (degrees)

Total force required for one cut is therefore:

$$F_t = 1.1 (F_c + F_s) \quad (24)$$

If we now take $L=200m$, $\mu_s=0.4$, $W_s=14 \text{ kg/m}$, $K=\text{capacity coefficient}$, $\mu_c=0.6$, $W_c=70\text{kg/m}$ and adding to these the facts that there will be 1,437 cuts needed for the total extraction of such panel, each cycle of the AFC takes 0.0855 hours and also that there will be 34 cycles for the AFC in each cut, we will have [4]:

$$P=58.483[\cos \alpha (2240+8400K) - \sin \alpha (14000K)] \text{ (KWh)}$$

$$(25)$$

If we now take US\$ 120,000 to be the capital cost of the AFC, assume the cost of energy to be US\$ 0.032/kwh and the reciprocal of the efficiency of the AFC motors to be 1.2, we then have:

$$C_3 = 120,000 + 0.032 \times \frac{1.2}{0.8} \times p \quad (26)$$

Or

$$C_3 = 120,000 + 2.807 [\cos \alpha (2240 + 8400K) - \sin \alpha (14000K)] \text{ US\$}$$

$$(27)$$

Capacity coefficient (K)	1	0.95	0.9
			0.85

Face gradient (α)	<10°	10°-15°	16°-20°
			>20°

8. ENTRIES' SUPPORT COSTS

The magnitude and characteristics of the load exerted on the roof and sides of the access entries vary with the gradient of these entries. The entries support system is therefore designed to suit the gradient of these entries and their support cost therefore depends on the gradient of these entries. According to rock mechanics principles [3] the intensity of the load applied on horizontal entries could be calculated using Equation 28:

$$q_t = \alpha .L.\gamma.a \quad (28)$$

This equation can be made applicable to dipping roadways:

$$q_t = \alpha.L.\gamma.a(\cos \beta + \frac{\sin \beta}{0.4}) \quad (29)$$

Where:

- q_t is intensity of the uniform load on the roof (ton.m)
- α is coefficient of load condition (normal condition = 0.5)
- L is length of the support canopy (m)
- γ is specific gravity of the immediate roof (tons/m³)
- a is the distance between each two powered support units (m)

Now if we substitute $L=2.5m$ and $\gamma=2.7 \text{ tons/m}^3$, then:

$$q_t = 0.5 \times 2.5 \times 2.7 \times a(\cos \alpha + \frac{\sin \alpha}{0.4}) \quad (30)$$

On the other hand, for beams of types Gl 120, Gl 130 and Gl 140, we have:

$$|\sigma| = 3375.657 \quad q_t \leq 14000$$

$$\text{Therefore} \quad q_t \leq 4.147$$

Substituting for the above equation we will have:

$$3.375 \times a(\cos \beta + \frac{\sin \beta}{0.4}) \leq 4.147 \quad (31)$$

If the price of powered support sets are also taken into account [5] then

$$\text{If } \beta \geq 0 \quad C = 197233.52(\cos \beta + \frac{\sin \beta}{0.4}) \quad \$$$

TABLE 1. The Component Models of C_T.

	Models	Parameters	Remarks
C ₁	1.02[5983.543+1587827.324(α)]	α=Face gradient in radians	α < 22° ⇒ α = 22°
C ₂	[1+0.0005(α)][88.976(26.72Cosα+0.314Sinα+238)+200000]	α=Face gradient in degrees	
C ₃	120000+2.807[Cosα(2240+8400 k)-Sinα(14000 k)]	α=Face gradient in degrees k=Capacity coefficient	α < 10 10-15 16-20 ≥21 k 1 0.95 0.9 0.85
C ₄	$K(\cos\beta + \frac{\sin\beta}{0.4})$	β=Entries gradient in degrees k=Capacity coefficient	β 0-9 10-19 >19 k 797235.52 181404.174 167634.04
C ₅	[116.2+61.4784(β)]×1200	β=Entries gradient in radians	
C ₆	244701.2		
C ₇	858550		
	$\sin\alpha^2 + \sin^2\beta - \sin^2\gamma$	α=Face gradient (°) β=Entries gradient (°) γ=seam full dip (°)	

