

Current Theories and Concepts for the Determination of Roof Loading over the Hydraulic Supports in Longwall Faces

Haroon P. E.^{a*}, Heshmat M.^b, Imbaby S. S.^a, and Ibrahim A. R.^a

^aMining and Metallurgical Engineering Department, Faculty of Engineering, Assuit University, Assuit 71515, Egypt.

^bMechanical Engineering Department, Faculty of Engineering, Assuit University, Assuit 71515, Egypt.

*Corresponding author peter.emad@eng.aun.edu.eg

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Abstract

Underground mining of ores affects in-situ rock conditions, resulting in a sequence of strata motions. Roof rock pressure, which is the basis of all ground control issues, is caused by these instabilities. The hydraulic supports are subjected to excessive stress due to the roof rock pressure. The correct forecast of Rock Roof Loading (RRL) provides longwall face stability during ore exploitation, allowing the hydraulic supports to move more freely. This paper presents some of the current theories, approaches, and concepts for the determination of roof loading on longwall faces, with emphasis on the current gaps. This could improve the ability to manage the roof during mining workings, and govern the roof loading conditions and the supporting system. From this study, it can be seen that the periodic weighting of the main roof is an important aspect in the determination of loading requirements. Moreover, many loading calculation methods failed to take into consideration the swelling pressure of immediate roof rocks, and the tilting of the main roof blocks, which exert excessive loads on the supporting systems.

Introduction

Determining the accurate roof loading in longwall faces is a very important matter in the selection of the optimum hydraulic supports and guarantees stability during mining workings [1,2]. For the successful employment of longwall systems in the underground exploitation of ores, a correct and deep understanding of the interaction between the hydraulic supports and the neighbouring rocks is vitally important. The connection between roof strata, hydraulic support, and floor strata is considered the main aspect affecting the stability of longwall faces. For the effective design of underground workings, the precise determination of Rock Roof Loading (RRL) is compulsory. Thus, the necessity for an accurate scale concept of rock strength and loading conditions is a need for effective structural design for the roof. Understanding the mining conditions practice helps to improve work in underground mines and reduce potential risks [3].

The efficiency and durability of longwall productivity is hampered by the undesired idle time caused by roof collapses and hydraulic support problems [4]. From studying the Main Roof Tilt (MRT) in longwall faces, it can be found that it affects the

working stability [5]. Many researchers have presented a variety of approaches, models, and theories to interpret the rock pressure in longwall faces, load conditions of the roof, and evaluate hydraulic support performance. There is no single set of formulae or approaches that have been established for determining the roof loading that acts on the hydraulic supports. These approaches, such as the cavability concept, Ryncarz's equation, Evans's formula, Wilson's formula, etc. [6].

Using numerical simulation, we can interpret underground mining activities, forecast the loads acting on working faces, and help in selecting the optimum supporting system. Underground simulations by the Finite Difference Method (FDM) to model face spall and roof collapse have found that hydraulic supports with a high capacity will reduce the risk of face falling and roof sag. The slow advance rate of support causes larger failures in the face area [7]. Applying of the finite element approach (by using the ANSYS software program), In the modelling of hydraulic support legs, we were able to predict the deformations, forces, and strains generated by the dynamic load [8]. Sarkar S. K. et al. suggested a technique for calculating support resistance as a function of span under different caving situations [9].

The micro-seismic method was used for the monitoring of the risks of face collapse and roof failure during mining operations [10].

Two-dimensional and three-dimensional numerical simulation tests have found that localized deformations in the shear zone at the roof frequently emerge before fractures. This approach was found to predict fracture and roof failure that were nearly identical to those observed in the field [11].

Via a FLAC3D® numerical model of a longwall mine, several mechanisms for roof loading have been identified. The Strain Softening Constitutive gives more accurate results than the principal of Mohr-Coulomb in the case of roof failure [12].

An innovative numerical approach for simulating longwall faces has been produced by investigating of underground mining observations. This approach may be used to obtain the optimal combination of longwall design and roof supporting system [13]. By evaluating the results obtained from a numerical modelling study, it may be found that the support's setting load was roughly 40% of the maximum load capacity [14].

