A REVIEW OF COMBINING OPEN-PIT AND UNDERGROUND MINING METHODS AROUND THE WORLD

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ABSTRACT. Currently, some of the largest and most influential open-pit mines in the world are planning, or are in the process of implementing, the underground mining method. This leads to transitioning to underground mining or to concurrently combining open-cast and underground operations. Those mines deal with the extraction of expensive ores, such as copper, gold, diamond, etc. This is why profitability, the expensive price of the mined ores, and the depletion of the deposits close to the surface of some open-pit mines are the main factors of such technological changes.

Keywords: open-pit mines, underground mines, transition, combined mining methods

КОМБИНИРАНЕ НА ОТКРИТИЯ И ПОДЗЕМЕНИЯ СПОСОБ НА РАЗРАБОТВАНЕ В СВЕТОВЕН ПЛАН

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РЕЗЮМЕ. В настоящия момент някои от откритите рудници, които са най-големите в световен план и оказват най-значително влияние върху цените на материалите, планират или са в процес на внедряване на подземно разработване на находището. Това води до преминаване от открит към подземен способ на разработване или до комбинирането на открит и подземен добив едновременно. Тези рудници извличат скъпи материали като мед, злато, диаманти и др. Основните фактори за осъществяване на такава технологична промяна при откритие рудници са реализирането на по-висока печалба, високата цена на добиваните материали и изчерпването на рудата в близост до повърхността в някои открити рудници.

Ключови думи: открит рудник, подземен рудник, преминаване, комбиниран добив

Introduction

The application of a suitable mining method has always been a topical problem. The dynamic conditions of our time impose specific requirements for the processes of mining mineral resources. The geological conditions, economical changes and the improvement of mining technology and techniques are few of the factors which determine the choice of mining method. In order to prosper, each mining organization needs to consider the possibilities of utilizing underground or open-pit mining or combining both methods depending on the conditions, as well as to look for certain tendencies in a global scale for a preferred method.

Factors influencing the choice of mining methods

The main factors which determine the mining process are the geological conditions, the level of technological development, and the ecological and economical aspects. These factors are interdependent. The geological conditions are related to certain spatial and quality parameters, such as depth, size, type, and quality of the minerals in the deposit. While the parameters representing depth and type are fixed, the spatial parameters of the deposit depend on the level of development of the mining technology and mechanization, as well as on the current economical condition, production costs, and the selling prices. This is why boundaries of the deposit and differentiation between resources and reserves are not fixed during the life of the mine. The ecological and social aspects of mining are also an important group of factors which affect the choice of a suitable mining technology that ensures safe and healthy conditions during the mining process, especially when mining takes place near residential areas. All these groups of factors influence the choice of the mining method in a complex manner.

Combining open-pit and underground mining

There are two main cases of utilizing open-pit and underground methods of ore extraction: 1) utilizing open-pit or underground mining separately for a single ore body and 2) combining both methods simultaneously.

In the first case, both open-cast and underground mining are utilized sequentially by transitioning between the methods. Transitioning from open-cast to underground mining is a popular and preferred method for further ore extraction. The stripping ratio is a commonly used index which gives information about the profitability of the mining operations and the maximum volume of overburden. A variation of the stripping ratio could directly yield the comparison between the costs of underground mining operations and open-cast operations. Transportation costs should also be taken into account, as well as the productivity of the dumpers per shift, which depends on the number of work cycles during the shift. Deep open-pit mines have the problem of increased fuel costs and the decreased number of working cycles of dumpers. Open-cast mining, on the other hand, gives the opportunity to fully extract the ore. However, the underground method allows for extracting selectively only the richest sections of the deposit. This is why each case requires the comparison between the two methods in terms of costs per m^3 or t of ore, as well as looking for suitable combination of both methods according to the conditions. Selling prices of the extracted minerals or concentrates are one of the most important factors. Increased prices provide the opportunity of investing more funds for further development of the deposit by transitioning to the underground method or combining underground with open-pit mining. Another significant factor is the development of the mechanization and the mining technology which provide the possibility of mining ore that contains less valuable components. This is especially beneficial for the open-pit mining method due to the larger volume of lower quality ore which could be extracted. Considering the ecological factors, as well as some social aspects of mining, the choice of a suitable method also depends on health and safety factors. Open-cast mining provides a less hazardous environment for the workers, but it has a more significant impact on the environment, while the underground mining method is more environmentally-friendly and gives the opportunity to manage waste more easily. However, it is related to more hazardous working conditions. Combining both methods eliminates some of the drawbacks of each method that would be obvious should those methods be applied separately.

