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Open pit limit optimization considering economic profit, ecological costs and social benefits

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Abstract: Pit limit design has, up to date, focused mainly on maximization of economic profit alone, with environmental and social issues largely ignored. This paper focuses on incorporating both environmental and social issues in the pit limit design process and provides an approach to pit limit optimization that is in compliance with sustainable development. The case study demonstrates that ecological costs have a substantial down-sizing effect and social benefits have a substantial up-sizing effect on the optimal pit limit. When the ecological costs are factored in, the optimal pit limit is 37.5% smaller than the economically optimal pit limit. However, when the social benefits are factored in, the optimal pit limit is 48.3% larger than the economically optimal one. The overall optimal pit limit, with the economic profit, ecological costs and social benefits simultaneously considered, is a result of balancing conflicting goals of maximizing economic profit, minimizing ecological cost, and maximizing social benefit.

Key words: open pit mine; pit limit; economic profit; ecological cost; social benefit; sustainable development

1 Introduction

Mineral exploitation has made significant contributions to human progress, social development and economic growth but, at the same time, has created serious problems such as resource shortage, environmental disruption and social conflict [1−3]. Such problems are more pronounced with open pit operations than underground ones. The first step of designing an open pit mine is to determine the optimal pit limit and maximizing economic profit has been the main focus, with environmental and social factors ignored in the design process. However, in the context of sustainable development, environmental and social factors are as important as the economic ones in designing open pit mines [4−6]. Therefore, a new pit design method, that is able to strike a balance among economic, environmental and social issues, is much needed.

In response to the growing public awareness of the importance of environmental protection and increasing pressure on addressing environmental problems caused by mining, some researchers have focused on addressing environmental issues in mine design [7,8]. However, shortcomings are observed in the previous studies. One is that certain important environmental issues caused by mining have not been taken into account. For example, dusting schemes [9−11], waste control [12−14], and reclamation plans [15−17], have been considered in mine design, but the loss of ecological functions (e.g., oxygen release, air purification, water conservation, soil conservation, and soil nutrient cycling) caused by mining, pollutant emissions from energy consumption and blasting are usually ignored [18,19]. Currently, the general practice for considering environmental issues is still by large a “pollution first and treatment later” approach (also

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referred to as “end-of-pipe” approach), that is, the environmental impacts of a finished mine design are assessed and corresponding measures are devised to alleviate the impacts as much as possible [20,21]. Measures often include tailings utilization, dust control, liquid membrane emulsion, acid leaching extraction, and impermeable tailing storage [22,23]. The end-of-pipe approach overlooks the fact that different design alternatives have different magnitudes of environmental impacts and, thus, the impacts should be considered in the design process in the first place.

Social issues have the characteristics of complexity, boundary fuzziness, and indicator uncertainty and, thus, are rarely considered in designing an open pit mine [8,24,25]. Some studies on the social issues associated with mining have mainly focused on extracting and assessing social indicators, such as salary, welfare, education, medical care, employment, work environment, regional economic development, and safety [26,27]. In general, a larger scale operation with more people employed by the miner brings greater investment to the local community; a longer mine life provides a more reliable employment guarantee but may delay the recovery of capital and reduce Net Present Value (NPV); a larger and deeper pit limit recovers more resource but the safety risk associated with the mine site (instability of the pit slope, waste dump, and tailings pond) is greater; the more the money a mining enterprise invests in local infrastructures and education, the more harmonious the community around the mine is, but the enterprise’s profit may be eroded; the land use after mine closure and reclamation affects the social development and social benefit of the local community [28]. It is very difficult, if not impossible, to quantify most of these social indicators both in their own magnitudes and in their conversion into benefits/costs. Therefore, existing studies in this field mostly adopt qualitative approaches in problem analyses, social sustainability assessment, and policy making [29−31].

In theory, a larger pit limit causes more extensive and serious environmental destruction which, in turn, inflicts higher ecological costs. Thus, a pit limit designed by considering the economic profit alone is greater than that when both economic profit and ecological costs are considered. On the other hand, a larger pit limit may bring more social benefits [25]. Thus, pit limit designed by considering the economic profit alone is smaller than that when both economic profit and social benefits are considered. Moreover, even with the same pit limit, different mining plans may lead to different production rates and mining sequences along the time horizon, resulting in different time dependent profiles of environmental and social impacts. Therefore, economic, environmental and social factors all play important roles in the pit limit design and production planning processes [32].

This work focuses on incorporating both environmental and social issues in the pit limit design process and provides an approach to pit limit optimization that is in compliance with sustainable development. In our previous work, a number of ecological cost items associated with open pit mining were quantified and incorporated in optimizing pit limit and production schedule, and the effects of these costs on the outcome were found to be significant [33,34]. However, social issues were not considered. This work is the result of our continuing research and aims at achieving three main goals: (1) defining and quantifying indicators, in terms of costs and benefits, to represent the environmental and social issues associated with open pit mining; (2) proposing a pit limit optimization approach that incorporates the environmental and social indicators so that the pit limit design is placed in the context of sustainable development; and (3) investigating the magnitude of influence of environmental and social issues on the pit design outcome, by applying the proposed approach to a large iron ore deposit in China.

2 Pit limit optimization

For a given deposit with its particular orebody geometry, ground topography, and maximum allowable wall slopes, there are theoretically an infinite number of pit limits with different sizes, shapes and locations. Even for a specified total quantity of ore and waste, V, there are many pit limits that have the same V but differ in size, shape, and/or location. Suppose that the total quantity to be mined is decided to be V, even without economic evaluation, among all pit limits of the same V, the one having the maximum metal content is most likely to be the best, and this pit limit is referred to as the “geologically optimal pit limit” for the specified V [35]. Thus, the optimal pit limit can be sought among the geologically optimal pit limits for different values of V. Therefore, a series of geologically optimal pit limits corresponding to a series of V values are first generated as the candidate pit limits. Let $\{V\}_J=\{V_1, V_2, \cdots, V_J\}$ denote the series of J geologically optimal pit limits sorted in an order of increasing V, with V_1 being the smallest and V_J the largest possible pit limit. The more detailed algorithm is given as follows.

Step 1: The open pit is divided into different sectors, according to lithology and hydrogeological conditions. Meanwhile, the maximum slope angle of the corresponding area is determined. A cone template is constructed with its vertex pointing upwards and its shell slopes equal to the maximum allowable slope angles in corresponding orientations.

Step 2: Optimize the largest pit limit, V_J, using a moving cone exclusion method. V_J is the current pit limit and is outlined in Fig. 1 by the dashed lines.

Step 3: Set the block column index, i, to 1, i.e., the first column in the current pit limit.

Step 4: Place the cone vertex at the center of the bottom block of column i.

