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Research Article

Extended Ultimate-Pit-Limit Methodology for Optimizing Surface-to-Underground Mining Transition in Metal Mines

Si-Tong Ren,[1] Yang Liu ,[2,3] Xin-Yi Yang,[4] Ding-Gui Tong,[5] and Gao-Feng Ren [2,3]

[1]*School of Resources and Civil Engineering, Northeastern University, Shenyang, Liaoning 110819, China*
[2]*School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan, Hubei 430070, China*
[3]*Key Laboratory of Mineral Resources Processing and Environment of Hubei Province, Wuhan University of Technology, Wuhan, Hubei 430070, China*
[4]*Department of Finance, Wuhan Vocational College of Software and Engineering, Wuhan, Hubei 430205, China*
[5]*China Resources Cement (Jinsha) Limited, Bijie, Guizhou 551800, China*

Correspondence should be addressed to Yang Liu; liuyoung711@whut.edu.cn

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The transition from surface mining to underground is a critical issue for metal mines. The commonly cited procedure cored by ultimate-pit-limit (UPL) methodology is restricted to maximize the profit from both surface and underground mining, due to the absence of the integration of the profit from either of them. Under the target for such maximization, this study proposes a new optimization approach, which directly relates the design of open-pit limit and underground stopes, by equalizing the marginal profit from either surface or underground mining. The variation of the crown pillar size is involved in this approach. The proposed approach is applied to the Dagushan iron mine, and results show the total profit increased from 3.79 billion CNYs (original design by conventional UPL methodology) to 4.17 billion CNYs (optimal design by the proposed approach), by 9.91%. Moreover, the marginal profit from surface and underground mining, as well as total profit, of all possible designs of surface-to-underground mining transition in Dagushan iron mine is calculated to validate the proposed approach. When the marginal profits satisfy the criterion of the proposed approach, the maximum value of the total profit appears, and this demonstrates the proposed approach is robust to maximize the total profit in surface-to-underground mining transition. This work contributes to existing literature studies primarily from practical aspect, by providing a unified approach to optimize the transition from surface to underground mining.

1. Introduction

Mining industry contributes billions of dollars to global economics annually. Surface and underground methods are two conventional methods to extract metal mineral from deposits. Surface mining is typically preferred for shallow embedded deposits [1]. Underground mining is also commonly utilized for the deposit occurs as strands under buildings, or the surface method is cost-prohibitive. When the deposit distributes in large range of depth, surface and underground methods are jointly employed to develop the benefits of mining projects [2]. This poses a critical issue to determine the transition from surface to underground mining [3], i.e., open-pit limit and underground stopes, on which the total benefit from both surface and underground mining heavily depends.

The mainstream procedure to conduct such determination can be described as follows [4]. Deposit extraction usually starts with the surface mining, which will continue until the open-pit limit reaches the ultimate pit limit (UPL). Then, the crown pillar is distributed under the UPL to maintain the safety of the surface slope and underground stopes. Subsequently, underground mining takes place under the protection of the crown pillar. The logic of this procedure is clear, and the optimization is simple. Such procedure has been implemented in numerous metal projects, such as the Chah-Gaz iron mine in Iran [5], the Kovdor Zheleznyi iron mine in Russia [6], and the Yanqianshan [7] and Shibao iron mine [8] in China.

In the mainstream procedure to determine surface-to-underground transition described above, UPL methodology plays a predominant role. The UPL methodology is the most commonly cited approach for open-pit limit design [9]. It is valid to provide an economic open-pit limit, beyond which the benefits from the extracted ore will not support the costs due to ore extraction and rock stripping. Gao [10] introduced the transition of surface-to-underground mining in the Miaogou iron mine based on the UPL methodology. Tan et al. [11] involved the benefit from excavating hanging-wall deposit in surface-to-underground transition in the Shilu iron mine. Fan et al. [12] applied the UPL methodology to optimize open-pit limit and underground mining boundary in the Dagushan iron mine. Adibe and Ataee-pour [13] involved the sustainable development principles in the UPL methodology to determine the position of surface-to-underground mining transition.

