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Application of geo-mining and techno-economic parameters for optimum selection of stoping method for underground metalliferous mines

The choice of the underground mining method in metalliferous mines is one of the most significant judgment that should be established by underground mining professional.To carry out extraction from a mineral body, ensuring a proper underground stoping method is particularly critical in terms of the techno-economic parameters. Many approaches do not include safety, production efficiency and the economic parameters. Over the years, a number of works have been carried out by various researchers to build up a systematic approach to help the engineers to make this selection. A study of techno-economic factors involved in this important decision making process have been presented in this paper.

Keywords: Mining method selection, techno-economic factors, classification of methods

1. Introduction

In underground hard rock mines, a variety of stoping methods are used for exploitation of ore bodies that may be classified into four broad groups – (i) self-supported methods, (ii) supported methods, (iii) caving methods, and (iv) novel and innovative methods. The selection of a particular stoping method depends on a number of factors – such as, geological considerations, ore body character, host rock (hanging wall and footwall) characteristics, ore grade and tonnage recovery, environmental parameters, economic parameters, and mining, safety and regulatory parameters (Sen and Paul, 2011).

For any given deposit, selection of the most appropriate mining method is of great importance from the economic, technical and safety considerations (Namin et. al., 2008). Proper method selection incorporates the flexibility to respond to changes in both internal and external conditions. Internal conditions are those that are dictated by the deposit itself, whereas external conditions are determined by outside considerations such as business or market requirements. (Krantz and Scott, 1992).

During the planning and design stage of a mine, it is necessary to select the optimum stoping method for a given deposit from amongst the feasible methods considering all the site specific geo-mining factors, the prevailing techno-economic parameters, and environmental and safety requirements so that the net present value (NPV) of the deposit is maximized (Sen and Paul, 2011).

Earlier, selection of an extraction method was generally based on operating experience at a similar type of mine or on methods already in use in other parts of the deposit. Though this approach may work satisfactorily in some cases; it cannot be followed for selection of optimal stoping methods for all situations.

2. Status of stoping method selection process

Mining methods are the systematic approaches, defining how to carry out the production in a mine. Among the various methods available, choosing the right method is of extreme importance for the economics, safety and the productivity of the underground mining workplace, thence they are commonly identified as the nucleus of the mining engineering discipline.The determination and resultant decision by a mining engineer regarding mining methods should provide healthy working conditions for the proletarians, a protective working process for the environment, a profitable business for the society and a productive mine for the benefit of the nation. However, unfortunately, in addition to the importance of the selection, the procedure of making the selection is rather confusing and difficult. The difficulty of the selection arises from some basic facts. One of them is the absence of a specific formulation for selecting a mining method, in spite of the studies performed by Boshkov and Wright (1973), Brady and Brown (1985), Hamrin (1982), Laubscher (1977, 1981), Morrison (1976), Nicholas (1981), andTymshore (1981) to obtain such a methodology. These studies were neither enough nor complete, as it is not possible to design a methodology that will automatically choose a mining method for the ore-body studied. Each orebody is unique with its own properties and engineering judgement has a great effect on the decisions in

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such a versatile work like mining. Therefore, it seems clear that only an experienced engineer who has improved his experience by working in several mines and gaining skills in different methods can give logical decisions about mining method selection.

A variety of historical schemes exists to classify and help select mining methods (Peele, 1941; Young, 1946; Lewis and Clerk, 1964), of which the oldest is probably still the best. The basis for method classification in these instances was some subjective combination of the spatial, geologic, and geotechnical factors has discussed. Recent schemes have introduced more quantitative or systematic approaches, but use the same basic approach as Peele (Morrison and Russel, 1973; Boshkov and Wright, 1973; Thomas, 1978; Nicholas , 1981; Hamrin , 1982) .

The categories utilized in these classification approaches are acceptance (traditional or novel), locale (surface or underground), class and subclass, and method, with applications as to commodities and relative cost.

The features of the various methods also needs to be examined. Like depiction of the method, sequence of development, cycle of operations, deposit conditions, advantages and dis- advantages, production rate (large scale vs. small – scale), relative cost. The majority of our attention will be devoted to a handful or traditional methods, the most important and commonly used in this country.