Step 5: Find those blocks falling in the cone and calculate the quantities of ore and waste as well as the average grade of the cone. If the quantity of ore in the cone is less than or equal to ΔQ, the cone is placed in a cone array and go to the next step; otherwise the cone is abandoned and proceeds to Step 7. Generally, the value of pit increment ΔV is determined according to the production scale of the mine. For example, adopting 1/10 of the production capacity can meet the accuracy requirements of optimization.

Step 6: Move the cone up a block height along column i. If the cone vertex is above the ground surface, go to the next step; otherwise, go back to Step 5.

Step 7: If block column i is not the last one in the current pit limit, advance i by 1 (moving to the next column) and go back to Step 4; otherwise, continue to the next step.

Step 8: Up to this point, all the block columns in the current pit limit have been scanned by the moving cone and an array of n cones is obtained. Sort the cone array in an order of increasing average grade. The first m cones ($m\leq n$) that, when combined, contain an ore quantity closest to ΔQ are identified and removed from the current pit limit, and a new and smaller pit limit is obtained.

Step 9: Calculate the ore quantity of the new pit limit obtained in the last step. If the ore quantity is greater than Q_1 specified for the smallest pit limit (V_1), the new pit limit is taken as the current pit limit and go back to Step 3 to generate the next smaller pit limit; otherwise, the entire series of geologically optimal pit limits, $\{V\}_J$, has been generated and the algorithm terminates.

The series of geologically optimal pit limits can be evaluated with respect to their economic profits, ecological costs, and social benefits.

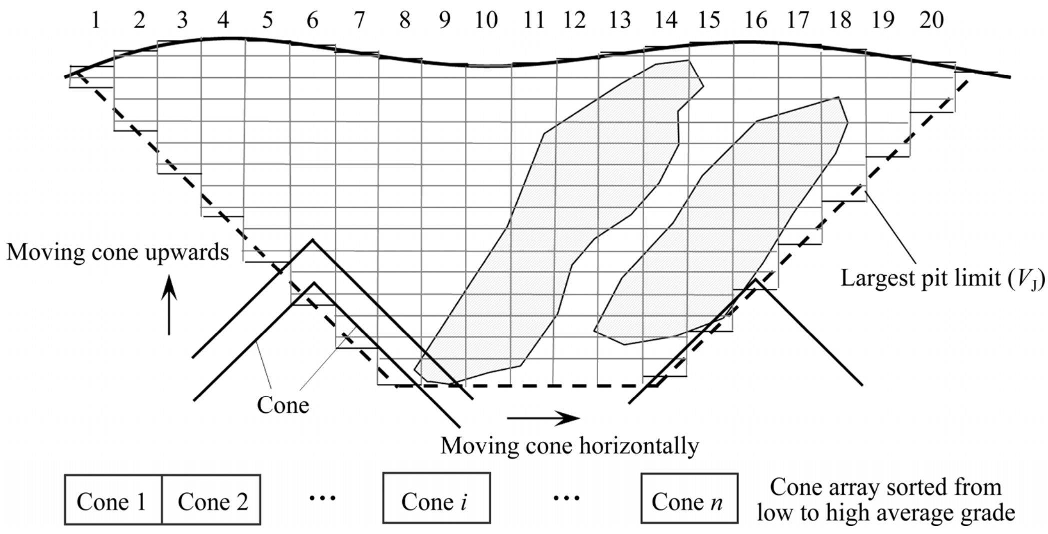

Fig. 1 Illustration of moving cone exclusion method for generating series of geologically optimal pit limits

3 Economic profit model

The parameters involved in evaluating the profitability of a pit limit mainly include: unit costs of ore mining (c_o, US$/t), waste stripping ($c_w$, US$/t) and ore processing (c_p, US$/t), price of concentrate (p, US$/t), ore recovery rate of mining (r_o, %), metal recovery rate of processing (r_p, %), mixing rate of waste in ore (r_w, %), the average grade of waste mixed in ore (g_w, %), and concentrate grade (g_p, %). Let O_i and W_i denote the in-situ ore and waste quantities, respectively, contained in the ith pit limit, V_i, of the series of geologically optimal pit limits, and let g_i denote the average grade of O_i before any dilution. The run-of-mine ore quantity mined from pit limit V_i and sent to the processing plant, $Q_{i,o}$ (in Mt), is calculated by

$$Q_{i,o}=\frac{O_i\cdot r_o}{1-r_w} \tag{1}$$

The average grade of $Q_{i,o}$, denoted by $g_{i,o}$ (in %), is

$$g_{i,o}=(1-r_w)g_i+g_w\cdot r_w \tag{2}$$

The quantity mined as waste from pit limit V_i and sent to the waste dump, denoted by $Q_{i,w}$ (in Mt), is calculated by

$$Q_{i,w}=W_i+O_i(1-r_o)-Q_{i,o}\cdot r_w \tag{3}$$

The quantity of concentrate that can be produced from mining pit limit V_i, denoted by $Q_{i,p}$ (in Mt), is given by

$$Q_{i,p}=\frac{Q_{i,o}\cdot g_{i,o}\cdot r_p}{g_p} \tag{4}$$

Finally, the profit of mining pit limit V_i, denoted by P_i (in MUS$), is

$$P_i=Q_{i,p}\cdot p-Q_{i,o}(c_o+c_p)-Q_{i,w}\cdot c_w \tag{5}$$

4 Ecological cost model

4.1 Area of land destruction

The excavated land area of the pit limit and the land areas occupied by the waste dump and tailings pond, together with the destruction of the associated ecosystems, constitute a significant part of the total environmental impact caused by open pit mining.

The land area of pit limit V_i, denoted by $A_{i,m}$ (in m^2), can be obtained by measuring the pit's surface perimeter. The land areas of waste dump and tailings pond, denoted by $A_{i,w}$ and $A_{i,t}$ (in m^2), respectively, can be estimated as follows:

$$A_{i,w}=\frac{Q_{i,w}\cdot\gamma_w}{\rho_w\cdot H_w}S_w\times10^4 \tag{6}$$

$$A_{i,t}=\frac{Q_{i,o}\cdot g_{i,o}(1-r_p)}{g_t\cdot\rho_t\cdot H_t}S_t\times10^4 \tag{7}$$

where γ_w is the swell factor of waste in the dump; ρ_w is the unit mass of waste in situ, t/m^3; ρ_t is the unit mass of tailings in the pond, t/m^3; g_t is the average grade of tailings; H_w and H_t are the heights of the waste dump and the depth of the tailings pond, respectively, measured in m; S_w and S_t are the shape factors of the waste dump and tailings pond, respectively.