Examples of utilizing both open-pit and underground mining

In this article, some of the world's biggest mines have been reviewed. Predictions are that those mines are going to be the ones to mostly influence the prices of materials in the next 10 years to come (http://www.mining.com/these-10-mines-will-set-the-copper-price-for-the-next-decade/). These mines could also serve as an example for some of the most technologically advanced mines that implement modern technological solutions.

Mines which transitioned or are planning to transition from underground to open-cast mining:

Although transitioning from underground to open-pit mining is not very common, some of the mines of the Freeport-McMoRan company could serve as examples of such transitioning, which took place during the 20th century.

1. Morenci – Arizona, USA – copper – 9.7 billion t of reserves (0.25% copper, 0.002% molybdenum); productivity is 115, 000 t/day – transitioned from underground to open-cast in 1937 (https://www.fcx.com/index.htm).
2. Bagdad – Arizona, USA – copper and molybdenum – productivity is 75, 000 t/day - transitioned from underground to open-cast in 1945 (ibid.)
3. Sieritta – Arizona, USA – copper and molybdenum – productivity is 102, 000 t/day – transitioned from underground to open-cast in 1957 (ibid.)
4. Miami – Arizona, USA – copper – transitioned from underground to open-cast after 1945 (ibid.)
5. Tyrone – Arizona, USA – copper – underground mining stops in 1921; open-pit mining continued in 1967 (ibid.)
6. Kalgoorlie – Australia – gold – from underground to open-cast mining in 1989 (http://superpit.com.au/about/mining/)
7. Cannington – Australia – silver and lead – plans on transitioning from underground to open-cast mining no sooner than 2023 (http://www.townsvillebulletin.com.au/business/bhp-to-shed-up-to-70-jobs-at-cannington-mine/news-story/cc7822ec0dabdf84985c1c229eccc8df)

Mines which transitioned from open-cast to underground mining for further exploitation of the deposit:

These mines follow the traditional technological scheme of transitioning to underground mining after the open-pit mine reaches its project depth.

1. Mir – Russia – diamond – more than 141 Mct of probable reserves; expected production for 2014 was 1 Mt – open-pit mining ceased in 2001; started underground mining in 2009 on the Mir kimberlite pipe (http://www.mining-technology.com/features/feature-the-worlds-top-10-biggest-diamond-mines/)

3. Venetia – South Africa – diamond – open-pit mine reserve is 32.8 Mct (0.975 ct/t diamond); underground reserve is 70 Mct (0.765 ct/t diamond) – production for 2012 was 3.066 Mct of diamonds from 5.618 Mt ore – the forecast is that the open-pit mine will function until 2021, followed by transitioning to underground mining which will function for another 20 years; it has the potential to produce 96 Mct within the period (ibid.)

4. Ernst Henry – Australia – copper – 72 Mt reserves of 1% copper, 0.5 g/t gold and 22% magnetite – transitioned from open-cast to underground mining in 2009 (https://www. australianmining.com.au/features/the-next-age-of-mining/)

5. Kiruna – Sweden – iron – proven reserves 602 Mt of 48.5% iron, probable reserves of 82 Mt grading 46.7% iron – functioned as an open-pit mine until the 1960s, after that transitioned from open-cast to underground mining (http:// www.mining-technology.com/projects/kiruna/), (http://www. mining-technology.com/projects/tropicanagoldproject/)

6. Kanowna Belle – Australia – gold – 14.87 Mt ore which is 2.4 Moz recoverable gold (5.1 g/t) – transitioned from open-cast to underground mining in 1998 (http://www.mining-technology.com/projects/kanowna/)