If $10 \leq \beta \leq 20$ $C = 181404174(\cos\beta + \frac{\sin\beta}{0.4})$ \$

If $\beta \geq 20$ $C = 167634.04(\cos\beta + \frac{\sin\beta}{0.4})$ \$

Or

$C_4 = K(\cos\beta + \frac{\sin\beta}{0.4})$ \$

9. ENTRIES' DRIVAGE COSTS

Driving inclined headings are generally expected to be more expensive than horizontal ones. In this case, headings with a cross section area of 6m² are considered appropriate and using data from the USBM the relation that shows this type of costs is found to be [6]:

$C_5 = [116.2 + 61.4784 (\beta)] \times 1200$ (32)

Where:

- C₅ is the cost of entries' drivage in \$US,
- β is the gradient of the entries in radians

10. TRANSPORT COSTS IN THE MAIN ENTRY

The cost of transporting coal in the main entry does not vary much with changes in the gradient of the entry itself, and is found to be [2]:

$C_6 = 244,700$ \$ (33)

Where C₆ is the transport cost of coal in \$US.

11. MISCELLANEOUS COSTS

All other costs, lighting, ventilation, communications, etc are considered here and found to be unrelated to face and entries gradient and therefore assumed

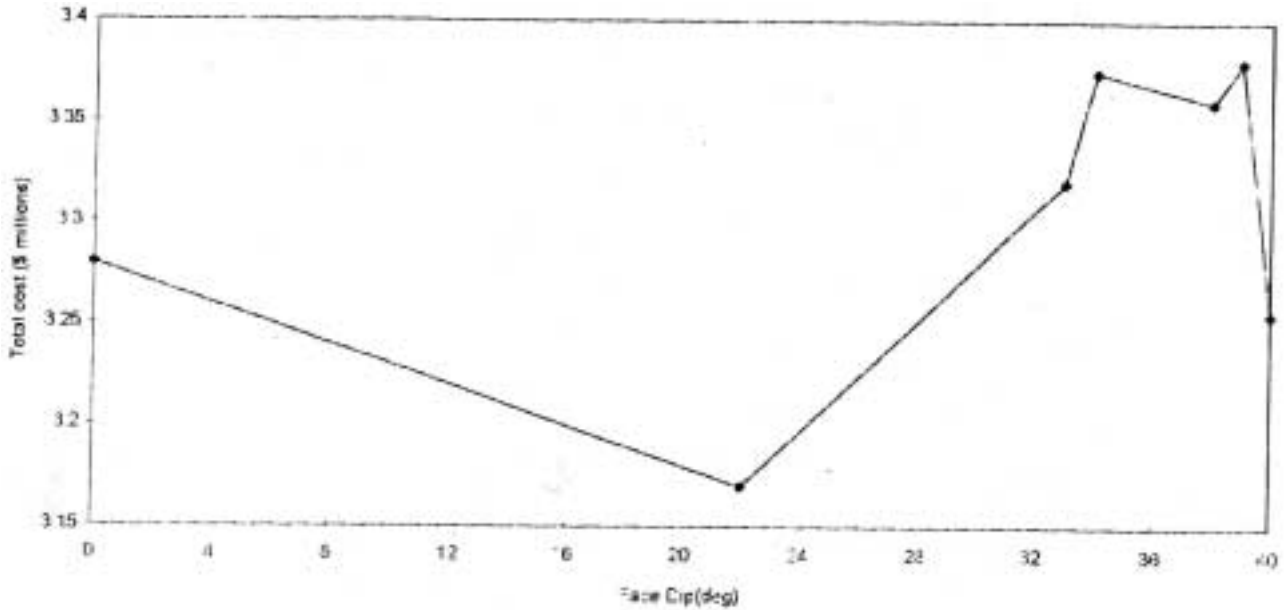


Figure 4. The relationship between face dip and total extraction cost.

constant [7]:

$$C7 = 858,500 \quad \$$$

Where C7 is the total miscellaneous costs in \$US.