The total area of land destruction caused by mining pit limit V_i, denoted by A_i (in m^2), is

$$A_i=A_{i,m}+A_{i,w}+A_{i,t} \tag{8}$$

4.2 Ecological costs

In order to incorporate the environmental issues associated with mining in the evaluation of pit limits, various environmental impacts of mining are converted into ecological costs. Four major types of ecological cost are considered in this study: the lost value of direct ecological services, restoration cost, carbon emission cost of energy consumption, and lost value of indirect ecological services.

(1) The lost value of direct ecological services is composed of lost value of woods, crops, and/or livestock, depending on the type of land (the ecosystem) destroyed by mining. When there is a market for the land, the market price of the land before mining is a good reflection of the long term value of ecological products provided by the land. Therefore, the lost value of direct ecological services, $C_{i,z}$ (in MUS$), corresponding to pit limit V_i, can be estimated by

$$C_{i,z}=A_i\cdot c_z\times10^{-6} \tag{9}$$

where c_z is the price of land acquisition, US$/$m^2$.

(2) The restoration cost is the expenditure required for restoring ecological functions of the destroyed land zones. The restoration cost, $C_{i,r}$ (in MUS$), corresponding to pit limit V_i, is calculated by

$$C_{i,r}=A_i\cdot c_r\times10^{-6} \tag{10}$$

where c_r is the reclamation cost per unit area, US\$/m^2.

(3) The carbon emission cost of energy consumption, $C_{i,e}$ (in MUS\$), corresponding to pit limit V_i, is estimated by the cost of capturing and storing carbon dioxide produced from consuming energy in mining and processing operations:

$$C_{i,\mathrm{e}}=\frac{(Q_{i,\mathrm{o}}+Q_{i,\mathrm{w}})e_\mathrm{m}+Q_{i,\mathrm{o}}\cdot e_\mathrm{p}}{1000}f_\mathrm{c}\cdot f_\mathrm{a}\cdot C_\mathrm{c} \tag{11}$$

where e_m is the amount of energy consumed in mining unit mass of ore or removing unit mass of waste, kg/t; e_p is the amount of energy consumed in processing unit mass of ore, kg/t; e_m and e_p are both in equivalent mass of standard coal; f_c is the carbon factor of standard coal; f_a is the conversion coefficient from carbon to carbon dioxide; C_c is the cost of carbon dioxide capture and storage (CCS), US\$/t.

(4) Indirect ecological services of an ecosystem refer to those services other than producing income−bringing biomass products. Seven major indirect ecological services are considered in this study: air purification (CO_2, SO_2, and NO_X absorption, dust suppression and phytoncide secreting), oxygen release, water conservation, soil conservation, nutrients cycling, climate regulation, and biodiversity protection. When the land and its associated ecosystem are destroyed by mining activities, these services are lost, inflicting costs equal to their values. The values of the first five services listed above have been estimated in a previous study [34] and are not repeated here. The total value of these services per unit area is denoted as f_{EE}.

The function of climate regulation of an ecosystem, especially forests, refers to its ability of adding humidity to the surrounding atmosphere through evapotranspiration, increasing local rainfall, blocking solar radiation, and thus reducing temperature change. Research shows that the rainfall in a forested area is 17%−26% higher than that in forest-free areas of the same region, and the temperature in a forested area can decrease by 4−5 °C in summer and increase by up to 3−4 °C in winter. The value of climate regulation, $F_{i,t}$ (in MUS\$), for pit limit V_i, is estimated as

$$F_{i,\mathrm{t}}=h_\mathrm{tem}\cdot d_\mathrm{tem}\cdot t_\mathrm{tem}\cdot m_\mathrm{tem}\cdot c_\mathrm{tem}\cdot A_i\times10^{-6} \tag{12}$$

where h_{tem} is the average height of trees, m; d_{tem} is the temperature difference between the forested area and the forest-free area, °C; t_{tem} is the number of days air-conditioning is required per year, d/a; m_{tem} is the efficiency of air-conditioners representing the power consumption of changing the temperature of a unit volume of space by 1 °C per day, kW·h/(m^3·°C·d); c_{tem} is the price of electricity, US\$/(kW·h).

Biodiversity refers to the sum of the ecological complex formed by organisms and their environment and the related ecological processes. It is the basis for the survival and sustainable development of human society. Forest is the best place for the survival and development of biodiversity and plays an irreplaceable role in biodiversity protection. The value of biodiversity conservation, $F_{i,b}$, for pit limit V_i, is estimated as

$$F_{i,\mathrm{b}}=s_\mathrm{bio}\cdot A_i\times10^{-6} \tag{13}$$

where s_{bio} is the biological resource protection value of the ecosystem per unit area, which can be calculated by the biodiversity indices (Shannon Wiener) of the ecosystem, US\$/(m^2·a).

Considering all the ecological functions mentioned above, the total lost value of indirect ecological services of destroyed land, $f'_{i,EE}$ (in MUS\$), for pit limit V_i, is

$$f'_{i,\mathrm{EE}}=(\frac{Q_{i,\mathrm{o}}}{q_\mathrm{a}}+n_\mathrm{e})[f_\mathrm{EE}\cdot A_i+(F_{i,\mathrm{t}}+F_{i,\mathrm{b}})] \tag{14}$$

where q_a is the annual ore production, Mt/a; n_e is the time for the ecological system to recover after mining, a; f_{EE} is the total value of air purification, oxygen release, water conservation, soil conservation and the soil nutrient cycle [34] (MUS\$/(m^2·a)).

5 Social benefit model

Mining inevitably promotes local economic development. Mines are usually located in remote areas and the taxes that they pay may account for over 80% of the local revenue [36]. Mining also attracts a large number of migrant workers, which not only boosts the local consumption but also increases the employment of residents [37]. Also, mining enterprises invest in education, scientific research and medical care [38]. However, mining also causes safety problems [39]. The social benefits considered in this study include the spiritual civilization benefit, regional economic promotion benefit, medical care benefit and safety investment benefit.

5.1 Spiritual civilization benefit

Spiritual civilization includes skill-based training of employees, reeducation of residents, teaching environmental improvement, and so on [40]. The effectiveness of spiritual civilization enhancement is related to investment funds from the mine enterprise and local government. The funds invested by government are mainly from the taxes paid by the mines. For pit limit V_i, the spiritual civilization benefit, $P_{i,\mathrm{spi}}$ (in MUS$), is estimated as

$$P_{i,\mathrm{spi}}=(P_i\cdot r_{\mathrm{edu1}}+R_{i,\mathrm{rev}}\cdot r_{\mathrm{edu2}})(f_{\mathrm{edu}}-1) \tag{15}$$

where r_{edu1} is the proportion of the mine's profit spent on education, %; $R_{i,\mathrm{rev}}$ is the taxes paid by the mine, MUS$; r_{edu2} is the proportion of taxes from the mine spent on education, %; f_{edu} is the ratio of output to input in education, %.

