Mining method selection and transition depth determination problems- which one is in priority of consideration?

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During this paper, in order to identify the priority of consideration between the problems of "mining method selection" and "determining transition depth from open-pit to underground mining" an accurate procedure is introduced step by step. First, it is essential to specify if an ore deposit that potentially will have mined by a combined method of open-pit and underground mining. In this case, optimal final open-pit limit and depth must be initially determined. After that, if the rest of deposit below open-pit limit is economically considerable, it is necessary to select the most adequate underground method with emphasis on the high production rate and low cost methods. Then, it is necessary to determine optimal transition depth from open-pit to underground mining considering a crown pillar immediately below open-pit mining. Finally, the procedure with its algorithm was used for an iron ore deposit with the combined mining potential.

Keywords: Mining method selection; transition depth; open-pit; underground; combined mining.

1. Introduction

Naturally, ore bodies come in every imaginable geometric shape. While surface hard rock mines apply the open-pit method to almost any ore configuration, a large number of underground mining methods have been developed primarily in response to the requirements of differing geometry and geomechanical properties of the host and surrounding rock.

The decision as to whether mining will be on the surface, underground or combined methods must be made before the land zoning and permitting process begins for the proposed mine site. Open-pit, underground or combined mining should be selected depending on the geometry properties of the deposit (such as size, shape, and depth of deposit), rock conditions, productivities, machinery capacities, capital requirements, operating costs, discount rate, investments, amortization, depreciation, ore recoveries, revenues, safety and injuries, environmental aspects, etc.

Open-pit is by and large regarded to be advantageous over underground methods, especially as regards recovery, production capacity, mechanizeability, grade control and cut off grade, ore loss and dilution, economics, and safety. Underground mining however can be considered as being more acceptable than surface mining from environmental and social perspectives. In addition, underground mining will often have a smaller footprint than an open-pit of comparable capacity.

Ore deposits should be evaluated meticulously in optimal way of mining method selection. In the method selection process, many controllable and uncontrollable parameters should be taken into account. Therefore, these parameters must be produced with scientific and technical studies for each ore deposit (Kahriman *et al.* 1993, Demirci *et al.* 1995).

Yore, selecting mining method for a new property was established principally on operating experience at similar type deposits and on methods already being used in the districts of the deposit. Then, the picked out method was adjusted during the early years of mining as ground conditions and ore character were better comprehended.

Today, however, the large capital investment required to open a new mine or change an existing mining system make it imperative that the mining methods examined during the feasibility studies and the method actually selected have a high probability of attaining the projected production rates (Nicholas 1981).

The use of numerical systems to evaluate the appropriateness of a mining method for a particular ore deposit has been in use for some time. These systems rely on ranking a finite number of geometrical, geological, and geomechanical parameters to arrive at a rating value for different mining methods and the higher the rating is the more suitable the mining method (Clayton 2002).

Several qualitative and quantitative systems have been developed to evaluate suitable mining methods for an ore deposit based on physical characteristics of the deposit such as shape, thickness, plunge, depth, grade distribution, grade value, and geo-mechanical properties of the rock. The systems have been presented by Boshkov and Wright (1973), Morrison (1976), Laubscher (1977, 1981, 1990), Nicholas (1981, 1992), Hamrin (1982), Hartman (1987), Miller *et al.* (1995), Clayton *et al.* (2002), recently Shahriar *et al.* (2007) and etc.

The system proposed by Boshkov and Wright in 1973 (based on Peele 1941), was one of the first quantitative classification schemes developed for underground method selection. This system assumes that the possibility of surface and underground mining has already been eliminated. It utilizes general descriptions of the ore thickness, ore dip, strength of the ore, and strength of the walls to identify common methods that have been applied in similar conditions.

The classification system proposed by Morrison in 1976 divides underground mining into three basic groups and helps to demonstrate the selection continuum, choosing one method over another based on the various combinations of ground conditions.

