Efficiency assessment for open selective dredge mining

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Abstract. The dredging method used for alluvial deposits was analyzed. A sufficient amount of dredge reserves in the Russian Federation was emphasized. Factors preventing dredging from development were identified. The article identified the current trend to convert dredging reserves into the reserves for open selective mining with lower productivity and higher production costs. The article provide data on a deep placer site which can be mined using different methods. Various options for complex mechanization schemes which can be used for mining this site were described. According to economic criteria, the use of the open selective mining method with excavation of the most enriched sands was justified.

1. Introduction

The dredging method was widely used in Russia in the 1950–1980s [1]. Due to continuous sand excavation and processing and waste disposal, this method has the highest labor productivity, lower energy intensity and a longer washing season which ensures the minimum mineral extraction cost [2]. At the same time, in the last decade, development of the dredging method has been hampered by the need for significant investment, negative environmental effects (primarily on water resources), hard mining conditions, use of outdated dredges and placer development technologies [3, 4]. Over the last 25 years, the volume of sand excavation and processing using dredges has decreased almost twice both in Russia and abroad.

Since the mid-1990s, due to the reduced number of dredges and lacking funds for purchasing new equipment, a significant share of dredging reserves was transferred to the reserves for open selective mining and has been already mined. However, gold-mining enterprises have a large number of placers with dredging reserves. In some cases, they do not purchase new dredges since they can use the available ones. However, due to a decrease in their performance (including due to excessive equipment depreciation rates and frequent failures), their further use is not efficient.

The present article describes a method for gold placer site mining using an OM-431 dredge which was considered economically inefficient.

The main causes of poor performance of this dredge were complication of mining conditions and a simultaneous decrease in the gold content in the placer deposit. In addition, due to the valley narrowing, increasing peat thickness and transverse slopes of the area complicated stripping operations. The available stripping equipment (ESH-10.70, EKG-5A dredgers and dump trucks) was not able to prepare the required amount of sand for dredging at the annual sand volume of 1.7–2.0 million m³, including the volume of...
stripping operations of more than 1.0 million m$^3$. The use of dredgers and dump trucks worsened economic indicators of gold mining.

2. Data
The total length of the described placer site is 2.286 m, the average width is 96 m. Mass thickness varies from 15.7 m to 47.0 m, the average mass thickness is 31.9 m. The distribution of gold in the placer is uneven both in plan and in vertical section. The average gold content varies from 0.005 to 0.490 g/m$^3$ per weight. The gold is small, the median grain size does not exceed 0.9 mm, the average grain size is 0.69 mm.

According to geological exploration data, sand reserves used for dredging amounted to more than 2.1 million m$^3$, gold reserves amounted to more than 800 kg with an average grade of 0.8 g/m$^3$. The industrial gold-bearing placer is located in a deep valley bottom, on low 2–5 m terraces. Throughout its length, the placer is whole, not affected by mining. It is associated with alluvial pebbles with 97.2% of gold and bedrock eluvium with 2.8% of gold. The placer is characterized by variable thickness, width and gold content both in plan and in section.

A characteristic feature of this placer is poor processing, especially in the upper part. Gold is dispersed in a large interval, grains are small and poorly rounded. The placer productivity varies from 150 kg/km to 550 kg/km. The industrial layer is often located at the bottom or near the top of alluvium. Visually, the layer is not pronounced and is identified only by sampling and thickness of the dredged reservoir. The thickness of the dredged layer varies from 3.4 to 14.9 m, the average thickness is 9.6 m. The sands have constant composition. There are some minor local changes in the composition which do not influence technological properties. The average gold content per dredged layer varies from 0.031 g/m$^3$ to 1.445 g/m$^3$. The gold content in the destroyed bedrock does not exceed 1.6 m (in single cases it is 2.2 m).