Longwall roof caving mechanism has been examined using the Finite Element Method (FEM), as well as the effect of the surrounding rocks' geological and mechanical parameters on periodic roof loading. The periodic roof weighting interval grows in lockstep with the Geological Strength Index (GSI) [15].

Using a combination of analytical, observational, and numerical modelling approaches, some parameters have been studied. It can be demonstrated that these parameters, such as deformation modulus, vertical pressure, horizontal pressure, seam thickness, and joint spacing, have an impact on the roof caving behaviour [16].

The aim of this paper is to discuss the most important methods used in the calculations, as well as to shed light on the importance of taking into account the effect of the main roof breaking and the swelling pressure of the immediate roof rocks.

The remainder of this manuscript is organized as follows. In Section 2, the rock pressure is discussed. In Section 3, the concepts of rock roof loading are clarified. In Section 4, we show the impact of main roof on the hydraulic supports. In section 5, applicable research directions are indicated.

Rock Pressure

Rock pressure can be defined as the pressure that surrounding rocks apply to the supporting system of underground workings. Rock pressure may be developed for a variety of reasons, which may be classified into different major categories:

- i. The rock formations loosening, which results in loosening pressure.
- ii. The rock masses weight and the tectonic processes provide genuine mountain pressure.
- iii. Swelling pressure is caused by the volume increase of the rock mass [17].

If the immediate roof rocks contain clay minerals such as clay shale, fireclay, or mudstone (which contain montmorillonite minerals), they will affect

roof stability. Montmorillonite minerals cause a volume expansion of immediate roof rocks, which will result in swelling that causes additional pressure on the supports [18].

Rock Pressure Theories

A lot of theories about the mechanics of rock pressure have been offered. Some popular theories include the following:

1. Arching Theory
2. Plate Theory (Beam Theory)
3. Theory of Soil Mechanics
4. Theory of Pseudoplasticity
5. Hypothesis based on Law of Deformation
6. Theory of Dynamic Rock Pressure [19, 20, 21].

By applying numerical simulation, Song Z. et al. have shown that there are two zones in the rock pressure distribution: elastic (outer zone) and plastic (inner zone). With the face advance, the impacting scope of induced rock pressure begins to rapidly expand [22]. According to laboratory tests on coal specimens, it has been shown that elastic energy drops slowly as confining pressure increases. As a result, improving the surface restraint and support strength of roadways is an essential step in insitu engineering practice to limit the occurrence of roof failure [23].

By using UDEC program simulation, Minggao Q. et al. suggested a new method for calculating support capacity based on the caving of the face area and the support angle in a region with a specific distance to the face [24,25]. It can be found that there is an effect of the stress path on the surrounding rock pressure in underground mines [26]. A long-span highway tunnel has been studied by experimental tests; it can be found that the vertical distribution features of the surrounding rock formations impact on rock pressure behaviour [27]. Some geo-mechanical features such as the Geological Strength Index (GSI), overburden depth, and in-situ stress ratio have a significant effect on surrounding rock pressure [28].

Concepts of Rock Roof Loading

Per the hypothesis of the pressure arch, the rock roof loading is transferred to the ore in front of the face during working in a longwall panel [29, 30, 31, 32, 33]. Roof collapse is a source of concern in the selection of supporting systems [34]. There are many methods to determine the loads acting on the hydraulic supports in longwall faces. Some of these methods are:

Cavability Concept

The cavability concept describes the loading of the immediate roof (caving height) over the support as shown in Figure 1. It depends on a few properties, such as seam thickness and bulking factor, so it gives low values of roof loading.

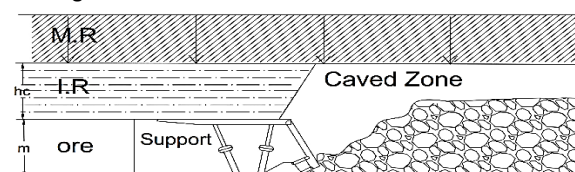


Figure 1 An Illustration of the cavability concept [35].

