Longwall face stability index (LFSI): A novel approach for estimation of chock-shield pressure and face convergence

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Synopsis

Several longwall faces in India have collapsed due to adverse geological conditions and/or inadequate capacity of powered supports. Thus it is imperative to access the capacity of a powered support and its interaction at longwall faces of varying geomining conditions in advance with lots of confidence. To achieve this, an index has been developed to ascertain the front leg pressure (FLP) of chock-shield support and roof-to-floor convergence (RFC) at longwall faces. The index called 'Longwall Face Stability Index' (LFSI) has been developed using statistics and Finite Element Modelling (FEM). The front leg pressure (FLP) and roof-to-floor convergence (RFC) predicted from the LFSI are validated with the field monitored data from two longwall panels. In this study, an attempt is also made to incorporate various geomining conditions into the finite element models typical of longwall mining practice. The index has taken into account the wide variations of geomining parameters like thickness, young's modulus and friction angle of main roof (small, large), coal type (soft, hard), powered support capacity, and depth of coal seam. Thus, LFSI can be thought of as an index representing combined effect of roof type, geomining conditions and powered support capacity.

Introduction

The longwall method of mining is the most productive and efficient underground coal mining method, especially for deep coal seams. Several longwall faces in India had collapsed due to adverse geological conditions and/or the inadequate capacity of powered supports[1]. In some cases, entire equipments of panels had to be abandoned due to the severity of the damage that occurred in the form of roof and face collapse. On this issue, Coal India Limited, the primary coal producing company in India had stated to the Planning Commission, Government of India in the 2006[2], 'barring few exceptions the performance of this technology has been below expectations in view of the involvement of multiple complex factors like inadequate geo-technical assessment, under-rated equipment, Inadequate infrastructure links, poor spare parts management, poor back-up services by overseas suppliers, etc.' With this background, it is imperative to access the capacity of a powered support and its interaction at longwall faces of varying geomining conditions in advance with lots of confidence.

In this context, an index is developed by statistical technique to ascertain the front leg pressure (FLP) of chock-shield support and roof-to-floor convergence (RFC) at longwall faces. The index has taken into account the wide variations of geomining parameters such as thickness, Young's modulus and the friction angle of main roof (small, large), coal type (soft, hard), powered support capacity, and depth of the coal seam. The number of variables mentioned here is limited in the context of the many more geological variations that can exist in nature (rock mass), which are even difficult to identify. Here the six variables and 324 combinations of geomining variations are modelled with finite element software ANSYS[3]. Selection of these variables among various parameters are based on due consideration of the parameters most affecting the stresses around longwall opening. With these simplifications, the numerical model becomes more reliable and effective in predicting the quantities sought (example: stress, strain, displacement, etc). The data thus generated from these models are used for the development of the index called the longwall face stability index (LFSI). The FLP and RFC predicted from the LFSI are validated with the field monitored data from two longwall panels. An example is solved to find the FLP and RFC for a longwall panel. This study provides an index to find the FLP and RFC for mine management/planners/design engineers to ascertain the face condition of longwall face in advance.

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Longwall face stability index (LFSI)

Finite element modelling of longwall panels

In this study, an attempt is made to incorporate various geomining conditions into the finite element models where longwall mining is being practised. For this purpose, 324 numerical models of longwall panels are developed, consisting of various parameters as shown in Table I. The variations are based on the analysis of the detailed borehole data results from various coalfields across India as well as from published literatures based on Indian coal measures[5].

However, in India, there is no longwall panel located at a depth of 400 m or any chock shield support having a capacity of 1 000 t. These extreme values are incorporated into the study, keeping in view the future prospects of longwall mining in deeper seams. All these models are developed, based on all possible interactions [depth (3) × modulus of main roof to coal seam (3) × thickness of main roof to coal seam (3) × powered support capacity (3) × friction angle of main roof (2) × coal type (2)] of these parameters. All finite element models are analysed with nonlinear material behaviour using the Drucker-Prager yield criterion and non-associative plastic flow condition. Each model is incorporated with an actual size 4-legged chock-shield, goaf/gob, coal seam and surrounding rock strata to assess the interaction between the powered support with coal measures. The immediate roof for all models is considered to be 1.8 m.

In general, immediate roof is defined as thin and laminated rock strata that exist just above the coal seam and cave in behind the shield shortly after the support advances. As they break periodically, transmission of horizontal stress along the direction of mining is minimal. The main roof, on the other hand, is represented by strong and thick strata above the immediate roof. In some mines, multiple competent rock strata can compose main roof layers, which can cause extensive loading on the PS. As the coal face advances, the main roof cantilever grows behind the PS and causes loading on the face and hydraulic legs. A periodic weighting occurs when the main roof layer(s) break(s) in front of the coal face and the dead weight of main roof rests on the PS[6].

Rock layers, coal seam and shield structure, except hydraulic leg and lamniscate links, are modelled with 6-noded quadratic triangular elements. Two-noded bar elements are used for hydraulic legs and lamniscate links. The finite element model of longwall panel represents the vertical cross-section along the middle of the longwall panel, as shown in Figure 1, and hence plane strain constitutive material behaviour is assumed. Figure 1 shows the finite element mesh of rock layers and Figure 2 shows the close view at the longwall face to show the finite element model of chock-shield and enclosing coal measures. These models are developed with ANSYS software. To simulate 250 m and 400 m of overburden additional loads are applied uniformly on top of the model as an external load. The height of extraction of coal is kept 2.4 m for all models. The details of the modelling procedure can be seen in[6].

The results of each model are recorded in terms of load on the front legs of powered support (FLP) and roof to floor convergence (RFC) at the longwall face for the development of the longwall face stability index (LFSI).