According to the data of geological exploration and operational works, the technological properties of gold deposits within the described and adjacent placers are as follows:
- industrial gold is in free form, 65% of industrial gold are fractions larger than 0.50 mm;
- lithologic granulometric composition and physical and mechanical properties of sands ensure good washability (class <1 mm not more than 12%);
- a simple sand enrichment scheme does not provide for the use of chemical reagents. Therefore, waste water treatment is not required;
- after gold recovery, waste of gold-bearing sand enrichment (effel, pebbles, boulders and lumps, schlich concentrate) is no interest.

Thus, alluvial sands are moderately rocky, medium-washable and easily enriched which contributes to maximum recovery of gravitated gold when dredging alluvial deposits.

The actual recovery of gold using an OM-431 dredge which is equipped with advanced jiggling equipment is 92%.

The peat layer is a thin soil-vegetative layer which lies on boulder-pebble-gravelly sediments cemented by loam with sand and silt interlayers. Peat thickness varies from 10.5 to 37.0 m, the average thickness is 22 m. Any significant gold content has not been identified.

According to exploratory drilling data, only seasonal freezing of alluvium to a depth of 0.5 to 3.0 m was identified. Seasonal frozen rocks amount to only 6.8% with a thickness of 0.5–3.0 m which does not complicate dredging operations.
3. Analysis

Mining conditions for the placer site under study are acceptable for dredging. The positive aspects of this method are as follows:
- large thickness of the productive layer;
- the absence of permafrost;
- allowable longitudinal slope of the valley;
- good water content of the deposit;
- acceptable boulderiness and clayiness of sands;
- good ratio of pebble and effel fractions.

Negative conditions for dredging:
- large thickness of the peat layer, hard conditions for placing dumps;
- narrowing valley and the need to divert surface watercourse along the slope of the valley;
- uneven bed slope complicating the regulation of the water level in the technological pit;
- low gold content.

Five mining options were selected: three options involve using an OM-431 dredge and two options involve using industrial equipment.

The first option involves dredging a sand layer with an average thickness of 11.6 m (the total sand volume is 1.34 million m³, the gold content is 349.4 kg, an average grade is 0.258 g/m³). The second option involves dredging a sand layer with an average thickness of 18.0 m (the sand volume is 2.072 million m³, the gold content is 362.6 kg, an average grade is 0.175 g/m³). The third option involves dredging a sand layer with an average thickness of 21.7 m (the sand volume is 2.5 million m³, the gold content is 362.7 kg, an average grade is 0.150 g/m³).

The fourth option involves dredging using an open separate selective mining method for enriched sands, including shallow, two-layer placers. The total volume of balance and off-balance sand reserves is 237 thousand m³, the gold content is 283.2 kg.

The fifth option involves excavation of enriched alluvial deposits with an average sand thickness of about 6.0 m (with total sand reserves of 705 thousand m³ and gold content of 350.5 kg).

Depending on the location of productive areas and depth of the overburden operations, either an ESh-10.70 excavator or a combination of an ESh-10.70 excavator, an EKG-5A excavator and dump trucks are used in all options [5].

Depending on the mining method and overburden technology, the volume of mining operations varies. Dredging is carried out in one longitudinal move with a face width of 56–138 m. Operating parameters of an OM-431 dredge ensure complete excavation of reserves without taking additional measures.

During the period of intensive development of the Russian dredge fleet, the average annual productivity of 380-liter dredges was 1600–1700 thousand m³. Over the last years, it was 850–950 thousand m³ for Bodaybo. An increase in the volume of dredging production to 1100–1200 thousand m³ is due to increasing duration of the season. At the same time, an increase in the season duration deteriorates technical and economic indicators of dredging. 380-liter dredges in the Lensky District show higher economic efficiency under the annual sand processing volume equal to 900–1100 thousand m³ [1].

The mining conditions are acceptable for dredging. However, taking into account considerable wear of dredges and hard mining and technical conditions, its annual productivity can be no more than 900 thousand m³. It is rather difficult to provide such a volume under high peat layer thickness. Therefore, the annual dredge performance depends on stripping equipment performance [6, 7, 8].

Dredging should be in advance of stripping. Therefore, preparation of the required amount of reserves for dredging requires one full season of stripping operations.