3. Classification of stoping methods

The basic classification of methods devised by the U.S. Bureau of Mines in1936 is still valid, and is being followed in many leading countries having metalliferous mines.For all practical purposes a generic classification of mining methods is that (i) which applies to both locales of mining, surface and underground, and all commodities, coal and non-coal, but is not excessively detailed; (ii) includes all current major methods and promising novel ones, under development but largely unproven; and (iii) recognizes the major class distinctions and relative costs. The classification is as follows:

A. STOPES NATURALLY SUPPORTED

1. Open stoping
(a) Open stopes in small ore bodies
(b) Sublevel stoping
(c) Longhole stoping
2. Open stopes with pillar supports
(a) Casual pillars
(b) Room (or stop) and pillar (regular arrangement)

B. STOPES ARTIFICIALLY SUPPORTED

3. Shrinkage stoping
(a) With pillars
(b) Without pillars
(c) With subsequent waste filling
4. Cut and fill stoping
5. Stulledstopes in narrow vein
6. Square-set stoping

C. Caved stopes

7. Caving (ore broken by induced collapse)
(a) Block caving: including caving to main levels and caving to chutes or branched raises
(b) Sublevel caving
8. Top slicing (working under a mat, which together with caved overburden follows the mining downward in successive stages).

D. Combination of supported and caved stopes, (as shrinkage stopingwith pillar caving cut and fill stoping and top slicing of pillars,etc.)

4. Factor affecting the selection of stoping methods

The cardinal rule of mine exploitation is to select a mining method that best matches the unique characteristics (natural, geologic, environmental, etc.) of the mineral deposit being mined, within the limits imposed by safety, technology, and economics, to yield the lowest cost and return the maximum profit. Let us now examine the factors which govern the method selection (Morrison and Russel, 1973; Boshkov and Wright, 1973).

4.1 GEO-MINING

A. Spatial characteristics of deposit. These factors are probably the most important determinant, because they largely decide the choice of surface vs. underground mining and affect the production rate, the method of materials handling, and layout of the mine in the ore body.

(a) Size (dimensions, especially height or thickness)
(b) Shape (tabular, lenticular, massive, irregular)
(c) Attitude (inclination or dip)
(d) Depth (mean and extreme values, stripping ration)

B. Geologic and hydrologic conditions. The geologic characteristics of both the mineral and the contiguous country rock (host material) influence method selection, especially choices between selective and nonselective methods and extent of support required for ground control underground. Hydrology affects drainage and pumping necessities, both surface and underground. Minerology governs mineral processing requirements.

(a) Minerology and petrography (sulfides/oxides)
(b) Chemical composition (primary, by-product minerals)
(c) Deposit Structure(folds, faults, discontinuities, intrusions)
(d) Planes of weakness (joints, fractures, cleavage in minerals)
(e) Uniformity, alteration, weathering (zones, boundaries)
(f) Groundwater and hydrology (occurrence, flow rate, water table)

C. Geotechnical (soil and rock mechanics) properties. Again, both ore and waste are involved. The mechanical properties of the materials comprising the deposit and country rock(and soil, if overburden) are the key factors in selecting the equipment in a surface mine and choosing among the classes of methods (unsupported, supported, and caving) if underground.

(a) Elastic properties (strength, modulus of elasticity, Poisson's ratio, etc.)

(b) Plastic or viscoelastic behavior(flow, creep)

(c) State of stress (original, modified by mining)

(d) Consolidation, compaction, and competence(ability of opening to stand unsupported)

(e) Other physical properties (specific gravity, voids, porosity, permeability, moisture Content)

4.2 Environmental Requirements

Not only the physical environment but the social-political-economic climate is Involved.

(a) Ground control to maintain integrity of openings

(b) Subsidence, or caving effects on the surface

(c) Atmosphere control (ventilation, quality control, heat and humidity control)

(d) Work force (recruitment, training, health and safety, living, community conditions)

4.3 Safety Requirements

The selection of the method also depends on the various safety requirements such as the technical safety aspects of working. Some of them are listed below

(a) Subsidence

(b) Spontaneous heating (in sulfides ore)

(c) Presence of water bodies, etc.