7. DeGrussa – Australia – copper-gold – annual productivity is up to 300, 000 t of high-grade copper concentrate – open-pit mining operations concluded in 2013; currently, production is based on long-term underground development (http://www. sandfire.com.au/operations/degrussa.html)

8. Palabora – South Africa – copper and rare metals – annual production of 80, 000t (0.7% copper) – open-pit mining ended in 2002, due to reaching its economic depth; transitioned to

underground mining and prolonging the life of the mine by at least 20 years (http://www.palabora.com/palabora.asp)

Mines which plan to transition from open-cast to underground mining for a further exploitation of the deposit:
1. Tropicana – Australia – gold – reserves are estimated to be 57.1 Mt (ore grade 2.12g/t) with annual production up to 350, 000 oz; it is rumored to transition from open-pit to underground mining (http://www.mining-technology.com/ projects/tropicanagoldproject/)
2. Mt Keith – Australia – nickel – more than 95 Mt/year; plans to transition to underground mining; currently, the project has not started due to the low price of nickel and the low grades of ore (https://www.thiess.com/projects/mt-keith-mine-alliance/ detail)
3. Rocky's reward – Australia – nickel – plans to transition to underground mining; currently, the project has not started due to the low price of nickel and the low grades of ore (https://www.thiess.com/projects/rockys-reward/detail)
4. Oyu Tolgoi – Mongolia – copper and gold – mined until now by open-cast method; since 2015, the planning stage takes place of transitioning from open-cast to underground mining; development started in 2016 and first production is expected in 2020 with an average copper grade of 1.66% and an annual production of 500, 000 t (http://www.riotinto.com/ copperanddiamonds/oyu-tolgoi-4025.aspx), (http://www. riotinto.com/media/media-releases-237_17323.aspx)
5. Grasberg – Indonesia – copper and gold – 2.8 billion t reserves (1.09% copper, 0.98 g/t gold, 3.87 g/t silver) – combined mining method; since 1990, the ores from the open-pit mine are depleting; the forecast is that the open-pit mine will function until the end of 2017; in planning stage for transitioning from open-cast to underground mining since 2015 (http://www.mining-technology.com/projects/grasbergopenpit/)
6. Los Bronces – Chili – copper and molybdenum – remaining reserves of 2.06 billion t (0.51% copper, 0.014% molybdenum); productivity is 145 Mt/y – transitioning from open-cast to underground mining no sooner than 2020 (http://www.mining. com/these-10-mines-will-set-the-copper-price-for-the-next-decade/)
7. Chuquicamata – Chili – copper and molybdenum – 1.7 billion t reserves (0.7% copper, 552 ppm molybdenum); copper productivity is 336, 000 t/year and molybdenum productivity is 18, 000 t/year – transitioning from open-cast to underground mining no sooner than 2018; the forecast is that this will extend the lifespan of the mine until 2060 (http://www.mining.com/ these-10-mines-will-set-the-copper-price-for-the-next-decade/)
8. Udachny – Russia – diamond – reserves estimated to be more than 152 Mct – currently considering the alternative of transitioning from open-cast to underground mining (http:// www.mining-technology.com/features/feature-the-worlds-top-10-biggest-diamond-mines/)
9. Bingham Canyon – USA – copper – continues to extract ore using open-pit mining; the forecast is that the open-pit mine will function until 2028; since 2014, the organization considers transitioning from open-cast to underground mining (http:// www.mining.com/rio-tinto-heads-underground-at-bingham-canyon-mine/)
10. Grib – Russia – diamond – reserves are estimated to be more than 98 Mct; annual production 4 Mct – transitioning from open-cast to underground mining no sooner than 2030 (http://www.mining-technology.com/features/feature-the-worlds - top-10-biggest-diamond-mines/)