Although the mainstream procedure, cored by UPL methodology, has been commonly utilized to determine the transition from open pit to underground mining, some drawbacks still restrict its application. The first drawback is that the optimization of open-pit limit and underground stope distribution is conducted individually, which means it is intractable to maximize the total benefit of metal projects from both surface and underground mining. The second shortcoming is that the variation of the size of the crown pillar in different depths is rarely considered in the mainstream procedure. But, numerous validated approaches, such as analytical solutions, numerical simulations, or scale tests [14–17], have been proposed to determine the size of the crown pillar, and these approaches imply such size heavily depends on the rock property and span of underground void. For instance, Hemant et al. [18] proposed a multivariate regression model to generate a chart, which enables the design for crown pillar thickness under different geological condition. Xu et al. [19] introduced an approach to design the size of the crown pillar by integrating analytical and empirical methods, numerical modeling, and on-site monitoring. The approaches proposed in existing literature studies enable the implementation of a crown pillar with variable thickness between open pit and underground mining. Such variation of the crown raises not only the recovery ratio of mineral deposit but also the total benefit of mining enterprises from both surface and underground mining, if the open-pit limit distributed at the position requires smaller size of the crown pillar.

Therefore, under the target to maximize the profit from both surface and underground mining, this study proposes a novel approach to optimize the surface-to-underground mining transition, which is extended from the conventional UPL methodology by equalizing the marginal profit from either surface mining or underground mining. The variation of the crown pillar in different depth is also involved in this model to develop total profit.

The rest of this study is organized as follows. In Section 2, the new approach extended from the conventional UPL methodology is introduced to optimize the surface-to-underground mining transition. In Section 3, the proposed approach is applied to the Dagushan iron mine to obtain the optimal design of open-pit limit and underground mining boundary. Additionally, the validity of the proposed model is tested by comparing the profit of all possible designs in this section. Finally, some conclusions from the proposed approach and case study are summarized in Section 4.

2. Extended UPL Methodology for Surface-to-Underground Mining Transition

2.1. Brief Introduction of Conventional UPL Methodology. The UPL methodology is originally developed to optimize the open-pit limit [20–22]. Figure 1 shows a cross-section of an inclined deposit, normal to its strike. When the depth of the open-pit limit increases by a marginal value (i.e., ΔH illustrated in Figure 1), the additional quantity of mined-out ore and stripped waste rocks can be analytically calculated, which are represented by ΔO and ΔR, respectively. If the attributes of deposit and mining production, e.g., mineralization degree, mining cost, stripping cost, and slope angle, are provided, the marginal benefit from extracting the deposit with thickness ΔH can be predicted by the following equation:

$$\Delta P = q\Delta O - C_m\Delta O - C_s\Delta R, \quad (1)$$

where ΔP is the marginal profit from mining the deposit with thickness ΔH, q is the price of mined-out minerals, ΔO is the quantity of minerals extracted from the deposit with thickness ΔH, C_m is the cost for excavating unit quantity of minerals, C_s is the cost for stripping unit quantity of waste rocks, and ΔR is the quantity of waste rocks that required to be stripped for excavating the deposit with thickness ΔH.

The total profit from surface mining can be obtained by accumulating the results of ΔP in varying depth, which can be expressed by the following equation:

$$P_{op} = \int_0^x \Delta P, \quad (2)$$

where P_{op} is the total profit from surface mining and x is the depth of the open-pit limit measured from local surface (Figure 1). Equation (2) shows P_{op} keeps increasing if the open-pit limit expands (i.e., x increases), until the ΔP in equation (1) equals to 0, and such relationship can be described by the following equation:

$$\frac{\Delta R}{\Delta O} = \frac{q - C_m}{C_s} = 0. \quad (3)$$

Equation (3) is the core criterion of conventional UPL methodology. It is a robust approach to determine open-pit limit, which maximizes the profit from surface mining.

2.2. Extended UPL Approach for Surface-to-Underground Mining Transition. The UPL methodology is the core in the current mainstream procedure for optimizing the transition from surface to underground mining. However, such a procedure cannot maximize the profit of mining projects, when both surface and underground mining are involved.

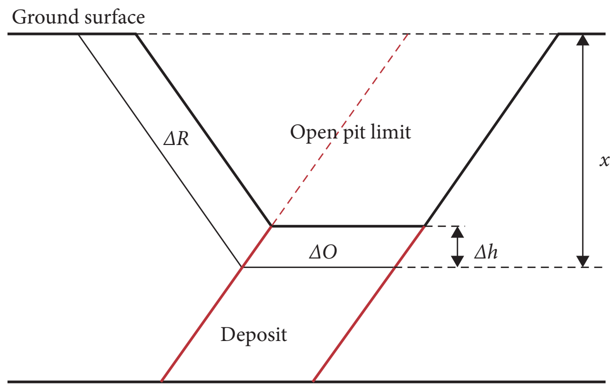

Figure 1: Schematic presentation for open-pit limit design by conventional UPL methodology.