Among of the drawbacks of the cavability concept is that it ignores the effect of the main roof loading on the support capacity [35,36].

The immediate roof bulking factor is dependent on the rock type as shown in Table 1.

The height of the caved zone in the cavability concept in the longwall mining method can be determined as follows:

$$h_c = m/k - 1 \tag{1}$$

So, the rock roof pressure acting on the support can be calculated as follows:

$$\sigma_s = h_c \cdot \gamma \tag{2}$$

Where:

σ_s : The roof loading over hydraulic supports in KN/m².

h_c : Caving height over the hydraulic support in m.

m : Thickness of the seam in m.

k : Bulking factor of I.R (Immediate Roof).

γ : Unit weight of immediate roof rocks in KN/m³.

Table 1 The immediate roof Bulking factor [37].

Immediate roof rocks type	Bulking factor (k)
Sandy formations	1.06-1.15
Clayey formations	1.15-1.2
Broken coal formations	1.2-1.3
Clayey shale formations	1.3-1.4
Sandy stone formations	1.5-1.8
Sandy shale formations	1.6-1.8

Terzaghi's formula

Terzaghi postulated that the rock load over the support in longwall faces is equal to the height of the loosening zone above the roof, as shown in Figure 2.

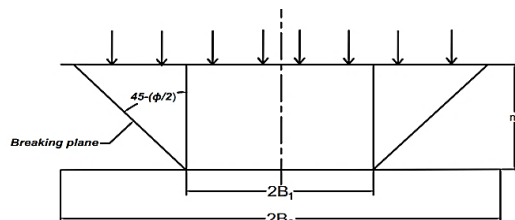


Figure 2 An Illustration of the Terzaghi formula [38].

This is the first significant approach to categorizing rock mass for engineering purposes [2, 38]. The drawbacks of this approach are that it ignores the roof characteristics and the panel geometry effect.

This formula can be presented as follows:

$$\sigma_s = \frac{\gamma B_0}{\lambda \tan \phi} \tag{3}$$

Where:

B_0 : The face half width (subjected to loading) in m.

B_1 : The half actual width of the face in m.

$$B = B_1 + m \tan (45 - \phi / 2) \tag{4}$$

ϕ : Internal friction angle of roof rocks in degree.

λ : An empirical coefficient, taken as unity.

Wilson's Formula

Wilson formula is considered one of the most important approaches as it gives reliable values of rock roof loading. This concept takes into consideration the properties of the immediate roof and rock mass. Yield stress or peak abutment can be determined by Wilson formula as follows [39,40]:

$$\sigma_s = \sigma_c + b p \tag{5}$$

Where:

σ_c : Uniaxial compressive strength for rock mass in KN/m².

$$b: \text{Flow factor } b = (1 + \sin \phi) / (1 - \sin \phi) \tag{6}$$

$$p: \text{Unit content } p = \gamma * h_0 \tag{7}$$

h_0 : Thickness of immediate roof in m.

Evans's Formula

Evans assumed that the broken strata in the roof of a longwall face were similar to granular material [41, 42]. He utilized standard equations and arching theory to determine the weight of roof rocks that the supports must sustain, as shown in Figure 3.

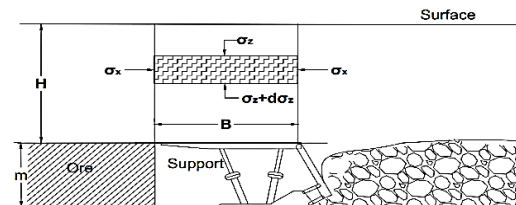


Figure 3 An Illustration of Evans's formula [42].

Evans's theory considered that the horizontal stress to vertical stress ratio to be unity, which is unrealistic. The formula can be proposed as follows:

$$\sigma_s = \frac{B(\gamma - \frac{2c}{B})}{2q \tan \phi} * [1 - \exp(\frac{-2qH \tan \phi}{B})] \tag{8}$$

Where:

B : Breadth of the face in m.

c : Cohesion of immediate roof rocks in KN/m².

q : Horizontal stress to vertical stress ratio.

H : Average cover depth in m.