In the Laubscher system (1981), the selection process was based on the presented rock mass classification system, which adjusts for expected mining effects on the rock mass strength.

The Nicholas method (1981) is one such procedure, which implements a numerical approach to rate different mining methods based on the rankings of particular input parameters. This method has a consequential characteristic of collecting and systemizing most of criteria.

The selection process described by Hamrin (1982) was intended to supply the techniques by which the candidate methods available for a given orebody can be reduced to one or two feasible approaches. The feasible approaches then can be evaluated in detail, and the particular modifications can be investigated.

Hartman (1987) has developed a flow chart selection process for defining the mining method, based on the geometry of the deposit and the ground conditions of the ore zone. This system is similar to the proposed Boshkov and Wright (1973), but is aimed at more specific mining methods.

Bandophadhyay and Venkatasubramanian (1987) developed one of the first studies on the implementation of expert system in the mining method selection process. It is developed to aid the mining engineers in selecting suitable mining methods for coal deposits minable by underground methods.

Second time, expert systems application in mining method selection decision was developed and a milling and mining method chosen expert was expressed utilizing a knowledge base that is comprised of alternative methods, experience, intuition, deposit types, mine plans and engineering studies (Camm and Smith 1992).

In 1990, Laubscher has recently modified his previous classification (1981) to relate the rock mass rating to the hydraulic radius (Hartman 1992).

A modification to the Nicholas system (1981) was the weighting of the categories for the ore geometry, ore zone, hanging and foot walls. To give each of these categories equal weight, the ore zone, hanging wall, and foot wall need to be multiplied by 1.33.

Kahriman and others (1994) stated in the method selection process, many controllable and uncontrollable parameters must be taken into determine by scientific and technical studies for each ore deposit.

Third expert system by Gershon *et al.* (1995) based on the Nicholas approach (1981) was developed.

The UBC mining method selection algorithm is a modification to the Nicholas approach with a various weighting factors system, which places more emphasis on stoping methods, thus better representing typical Canadian mining design practices (Miller *et al.* 1995).

Due to the performed study by Tatiya (1998) a mining method was selected between three stoping methods namely sublevel, down the hole and cut and fill established on an itemized economic analysis.

In 1999, due to Basu efforts for improving practically and technically the Gershon *et al.* system, a similar expert system was developed.

In 2002 the mining method selection system was suggested based on the UBC algorithm but supplies the opportunity to describe the parameters using fuzzy logic (Clayton *et al.* 2002).

According to the study of Guray *et al.* (2003) which concerned the Nicholas system (1981) and based on a neuro-fuzzy training algorithm, as well as, a number of expert systems and one interface agent, a new expert system was achieved. In this system, the intuitive knowledge and the judgment capability of the expert users or in other words "experienced engineers" can be directly added to the databases of the virtual experts.

It is notable that recently numerous researches have been done and published in relation to select a suitable mining method for an ore deposit using the numerical approaches and decision-making systems such as AHP, ANP, TOPSIS, PROMETHEE, ELECTRE, Fuzzy logic and so on separately and together.

All the recent researches have been initialized the mining method selection process in a mistake way. On the other hand, the researchers and authors have not been taken into account this note that:

There are many deposits that potentially will have mined by a combined method of open-pit and underground.

During the researches, it is assumed that the ore deposits will have mined only by a single method among surface methods (especially open-pit), supported, unsupported, or caving underground methods.

This study represents a procedure with an accurate and reliable way in relation to identify the priority of consideration between the problems of mining method selection and determining transition depth from open-pit to underground mining.

2. Procedure description

Generally, many deposits can be mined entirely with open-pit method; others must be worked underground from the very beginning. Besides these two kinds of deposits, there are the near surface deposits with considerable vertical extent. Although they are initially exploited by open-pit method, there is often a point where decision has to be made whether to continue deepening the mine or changing to underground methods. The point at which economic considerations dictate to change of method from open-pit to underground is called "transition depth". Accurate determination of this depth-mines where both methods are used, is of utmost important.