Such drawback can be described as follows based on variables defined in Figure 2.

Figure 2 shows a cross-section of an inclined deposit, and either open-pit limit or underground stope distribution is defined, respectively. Under the assumption that the size of the crown pillar maintains constant, Figure 2 implies the expanding of open-pit limit (i.e., x increases) and shrinking of underground stope distribution (i.e., y decreases) take place simultaneously, or vice versa. If underground mining has been decided to be utilized, excavating the deposit with marginal thickness ΔH by the underground method is profitable. Therefore, if such deposit with marginal thickness ΔH at the open-pit limit determined by conventional UPL methodology is excavated by the underground method rather than the open-pit method, the total profit from both surface and underground mining can be expected to increase.

Therefore, under the target to maximize the total profit from both surface and underground mining, we propose a new approach by extending the conventional UPL methodology. If both surface and underground methods are involved in a project, the object of the optimization for surface-to-underground transition can be expressed by the following equations:

$$\max\left(\int_0^x \Delta P^{op} + \int_0^y \Delta P^{un}\right), \quad (4)$$

$$s.t. \quad x + y + h_p = h_{\text{total}}, \quad (5)$$

$$h_p \geq h_0, \quad (6)$$

where ΔP^{op} and ΔP^{un} are the profit from excavating the deposit with marginal thickness ΔH by surface and underground methods, respectively; y is the thickness of deposit excavated by the underground method, measured from the bottom of the optimizing area to the roof of underground stopes; h_p is the thickness of the crown pillar; h_0 is the required thickness of the crown pillar to maintain open pit and underground stope safe, which can be determined by analytical solution, numerical simulation, or scaled test; h_{total} is the depth of the optimizing area where the surface-to-underground transition takes place, as illustrated in Figure 2.

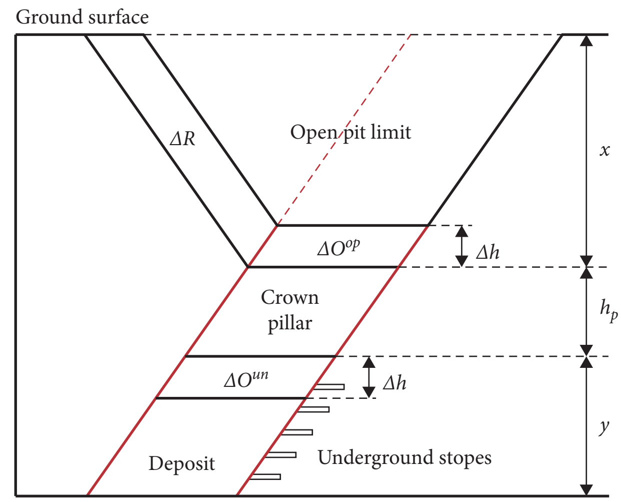

Figure 2: Schematic presentation for the optimization of surface-to-underground mining transition.

Equation (4) shows the profit of a mining project from both surface and underground mining is the function of the thickness of deposit excavated by surface (x) or underground method (y), respectively. If a design for the transition from surface to underground mining (i.e., x' and y') is provided, such profit can by expressed by the following equation:

$$P_{\text{total}} = f(x') + g(y'), \quad (7)$$

where x' and y' are the thickness of deposit that either surface or underground method accounts for. When the design is optimized, the redistribution of x and y occurs. Under the assumption that the size of the crown pillar (h_p) maintains constant, the variation of the total profit of the mining project after optimization can be predicted by equation (8), due to constraint (5):

$$\Delta P_{\text{total}}\big|_{x=x'+\Delta h'} = \frac{\partial f\left(x' + \Delta h'\right)}{\partial x} - \frac{\partial g\left(y' - \Delta h'\right)}{\partial y}, \quad (8)$$

where ΔP_{total} is the variation in the total profit of the mining project due to the redistribution of open-pit limit (x) and underground stope distribution (y); $\Delta h'$ is the marginal thickness of deposit, which indicates the redistribution of x and y due to the optimization of surface-to-underground transition. Under the assumption of $(\partial f(0)/\partial x) > (\partial g(y)/\partial y) > 0$, the following discussions for equation (8) can be expressed.