Mines which combine underground and open-cast mining:
1. Andina – Chili – copper and molybdenum – combines open-cast and underground mining in the Rio Blanco deposit (https:// mining-atlas.com/operation/Andina-Copper-Molybdenum-Mine. php)
2. Telfer – Australia – copper and gold – reserves are 65 Moz gold, 11 Mt copper, 38 Moz silver; productivity for 2016 was 462, 461oz gold and 18, 940 t copper – the forecast from 2016 is that the open-pit mine will function until 2018 and the underground mine until 2021; since 2002, the underground extraction has a greater priority (http://www.newcrest.com.au/ our-business/operations/telfer-wa/)
3. Diavik – Canada – diamond – 18.1 Mt ore reserve (2.9 ct/t diamond) – transitioned to underground mining in 2012 for further extraction of the deposit; the forecast is that a new open-pit mine will start functioning in 2018 (http://www.riotinto. com/canada/diavik/operations-12110.aspx)
4. Argyle – Australia – diamond – reserve estimated to be 140 Mct (2.1 ct/t diamond) – currently transitioning from open-cast to underground mining; the forecast is that the open-pit mine will function as well after 2020 (http://www.mining-technology.com/features/feature-the-worlds - top-10-biggest-diamond-mines/)
5. Jundee - Australia - gold – ore production is 1 Mt per year – open-pit mining took place from 1995 to 2007; underground mining started in 1997 and currently the mine produces 1 Mt of ore annually using underground extraction (https://www.nsrltd. com/our-assets/jundee/)
6. Olympic Dam – Australia – poly-metallic mine (copper, uranium, gold, silver) – reserves estimated to be 2.95 billion t (1.2% copper, 0.04% uranium, 5 g/t gold, 6 g/t silver) currently mined underground; plans to expand with open-pit mining in the near future (http://www.mining-technology.com/projects/ olympic-dam/)
7. Carlin – Nevada, USA – gold – reserves estimated to 33.3 Moz gold – in 2005, the mine operated with 13 open pit mines and 4 underground mines (http://www.mining-technology.com/ projects/carlin/)
8. Goldstrike – Nevada, USA – gold – ore body is mined by combined method; Betze-Post is the open-pit mine (94.9 Mt reserve with ore grading 0.128 oz/t), Meikle underground mine (7.42 Mt estimated reserves with ore grading 0.364 oz/t) (http://www.infomine.com/library/publications/docs/Mining.com/ Sep2008i.pdf)
9. Raspadskaya – Russia – coal – estimated recoverable reserve 782 Mt; total annual productivity is 13.6 Mt; consisted of 2 underground mines and 1 open-pit mine (http://www. mining-technology.com/features/feature-the-10-biggest-coal-mines-in-the-world/)

Conclusion

The conclusion is drawn that combining the underground and open-cast method is a viable option when extracting ore from deposits of expensive mineral resources which offer a great volume of ore reserves, because it requires a lot of investments. The decision of combining the two methods, as well as implementing any other mining method, is heavily dependent on the profitability of the selected method. There is a certain tendency that the richest deposits which are close to the surface are gradually depleting. This leads to the future transition of a number of open-pit mines to underground mining technology or to combining underground mining operations with open-cast mining for certain ore bodies. This applies to the deposits of expensive materials such as diamond, copper, gold, etc. The main reason for this choice of transitioning from open-pit to underground mining is the high price of these minerals, as well as the technological innovations in underground mining. According to M. Campbell, a specialist in Sandvik Mining, many open-pit mines are coming to the end of their lifespans because of the enormous volume of burden required to be mined in order to reach the ore in depth (https://www.australianmining.com.au/features/the-next-age-of-mining/). The Rio Tinto company has shared their forecast that, by the year 2025, 40% of the production of copper on a global scale would be done by underground mining, while during the period 2009-2010 it was 26% (ibid.). Although many open-pit mines are planning to combine extraction with underground mining or to transition to underground mining, the viability and potential the open-cast mining method have not diminished. The modernization of the mines, the technological advancements in mining, beneficiation and metallurgic processes all lead to the increased volume of lower quality ore which could be extracted by open-cast mining (http://www. mining.com/web/emerging-trends-in-the-mining-industry/). In addition, the open-pit mining method continues to be leading in the extraction of less expensive materials, such as coal, as well as construction materials. Due to the specific geological conditions in Bulgaria, the combined mining method is not a popular one in this country because of the smaller volume of expensive minerals, as well as to the less valuable content in the ore compared to the mines from the above world review.

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