Ryncarz's Concept

Ryncarz proposed a concept to determine the loads acting on the longwall support based on an examination of various approaches. Ryncarz demonstrated that the downward movement of the broken rock above the face area is opposed by frictional resistance along inclined boundaries [41,43]. These boundaries are formed by the planes of break and their position is determined by the angle of break, as shown in Figure 4.

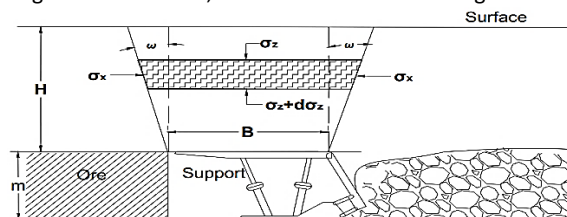


Figure 4 An Illustration of Ryncarz's formula [41,43].

The angle of break is directly related to the angle of draw ($\tan \omega = 0.4 \tan \delta$). The angle of draw ranges from 0° to 45° depending on the local conditions of working. This approach gives low values of support requirement as it ignores the roof caving parameters.

Ryncarz's concept can be presented as follows:

$$\sigma_s = \frac{B H \gamma (B + H \tan \omega)}{(B + 2H \tan \omega)^2} \tag{9}$$

Where:

ω : Angle of break of inclined boundaries in degree.

δ : Angle of draw due to strata displacement during ore exploitation in degree.

Xiong’s Approach

Using physical and numerical simulation, Xiong demonstrated an approach for determining the roof loading requirements on longwall faces. In this approach, the immediate roof loading and the impact load of the main roof must be shielded by the hydraulic supports as shown in Figure 5. The main roof is classified into two different structures. The first structure is the lower main roof, which lost its stability due to sliding by acting as a cantilever beam. The second structure is the upper main roof, which retains its relative stability by acting as a masonry beam [44,45, 46]. One of the advantages of this approach is taking into consideration the effect of main roof. This concept ignores the swelling properties of the immediate roof rocks.

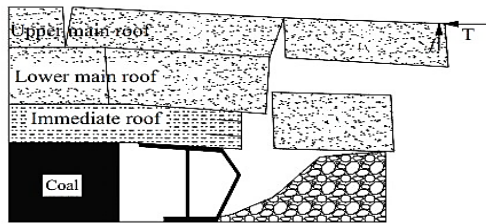


Figure 5 An Illustration of Xiong’s approach [44].

This approach can be presented as follows:

$$\sigma_s = \frac{1}{2} (h_o + h_1) * [2l + (h_o + h_1) \cot \beta] w_s * \mu + \frac{f w_s h_2 L_o}{h_2 + (L_o - l) \mu} \quad (10)$$

Where:

- h₁: The lower main roof thickness in m.
- h₂: The upper main roof thickness in m.
- L_o: The first roof weighting interval in m.
- l: The distance between the support beam edge and the breakage points of the main roof in m.
- β: Breaking angle of the main roof block in degree.
- w_s: The support width in m.
- f: Loading weight of the overburden rocks in KN/m².
- μ: Coefficient of friction of main roof blocks (Ranges from 0.6 - 1).

Kumar’s Approach

Based on comprehensive research work, Kumar established a mathematical approach to determine the rock roof loading acting on the hydraulic supports in the longwall faces as shown in Figure 6.

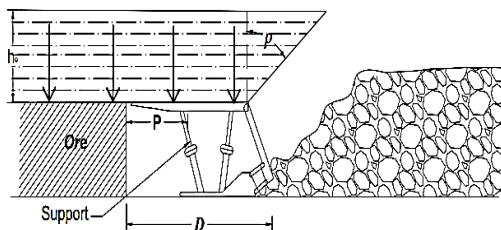


Figure 6 An Illustration of Kumar’s approach [47].

This concept assumed that the actual loading during ore exploitation was coming from two sources. The first source was the loading provided by the strata block separation from the face. The second source was the loading, which came from the strata collapse of the roof rock-mass [47, 48]. This approach focus on the impact of support geonetry. It ignores the

effect of the main roof breaking on the support capacity required.