Taking into account the need to create a channel for one of the ridges of the valley, the storage of overburden rocks is possible only on one side of the dredging section. This circumstance sharply reduces
performance of the ES-10.70 dragline excavator. Peat extraction is carried out by re-excavation. The coefficient of re-excavation for different drill lines varies from 0.68 to 1.72.

In order to ensure normal operation of the dredge, a large average bed angle (0.018) requires a significant number of water retaining dams. To construct them, an additional volume of gali has to be removed. The water level rise relative to the existing mark in the dredged section varies from 38 m (option 1) to 48 m (option 3).

For option 1, stripping operations are carried out with:

a) an ES-10.70 excavator;
b) a combination of an ESH-10.70 excavator, an EKG-5A excavator and BelAZ dump trucks.

For options 2 and 3, stripping operations are carried out with an ESh-10.70 excavator.

For all the options, stripping schemes involve dragline peat laying on the right side of the valley. The left side of the valley is used for channel construction. In option 3, stripping operations are accompanied by partial overburden rock transportation to dredging dumps.

According to the results of construction of technological schemes of stripping operations, the coefficients of re-excavation were calculated depending on overburden working depth and width.

Taking into account the volume of stripping operations and annual performance of an ES 10.70 excavator, the number of reserves prepared for dredging for a transport-free scheme of overburden operations was identified. The annual dredge performance is limited to the volume of reserves prepared for excavation. Sand losses in the inter-move pillars are taken into account for options 2 and 3. They are 0.5 % and 1.0 % which is associated with an increase in the depth of digging. Due to increasing thickness of the rock mass which does not contain metal, there is no protective overburden in option 3.

The volume of operations for construction of the hydraulic station for all options is calculated taking into account the topographic plan of the area, selected routes of the river-channel, the maximum river flow rate and the longitudinal profile of gold-bearing reserves.

The volume of reclamation operations depends on the amount of overburden, mining and HS (respectively 30 %, 10% and 80 % of the volume of these operations).

Mining operations will be carried under the conditions of the existing enterprise. Economic indicators were calculated in accordance with “Methodological Recommendations for Evaluating Efficiency of Investment Projects (2nd edition)”. Current regulatory documents and teaching materials were used in the document [9, 10, 11].

When drawing up the schedule for option 1, the maximum load of the ES 10.70 was assumed to ensure a lower cost price of overburden operations. The ECG-5A is used only for areas with a thick peat layer. However, preparation of reserves is slow. An increase in the volume of overburden transportation using ECG 5A dump trucks increases costs in comparison with the cost of gold produced. The total mining term is 9 years. Dredging can be used only within the seventh mining year for no more than 2.5 years. The described option is characterized by negative economic efficiency – the NPV for the entire period is minus 267.5 million rubles.

According to the schedule, the start of dredging for option 2 is the fifth mining year. The use of the ES 10.70 excavator ensuring lower costs of stripping operations can significantly reduce the cost of gold production. However, preparation of reserves is slow. The total mining period is 8 years, while dredging is carried out for 4 years. The described option is also characterized by negative economic efficiency – the NPV for the entire period is minus 128.79 million rubles.

When drawing up the schedule for option 3, it was planned to load the ES 10.70 excavator and use the ECG-5A excavator only during the first year. Due to the combined overburden, reserves preparation is accelerated. However, overburden transportation using the ECG 5A and dump trucks worsens efficiency during the first mining year. At the same time, due to the use of a dredge, the enterprise can improve performance within the second year in comparison with the options studied above. The total mining term...
is 5 years. Dredging begins within the second mining year and takes 4 years. However, the described option has a negative economic effect – the NPV for the entire period is minus 41.3 million rubles.

For options 4 and 5, equipment for open selective mining has to be purchased. Capital expenditures on mining transport equipment were calculated on the basis of data on the market value of equipment measured in 2018 dollars.

Sand reserves for open selective mining are characterized by a large depth of formation. The average thickness of peat for option 4 is 25.3 m, for option 5 it is 19.0 m. The geological overburden for option 4 is 10.4 and for option 5 it is 4.4.