Longwall face stability index (LFSI)

Before explaining the concept of LFSI and its application in determining the longwall face stability factors (FLP and RFC), an index is introduced here as main roof index (MI). The Main roof index (MI) points to the behaviour of the main roof in terms of powered support (PS) loading. For example, the load on the PS increases with the thickness of main roof but decreases with its modulus. Hence, the PS load increases with MI as defined in Equation [1]. The different values of MI are 0.2, 0.4, 0.5, 0.8, 1, 1.6, 2, 5 and 8.

$$MI = \frac{T_m / T_c}{\left(E_m / E_c\right)} \qquad [1]$$

Apart from MI, the load on the PS depends on coal type, friction angle and cohesion of the main roof, thickness and modulus of the main roof, the depth of coal seam, PS capacity, and other geomining parameters. In general, the friction angle of rock mass is more sensitive to Drucker-Prager yield criterion than the cohesion. Hence, in this analysis, the variation of friction angle of the main roof (small, large) is considered. This study attempts to forecast FLP and RFC based on the combined effect of MI, friction angle (small, large) of the main roof, thickness and modulus of the main roof, depth of coal seam, and PS capacity, for soft and hard coal separately. The combined index is termed the longwall face stability index (LFSI), which is a function of coal type, and its value depends on the type of output variables such as FLP and RFC. Thus, LFSI can be thought of an index representing the combined effect of roof type, geomining conditions and PS capacity. Mathematically, the output variable can be expressed as

$$\Phi = f(\text{LFSI}, \text{C}), \qquad [2]$$

where, Φ represents the output variables (FLP and RFC) and C represents the coal type.

Table I

Various parameters used for finite element modeling

Parameters			
Mining depth, *D* in m	100	250	400
Main roof/coal Young's modulus ratio, E_m/E_c	1	5	10
Main roof/coal seam thickness ratio, T_m/T_c	2	5	8
Powered support capacity, *t*	550	800	1 000
Friction angle of main roof, φ, deg.	20 (small)	35 (large)	
Coal type	Soft	Hard	

Longwall face stability index (LFSI)

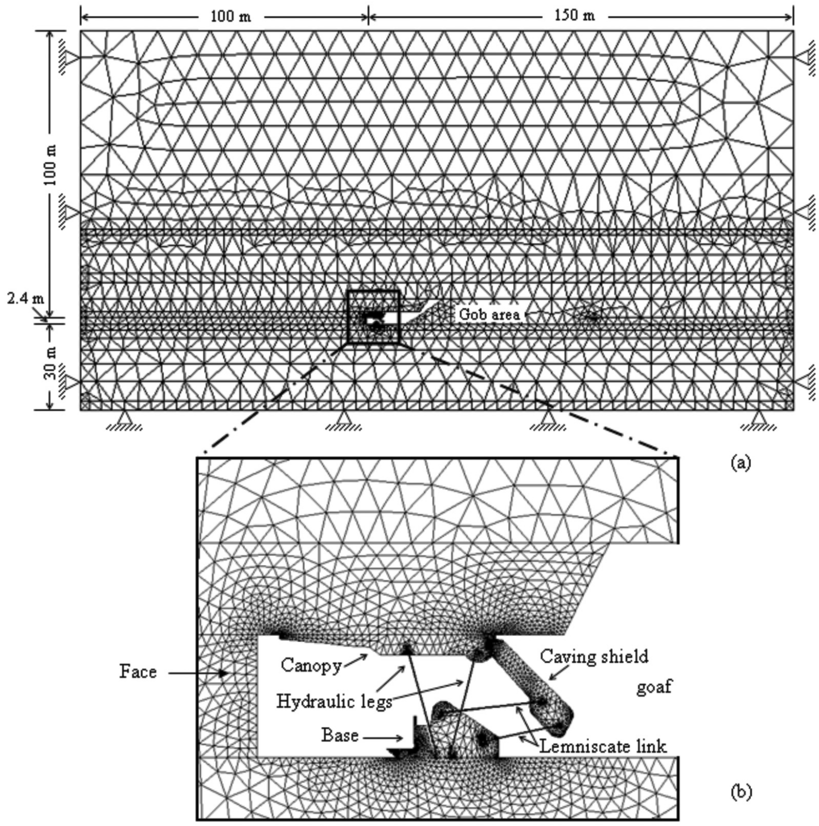


Figure 1—(a) A finite element model of longwall panel along central axis; Figure 2—(b) Close view of finite element model of longwall face

Once the LFSI is estimated, the leg pressure of chock-shield and roof to floor convergence can be forecast for a given geomining condition. Based on that, mine management can take a decision on the required capacity of the chock-shield support.

Determination of LFSI for forecasting FLP

STEP – 1: PS = constant, D = constant, ϕ = constant, and C = constant

Recall that there are nine variations of MI, three variations each for depth (D) and PS capacity, and two variations each for friction angle of the main roof (small, large) and coal type (soft, hard). Out of 324 observations/data sets, 36 groups are formed by nine data points having PS capacity, D, φ and C constants. The plot of FLP versus MI for one such group having PS = 1 000 t, D = 100 m, a small friction angle of the main roof and soft coal condition, is shown in Figure 3. The quadratic equation of the curve is given in Figure 3. Thus, 36 curves can be plotted from various combinations of PS capacity, depth (D), friction angle of main roof, φ and coal type, C.

STEP – 2: D = constant, φ = constant, and C = constant

Figure 4 shows plots of FLP versus MI for different values of

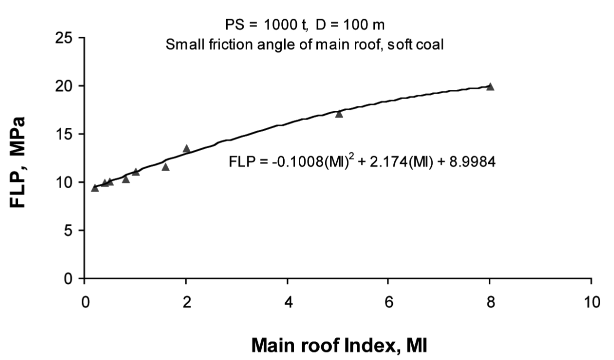


Figure 3—Variation of FLP for index MI

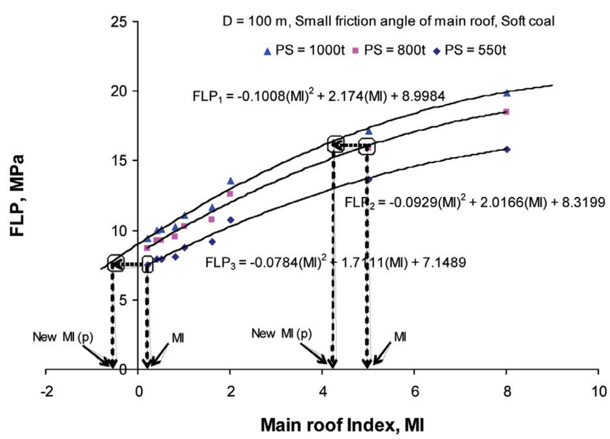


Figure 4—Variation of FLP with MI

PS for one such combination of depth, friction angle of main roof and coal type. From Figure 4, the effect of PS with the index MI is combined such that FLP for each data point remains the same. The equation of the curves given in Figure 4 can be generalized as:

$$FLP_l = a_l\,(MI)^2 + b_l\,(MI) + c_l, \qquad [3]$$

where, l = 1, 2, and 3 representing curves for PS = 550, 800 and 1 000 t respectively. The major idea is to transfer data points of FLP_2 and FLP_3 onto curve FLP_1 by changing the abscissa (or MI) of each data point (of curves FLP_2 and FLP_3)