This approach can be presented as follows:

$$\sigma_s = \frac{[\frac{D}{2} + \frac{h_o * \tan \rho}{2}] * W * S_f}{P * \mu_1 * \mu_2} \quad (11)$$

Where:

- D: Distance between the caving edge and the face in m.
- ρ: Angle of the caving of the immediate roof layers in degree. This angle depends on the caving conditions of the immediate roof rocks as shown in Table 2.
- W: the induced stress due to the weight of the immediate roof rocks in KN/m².
- P: Distance between the canopy centre resistance to the face in m.
- S_f: Factor of safety.
- μ₁: The efficiency factor of the support as a result of pipeline and valve system leaking (Taken to be 0.9).
- μ₂: The efficiency factor of the support because of the leg’s inclination. This factor differs according to the support type and leg inclination as listed in Table 3.

Table 2 Caving angle of the immediate roof [6].

Immediate roof condition	Caving angle (ρ)
Easily caved of roof rocks	0 - 10
Strong roof rocks	10 - 15
Regularly caved roof rocks	15 - 40

Table 3 Efficiency factor due to inclination of the support legs [47].

Support type	Efficiency factor
Shield supports	0.8
Chock shield support	0.85
All legs of the support are vertical	0.90

Bilinski’s Approach

Based on field investigations and gained experience, Bilinski established an approach for forecasting the rock roof load. In this approach, the loading conditions are influenced by the hydraulic support situation during the working and advancing process.

This approach was first applied in Poland on underground longwall faces. One of the disadvantages of this approach it ignores the roof conditions over the supports [13, 49]. This approach can be offered as follows:

$$\sigma_s = \frac{U_1 + U_2 + U_3}{A} n \quad (12)$$

Where:

- σ_s : Average carrying capacity of the support due to roof loading in KN/m².
 - U₁: The load for one unit in KN.
 - U₂: Load on the unit when advancing in KN (taken as zero).
 - U₃: Carrying load of the unit just set in KN.
 - A: The face area which is covered by three supports in m².
 - n: The support efficiency factor, (taken around 0.8).
- The application and the criticism of each concept are presented in Table 4.

Table 4 Application and criticism of each concept.

Concept	Application and Criticism of the Concept
Cavability concept	The loading of the caving height above the support is characterized by this concept. Since it is based on a few characteristics, such as seam thickness and bulking factor, it gives low roof loading values. One of the drawbacks is that it disregards the influence of main roof loading on support resistance.
Terzaghi's formula	In longwall faces, it is assumed that the rock pressure over the support is equal to the height of the cracking section above the roof. This method has the downside of ignoring the roof characteristics as well as the panel geometric impact.
Wilson's formula	Wilson formula is one of the most relevant methodologies because it provides accurate rock roof loading values. The features of the immediate roof and rock mass are taken into account in this approach.
Evans's formula	In this concept, the broken strata of the roof were considered to be reminiscent of granular material. Evans assumed that the ratio of horizontal to vertical stress was unity, which is impractical.
Ryncarz's concept	As Ryncarz proved, frictional resistance along inclined boundaries opposes the downward movement of the broken rock above the face region. The planes of break are responsible for shaping these boundaries. Because the roof caving parameters are ignored, this method provides low support requirements.
Xiong's approach	The main roof consists of two distinct sections. By operating as a cantilever beam, the first structure lost its stability owing to sliding. By serving as masonry, the second structure maintains its relative stability. Taking into account the influence of the main roof is one of the advantages of this method. The swelling properties of the immediate roof rocks are ignored in this approach.
Kumar's approach	According to this concept, the exact loading during ore exploitation was assumed to come from two sources. The loading from the strata collapse of the roof rock-mass and the strata block separation from the face are the two sources. The influence of support geometry is the focus of this technique. It ignores the impact of the main roof collapsing on the required support capacity.
Bilinski's approach	The hydraulic support situation during the working and advancing processes has an impact on the loading requirements. One disadvantage of this method is that it ignores the influence of the immediate and main roof parameters on the loading assessment.