In China, the taxes paid by the mine include resource tax, added-value tax, urban construction and education surcharge, income tax and resource compensation tax. So, $R_{i,\mathrm{rev}}$ (in MUS$) is

$$R_{i,\mathrm{rev}}=Q_{i,\mathrm{o}}\cdot y_{\mathrm{z}}+\frac{Q_{i,\mathrm{p}}\cdot p}{1+d_{\mathrm{z}}}d_{\mathrm{z}}+\frac{Q_{i,\mathrm{p}}\cdot p}{1+d_{\mathrm{z}}}d_{\mathrm{z}}\cdot d_{\mathrm{c}}+P_i\cdot d_{\mathrm{s}} \tag{16}$$

where y_{z} is the resource tax rate, %; d_{z} is the rate of value added tax, %; d_{c} is the surcharge rate of urban construction and education, %; d_{s} is the income tax rate, %.

5.2 Regional economy promoting benefit

Mining drives the growth of the service sector (e.g., restaurants, hotels, and retail stores), which in turn increases employment [41] and personal incomes [42,43]. Science and technology are the primary productive forces and important drivers of economic development. Therefore, local governments invest taxes paid by mining enterprises in scientific research to promote economic growth. The regional economy promoting benefit, $P_{i,\mathrm{reg}}$ (in MUS$), corresponding to pit limit V_i, is estimated as

$$P_{i,\mathrm{reg}}=Q_{i,\mathrm{o}}\cdot y_{\mathrm{c}}+W_{\mathrm{ork}}\frac{Q_{i,\mathrm{o}}+Q_{i,\mathrm{w}}}{q_x}+R_{i,\mathrm{rev}}\cdot r_{\mathrm{sci}}(f_{\mathrm{sci}}-1) \tag{17}$$

where y_{c} is the service sector output value per ton of ore mined, US$/t; W_{ork} is the difference in per capita income of local miners in comparison with their former jobs, US$/person; q_{x} is the average productivity of the mining employees, t/person; r_{sci} is the proportion of taxes collected from the mine spent on science and technology, %; f_{sci} is the ratio of output to input in science and technology, %.

5.3 Medical care benefit

Medical care plays an important part in creating harmony for mining operations, and is also a fundamental right of residents [44]. The expenditures on medical care include donations from the mine and government spending which mainly comes from taxes paid by the mine. Medical care benefit, $P_{i,\mathrm{med}}$ (in MUS$), provided by mining pit limit V_i, is estimated as

$$P_{i,\mathrm{med}}=(P_i\cdot r_{\mathrm{med1}}+R_{i,\mathrm{eve}}\cdot r_{\mathrm{med2}})(f_{\mathrm{med}}-1) \tag{18}$$

where r_{med1} and r_{med2} are the proportions of the mine's profit and taxes from the mine, respectively, spent on medical care, %; f_{med} is the ratio of output to input in medical care, %.

5.4 Safety investment benefit

Safety issues have the characteristics of abruptness and unpredictability, and the associated losses are difficult to estimate. Mining is categorized as a high-risk industry, especially with deep open pit mining. The slope stability is the largest safety threat in open pit mining, and large funds are invested in preventing slope failure [45]. Mines invest in safety to achieve safe operation and avoid hidden dangers. The benefit of safety investments is reflected in reducing production risk, which is difficult to quantify. The regulation on enterprise safety production funds in China stipulate that, for metal mines, the safety cost be calculated based the quantities of mined raw ore and discharged tailings. The safety investments are cost outlays (negative "benefit") and the safety investment benefit for pit limit V_i, $C_{i,\mathrm{saf}}$ (in MUS$), is

$$C_{i,\mathrm{saf}}=-(Q_{i,\mathrm{o}}\cdot c_{\mathrm{ore}}+\frac{Q_{i,\mathrm{o}}\cdot g_{i,\mathrm{o}}(1-r_{\mathrm{p}})}{g_{\mathrm{t}}}c_{\mathrm{tai}})(1-v_{i,\mathrm{saf}}) \tag{19}$$

where c_{ore} is the safety cost of mining operations attributed to unit mass of ore, US$/t; c_{tai} is the safety cost of tailings discharge attributed to unit mass of tailings, US\$/t; $v_{i,\mathrm{saf}}$ is the accident rate of the mine, 10^{-3}.

The accident rate of the mine can be estimated based on data from similar mines:

$$v_{i,\mathrm{saf}}=f_{\mathrm{acc}}\frac{Q_{i,\mathrm{o}}+Q_{i,\mathrm{w}}}{\dfrac{Q_{i,\mathrm{o}}}{q_{\mathrm{a}}}q_{\mathrm{x}}\times 1000} \tag{20}$$

where f_{acc} is the accident rate per thousand people per year, 10^{-3}.

6 Case study

The mine used for case study is located in northeastern China and is one of the largest open pit metal mines in the country. The ore body is 4650 m from east to west, 800 m in depth with a dip of 75°−90°. The ore reserve is 1690 Mt with an average geologic grade of 31.35%. The mine has been in production for many years and the current annual ore production is 17 Mt. The first phase mining has been completed and is now in transition to the second phase. The bottom level of the current mine is at −217 m, and the surface topography of the mine is shown in Fig. 2.

One longitudinal section and three cross sections of the ore body, along section lines shown in Fig. 2, are illustrated in Fig. 3 and Fig. 4, respectively. Blue, pink and red indicate ore grades of 20%−25%, 25%−30% and above 30%, respectively.