If $\Delta P_{\text{total}}\big|\big|_{x=x'+\Delta h} > 0$, redistributing the deposit from underground to surface mining (i.e., x increases and y decreases) is profitable, i.e., P_{total} increases. Due to the assumption of $(\partial g(y))/(\partial y) > 0$, such increase of P_{total} can be expected to keep occurring until equation (9) is satisfied:

$$\frac{\partial f(x_1')}{\partial x} - \frac{\partial g(y_1')}{\partial y} = 0, \quad (9)$$

where x_1' and y_1' are the solutions that satisfy $(\partial f(x)/\partial x) - (\partial g(y)/\partial y) = 0$.On the other hand, if $\Delta P_{\text{total}}\big|_{x=x'+\Delta h} < 0$, redistributing the deposit from surface to underground mining (i.e., x decreases and y increases) is profitable. Due to the assumption of $(\partial f(0)/\partial x) > (\partial g(y)/\partial y) > 0$, the increase of P_{total} can be expected to keep occurring until equation (10) is satisfied:

$$\frac{\partial f(x_2')}{\partial x} - \frac{\partial g(y_2')}{\partial y} = 0, \tag{10}$$

where x_2' and y_2' are the solutions that satisfy $(\partial f(x)/\partial x) - (\partial g(y)/\partial y) = 0$. Because $(\partial^2 f(x))/(\partial x^2) < 0$ (i.e., the profit from excavating the deposit with a marginal thickness by surface decreases, when the open-pit limit expands) and $(\partial g(y))/(\partial y)$ is a constant (i.e., the profit from excavating the deposit with a marginal thickness by the underground method is a constant), there is only one solution that satisfies $(\partial f(x)/\partial x) - (\partial g(y)/\partial y) = 0$, i.e., $x_1' = x_2'$ and $y_1' = y_2'$. Thus, the optimal design that maximizes the total profit of a mining project from both surface and underground mining should satisfy the following equation:

$$\frac{\partial f(x_1')}{\partial x} - \frac{\partial g\left(h_{\text{total}} - h_p - x_1'\right)}{\partial y} = 0. \tag{11}$$

The total profit can be predicted by the following equation:

$$P_{\text{total}} = f(x_1') + g\left(h_{\text{total}} - h_p - x_1'\right). \tag{12}$$

Equation (11) is the criterion of the proposed approach to maximize the total profit in the transition from surface to underground mining. Compared with the mainstream procedure cored by conventional UPL methodology, the contribution of this approach is to relate the marginal profit from surface mining to that from underground mining directly, which means it can be expected to maximize the total profit from both surface and underground mining.

Additionally, the assumptions, as well as associated limitations of the proposed model, should be discussed. First, some illustrations for the assumption $(\partial f(0)/\partial x) > (\partial g(y)/\partial y) > 0$ should be noted. Since no waste rocks are required to be stripped (Figure 1), $(\partial f(x))/(\partial x)$ has a maximum value when $x = 0$. If the assumption $(\partial f(0)/\partial x) > (\partial g(y)/\partial y)$ is not satisfied, extracting deposit by the underground method will be more profitable than ore extraction by the surface method in all depth. This means undergrounding mining should be individually employed. On the other hand, if $(\partial g(y))/(\partial y) > 0$ is not satisfied, underground mining should not be involved in the mining project. Thus, if both surface and underground methods have been decided to be employed, the relationship $(\partial f(0)/\partial x) > (\partial g(y)/\partial y) > 0$ should be satisfied. Second, the size of the crown pillar is assumed to be a constant, but numerous literature studies show such size varies with the rock property and the size of underground void [14–19]. To develop the profit of mining projects, as well as to enhance the safety of open-pit slope and underground stope, the variation of the size of the crown pillar is considered in the proposed approach.

Numerous literature studies have demonstrated that the size of the crown pillar heavily depends on the rock property and the shape of deposit. This implies the size of the crown pillar can be expected to keep constant in a range of depth, in which the rock property and deposit shape do not present significant variation. Thus, the proposed model is valid to optimize the surface-to-underground mining transition in such range. If all the alternative optimal designs in each range have been calculated, the optimal design that maximizes the total profit of a mining profit can be obtained by selecting the design with maximum total profit (P_{total}) from these alternative ones.

3. Optimization of Surface-to-Underground Mining Transition in Dagushan Iron Mine

3.1. Case Background. The Dagushan iron mine is located in Anshan, China, whose reserves are more than 340 million tons [23]. Surface mining has been implemented for more than 100 years. Figure 3 shows the current open pit and the 3D model of open pit and iron deposit.