4.4 Techno-economic

A. Technological factors. The best match between natural conditions and mining method is sought. While a particular method may not be ruled out in mining, it may have deleterious effects on other dependent activities (e.g. , processing, smelting)

(a) Mine Recovery (portion of deposit actually extracted) and Dilution (amount of waste produced with ore)

Mining seldom recuperates all resource present in an ore deposit. The amount of ore genuinely extracted from a deposit is referred to as therecovery factor and is expressed as a percent. In some case a certain amount of waste is usually mixed in with the ore during mining. This waste commixed in ore is called dilution and is usually expressed as a dilution factor (in %). Both recovery and dilution vary with each ore body, but tend to be within a similar range for each mining method. Table summarizes the assumed dilution and recovery factors used for the mine models and reflects values commonly encountered when these mining methods are applied. (Thomas W. Camm)

(b) Flexibility of method with changing conditions

(c) Selectivity of method to distinguish ore and waste

(d) Concentration or Dispersion of workings

(e) Capital, labor, and mechanization intensities

B. Economic considerations: Ultimately, economics determines the success of a mining venture. These factors govern the choice of the method because they affect output, investment, cash flow, payback period, and profit.

(a) Reserves (tonnage and grades)

The reserve determination from the identification phase is thebasis for semi-quantitative mine plan comparisons. Competingmine design alternatives are compared in pro forma economicevaluations and

Table: 1 Application of Geo-technical parameter for the selection of Underground metal mining methods.

Types of orebody	Dip	Strength of ore	Strength of walls	Possible Method of Mining
Thin Bodies	Flat	Strong	Strong	Room and Pillar, Casual Pillar, Open Stopes
		Weak or Strong	Weak	Top Slicing, Longwall
Thick Bodies	Flat	Strong	Strong	Sub-level stopping, Room and Pillar, Cut and Fill
		Weak or Strong	Weak	Sub level caving. Top Slicing
		Weak	Strong	Square Set, Cut and Fill, Sub-level Stoping
Narrow Veins	Steep	Weak or Strong	Weak or Strong	Resuing in (a) Open Stopes or (b) Stulled Stopes
Thick Veins	Steep	Strong	Strong	Open Stopes, Sublevel Stoping, Shrinkage Stope, Cut and Fill method
		Strong	Weak	Cut and Fill method, Square Set, Top Slicing, Sub-level Caving
		Weak	Strong	Open Casual Pillar, Square Set, Top Slicing, Block Caving, Sub-level Caving
		Weak	Weak	Square Set, Top Slicing, Sub-level Caving
Massive		Strong	Strong	Shrinkage Stope, Sublevel Stoping, Cut and Fill Stoping
		Weak	Weak or Strong	Square SetTop SlicingSub-level CavingBlock Caving

TABLE: 2 MINE DILUTION AND RECOVERY FACTORS

Mining method	Dilution factor, %	Recovery factor, %
Open pit	5	90
Block caving	15	95
Cut-and-fill	5	85
Room-and-pillar	5	185
Shrinkage	10	90
Sublevel longhole	15	85
Vertical crater retreat.	10	90

investment performance measures such as netpresent value, along with scored risk assessments. Uncertaintythat leads to variability of outcomes (risk) will be characterized,and mitigating strategies or controls will be developedshould the decision to move into the implementation phasebe approved. The preferred mine design (in terms of financialvalue and technical feasibility) results from this stage of planning.At the conclusion of this phase, a single preferred alternativefor the mine plan should be selected for optimization inthe definition phase.

(b) Production rate (output and grades)

There is a considerable amount of literature available on the selection of a production rate to yield the greatest value to the owners (Carlisle 1955; Lama 1964; Tessaro 1960; Christie 1997). Basic to all modern mine evaluations and design concepts is the desire to optimize the net present value or to operate the property in such a way that the maximum internal rate of return is generated from the discounted cash flows. Anyone involved in the planning of a new operation must be thoroughly familiar with these concepts. Equally important is the fact that, solely from the financial aspects of optimization, any entrepreneur planning a mining operation and who is not familiar with the problems of maintaining high levels of concentrated production at low operating costs per tonne over a prolonged period is likely to experience unexpected disappointments in some years when returns are low (or there are none).