Main Roof Behavior

The main roof is that portion of overburden just above the immediate roof. According to longwall observations, the roof pressure acting on the working region is influenced by the main roof behaviour. As a result, whatever the kind of hydraulic support is used, controlling the movement of the main roof is essential [50,51]. The periodic roof weighting is induced by the main roof movement. Considerable movement of the main roof will almost certainly result in considerable changes to the supporting systems. The periodic roof weighting interval (length of the main roof block) is an important parameter that affects the stability of the work. The support capacity should cover both the load of the immediate roof and the additional load from the main roof [52].

The main roof breaks into blocks. There are two forms of main roof breakage as follows:

Short Block Breakage of Main Roof

When the main roof breaks into smaller block (short block), then it will not rest on the rock piles in the goaf, as shown in Figure 7. Underground observations have shown that the rear end of the main roof broken block did not touch the rock piles [7, 53, 54].

The short block is subjected to these forces:

i. The frictional force from the neighbouring blocks equals: $F = \mu T$ (13)

ii. The upward supporting force (R_1), which is an additional load of main roof breakage

iii. The weight of the broken block ($W = H_m \gamma L$) (14)

At equilibrium: $R_1 = W - F = H_m \gamma L - \mu T$ (15)

When taking moment about point A, the upward supporting force (R_1) equals:

$$R_1 = H_m \gamma L - \frac{(\mu H_m \gamma L)}{2(H_m - L \sin \theta)} * [L \cos \theta + H_m - L \sin \theta] \tan \beta$$
 (16)

Where:

H_m : Thickness of main roof block in m.

γ : Unit weight of main roof rocks in KN/m^3 .

L : Length of main roof block in m.

T : Compressional forces from the neighboring blocks in KN/m^2 .

θ : Angle of inclination of main roof block due to sagging in degree.

Long Block Breakage of Main Roof

When the main roof block rests on the rock piles in the goaf, the breaking length will be longer (a long block).

The short block is subjected to these forces:

i. The frictional force from the neighboring blocks

ii. The upward supporting force (R_1), which is an additional load of main roof breakage

iii. The weight of the broken block

iv. The additional supporting force (R_2), from the rock piles [37, 55, 56].

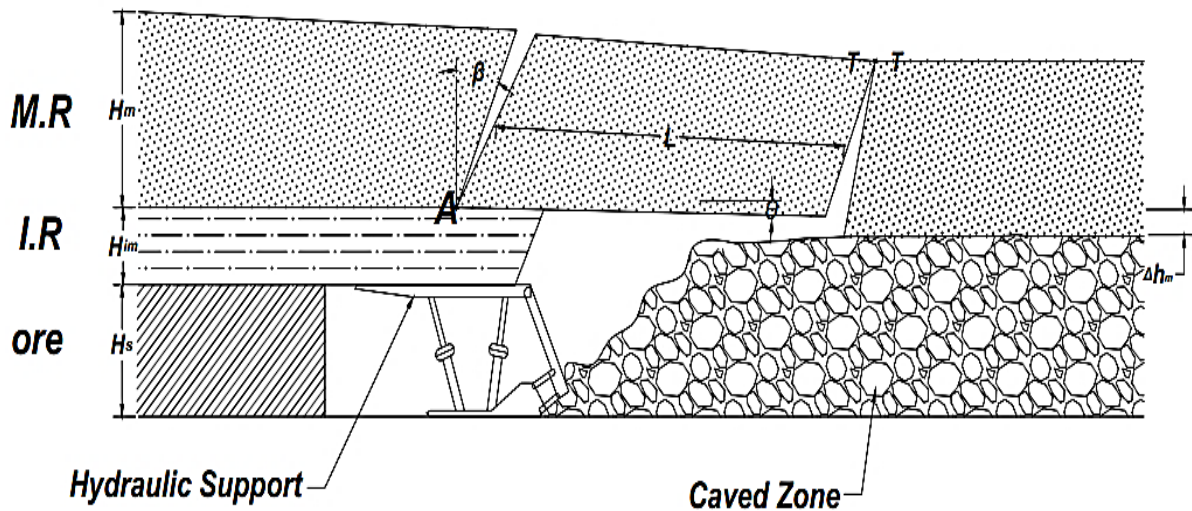


Figure 7 Conceptual drawing showing short block breakage of main roof [53].