Figure 3(b) shows the current open-pit limit in the Dagushan iron mine located at −320 m and residual deposit distributes from the current open-pit limit to −703 m. In the original design, surface mining will be implemented until the open-pit limit reach −485 m, which is determined by the mainstream procedure cored by conventional UPL methodology. Underground mining starts from −535 m, under the protection of a 50 m thickness crown pillar.

3.2. Optimization for Surface-to-Underground Mining Transition in Dagushan Iron Mine. In order to develop the profit of the Dagushan iron mine from both surface and underground mining, we employed the proposed approach to optimize the transition from surface to underground mining, as described by equations (11) and (12).

The crown pillar in the optimal design should distribute between −320 m (transiting to underground mining immediately) and −535 m (transiting to underground mining until the surface mining reaches the open-pit limit determined by conventional UPL methodology), as illustrated in Figure 4. Such range, i.e., between −320 m and −535 m, is defined as the optimization area. The variation of the size of the crown pillar is firstly calculated, when its position changes in this optimization area. It should be noted that the size of the crown pillar in original design (50 m) has been validated by both numerical simulations and scaled tests. We just slightly modified the size in accordance with the original design to enhance the safety of open pit and underground stopes. Because the length of the deposit along the strike (more than 500 m) is much larger than the width normal to the strike (less than 120 m), the beam model is valid for such modification [24–26]. The parameters of rock property involved are listed in Table 1.

The results calculated by the beam model show the size of the crown pillar varies between 50 m and 55 m. The proposed approach is valid to obtain the alternative optimal designs for surface-to-underground transition in each range, where the required size of the crown pillar maintains constant. The inputs required by the proposed approach to optimize the

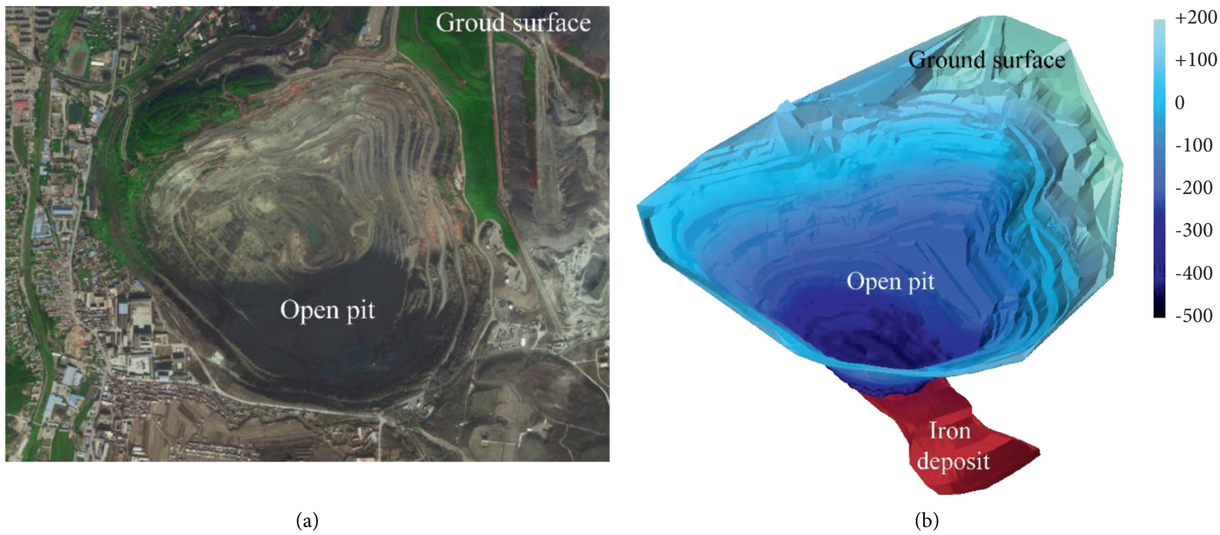

Figure 3: (a) Current open pit in the Dagushan iron mine, observed by satellite images; (b) 3D model of the current open pit and the iron deposit in the Dagushan iron mine.