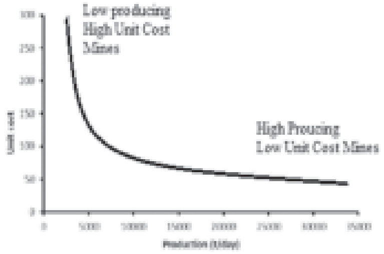

Fig.1 Unit cost-volume relationship(Source: Western Mine Engineering, Inc. 2000 and the Cost Reference Guide, Primedia 2000.)

(c) Mine life (Operating period for development and exploitation)

Given a known ore reserve tonnage, the life and daily capacity for a typical mining operation can be determined. Taylor developed an equation commonly used in prefeasibility studies to determine mine life, known as Taylor's rule (equation 3). Based on this rule, the basic equation for C (capacity of ore production in t/d) is:

(1) $C = T / L * dpy$

where L = mine life in years,

T = total tonnage (in t) of ore to be mined,

dpy = operating days/yr.

To find T, recovery and dilution factors are applied to the total amount of ore in the deposit.

(2) $T = rt * rf * (1+ df)$

where rt = total deposit reserve tonnage in t,

rf = recovery factor for the particular min-ing method

df = dilution factor from

Substituting for L using Taylor's rule.

(3) $L = 0.2 * T^{0.25}$

The daily mining capacity can be determined using either equation 4 or 5 below, depending on whether the oper-ating days per year are 350 or 260 (equivalent to operating 7 d/wk or 5 d/wk, respectively)..

(4) $C_1 = T / 350*L = T^{0.75} /70$

(5) $C_2 = T/ 260*L = T^{0.75}/52$

where C_1 = mine capacity in t/d for 350 d/yr(7 d/wk),

C_2 = mine capacity in t/d for 260 d/yr(5 d/wk).

Capital costs

Capital costs are based on actual equipment list prices in most cases. An additional cost of 7.5% is applied to all equipment purchase costs for freight. Equipment lists for the open pit models were based on actual operations, ad-justed to fit the generic nature of the handbook. Under-ground capital costs were determined by the amount of development necessary for an underground mine of the size and type under consideration to begin operating at design capacity. A cost factoring method similar to the approach developed by Mular was used for many of the mill models. Working capital, based on 2 months of operating costs, was included in the capital cost of each mine and mill model. Working capital covers the cost of meeting operating costs in the initial stages of production, before revenue is generated from the first shipments of product (concentrates or dote). This value can vary from 2 to 6 months. Engineering and construction management fees are also included in the capital cost models.

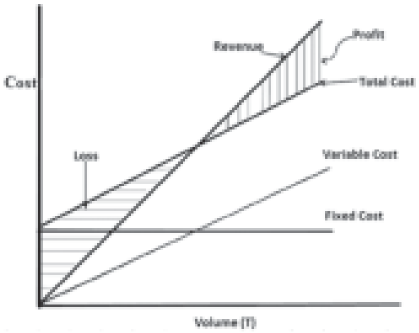

Fig.2 Cost-volume (tonne) relationship (Source: Western Mine Engineering, Inc. 2000 and the Cost Reference Guide, Primedia 2000.)

Operating costs

Operating costs are based on daily capacity (tonnes per day) and are expressed in money value per

Table 3: Ranking Sheet for recording ranks to each sub-parameter indicating suitability for the given stoping method

		Unsupported				Supported				Caving	
Factor		Room and Pillar	Stope and Pillar	Shrinkage	Sublevel	Cut and fill	Stull	Square set	Longwall	Sublevel Caving	Block Caving
Ore Strength	1. Weak										
	2. Moderate										
	3. Weak to Moderate										
	4. Moderate to strong										
	5. Strong										
Rock Strength	1. Weak										
	2. Weak to Moderate										
	3. Moderate										
	4. Moderate to strong										
	5. Strong										
Deposit Shape	1. Tabular										
	2. Lenticular										
	3. Tabular to irregular										
	4. Tabular or Massive										
	5. Any										
Deposit Dip	1. Flat										
	2. Flat to Moderate										
	3. Moderate										
	4. Moderate to Steep										
	5. Steep										
Deposit Size	1. Large thin										
	2. Thin to moderate										
	3. Any, preferably large, mod. Ck										
	4. Fairly thick to moderate										
	5. Large thick										
Ore Grade	1. Low										
	2. Low to Moderate										
	3. Moderate to High										
	4. Fairly High to High										
	5. High										
Ore Uniformity	1. Variable										
	2. Moderate to Variable										
	3. Moderate										
	4. Fairly Uniform										
	5. Uniform										
Depth	1. Shallow										
	2. Shallow to Moderate										
	3. Moderate										
	4. Moderate to Deep										
	5. Deep										

tonne. All the underground models are based on tonnes per dayof production, and costs are in Money value per tonne.