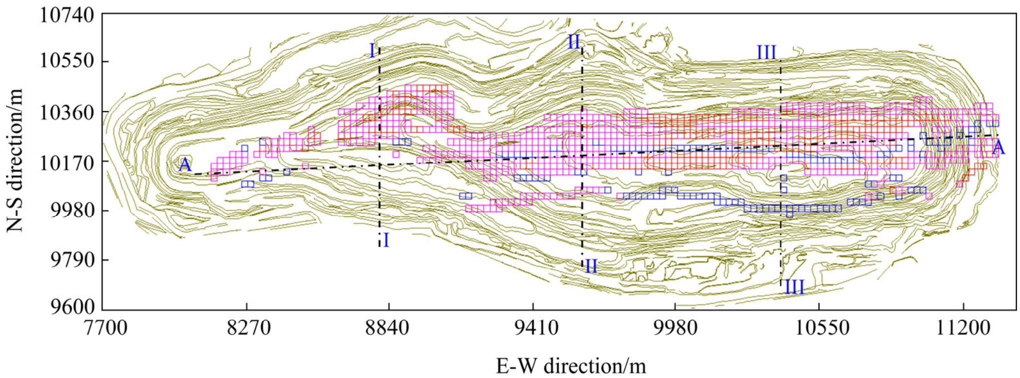

Fig. 2 Surface topography of mine and ore body at −217 m

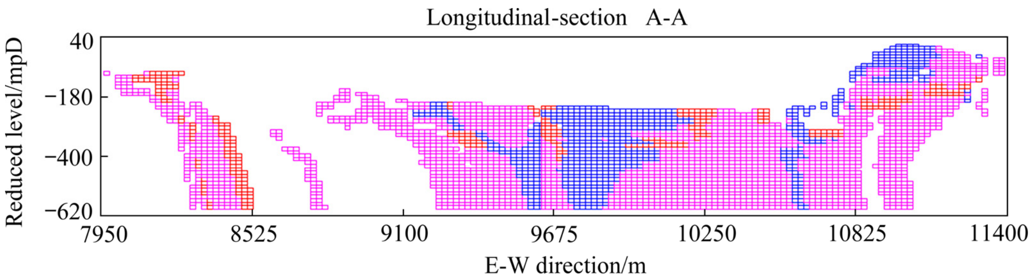

Fig. 3 Ore body longitudinal section

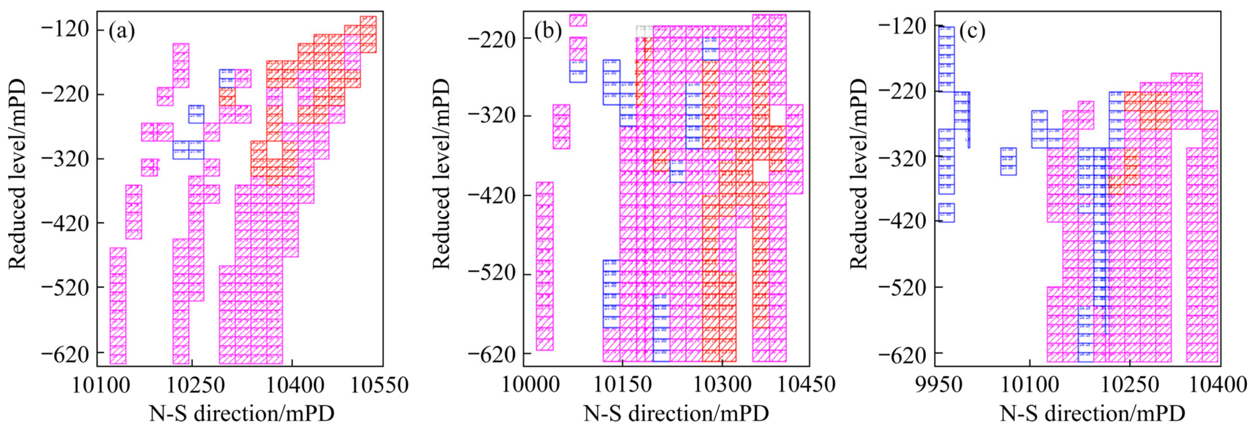

Fig. 4 Ore body cross sections: (a) Cross-section I-I; (b) Cross-section II-II; (c) Cross-section III-III

6.1 Geologically optimal pit limits

The instantaneous strip ratio used in obtaining the largest pit limit, V_J, is set to be 8, which is much higher than the breakeven strip ratio (3.5366 for the specified technical and economic parameter values), so the optimal pit limit will be contained in V_J. Since the current ore production capacity of the mine is 17 Mt/a, the ore quantity increment, ΔQ, between two consecutive pit limits is set to be 17 Mt. According to the ore reserve, the remaining mine life is at least 20 years. Therefore, the ore amount of the minimum pit limit, Q_1, is set to be 340 Mt. The maximum allowable pit slope angles are 41.8°, 40.5°, 43.1°, 41.3°, 39.5°, 41.7° and 43.2° at orientations of 50°, 104°, 136°, 192°, 260°, 290° and 350° measured counterclockwise from the east, respectively. By applying the algorithm described above, a series of 20 geologically optimal pit limits are generated, as given in Table 1.

In Table 1, the ores and waste quantities are in situ values before mining recovery and dilution are considered. The ore increment, ΔQ, between any two consecutive pit limits is very close to the specified value of 17 Mt. The next step is to determine which of these pit limits is the optimal one when different factors (economic, ecological and social) are considered.

6.2 Economic profits of pit limits

According to the current market condition and actual production data, the technical and economic parameters used to calculate the economic profits of the pit limits are given in Table 2.

Based on the data in Table 1 and Table 2, Eqs. (1)−(5) are used to calculate the costs of ore mining, waste stripping and ore processing, and the revenues, and economic profits of all the pit limits. The results are shown in Fig. 5.

Table 1 Geologically optimal pit limits

Pit limit, V_i	Ore quantity/Mt	Waste quantity/Mt	Ore grade/%	Increment in ore quantity/Mt	Increment in waste quantity/Mt	Surface area/10^4m^2	Pit bottom/m
1	328.66	420.098	27.853	328.66	420.098	293.00	−390
2	345.703	457.478	27.848	17.043	37.380	297.75	−405
3	362.707	497.896	27.869	17.005	40.419	304.09	−405
4	379.804	538.324	27.876	17.096	40.428	311.25	−405
5	396.807	580.395	27.880	17.004	42.071	319.03	−420
6	413.849	623.951	27.892	17.042	43.557	326.47	−420
7	430.907	671.561	27.938	17.058	47.610	334.53	−435
8	447.906	722.795	27.989	16.999	51.234	343.53	−435
9	464.912	770.329	27.980	17.006	47.534	349.31	−450
10	481.993	821.473	28.006	17.080	51.144	357.41	−450
11	499.004	878.729	28.051	17.011	57.256	363.59	−465
12	516.098	935.667	28.062	17.094	56.938	370.34	−480
13	533.133	995.757	28.087	17.035	60.090	379.78	−480
14	550.211	1055.197	28.112	17.078	59.441	389.84	−495
15	567.300	1119.542	28.135	17.089	64.345	396.53	−510
16	584.329	1186.468	28.159	17.029	66.926	404.66	−510
17	601.378	1255.767	28.184	17.049	69.300	411.97	−525
18	618.395	1327.781	28.197	17.017	72.014	419.59	−540
19	635.402	1407.858	28.225	17.008	80.077	429.34	−540
20	652.424	1513.252	28.268	17.021	105.394	444.47	−540

Table 2 Technical and economic parameters

Parameter	value
c_o/(US\$·t^{-1})	3.977
c_w/(US\$·t^{-1})	3.093
c_p/(US\$·t^{-1})	18.118
p/(US\$·t^{-1})	96.04
r_w/%	3
r_o/%	99
r_p/%	80
g_p/%	66

The economic profit initially increases and then decreases as the pit limit expands, and the 11th pit limit (V_{11}) is the best and has an economic profit of 2192.4 MUS\$. The amounts of ore and waste increase as the pit limit becomes larger, and the growth rate of waste is faster than that of ore (see Table 1). Therefore, the strip ratio increases and the incremental profit decreases. As the strip ratio increases to a certain value, the added economic profit of the increased ore just covers the added cost of increased waste, and the profit remains about the same. When the pit size increases further (the strip ratio also increases), the added economic profit of the increased ore cannot cover the added cost of the increased waste, and the profit decreases quickly. Therefore, when economic profit alone is considered, the optimal pit limit is V_{11}.