In option 4, anticipated stripping and mining of a shallow deposit using a bulldozer are planned. Subsequently, for preparation of interlayer and subsurface deposits, overburden operations are carried out with an ESh-10.70 dragline and an EKG-5A shovel. Sand is excavated by a Komatsu PC-400 excavator. Sand is transported by dump trucks to the PGS-II-50 industrial equipment originally located at the silt-sinker in a dredging section, and later on the silt-drainers in the mined area. Transport overburden is stored in a dump located in the mined area (in dredge section and open-cast mines). The average distance of peat transportation is 600 m. The total mining period is 4 years. Sand washing is carried out using three GUI-II-50 units. This option is efficient and ensures the NPV in the amount of 22.4 million rubles.

Due to a sufficiently large amount of sand, option 5 involves using two industrial units (PGSH-II-50) within four years and one industrial unit within the first and the last years. Stripping operations are carried out according to a combined scheme using ES 10.70 and EKG-5A dredgers and dump trucks. Due to a full load of EKG-5A, sand is excavated with a Komatsu PC-400 excavator. Sand transportation is carried out by dump trucks to the PGS-II-50 industrial unit originally located near the silt-pits in a dredging section, and later near the silt-pits in the mined space. An average transportation distance is 600 m. The total mining term is 6 years. Silt-pits are filled with pit water during the draining process. The described option is characterized by negative economic efficiency: the NPV is minus 29.2 million rubles.

4. Results
Calculation results for technical and economic indicators for options 1–5 are shown in Table 1.

| Parameters                        | Indicators            | Dredging | Selective mining |
|-----------------------------------|-----------------------|----------|------------------|
|                                   | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
| Average geological sand power, m  |          |          |          |          |          |
| Geological reserves, kg           | 349.45   | 362.70   | 362.70   | 283.24   | 350.52   |
| Mineable reserves, kg             | 340.82   | 353.86   | 352.10   | 275.27   | 340.34   |
| Reserves/production ratio          | 3.00     | 4.00     | 4.00     | 4.00     | 6.00     |
| Production for the entire mining period, kg | 313.28 | 325.37   | 323.76   | 253.58   | 316.67   |
| Product cost per 1 g, RUB         | 2 619.44 | 2 078.86 | 1 900.88 | 1 589.10 | 1 836.68 |
| NPV, thousand RUB                 | -267 520.30 | -128 789.65 | -41 281.37 | 22 358.38 | -29 223.67 |

The economic effect of technical solutions was calculated by comparing multi-time financial costs and income and reducing them to a single time period. Operating costs, capital investment and profit were reduced to the beginning of quarry construction with regard to the discount rate.
Average annual capital investment has a reduction period equal to the construction period. Average annual operating costs and revenues of an enterprise are assumed to be constant over the entire mining period and have a reduction period equal to the mining period.

In order to reduce costs or revenues of each year to the initial point, discount factors calculated by generally accepted formulas [9] were used. The discount factors were calculated based on the reduction periods and the discount rate.

The main economic indicators are the price of products sold, the discount rate, the net present value, the profitability index, the payback period of capital investment.

To compare multi-time financial costs and revenues, summary indicators accounting for operating costs, net present value and gold production are presented for five options (Figure 1).

Only option 4 (open selective mining) has positive economic indicators. Economic indicators for option 3 can be improved by taking into account gold extracted when processing upper layers of the dredged rock mass. Economic indicators for option 4 (open selective mining) can be improved through the use of an industrial unit.

5. Conclusion
Economic efficiency was assessed based on the following criteria: net profit, net income, net present value, profitability, cost-effectiveness index, budget revenues.

From an economic point of view, the most profitable option is option 4 (open selective mining of a placer site and selective excavation of a shallow, two-interbedded and near-lying placers ensuring the
maximum NPV in the amount of 22.36 million rubles and contributing to rapid mining of reserves (during four years) with gold production within the first mining year.

Thus, despite the advantages of the dredging method and the lower cost of mining, the use of a less productive open selective method is economically sound.

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