d) Productivity (output per unit oflabor and time-e.g., tons or tones/employee-shift)

e) Comparative mining costs of suitable methods

5. Stoping method selection approach

Looking at the complexity of the decision problem of selection of most appropriate method for underground metalliferous mines, the authors propose a ranking based Multi-Criteria Decision Making process which is as under

- Inclusion of all the main parameters and for selection of the method of stoping – 1. Ore Strength, 2. Rock Strength, 3. Deposit Shape, 4. Deposit Dip, 5. DepositSize, 6. Ore Grade, 7. Ore Uniformity, 8. Depth
- Ranking of all main parameters according to their applicability to various stoping methods through expert opinion.
- Absolute rank weights will be available for each main parameter for various available stoping method. One of the suitable Ranking order methods will be employed.
- Consideration of sub parameters under each respective main parameter
- Ranking of each and every sub parameter using the expert opinion will be taken and converted into absolute weights as given below in Table 2. The expert will give rank 1 to the most suitable sub parameter for the particular method and rank 5 to the least preferred sub parameter accordingly. This exercise will cover all five sub parameters of main 8 parameters listed in point 1 and will be required for all 10 given stoping methods
- Combining the rank weights of the main parameter and the absolute weight of the sub parameter the overall rating of the method of stoping will be calculated.
- The decision maker (usually a mine planner) will input all the values of the sub parameters related to the relevant mine for which the method is to be selected.
- The alternative methods with comparative score will be given and the one with the highest score will be selected as the most suitable method.
- Once the most suitable methods chosen on the basis of geo-technical parameters is available then these methods are compared on the basis of economic evaluation and the best economically and technically feasible method will be selected.

6. Concluding remarks

The method demonstrated here for selection of optimum stoping method for hard rock mines through a tool useful to mine planner's needs through the application of the multi criteria decision making methods.The paper discusses the new approach and in reality the computer model, when developed, will be much more complicated due to the complexities involved. The model will be tested and evaluated based on current mining situations and will become a handy application for selection of underground stoping method for metalliferous mines in India.

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3.6 Reflection loss of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin coating materials

According to the test results and discussion above, the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration should be ranged between 20% and 30% from the aspect of impedance matching in order to obtain an absorber with strong absorption and broad bandwidth in 8-18GHz. So, the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin single-layer coating materials with five $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentrations (20%, 23%, 25%, 28%, 30%) were prepared on aluminum plate with 18 centimeters in length. The results of reflection loss are displayed in Fig.6 and Table 2.

It can be seen from Fig.6 and Table 2 that the single-layer coating specimen with $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration 23% has the largest effective bandwidth (in which the reflection loss is less than -10 dB) 6.4 GHz, and the minimum value of reflection loss, thickness of absorbing layer and surface density are -24 dB, 1.4 mm and 3.39 kg/m^2 respectively, indicating a strong absorption, thin thickness and relatively wide effective bandwidth characteristic.

4. Conclusions

(1) The real part of permittivity of the $Ce_2(Co_{0.3}Fe_{0.7})_{17}$/epoxy resin composites will not be too high at a high imaginary part of permeability so that can avoid impedance mismatch to same extent.

(2) The peak frequencies corresponding to minimum reflection loss shift to the lower frequencies with increase of $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration at a giving thickness. And also the peak frequencies corresponding to minimum reflection loss will shift to the lower frequencies with increase of thickness at a giving $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration, which can be explained by the interface reflection model.

(3) The single-layer coating specimen with $Ce_2(Co_{0.3}Fe_{0.7})_{17}$ volume concentration 23% has effective bandwidth, minimum value of reflection loss, thickness of absorbing layer and surface density of 6.4 GHz, -24 dB, 1.4 mm and 3.39 kg/m^2 respectively, indicating a strong absorption, thin thickness and relatively wide effective bandwidth characteristic.

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