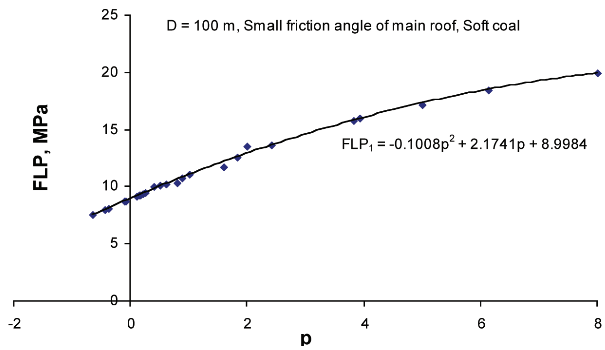


Figure 5—Variation of front leg pressure (FLP) for index *p*

such that FLP values remain constant, as shown by the dotted lines in Figure 4. Thus, a new abscissa (p) for each data point of the curve representing FLP_2 and FLP_3 are found by simply replotting the ordinates of FLP_2 and FLP_3 into the Equation of FLP_1 as given below.

$$a_1(p)^2 + b_1(p)^2 + c_1 - FLP_2 = 0 \qquad [4]$$

$$a_1(p)^2 + b_1(p)^2 + c_1 - FLP_3 = 0 \qquad [5]$$

By solving the quadratic Equations [4] and [5], the solution of p is obtained for FLP_2 and FLP_3. It is clear that p for FLP_1 (plot for PS = 1 000 t) remain the same, as the data points on these curves have not changed. A curve in Figure 4 represents the combined effects of PS and MI, and hence three curves in Figure 4 are combined into one. It should be noted that the abscissa of Figure 5 is now p instead of MI in Figure 4.

Now, the linear relationship between indices p and MI can be established to obtain the effect of PS, as shown in Figure 6, for one such case. The trend line in figure shows R^2 of 1, 0.99 and 0.98 for the straight line relationship between p and MI for PS = 1 000 t, 800 t and 550 t respectively. The generalized relation between p and MI for all 12 plots having a total of 36 curves is given in Equation [6].

$$p = \alpha \times MI + \beta \qquad [6]$$

The values of slope α and intercept β are listed in Table II.

Table II

Slopes (α) and intercepts (β) of the linear relation (Equation [6])

Sl. no	PS capacity, t	Depth (D), m	Fiction angle of main roof φ	Coal type C	α	β
1	550	100	20	Soft	0.5850	-0.6895
2	800	100	20	Soft	0.8073	-0.2188
3	1000	100	20	Soft	1.0000	0.0000
4	550	100	35	Soft	0.5844	-0.6831
5	800	100	35	Soft	0.8065	-0.2130
6	1000	100	35	Soft	1.0000	0.0000
7	550	100	20	Hard	0.4651	-1.7089
8	800	100	20	Hard	0.7110	-0.5312
9	1000	100	20	Hard	1.0000	0.0000
10	550	100	35	Hard	0.4647	-1.7050
11	800	100	35	Hard	0.7106	-0.5296
12	1000	100	35	Hard	1.0000	0.0000
13	550	250	20	Soft	0.7158	-1.0131
14	800	250	20	Soft	0.8896	-0.3661
15	1000	250	20	Soft	1.0000	0.0000
16	550	250	35	Soft	0.6661	-0.8705
17	800	250	35	Soft	0.8575	-0.3025
18	1000	250	35	Soft	1.0000	0.0000
19	550	250	20	Hard	0.6270	-1.9680
20	800	250	20	Hard	0.8398	-0.7109
21	1000	250	20	Hard	1.0000	0.0000
22	550	250	35	Hard	0.7570	-2.1147
23	800	250	35	Hard	0.7642	-0.7155
24	1000	250	35	Hard	1.0000	0.0000
25	550	400	20	Soft	0.6873	-0.8740
26	800	400	20	Soft	0.8720	-0.3167
27	1000	400	20	Soft	1.0000	0.0000
28	550	400	35	Soft	0.6524	-0.7806
29	800	400	35	Soft	0.7530	-0.3671
30	1000	400	35	Soft	1.0000	0.0000
31	550	400	20	Hard	0.6728	-1.6969
32	800	400	20	Hard	0.8542	-0.6145
33	1000	400	20	Hard	1.0000	0.0000
34	550	400	35	Hard	0.5782	-1.5818
35	800	400	35	Hard	0.7986	-0.5821
36	1000	400	35	Hard	1.0000	0.0000

Longwall face stability index (LFSI)

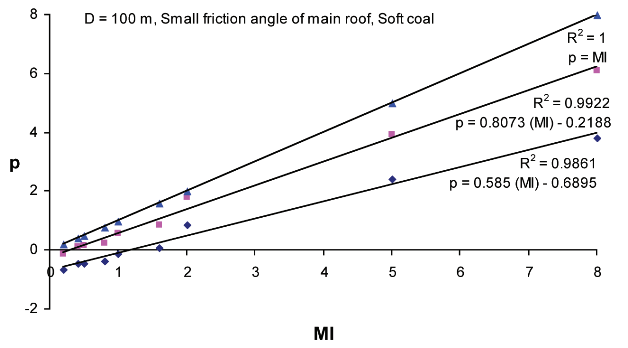


Figure 6—Relationship between index *p* and main roof index (MI)