Also, it is notable that there are an interdependency and mutual effect between problems of "mining method selection", "possibility of combinational mining of open-pit and underground methods", and consequently "determination of optimal transition depth from open-pit to underground". Therefore, taking into account each mentioned problem separately can be caused to a mistake in response.

In order to solve these problems with respect to their priority of consideration in a reliable way, it is offered that they consider during the feasibility study and design stage by the procedure is introduced here. Algorithm of the procedure is shown in figure 1.

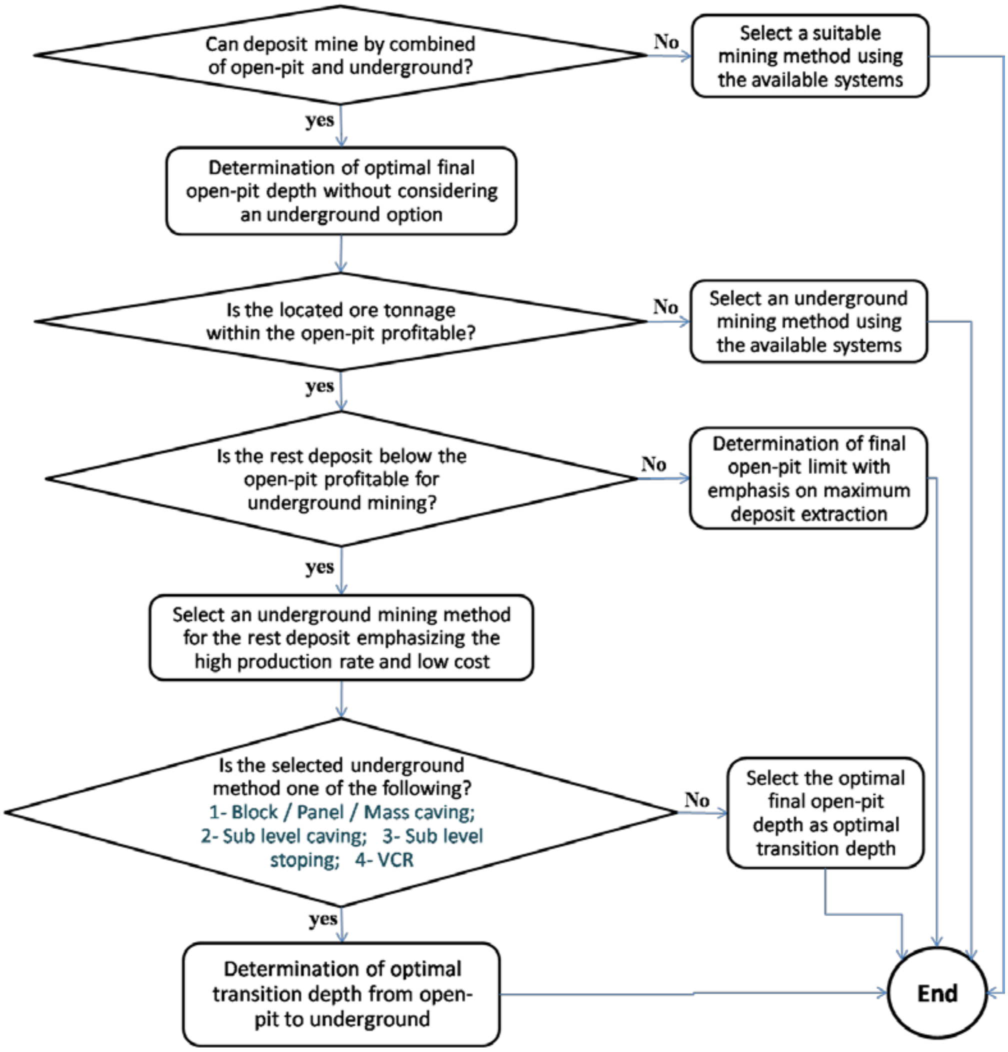

Figure 1- Procedure to find priority of consideration between "mining method selection" and "determination of transition depth"