12. OPTIMUM LOCATION OF THE PANEL

Combining the models for C1 to C7, the model for CT, the total cost of the panel will be deduced, as follows:

$$CT = C1 + C2 + C3 + 2(C4 + C5) + C6 + C7$$

The above models are summarized in table 1. The graph shown in Figure 4 shows the total cost of developing the typical panel, at different gradients of the face and hence that of the entries'. This graph shows that the minimum cost of developing the panel occurs when the face line dips at 22 degrees.

13. GENERAL MODEL

The procedure described shows how to locate

longwall panels with respect to dip, so that the total cost is minimum. In other words, the seam gradient and consequently those of the face and the entries' vary while all other parameters are kept constant. If other variables are allowed to change simultaneously, we could obtain models for other panels that have different characteristics from the typical panel assumed earlier. For this purpose some variables have been added to the original model and therefore the general model has been devised as follows:

$$CT = S1C1...S5C1 [C1] + S1C2...S5C2 [C2] + S1C3...S5C3 [C3] + S1C4...S5C4 [C4] \times 2 + S1C5...S5C5 [C5] \times 2 + S1C6...S5C6 [C6] + S1C7...S5C7 [C7]$$

S1C1...S1C7 are sensitivity coefficients with respect to panel length (original panel length is 1,200m)
 S2C1...S2C7 are sensitivity coefficients with respect to face length (original face length 200m)
 S3C1...S3C7 are sensitivity coefficients with respect to seam thickness (original seam thickness is 2m)
 S4C1...S4C7 are sensitivity coefficients with respect to seam gradient (original seam gradient is 40°)
 S5C1...S5C7 are sensitivity coefficients with respect to the cost of energy (original energy cost is assumed to be 0.30 \$US per KW hours).

TABLE 2. Sensitivity Coefficient Models.

Coefficient Model	S ₁	S ₂	S ₃	S ₄	S ₅
C ₁	0.0083(P)	$\frac{L}{200}$	$t \geq 1.5\{0.4222e^{0.55979(t)}\}$ $t > 1.5\{0.838(t)-0.676\}$	$0.751e^{0.4624(\alpha)}$	1
C ₂	$[1+8 \times 10^{-5}(P-1200)]8.3 \times 10^{-4}(P)$	$e^{4.995 \times 10^{-5}(L-200)}$	$\left(\frac{5.0245}{1+t}\right)0.73197^{-1}$	1	1+2.6(Δe)
C ₃	$1-8.3349 \times 10^{-4}(1200-P)$	$1-5 \times 10^{-3}(200-L)$ $150 \leq L \leq 250$	$0.8977+0.0514(t)$ $1 \leq t \leq 2.5$	1	1+3.2(Δe)
C ₄	$1+8.4 \times 10^{-4}(P-1200)$	1 $150 \leq L \leq 250$	1 $1 \leq t \leq 2.5$	1	1
C ₅	$1-8.7 \times 10^{-4}(1200-P)$	1 $150 \leq L \leq 250$	1 $1 \leq t \leq 2.5$		1+0.805(Δe)
C ₆	$1-0.00067(1200-P)$	1	1	1	1+6.74(Δe)
C ₇	$1-5.35 \times 10^{-4}(200-P)$	$1-3.205 \times 10^{-3}(200-L)$	$1-0.3206(2-t)$	1	$e^{9.744(\Delta e)}$

P=Length (m)

t=Seam thickness (m)

Δe=Variations in unit power cost

L=Face length (m)

α=Seam full dip (radians)