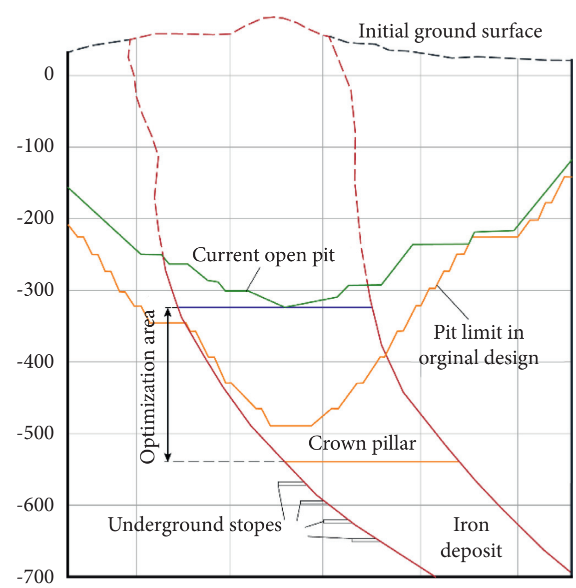

Figure 4: Cross-section of deposit in the Dagushan iron mine for optimizing surface-to-underground mining transition.

Table 1: Rock property for modifying the size of the crown pillar by the beam model.

ρ ($t{\cdot}m^{-3}$)	σ_c (kPa)	k	l (m^{-1})
4.1	77.84	3	1

Note. The beam model can be analytically described by $H = 0.25b\rho b + \sqrt{(\rho b)^2 + 8bg\sigma_T/l\sigma_T}$, where H is the size of the crown pillar required to maintain the open pit and underground stopes stable, ρ is the density of overburdened rocks, b is the goaf span, l is a unit calculated width of the beam, σ_T is the limiting tensile stress of the rock mass, and $\sigma_T = \sigma_c/k$, in which σ_c is the uniaxial compressive strength of rocks and k is the safety coefficient; b can be obtained from the cross-section of the iron deposit, i.e., Figure 4.

transition, as well as the results of these alternative optimal designs in different ranges, are listed in Tables 2 and 3, respectively.

Among all the alternative optimal designs listed in Table 3, the design whose open-pit limit locates at −328 m with a 52 m thick crown pillar presents highest profit from both surface and underground mining (4.17 billion CNYs). The distribution of this optimal open-pit limit, as well as the boundary of underground mining, is illustrated in Figure 5.

Table 3 shows the total benefit from both surface and underground mining increases from 3.79 billion CNYs in the original design by conventional UPL methodology to

Table 2: Inputs for optimizing the surface-to-underground mining transition in the Dagushan iron mine.

q (CNY·t^{-1})	C_m (CNY·t^{-1})	C_s (CNY·t^{-1})	C_u (CNY·t^{-1})	ρ^{ore} (t·m^{-3})	ρ^{rock} (t/m^{-3})
100	20	13	72	4.1	3.9

Note. The variables of q, C_m, and C_s have been explained in the definition for equation (1). C_u is the cost for excavating unit quantity of ore by the underground method; ρ^{ore} and ρ^{rock} are the weight of ores and surrounding rocks, respectively.

Table 3: Alternative optimal design for surface-to-underground transition in the Dagushan iron mine.

Size of crown pillar (m)	Depth of open-pit limit (m)	Depth of underground stope roof (m)	Total benefit (million CNY)
55	−330	−385	2733.43
54	−351	−405	3300.66
53	−367	−420	3643.94
52	−383	−435	3888.00
51	−409	−460	4114.02
52	−428	−480	4170.73
51	−459	−510	4058.11
50	−480	−530	3859.73
50	−485 (original design)	−535	3794.52