Algorithm of the presented procedure is described in detail and step by step as below:

Step 1: It is necessary to assess (as the rule of thumb) an ore deposit, in relation to its potential to extract by single or combined method of open-pit or/and underground mining. If the ore deposit potentially will have mined by a combined method of open-pit and underground, determine optimal final open-pit limit without considering an underground alternative and go to the next step. Otherwise, select the most suitable mining method using the mentioned qualitative and quantitative systems with the decision-making systems, and in this case process is closed.

It is notable that except in cases that an ore deposit begins from the very high depth and it should be certainly mined only by underground methods; in other cases the potential of combined mining of open-pit and underground must be carefully investigated.

Step 2: After determining the optimal final open-pit limit, the ore tonnage located within the open-pit limit should be evaluated considering economical aspects. If the amount of ore tonnage (with the related grade) within the open-pit limit is economically considerable and if expending an investment for this project could be caused to profit, go to the next step. Otherwise, select a most adequate underground method using the existing systems, and in this situation process is closed.

Step 3: The rest of ore tonnage and the related grade below the open-pit depth should be evaluated considering economical aspects. If the amount of the rest of ore deposit below the open-pit depth is economically considerable for underground mining and if expending an investment for the rest of ore deposit could be caused to profit; go to the next step. Otherwise, determine final open-pit limit with emphasis to maximize extractable ore deposit and in this situation process is closed.

Step 4: It is essential to select a most suitable underground mining method for the rest of ore deposit with emphasis on high production rate and low costs such as the stope cave mining methods. In this regard, if the selected underground alternative is one of the methods: Block / Panel / Mass caving, Sub level caving, Sub level stoping, or VCR, go to the next step. Otherwise, select the optimal final open-pit depth as optimal transition depth from open-pit to underground mining and process is closed.

Step 5: Finally optimal transition depth from open-pit to underground mining should be determined using the available methods presented by Nilsson (1982, 1992, and 1997), Bakhtavar and Shahriar (2007), Bakhtavar *et al.* (2008a, 2008b, and 2009), etc. Then, the process is closed.

3. Case study

The presented procedure has been used in Gol-e-Gohar Area 3 iron ore deposit.

The Gol-e-Gohar iron ore complex (including six Areas) is located approximately 60 km southwest of Sirjan city, in the Kerman province of Iran (fig. 2). The Area 3 zone is approximately 1730 meters above sea level in an area of planar desert topography. The Area 3 ore body is generally of tabulate form with an area covering approximately 2200 m in the N-S direction and nearly 3.5 km west of the centre of the presently mined Area 1 ore body. The closest approach of the two ore bodies is approximately 1 km (ADC 2000).

It has been estimated that the Gol-e-Gohar Area 3 ore body has a length of about 2200 m (N-S) and an average width of nearly 1800 m (E-W). Overburden and waste rock above the ore zone varies from 95 to 560 m in thickness and the depth of the ore body varies from 95 m at the north end to 600 m at the southern end. Ore body thickness varies from 15 to 130 m with an average thickness of 40 m.

The indicated resources have been estimated to be 496 Mt. In addition, there is an inferred resource of 147 Mt.