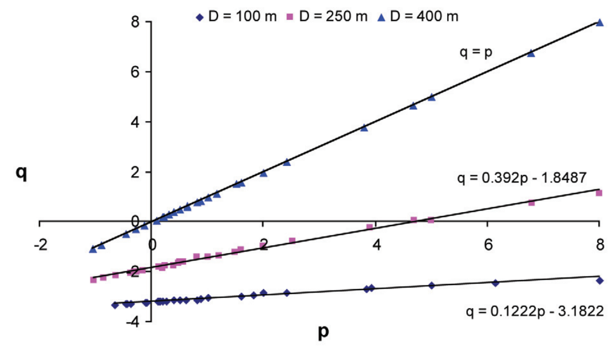


Figure 8—Linear relationship between indices *q* and *p*

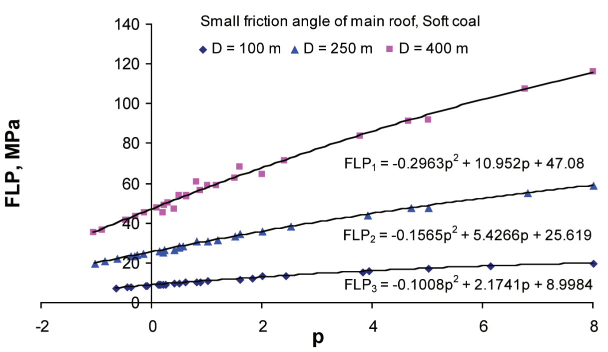


Figure 7—Variation of FLP for index *p*

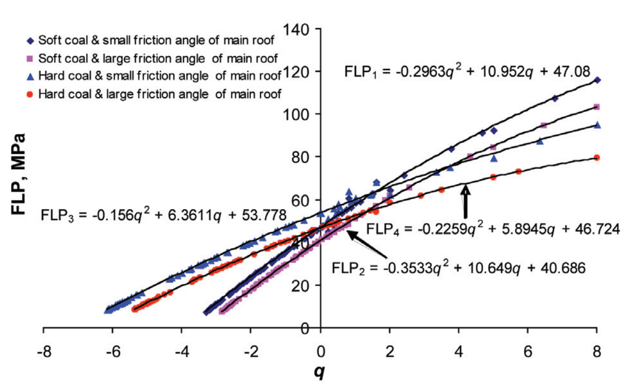


Figure 9—Relationship between front leg pressure (FLP) and the index *q*

Table III

Slopes (ζ) and intercepts (η) of the linear relation (Equation [7])

Sl. no	Depth D	Friction angle of main roof φ	Coal type C	ζ	η
1	100	20	Soft	0.1222	-3.1822
2	250	20	Soft	0.3920	-1.8487
3	400	20	Soft	1.0000	0.0000
4	100	35	Soft	0.1255	-2.7112
5	250	35	Soft	0.4128	-1.4708
6	400	35	Soft	1.0000	0.0000
7	100	20	Hard	0.1129	-0.5899
8	250	20	Hard	0.3662	-3.4729
9	400	20	Hard	1.0000	0.0000
10	100	35	Hard	0.1135	-5.0957
11	250	35	Hard	0.3856	-2.8547
12	400	35	Hard	1.0000	0.0000

STEP – 3: φ = constant and C = constant

In the previous step, the effects of MI and PS are incorporated into an index p for different combinations of depth (D), friction angle of main roof (φ) and coal type (C). In this step, D is incorporated into index p to develop a new index q. It may be noted that the value of index q is different for different combinations of friction angles of the main roof and coal types. Figure 7 shows the plots of FLP versus index p for three variations of D for one such combination of small friction angle of the main roof with soft coal. The index q is obtained by transferring the data points of FLP_2 and FLP_3 onto the curve FLP_1 in Figure 7 by changing the abscissa (or p) of each data point. Figure 8 shows the linear relationship between indices p and q. The procedure followed here is the same as that discussed in Step 2. Equation [7] shows the functional relation between the indices q and p.

$$q = \zeta p + \eta \qquad [7]$$

where, ζ and η are the slope and intercept respectively. Table III shows the slopes (ζ) and intercepts (η) for 12 combinations of D, φ and C.

In this step, 12 curves are combined based on their D variations to generate 4 curves each with similar friction angle of the main roof and coal type. Figure 9 shows four curves each consisting of 81 data points and represents the aforementioned groups. Front leg pressures are now grouped based on the friction angles of the main roof and coal types as:

- Soft coal with small friction angle of the main roof
- Soft coal with large friction angle of the main roof
- Hard coal with small friction angle of the main roof
- Hard coal with large friction angle of the main roof.

STEP – 4: Coal type (C) = constant

In the last step, the friction angle of the main roof is incorporated into the index q to develop LFSI, which varies only with the coal type (C). Based on similar procedures mentioned in previous steps, large and small friction angles are incorporated into the index q for both soft and hard coal types.

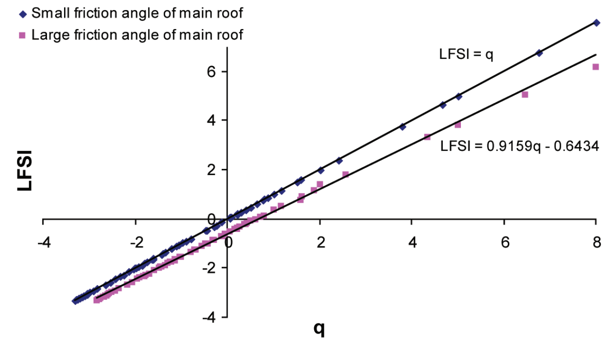


Figure 10—Relationship between LFSI and the index *q*

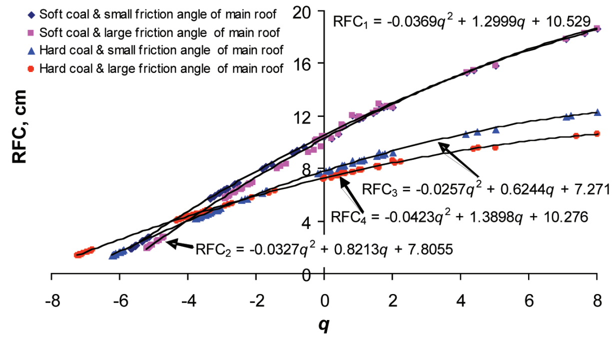


Figure 12—Relationship between RFC and index *q*

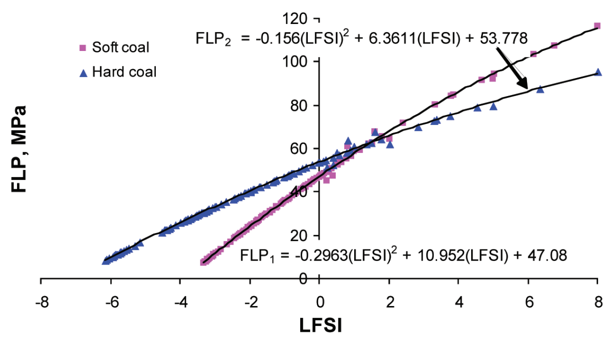


Figure 11—Relationship between FLP and LFSI

Table IV

Slopes (κ) and intercepts (γ) of the linear relation (Equation [8])