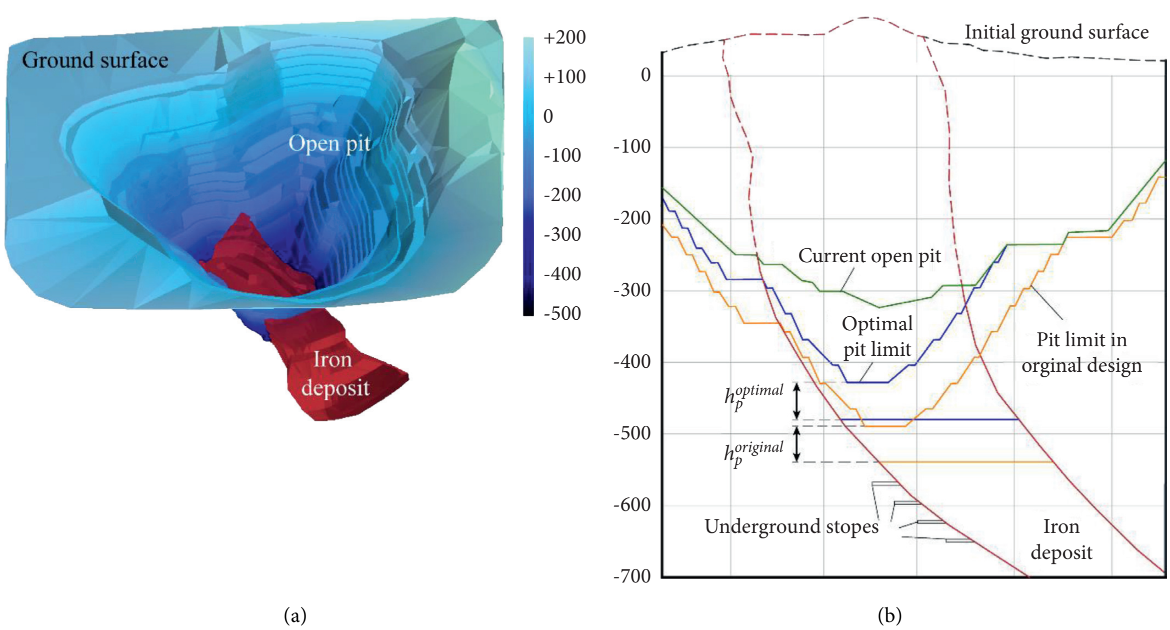

Figure 5: (a) 3D model of optimal design for surface-to-underground mining transition in the Dagushan iron mine; (b) distribution of current open pit, optimal and original design for surface-to-underground mining transition by the proposed approach and conventional UPL methodology, in a cross-section of the iron deposit. *Note.* (1) h_p^{optimal} and h_p^{orginal} are the size of the crown pillar in the optimal and original designs, respectively. (2) The iron deposit illustrated in Figure 5(a) provides the current shape, which is the same as the deposit in Figure 4.

4.17 billion CNYs in the optimal design by the proposed approach. Figure 5 provides more details for the difference of the design by either conventional UPL methodology or the proposed approach. In the original design, surface mining will be implemented from current limit (Figure 3 or "current open pit" in Figures 4 and 5(b)) to the UPL (at −485 m), whose marginal profit from either surface $((\partial f(x)/\partial x)|_{x=165})$ or underground $((\partial f(y)/\partial y)|_{y=0})$ mining is 708.83 and 7692.36 kCNY, respectively. In the optimal design ("optimal pit limit" in Figure 5(b)), such values are 7917.77 and 7861.29 kCNY, respectively. Although the optimal design requires a larger crown pillar (52 m in the optimal design, and 50 m the original design), the total profit of the Dagushan iron mine presents a notable increase by 9.91% after optimization, due to equilibrium of marginal profit from either surface or underground mining.

3.3. Validation for the Proposed Approach. To validate the proposed approach, the marginal profit from either surface or underground mining, as well as the total profit, of all possible designs for surface-to-underground mining transition in Dagushan iron mine is calculated. The results are illustrated in Figure 6.

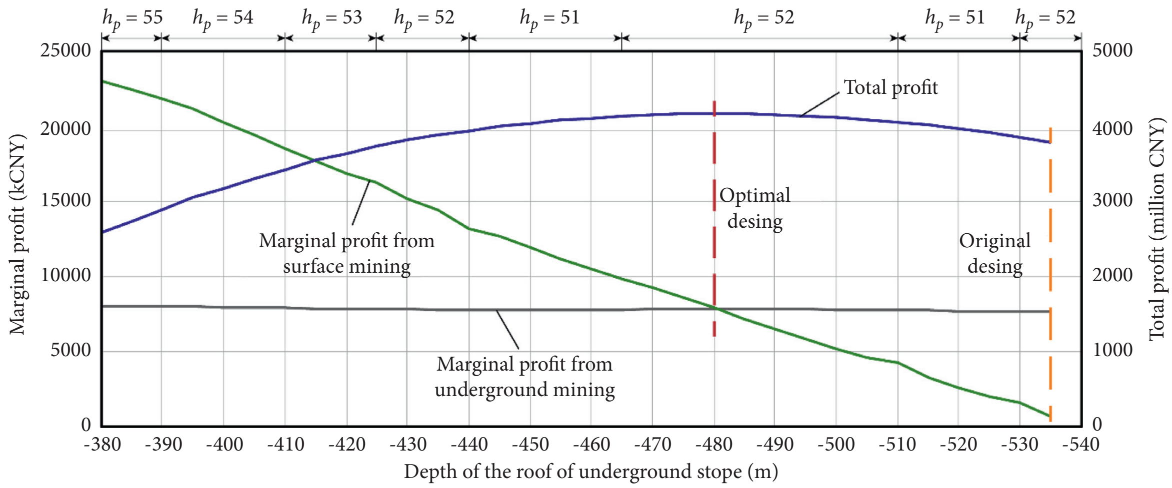

Figure 6: Marginal and total profit of all possible designs for surface-to-underground transition in the Dagushan iron mine.