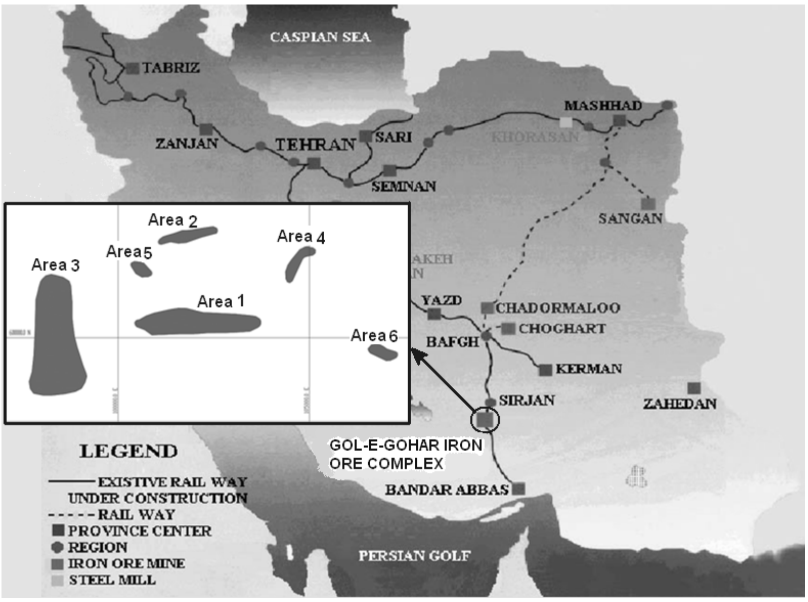

Figure 2- Location of Gol-e-Gohar iron ore complex and Area 3 mine

It is considered that the most economical method for the exploitation of Gol-e-Gohar Area 3 iron ore deposit is to combine open-pit and underground methods. In this regard, the most critical problems are “mining method selection” and “determination of optimal transition depth”.

According to the presented procedure, after specifying the combined mining potential of the ore deposit, it is essential to determine optimal final open-pit depth. In this relation, optimal final open-pit depth is determined to be equal to 285 m.

During the second step it is proved that there is a considerable ore tonnage within the Gol-e-Gohar Area 3 open-pit.

According to the third step, it has been specified that the rest of ore deposit for underground mining is profitable. For this reason during the next step and underground mining method selection process, stope and pillar method is selected.

After that, depth of 285 m is assigned being the optimal transition depth over from open-pit to underground mining. The input parameters of the rest of Gol-e-Gohar Area 3 iron ore deposit for underground mining method selection process are given in table 1.

Table 1: Input parameters of third anomaly of Gol-E-Gohar iron ore mine

	Input Parameters	**Description**		**Input Parameters**	**Description**
	Ore Thickness	40 meters		RQD	38%
	Ore Plunge	20 degrees	**Hanging Wall**	Joint Condition	Clean joint with a smooth surface
	Deposit Shape	Platy		RSS	4.9
	Grade Distribution	Gradational		RMR	50
Ore Zone	Grade Value	High		UCS	46 MPa
	Depth	285 meters		RQD	38%
	RQD	75%		Joint Condition	Clean joint with a smooth surface
	Joint Condition	Filled with talk strength less than RSS	**Foot Wall**	RSS	4.9
	RSS	8.7		RMR	50
	RMR	63.5		UCS	46 MPa
	UCS	128 MPa			

4. Conclusion

Usually due to improving technology of the mine design and developing the exploitation equipment also variation of marketing demand for the raw material in relation to expire time, it is necessary to improve and modified some basic employed rules and methods in mining industry. Therefore, during this study a basic procedure has been presented to show the interdependency of problems “mining method selection” and “determination of optimal transition depth from open-pit to underground in combined mining” as well as to find their priority in consideration.

If an ore deposit changes much in geometry along the strike, especially if the change occurs at the end of it, the stripping ratio will be too large when the whole deposit is mined by open-pit mining. In this case, it is more suitable to have the deposit mined by combined method, that is to say, the end part of the ore deposit should be mined by underground method. In this regard, a most suitable underground method should be selected for the rest of ore deposit below open-pit depth.

The presented procedure was assessed during underground mining method selection and determination of optimal transition depth from open-pit to underground for Gol-e-Gohar Area 3 iron ore deposit in Iran. It is concluded that the most suitable underground method for mining the rest of ore deposit below the open-pit is stope and pillar. Also, a depth of 185 m was specified as the optimal transition depth for Gol-e-Gohar Area 3 iron ore deposit.

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