Research Directions

The most commonly used techniques and concepts for determining loads acting on supporting systems are presented in this study. The influence of the main roof tilting on the loading conditions over the supports was neglected in several theories. The impact of the swelling pressure of the immediate roof rocks, which generates an increase in the load affecting the supporting systems, was not taken into consideration in many approaches.

This article may be considered a good attempt to highlight the significance of studying the effect of main roof movement on working stability. Furthermore, providing a methodical research direction for determining rock roof loads over hydraulic supports in the longwall mining method, based on current understanding and knowledge.

Based on the information presented in this study, the following research directions can be drawn:

1. Studying the influence of rock pressure through:
 - i. Roof pressure distribution
 - ii. Swelling pressure effect
2. Rock roof loading (RRL)
3. The main roof activity
4. Mechanisms for estimating support capacity
5. Forecasting of loading conditions through:
 - i. Monitoring
 - ii. Identifying failure mode on a mining site
6. Control techniques by:
 - i. Preventive measures (Mine design criteria)
 - ii. Risk aversion (Selection of suitable supports).

Conclusions

The longwall mining method is the best choice with high productivity for the exploitation of underground ore deposits. Rock Roof Loading (RRL) is one of the most essential aspects of the design and selection of supporting systems. Understanding the roof strata's behaviour is an important topic for enhancing safety during work in longwall faces. Hydraulic supports are one of the most vital machines while working on longwall faces. They enable both production and productivity to grow significantly. Several techniques and concepts have been presented and assessed for determining and predicting the rock roof loading acting on the supports, such as Ryncarz's formula, the cavability concept, etc. These approaches are, as of now, being evaluated to achieve a better degree of comprehension and remove obstacles in design and machine usage in a particular geo-mining situation.

The analysis of the above-mentioned methods reveals a research gap that was highlighted in this paper is that many approaches ignore the influence of main roof behaviour and swelling pressure of the immediate roof on rock loading conditions which exert excessive loads on the supporting systems. So, while determining the rock roof loading acting over the hydraulic supports, three factors must be considered: main roof tilting, swelling pressure, and the caved zone of the immediate roof. Whatever the concept adopted, two key requirements must be met, the hydraulic support characteristics must comply with the loading conditions resulting from the roof strata and there must be efficient management of the unsupported distance between the face line and the canopy tip.

List of Symbols and Abbreviations

A	Face area which is covered by 3 supports
B_o	The face half width
c	Cohesion of immediate roof rocks
D	Distance between caving edge and face
f	Loading weight of the overburden rocks
IR	Immediate Roof
H	Average cover depth
h_c	Caving height over the hydraulic support
H_m	Thickness of Main roof
h_o	Thickness of immediate roof
h₁	The lower main roof thickness
h₂	The upper main roof thickness
K	Bulking factor of the immediate roof
L	Length of main roof block
L_o	The first roof weighting interval
m	Thickness of the seam
MR	Main Roof
MRT	Main Roof Tilting
n	The support efficiency factor
P	Distance between canopy center to face
p	Unit content of immediate roof
Q	Horizontal stress to vertical stress ratio
RRL	Rock Roof Loading
S_f	Factor of safety
T	Compressional force of neighboring blocks
U₁	The load for one supporting unit
U₂	Load on the unit when advancing
U₃	Carrying load of the unit just set
W	The induced stress due to the weight of I.R
w_s	The support width
β	Breaking angle of the main roof block
γ	Unit weight of roof rocks
δ	Angle of draw due to strata displacement
θ	Angle of inclination of roof due to sagging
λ	Empirical coefficient taken as unity
μ	Coefficient of friction of main roof blocks
ρ	Angle of the caving of the immediate roof
σ_c	Uniaxial compressive strength for rocks
σ_s	The roof loading over hydraulic supports
φ	Internal friction angle of roof rocks
ω	Angle of break of inclined boundaries

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Conflicts of interest

There are no conflicts to declare.

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