6.3 Ecological costs of pit limits

The destroyed land areas of all the pit limits were obtained by measuring their perimeters on the ground surface and are listed in Table 1. The land areas of the waste dump and tailings pond are estimated using Eqs. (6) and (7). The ecological costs of the pit limits are estimated using Eqs. (9)−(14). The relevant parameters for calculating the ecological costs are listed in Table 3.

The time for ecological functions to recover after mine closure, n_e, is assumed to be 5 years, which means that the lost value of indirect ecological services will continue for another 5 years after the mine ceases operation. The estimated ecological costs of the pit limits are shown in Fig. 6.

The carbon emission cost of energy consumption is the largest, the lost value of direct ecological services is the second largest, and the restoration cost is the lowest. Taking V_1 as an example, the lost value of direct ecological services, the restoration cost, the lost value of indirect ecological services, and the carbon emission cost of energy consumption account for 27.37%, 4.56%, 15.31%, and 52.76% of the total ecological cost, respectively.

6.4 Social benefits of pit limits

The relevant parameters for estimating social benefits are listed in Table 4, which were determined from sources such as The China Educational Finance Statistical Yearbook, China Statistical Yearbook, China Industry Yearbook, Key Unit Statistical Yearbook of Metallurgical Mine and Extraction, and Management Method of Enterprise Safety Production Funds. The social benefits for the pit limits are estimated using Eqs. (15)−(20) and shown in Fig. 7.

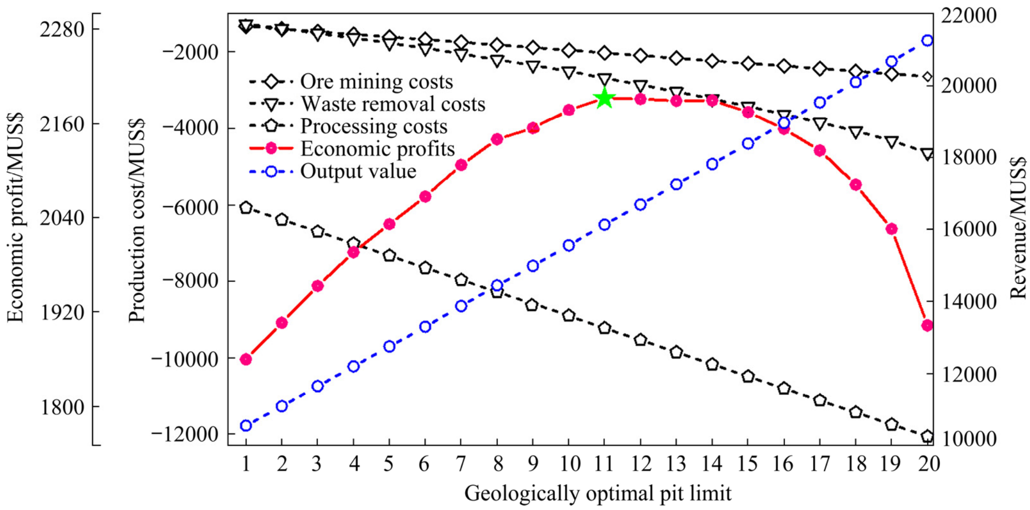

Fig. 5 Economic profits of geologically optimal pit limits

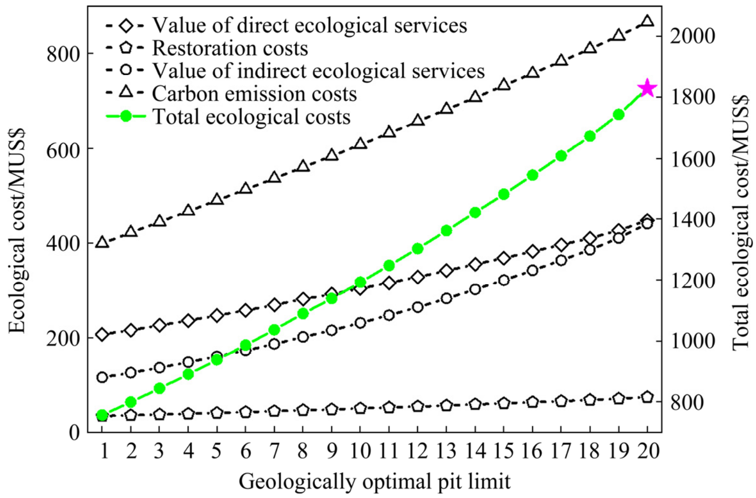

Fig. 6 Ecological costs of geologically optimal pit limits

Table 3 Parameters for ecological cost estimation

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
γ_w	1.25	S_w	1.5	$\rho_w/(t\cdot m^{-3})$	2.7	H_w/m	200
S_t	1.5	$\rho_t/(t\cdot m^{-3})$	1.75	$g_t/\%$	0.104	H_t/m	100
$c_z/(US\$\cdot m^{-2})$	35.352	$c_r/(US\$\cdot m^{-2})$	5.892	$e_m/(kg\cdot t^{-1})$	0.85	$e_d/(kg\cdot t^{-1})$	7.50
f_c	0.67	f_a	3.6667	$C_c/(US\$\cdot t^{-1})$	51.555	h_{tem}/m	5
$d_{tem}/°C$	0.5	$t_{tem}/(d\cdot a^{-1})$	60	$m_{tem}/(kW\cdot h\cdot m^{-3}\cdot °C^{-1}\cdot d^{-1})$	0.0232	$c_{tem}/(US\$\cdot kW^{-1}\cdot h^{-1})$	0.0663
$s_{bio}/(US\$\cdot m^{-2}\cdot a^{-1})$	7.365×10^{-2}	$q_f/(t\cdot m^{-2}\cdot a^{-1})$	6.56×10^{-4}	λ_c	1.62	$y_S/(t\cdot m^{-2}\cdot a^{-1})$	1.521×10^{-5}
$c_s/(US\$\cdot t^{-1})$	338.79	$y_n/(t\cdot m^{-2}\cdot a^{-1})$	3.8×10^{-5}	$c_n/(US\$\cdot t^{-1})$	589.2	$y_d/(t\cdot m^{-2}\cdot a^{-1})$	2.1655×10^{-3}
$c_d/(US\$\cdot t^{-1})$	40.5075	$y_g/(t\cdot m^{-2}\cdot a^{-1})$	1.095×10^{-3}	$c_g/(US\$\cdot t^{-1})$	103.11	λ_o	1.2
$c_o/(US\$\cdot t^{-1})$	147.3	$j/(mm\cdot a^{-1})$	800	k	0.4	r_h	0.26
$c_h/(US\$\cdot t^{-1})$	0.9869	$s_p/(t\cdot a^{-1}\cdot m^{-2})$	6.02915×10^{-3}	$\rho/(t\cdot m^{-3})$	1.3	h/m	0.5
$v/(US\$\cdot m^{-2})$	0.53028	k_N	4.3×10^{-3}	k_P	3.9×10^{-4}	k_K	2.16×10^{-3}
$p_N/(US\$\cdot t^{-1})$	309.33	$p_P/(US\$\cdot t^{-1})$	132.57	$p_K/(US\$\cdot t^{-1})$	324.06	f_P	2.2903