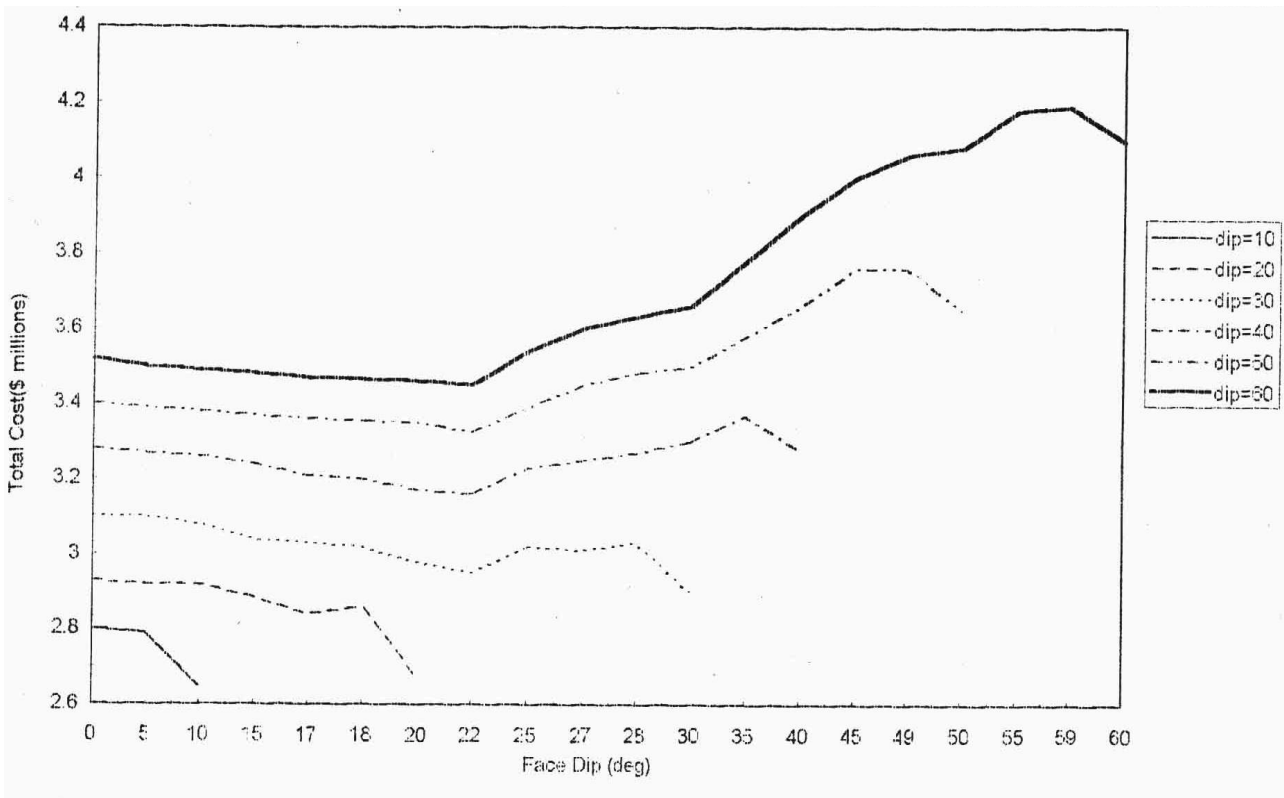


Figure 5. The relationship between face dip and total cost at different seam gradients.

The resulting models for sensitivity coefficients are summarized in Table 2.

14. CONCLUSIONS

Since the variations in seam gradient are of primary interest here, the general model is subject to sensitivity analysis with respect to variations of seam gradient, that is, the coefficient S. The graphs of Figure 5 are hence obtained. Figure 5 shows that when the seam gradient is higher than 50 degrees (steep seams), an alternative route to finding optimum panel location has to be adopted. This implies that in such cases other methods of working than longwall should be applied.

It is concluded that if the seam full dip is less than 30 degrees, as is shown on the graph of Figure 5, it is most economical to design the panels in a way that full gradient is transferred to the face and the entries are near horizontal. If, on the other hand the seam dips at 30-50 degrees, it is most economical that the gradient is divided between the face and

the entries. For this purpose the model introduced earlier could be used to determine the exact position of the panel.

The model and the analyses described could prove useful in planning and development of longwall panels.

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