Sl. no.	Friction angle of main roof φ	Coal type C	κ	γ
1	20	Soft	1.0000	0.0000
2	35	Soft	0.9159	-0.6434
3	20	Hard	1.0000	0.0000
4	35	Hard	0.8815	-1.2592

It may be noted that due to this transformation, LFSI = q for a small friction angle, whereas for a large friction angle of the main roof, LFSI is expressed by Equation [8]. The values of slope κ and intercept γ thus, obtained from linear relationships between LFSI and q, is given in Table IV. Figure 10 shows the relationship between LFSI and q for soft coal types.

$$\text{LFSI} = \kappa q + \gamma, \qquad [8]$$

Figure 11 shows the plots between FLP and LFSI for soft and hard coal. The longwall face stability index thus developed varies between -3.31 and 8 and -6.17 and 8 for soft and hard coal respectively. The LFSI for FLP then combines the independent variables MI, PS, D and the friction angle of the main roof (φ). The relationship between FLP and LFSI is given by the Equations [9] and [10] respectively for soft (C = 1) and hard (C = 2) coal types.

For soft coal, FLP can be given by

$$\text{FLP} = -0.2963(\text{LFSI (C = 1)})^2 + 10.952$$
$$(\text{LFSI (C = 1)}) + 47.08 \qquad [9]$$

For hard coal, FLP can be given by

$$\text{FLP} = -0.156(\text{LFSI (C = 2)})^2 + 6.3611$$
$$(\text{LFSI (C = 2)}) + 53.778 \qquad [10]$$

Determination of LFSI for forecasting of RFC

The procedure to develop LFSI for RFC is the same as that discussed in the previous section. Only important results are discussed here. In first step, out of 324 data-sets, 36 groups are formed by nine data points having PS, D, φ and C constant. The nine (9) data point means nine variations of MI and so 36 curves can be plotted between RFC and MI.

In the second step, the effect of PS is incorporated and so a plot of RFC versus MI for three different variations of PS is plotted. A single plot consists of 27 data points, or three curves for three PS variations with individual curves having 9 data points. Here again, the effect of PS with the index MI is combined by keeping the RFC for each data point the same. In the course of combining the effect of PS, an index parameter p is developed in place of MI. It is found that MI and p are linearly related by Equation [6]. The values of slope α and intercept β for the linear relation between MI and p are listed in Table V. In this step, a total of 12 different curves can be plotted between RFC and index p. These curves have the variations of D, friction angle of the main roof, and coal type.

In step 3, the effect of D is incorporated into index p to develop a new index q. This step combines 12 curves (plots between RFC and p, as developed in step 2) to generate four curves with a similar friction angle of the main roof and coal type. Now, these four curves shown in Figure 12 incorporate the variation of depth (D). Each curve consists of 81 data points. A linear relationship between index p and q can be expressed by Equation [7]. Table VI shows the slope ζ and an intercept η for 12 combinations of D, φ and C.

In the last step, by keeping coal type (C) constant, the effect of the friction angle is combined with index q to develop LFSI for RFC. All the procedures are the same as that discussed for the development of LFSI for FLP. It may be noted that due to this transformation, the linear relationship between q and LFSI is expressed by Equation [8]. The values of slope κ and intercept γ are obtained from linear

Longwall face stability index (LFSI)

Table V

Slopes and intercepts of the linear relation (Equation [6]) between MI and *p*

Sl. no	PS capacity, t	Depth (D), m	Friction angle of main roof φ	Coal type C	α	β
1	550	100	20	Soft	1.0000	0.0000
2	800	100	20	Soft	0.9074	-0.0156
3	1000	100	20	Soft	0.8477	-0.0320
4	550	100	35	Soft	1.0000	0.0000
5	800	100	35	Soft	0.9074	-0.0156
6	1000	100	35	Soft	0.8519	-0.0602
7	550	100	20	Hard	1.0000	0.0000
8	800	100	20	Hard	0.8945	-0.0642
9	1000	100	20	Hard	0.8320	-0.1123
10	550	100	35	Hard	1.0000	0.0000
11	800	100	35	Hard	0.8934	-0.0623
12	1000	100	35	Hard	0.8315	-0.1096
13	550	250	20	Soft	1.0000	0.0000
14	800	250	20	Soft	0.9087	-0.0483
15	1000	250	20	Soft	0.8443	-0.0662
16	550	250	35	Soft	1.0000	0.0000
17	800	250	35	Soft	0.9186	-0.0112
18	1000	250	35	Soft	0.8578	-0.0148
19	550	250	20	Hard	1.0000	0.0000
20	800	250	20	Hard	1.0060	-0.1513
21	1000	250	20	Hard	0.8875	-0.1446
22	550	250	35	Hard	1.0000	0.0000
23	800	250	35	Hard	0.7946	-0.1270
24	1000	250	35	Hard	0.9640	-0.4114
25	550	400	20	Soft	1.0000	0.0000
26	800	400	20	Soft	0.9449	-0.0628
27	1000	400	20	Soft	0.8904	-0.0891
28	550	400	35	Soft	1.0000	0.0000
29	800	400	35	Soft	0.8617	-0.1421
30	1000	400	35	Soft	0.9344	-0.0529
31	550	400	20	Hard	1.0000	0.0000
32	800	400	20	Hard	0.8917	0.0188
33	1000	400	20	Hard	0.8916	-0.0371
34	550	400	35	Hard	1.0000	0.0000
35	800	400	35	Hard	1.0055	-0.0256
36	1000	400	35	Hard	0.9097	0.0571