Table 4 Social economic parameters

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$r_{edu1}/\%$	0.016	$y_z/(US\$\cdot t^{-1})$	0.577416	$d_z/\%$	17	$d_c/\%$	3
$d_s/\%$	25	$r_{edu2}/\%$	4.136	$f_{edu}/\%$	387.76	$y_c/(US\$\cdot t^{-1})$	1.82652
$W_{ork}/US\$$	8248.8	q_x/t	29330	$r_{sci}/\%$	5.04	$f_{sci}/\%$	330.517
$r_{med1}/\%$	2.3956	$r_{med2}/\%$	1.8105	$f_{med}/\%$	158.727	$c_{ore}/(US\$\cdot t^{-1})$	0.7365
$c_{tai}/(US\$\cdot t^{-1})$	0.22095	$f_{acc}/10^{-3}$	3				

It can be seen that the spiritual civilization benefit, local economy promoting benefit, and medical care benefit are positively, while the safety investment benefit is negatively, correlated to pit limit size. Overall, a larger pit limit brings about a higher total social benefit.

6.5 Effects of ecological costs and social benefits on optimal pit limit

Curve 1 in Fig. 8 depicts the variation of economic profit alone with the pit limit. The curve reaches its maximum at pit limit V_{11}, meaning that, when maximizing the total profit to the mining

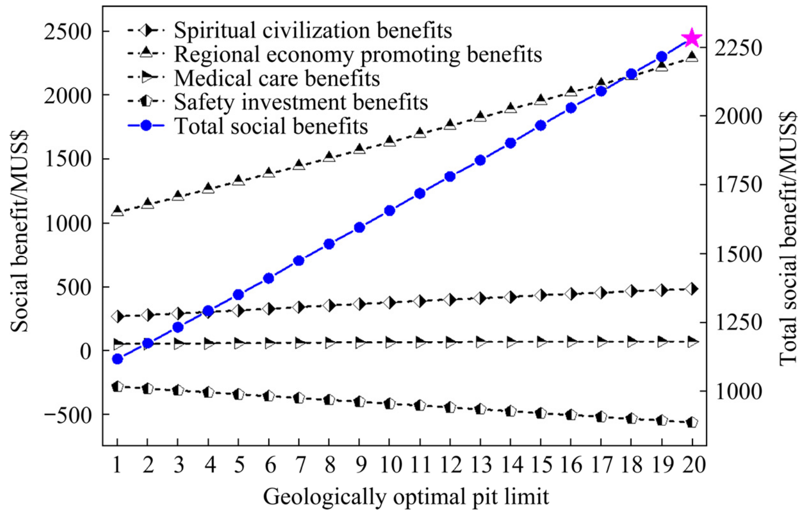

Fig. 7 Social benefits of geologically optimal pit limits

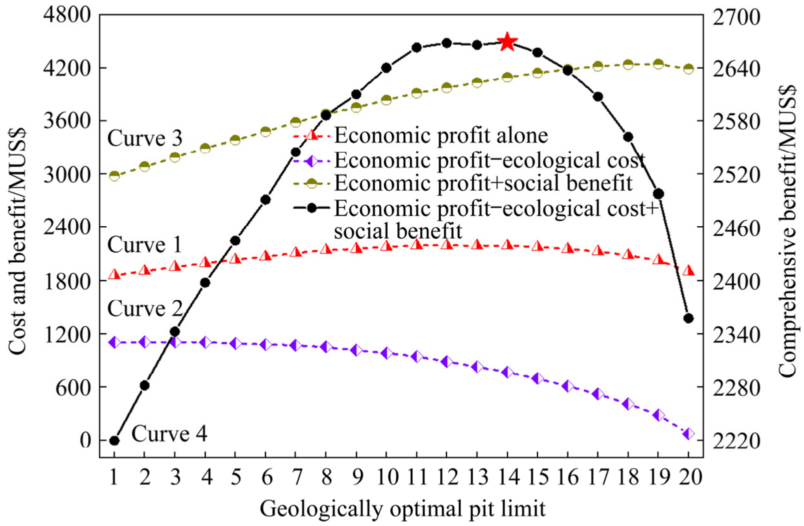

Fig. 8 Economic profits, total ecological costs and total social benefits of geologically optimal pit limits

company is taken as the sole objective, the optimal pit limit (referred to as the "economically optimal pit limit" hereafter) is V_{11}.

When the ecological costs are factored in, the value of economic profit minus total ecological cost is shown as Curve 2 in Fig. 8, which reaches its maximum at pit limit V_3. Therefore, the optimal pit limit in this case becomes V_3. When compared with the economically optimal pit limit, this pit (V_3) is 37.5% smaller in terms of total material, 19.1% smaller in pit limit area, and 60 m shallower in mining depth (Table 1). While the total economic profit to the mining company is reduced by 239.2 MUS$, caused by forgoing some economically profitable parts of the deposit, the total ecological cost is reduced by 403.6 MUS$. So, the optimal pit limit becomes more environmentally friendly after ecological costs are considered.

When the social benefits are factored in (without ecological costs), the value of economic profit plus total social benefit is shown as Curve 3 in Fig. 8, which reaches its maximum at pit limit V_{19}. Therefore, the optimal pit limit in this case becomes V_{19}. When compared with the economically optimal pit limit, this pit (V_{19}) is 48.3% larger in terms of total material, 18.1% larger in pit limit area, and 75 m deeper in mining depth (Table 1). While the total economic profit to the mining company is reduced by 166.7 MUS$, caused by mining some economically unprofitable parts of the deposit, the total social benefit is increased by 497.4 MUS$. So, the optimal pit limit becomes more socially beneficial after social benefits are considered.