Figure 6 provides the marginal profit from either surface or underground mining and the total profit of all possible designs in the Dagushan iron mine. Figure 6 shows the marginal profit from surface mining presents a monotone decrease due to the expansion of open-pit limit (i.e., decrease of the depth of the roof of underground stope in Figure 6); meanwhile, no significant variation of the marginal profit from underground mining is observed. The maximum value of total profit (i.e., optimal design in Figure 6) from both surface and underground mining appears when the marginal profit from surface mining decreases to the value that equals to that from underground mining. It can be observed that the optimal design appears in the range that crown pillar thickness equals to 52 m (i.e., $h_p = 52$ m). This demonstrates that maximizing total profit, rather than developing recovery ratio, is critical to design surface-to-underground transition, although more minerals can be extracted when recovery ratio increases. On the other hand, in each range where the size of the crown pillar maintains constant, the alternative optimal designs (listed in Table 3) appear near to the optimal design shown in Figure 6 because the difference of the marginal profit between surface and underground mining is lower than the value of other designs in each range. This validates the proposed approach to optimize the transition from surface to underground mining.

Some implications from the proposed approach and the studied case should be addressed. The contribution of this work should be clarified firstly. In the mainstream procedure cored by conventional UPL methodology, it is intractable to maximize the total benefit from both surface and underground mining because the design for open-pit limit and underground stopes is separated. The primary contribution of this study is to provide a unified approach for metal mines to obtain the maximum total profit in surface-to-underground mining transition because it directly relates the design for open-pit limit and underground stopes by equalizing the marginal profit from either surface or underground mining. Moreover, the validity of this approach has been tested by comparing the total profit of all possible designs in the Dagushan iron mine. Second, the assumptions, as well as the associated limitations, should be noted, which guides the improvement for the proposed approach in the future. Although the proposed approach is valid to maximize the total profit from both surface and underground mining, the profit from excavating the ore on the hanging wall is not considered in the proposed approach. But some literature studies revealed such profit presents significant impact on the total profit [11, 27]; this means the absence of the consideration for the profit from excavating hanging-wall ore potentially reduces the accuracy of the proposed approach. On the other hand, the proposed approach is a static analysis for surface-to-underground mining transition because the production schedule, as well as some related parameter, e.g., discount rate, annual production of excavated ore, and stripped rock, is not involved. Such discussions for the limitation of proposed approach indicate the accuracy and applicability can be improved if the profit from excavating hanging-wall ore and the production schedule for ore excavating and rock stripping are involved.

4. Conclusion

Determination for the transition from surface to underground mining is a critical issue for numerous metal mines. Different from the conventional UPL methodology, which is the core in the mainstream procedure commonly employed, this study proposes a new approach by testing the equilibrium of the marginal profit from either surface or underground mining. This approach is valid to maximize the total profit from both surface and underground mining because it directly relates the design of open-pit limit and underground stopes. Additionally, the variation of the size of the crown pillar is involved in the proposed approach to enhance the safety, as well as to develop the profit.

The proposed approach is applied to optimize surface-to-underground mining transition in the Dagushan iron mine. The results show the optimal design of the transition creates 4.17 billion CNYs from both surface and underground mining, which is 9.91% higher than the original design based on conventional UPL methodology. In order to test the validity of the proposed approach, the marginal and total profits of all possible designs are calculated, and the results reveal the maximum value of the total profit of the Dagushan iron mine occurs when the criterion of the proposed approach is satisfied, which demonstrated the proposed method is robust for the issue of surface-to-underground mining transition in metal mines.

This work contributes to existing literature studies primarily from practical aspect. The analytical approach proposed can be implemented to metal deposit involving both surface and underground mining to develop the total profit. Additionally, the future improvements for the proposed approach should emphasize on taking the profit from excavating hanging-wall ore and the production schedule for mining projects into consideration. Such improvements can be expected to facilitate the accuracy and applicability of the proposed approach.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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