Table VI

Slope and intercept of the linear relation between indices *p* and *q*

Sl. no	Depth D	Friction angle of main roof φ	Coal type C	ζ	η
1	100	20	Soft	1.0000	0.0000
2	250	20	Soft	0.3361	-3.2288
3	400	20	Soft	0.0655	-5.6544
4	100	35	Soft	1.0000	0.0000
5	250	35	Soft	0.3456	-2.8026
6	400	35	Soft	0.0636	-5.1835
7	100	20	Hard	1.0000	0.0000
8	250	20	Hard	0.2579	-3.6463
9	400	20	Hard	0.0435	-6.2278
10	100	35	Hard	1.0000	0.0000
11	250	35	Hard	0.3333	-4.1657
12	400	35	Hard	0.0540	-7.2212

Table VII

Slope and intercept of the linear relation between *q* and LFSI

Sl. no.	Friction angle of main roof φ	Coal type C	κ	γ
1	20	Soft	1.0000	0.0000
2	35	Soft	1.0549	-0.2086
3	20	Hard	1.0000	0.0000
4	35	Hard	0.7262	-0.8358

relationships between LFSI and q as given in Table VII.

Figure 13 shows the plots between RFC and LFSI for soft and hard coal. The longwall face stability index thus developed varies between –5.68 and 8.13 and 6.25 and 8 for soft and hard coal respectively. The LFSI is then combined with the independent variables MI, PS, D and the friction angle of the main roof, φ.

For soft coal, RFC (in cm) is given by

$$RFC = -0.0369(LFSI(C=1))^2 + 1.2999 (LFSI(C=1)) + 10.529 \quad [11]$$

For hard coal, RFC (in cm) is given by

$$RFC = -0.0327(LFSI(C=2))^2 + 0.8213 (LFSI(C=2)) + 7.8055 \quad [12]$$

The LFSI relation for FLP and RFC are given by Equations [9], [10] and [11], [12] respectively.

The index LFSI from Equation [8] is further expanded by using Equation [6] and [7], as follows:

$$LFSI(C) = \Psi \times MI + \Omega \quad [13]$$

Transaction Paper

Longwall face stability index (LFSI)

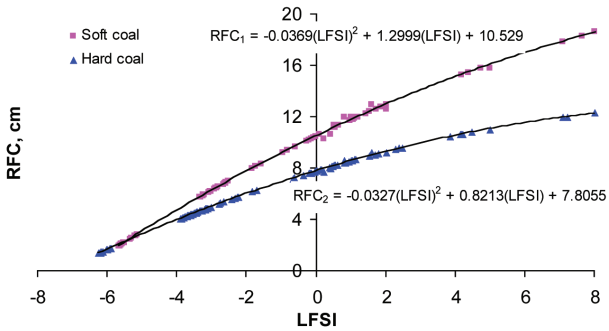


Figure 13—Relationship between RFC with LFSI

where, $\Psi = \kappa\xi\alpha$ and $\Omega = \kappa\xi\beta + \kappa\eta + \gamma$.

Thus LFSI is linearly related to index MI with the slope Ψ and intercept Ω.

Summary of the various steps

As discussed in previous sections, the steps to develop an index can be summarized as follows:

Step 1

324 data are classified based on 9 variations of MI, so 36 curves are plotted between FLP/RFC and MI. Each curve consists of 9 data points.

Step 2

36 groups are further classified based on three variations of PS type and so 12 groups or curves are plotted between FLP/RFC and *p*. Hence, the new index *p* incorporates the variation of PS type.

Step 3

12 groups are then classified based on 3 variations of depth and so 4 curves are plotted between FLP/RFC and *q*. Index *q* combines the variations of depth.

Step 4

Finally, 4 curves are combined based on variations of friction angle and so 2 curves are plotted between FLP/RFC and LFSI each for soft and hard coal type.

Numerical example for evaluation of LFSIs

Example

A longwall panel in the eastern part of India is proposed to work at a depth of 288 m with PS capacity of 4 × 800 t having setting pressure 80% of total pressure. The main roof thickness, modulus of elasticity and friction angle are 21 m, 8 GPa, and 25° respectively. The coal seam is soft in nature. It is required to determine the proper capacity of powered support and face convergence at the proposed longwall face.

Solution

The following preliminary information can be drawn from the problem:

Effective PS capacity will be 80% of 800 t or 640 t.

PS = 640 t, D = 288 m, $T_m/T_c = 21 / 3 = 7$, $E_m/E_c = 8 / 1 = 8$, MI = 7 / 8 = 0.875, coal type = soft.

Numerical solution of LFSI for FLP

FLP can be determined by calculating the indices *p, q* and LFSI with the help of Tables (II to IV) and Equation [9] for soft coal types. The procedure is explained as follows.

Table VIII

Slope and intercept for Interpolation level of 640 t PS capacity (See Table II)

Sl. No of Table II	PS Capacity, t	Depth D	Friction angle of main roof φ	Coal type C	α	β
13	550	250	20	Soft	0.7158	-1.0131
14	800	250	20	Soft	0.8896	-0.3661
16	550	250	35	Soft	0.6661	-0.8705
17	800	250	35	Soft	0.8575	-0.3025
27	550	400	20	Soft	0.6873	-0.8740
28	800	400	20	Soft	0.8720	-0.3167
30	550	400	35	Soft	0.6524	-0.7806
31	800	400	35	Soft	0.7530	-0.3671

Table IX

Interpolation of slopes, intercepts and index *p* for 640 t PS capacity

Interpolated Sl. no (see Table VIII)	PS Capacity, t	Depth D	Friction angle of main roof φ	Coal type C	α	β	p (= α x MI + β)
13 and 14	640	250	20	Soft	0.778368	-0.78018	-0.099108
16 and 17	640	250	35	Soft	0.735004	-0.66602	-0.022892
27 and 28	640	400	20	Soft	0.753792	-0.67337	-0.013804
30 and 31	640	400	35	Soft	0.688616	-0.63174	-0.029201

Longwall face stability index (LFSI)

First step

The solution of this problem lies in identifying the similar cases that exist in 36 groups as shown in Table II. If any of the 36 groups do not match directly with the given problem, a linear interpolation in between neighbouring higher and lower values is to be considered.

As the values of MI, PS, D, and ϕ do not match with any group from Table II, linear interpolations are carried out to obtain these values. For PS = 640 t, the next higher and lower values are 800 t and 550 t respectively. Accordingly, all others parametric values are identified and given in Table VIII. The first column of Table VIII shows the corresponding serial number from Table II.