When both the ecological costs and social benefits are factored in, the value of economic profit minus total ecological cost and plus total social benefit is shown as Curve 4 in Fig. 8, which reaches its maximum at pit limit V_{14}. So, the overall optimal pit limit is V_{14}. The size of this pit limit is in between the economically optimal one and the one with social benefits but without ecological costs factored in. When compared with the economically optimal pit limit, this pit has an overall benefit increase of 6.0 MUS$, with an economic profit loss of 2.9 MUS$, an ecological cost increase of 174.6 MUS$, and a social benefit increase of 183.5 MUS$. Thus, this overall optimal pit limit strikes a balance among the conflicting goals of maximizing economic profit, minimizing ecological cost, and maximizing social benefit, and should, therefore, be considered as the final design for the mine. The 3D model of the overall optimal pit limit is shown in Fig. 9.

A cross section of the optimal pit limits considering different factors is shown in Fig. 10.

There are no commonly accepted methods and procedures for quantifying ecological costs and social benefits related to mining operations, yet. The models for their estimation given in this work present one possible approach. When a different approach is used, the outcomes may differ to a large extent from the results of this work. But the directions in which ecological costs and social benefits affect the optimal pit limit should remain the same. Moreover, the ecological and social effects as estimated in this work are likely to be on the conservative side, because it is currently impossible for the models to include all aspects of ecological and social issues connected with mining operations. However, the proposed sustainable mine optimization ideas can be used as a reference to all kinds of mines.

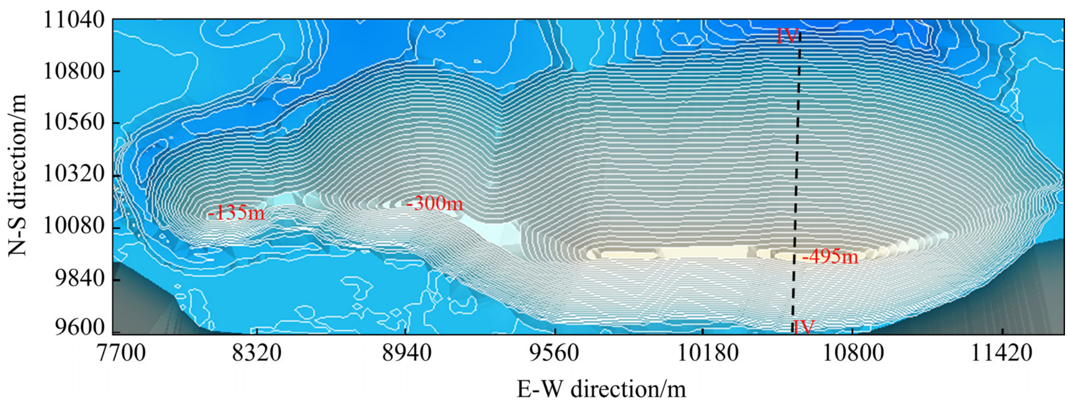

Fig. 9 Three-dimensional model of optimal pit limit considering economic profit, ecological costs, and social benefits

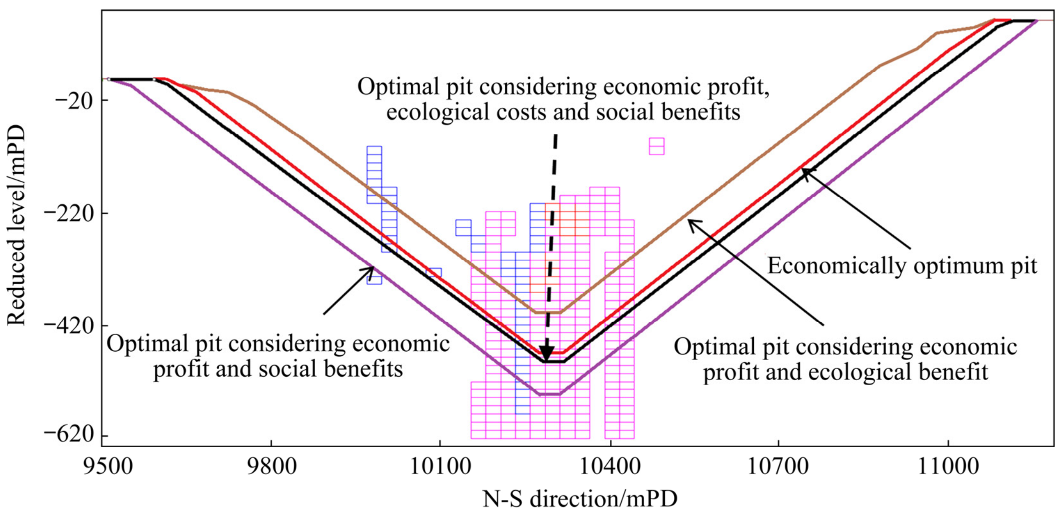

Fig. 10 Cross section of optimal pit limits considering single factor and multiple factors

7 Conclusions

(1) Ecological costs have a substantial down-sizing effect on the optimal pit. When the ecological costs are factored in, the optimal pit limit is 37.5% smaller, in terms of total material, than the economically optimal pit limit with only economic profit considered. When the total economic profit to the mining company is reduced by 239.2 MUS$, caused by forgoing some economically profitable parts of the deposit, the total ecological cost is reduced by 403.6 MUS$, so the optimal pit limit becomes more environmentally friendly after ecological costs are considered.

(2) Social benefits have a substantial up-sizing effect on the optimal pit. When the social benefits are factored in (without ecological costs), the optimal pit limit is 48.3% larger than the economically optimal one. The total economic profit to the mining company is reduced by 166.7 MUS$, caused by mining some economically unprofitable parts of the deposit, but the total social benefit is increased by 497.4 MUS$, so the optimal pit limit becomes more socially beneficial after social benefits are considered.

(3) When both ecological costs and social benefits are factored in, the size of the overall optimal pit limit is in between the economically optimal one and the one with social benefits but without ecological costs factored in. This overall optimal pit limit strikes a balance among the conflicting goals of maximizing economic profit, minimizing ecological cost, and maximizing social benefit, and should, therefore, be chosen as the final design to promote sustainable development.

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同时考虑经济利润、生态成本和社会效益的露天矿开采境界优化

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摘　要：开采境界设计主要是考虑经济利润的最大化，忽略了环境和社会问题的影响。本文重点考虑将环境和社会问题纳入最终开采境界设计过程，并提供一种符合可持续发展的最终开采境界优化方法。研究表明，生态成本对最终开采境界具有显著的缩减效应，而社会效益具有显著的扩增效应。考虑生态成本后，最终开采境界比经济最优境界小 37.5%。然而，当考虑到社会效益时，最终开采境界比经济最优境界大 48.3%。综合考虑经济利润、生态成本和社会效益得到的总体最优开采境界是通过平衡经济利润最大化、生态成本最小化和社会效益最大化相互冲突的结果。

关键词：露天矿；开采境界；经济利润；生态成本；社会效益；可持续发展

(Edited by Bing YANG)