Now, linear interpolation is performed (between Sl. no. 13 and 14, 27 and 28, 16 and 17, 30 and 31 of Table VIII) to find the slope and intercept for a PS capacity of 640 t. Equation [14] is used for linear interpolation. Table IX shows the interpolated values and corresponding values of index p.

$$y = y_1 + \frac{(y_1 - y_2)}{(x_1 - x_2)} \times (x - x_1) \qquad [14]$$

where, y_1, y_2 : Higher and lower value of slope/intercept
x_1, x_2 : Higher and lower value of parameter
x: Interpolation level of parameter
y: Interpolated intercept/slope

So far, we have calculated the index p. In next step, the index q is calculated. To find the index q select the next higher and lower values from Table III as per the problem definition i.e. D = 288m, φ = 25°, as coal type = soft, and is shown in Table X.

Linear interpolation for depth of 288 m is performed in Table X between sl. no. 7 and 8, 10 and 11 for to find slope (ζ), intercept (η) and index (p), and are shown in Table XI.

In the last step, similar cases of φ = 25° and coal type = soft are chosen for linear interpolation from Table IV, as

Table X

Slopes, intercepts and index *q* for interpolation level of 288 m depth (see Table III)

Sl. No. of Table III	Depth D	Friction angle of main roof φ	Coal type C	ζ	η	q (= $\zeta p^* + \eta$)
7	250	20	Soft	0.3920	-1.8487	-1.88755
8	400	20	Soft	1.0000	0.0000	-0.01380
10	250	35	Soft	0.4128	-1.4708	-1.48025
11	400	35	Soft	1.0000	0.0000	-0.02920

Table XI

Interpolation of slope, intercept and index *q* for 288 m depth

Interpolated Sl. no (see Table X)	Depth D	Friction angle of main roof φ	Coal type C	ζ	η	q
7 and 8	288	20	Soft	0.5460	-1.380	-1.41287
10 and 11	288	35	Soft	0.5615	-1.098	-1.11265

Table XII

Slope, intercept and LFSI for interpolation level of 25° friction angle (see Table IV)

Sl. no.	Friction angle of main roof φ	Coal type C	κ	γ	LFSI (= $\kappa q + \gamma$)
3	20	Soft	1	0	-1.41287
4	35	Soft	0.9159	-0.6395	-1.65858

Table XIII

Interpolation of slope, intercept and LFSI for 25° friction angle

Friction angle of main roof φ	Coal type C	κ	γ	LFSI
25	Soft	0.9719	-0.2131	-1.49477

shown in Table XII. Table XII shows the intercept, slope and index q for soft coal with a variation of friction angle. The value of the index q, in Table XII is calculated by using Equation [7].

Finally, the linear interpolation of intercept, slope and the index q provide the corresponding values for the friction angle of 25° and soft coal type, as shown in Table XIII.

The LFSI from Table XIII is used in Equation [9] for the front leg pressure calculation.

$$FLP = -0.2963(-1.49477)^2 = 10.952(-1.49477) + 47.08$$

$= 30.91$ MPa.

For this calculated stress level (σ) and for the given equivalent cross-sectional area of leg ($A = 0.0431$ m^2), the load in a leg will be

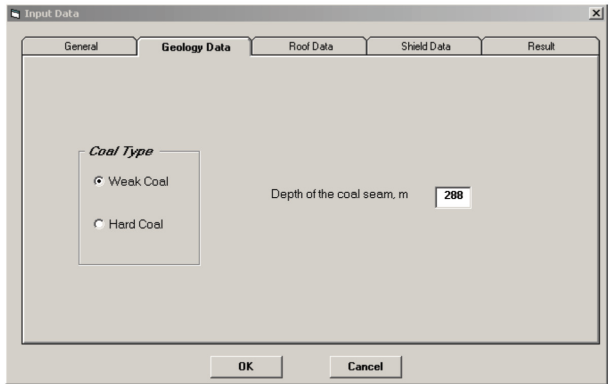
Load per leg $= \sigma \times A = 30.91$ MPa $\times 0.0431$ m^2 = 1.332 MN = 135.8 tons

Then, the capacity of the powered support four legged chock-shield support

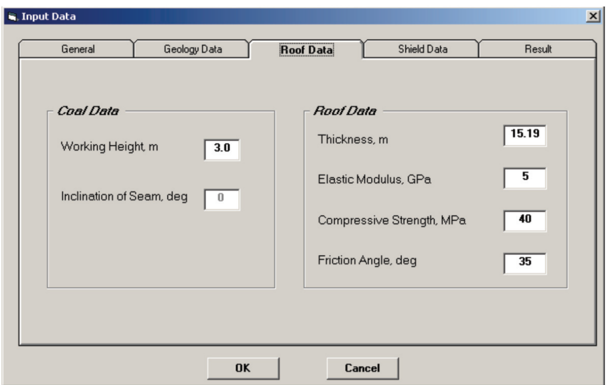
$= 4 \times 135.8 = 543.2$ tons.

The required capacity of powered support can be written

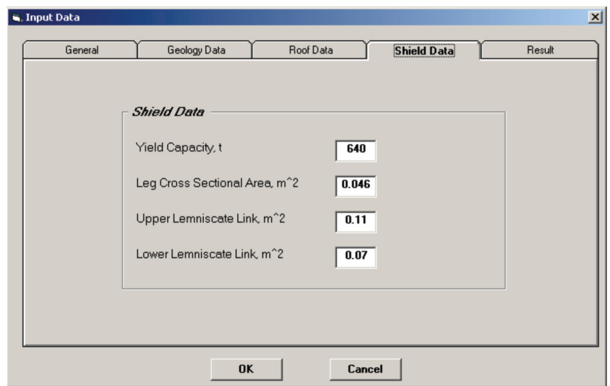
(a) LOFAST-model starting interface



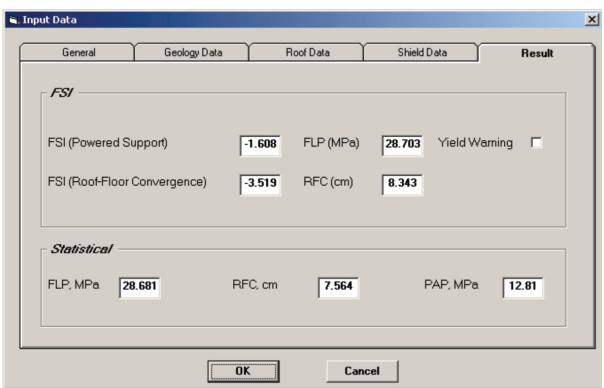
(b) Geological data input



(c) Roof data input interface



(d) Shield data input



(e) Result interface

Figure 14—Snapshot of LOFAST Windows based program

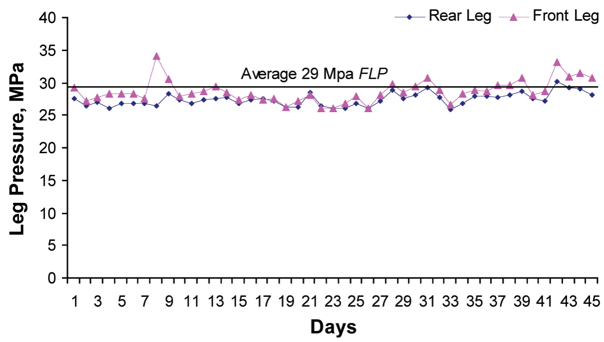


Figure 15—Field monitored leg pressure data at longwall panel A

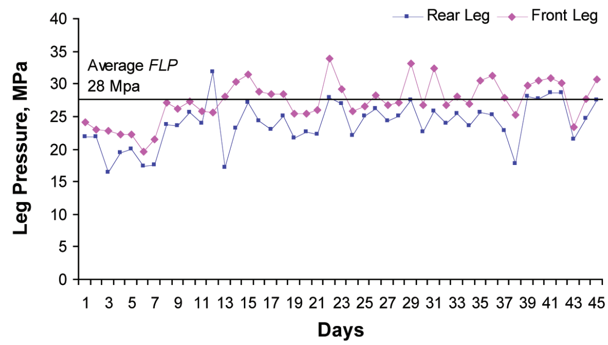


Figure 16—Field monitored leg pressure data at longwall panel B

as 4 × 543, where 4 represents the four legs of chock-shield support and 543 the total capacity of the support in tons.

Numerical solution of LFSI for RFC

Based on the procedure outlined in earlier sections, LFSI for RFC is calculated for the given mine. LFSI is found to be -3.6. Hence, the expected roof to floor convergence will be

$$RFC = -0.0369(-3.6)^2 + 1.2999(-3.6) + 10.529 = 5.37 \text{ cm}$$

A program is developed using VISUAL BASIC language to calculate both FLP and RFC, as shown in Figure 14. The above procedures are incorporated into the program.

Case studies and validation

The results obtained from this study are verified with the monitored data from two different longwall panels designated as Panel A and Panel B located in the same area. However, the depth of the coal seam at panel A and that of panel B is 288 and 275 m respectively. Both panels used 4 × 800 t chock shield support. The main roof consists of 95% sandstone with variation in grain size having a small percentage of quartz, feldspar pebbles, and thin mica laminae. The nearest borehole is located at 2.5 km from panel A and 500 m from panel B. The dip of the coal seam is 1 in 5.8 (avg.). The coal seam is soft in nature.

Figures 15 and 16 show the monitored data for panel A and panel B for over 45 days. Both the monitored data shows that, the front leg pressure carries more load than the rear leg in most of the cases. The average leg pressure for the front legs in panel A and panel B are 29 and 28 MPa respectively.

Table XIV shows the face stability measures predicted by the regression analysis models (not presented in this paper) and from LFSI. Some of the data (such as thickness and the friction angle of the main roof strata) required for the prediction of FLP and RFC for panel A and panel B are approximate values as these data are not readily available from the mine.

Conclusions

The concept of a longwall face stability index (LFSI) is introduced to estimate chock-shield leg pressure and RFC. The significance of LFSI can be summarized as a combination of all independent variables, D, PS, the friction angle of main roof and MI into one index. This index is unique for each longwall panel. Once LFSI indices are estimated from the known independent variables from Table II to IV (for FLP) and Table V to VII (for RFC), then chock-shield leg pressure and roof to floor convergence can be estimated easily. This study concludes the followings:

- This methodology is quite useful for the development of an index in any area of science and technology. The index can account for more number of independent variables without any specific limitations. The best fit curves can vary based on the nature of data-sets.
- The study shows that LFSI for FLP varies between -3.31 ~ 8 for soft and -6.17 ~ 8 for hard coal. For LFSI < 1.34, FLP for hard coal is greater than soft coal whereas the leg pressure in the case of soft coal for LFSI > 1.34, is more than that for hard coal; For LFSI = 1.34, FLP for soft and hard coal are same.

Table XIV

Face stability measures for both the panels

Input data			Output data				
	Panel A	Panel B		LFSI	FLP, MPa	LFSI	RFC, cm
D	288	275	Panel A	-1.61	28.70	-3.52	8.34
T_m	15.19	15.19	Panel B	-1.73	27.28	-3.28	8.17
T_c	3	3					
E_m	5	5					
E_c	1	1					
MI	1.013	1.013		Field monitored leg pressure data, MPa		LFSI calculated leg pressure, MPa	
PS	640	640	Panel A	29		28.70	
φ	35	35	Panel B	28		27.28	

- Similarly, LFSI for RFC ranges between -5.68 and 8.13 for soft coal whereas for hard coal -6.25 and 8. For a particular LFSI, the roof-to-floor convergence for soft coal is more than the hard coal.
- The field monitored leg pressure data from two longwall panels show the close resemblance with the predicted values from LFSI. As there is no field monitored RFC data, they cannot be verified with the results of the study. However, leg pressure data were monitored and it is found that the LFSI approach can effectively be used to ascertain the load of the shield legs.

List of symbols

C	coal type
c	cohesion
D	depth
E_m	modulus of elasticity of main roof
E_c	modulus of elasticity of coal seam
FLP	front leg pressure
LFSI	longwall face stability index
MI	main roof index
PS	powered support
RFC	roof to floor convergence
p, q	index
T_m	thickness of main roof
T_c	thickness of coal seam
φ	friction angle
$\alpha, \zeta, \kappa, \psi$	slopes
$\beta, \eta, \gamma, \Omega$	intercepts

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