Review of the placer mining methods with regard to geotechnical conditions and climate in Yakutia

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Abstract. The author reviews the current situation in opencast mining placers in Yakutia and characterizes geotechnical conditions and climate in the major mining regions in the Republic. In the most placers under mining, sands and peat have thickness of 1.5–1.6 and 5.2 m, respectively. Dozer cutting is applicable to peat with maximum thickness of 15.2 m; the combinations of dozer–shovel–dump truck and dozer–loader–dump truck are bet suitable to peat thicknesses from 17.5 and 11.5 m, respectively. Permafrost rocks are widely prepared to mining through natural thawing (71–76% in the Aldan, North and East regions). The common method of stripping is dozers. The most popular method of actual extraction is the combination of dozer–loader–dump truck. The most efficient approach to stripping is the combination of dozer–shovel–dump truck as its cost is lower than in stripping with dozers or with the dozer–loader combination.

1. Introduction
Gold demand persistently grows both in the world and in Russia, while gold mining conditions increasingly complicate. This is also true for gold placers in the Republic of Sakha (Yakutia) where all process flows are subjected to such impacts as higher gas content of rocks, low gold content, complex structure, low temperature and permafrost, including sluicing in spring and in autumn. In this case, a mining technology should take into account geological conditions of every specific placer, and the mining experience gained in development of similar placers [1–3].

2. Placer mining methods
At the Institute of Mining of the North, SB RAS, after reviewing archived data (geological reports, project documentation, feasibility studies, mineral quality appraisals, etc.), the data base on placers in the Republic of Sakha (Yakutia) was compiled [4]. The scope of the analysis of geotechnical and climatic conditions embraces information on 108 placers in operation between 2009 and 2018, divided into four groups with respect to the climate (Table 1). Majority of the placers are located in the East mining region in Yakutia (55%), and mostly in the Oymyakon area. The other placers are distributed between the Aldan area (20%), Neryungri (16%) and North (9%) [5]. In the coldest East mining region, the average annual temperature ranges between -15 and -17 °C. In the Aldan and Neryungri areas, the average annual temperatures are higher by 5–10 °C.

Alongside with climate, geotechnical conditions of mining have influence too, namely, thickness and particle size composition [6]. The analytical review shows that gold sand and peat under placer mining in Yakutia have average thickness of 1.5–1.6 and 5.2 m, respectively (Table 2). The maximal
average thickness of peat under dozer cutting is 15.2 in the East region, 8 m in the North region, 9.3 m in Neryungri and 5 m in Aldan (Table 3). In case of combinations of mining techniques, the maximal peat thickness is also in the East region (to 17.5 m in shoveling); this value in the North and Aldan regions reaches 11.5 m in cutting with shovels and loaders, and is 8.5 m in Neryungri, in digging.

Table 1. Conditional grouping of main mining regions in Yakutia and climatic characteristics

| Mining region | Administrative area          | Minimal air temperature, ºС | Maximal air temperature, ºС | Average annual air temperature, ºС |
|---------------|------------------------------|-----------------------------|-------------------------------|-----------------------------------|
| East          | Oymyakon, Muoma              | -59.7 - -65                 | +30 - +35                     | -15 - -17                         |
| North         | Ust Yana, Upper Yana, Lower Kolyma | -55 - -59.7                 | +30 - +35                     | -12 - -16                         |
| Aldan         | Aldan                        | -37 - -60                   | +20 - +40                     | -6.6 - -10.9                      |
| Neryungri     | Neryungri                    | -36.6 - -61                 | +15.9 - +40                   | -6.5 - -7.8                       |

Table 2. Ranges of peat and gold sand thickness typical of placers under dozer cutting in Yakutia

| Mining region | Thickness |
|---------------|-----------|
|               | Peat      | Gold sand |
| East          | 2.2–8     | -         |
| North         | 1.7–15.2  | -         |
| Aldan         | 0.6–9.3   | 1.2–2.2   |
| Neryungri     | 2.3–5     | 0.9–1.8   |

Host rocks of placers in Yakutia feature different size compositions. In terms of the placers included in the database, size fractions were divided into two coarseness groups (Table 4): under 2 mm (sand-and-clay) and above 2 mm (pebble-and-boulder). The lowest content of sand-and-clay fractions is typical of the East placers, which is 2.7 times lower than in the Aldan placers featuring the maximal content of sand-and-clay.

Table 3. Peat and gold sand thickness in placers under mining using a combination of methods in Yakutia

| Mining region | Combinations of mining methods |
|---------------|--------------------------------|
|               | Dozer–loader | Dozer–loader–dump truck | Shovel–dozer | Shovel–dozer–dump truck |
|               | Peat | Sand | Peat | Sand | Peat | Sand | Peat | Sand |
| East          | -    | 1.4–1.6 | 5.1–11.5 | 1–2.6 | -    | -    | 5–6.4 | 1–1.8 |
| North         | 1.8–6.1 | 1.1–2.1 | 2–7.5 | 0.9–3.2 | 4.3–14 | -    | 3.1–17.5 | 0.9–2 |
| Aldan         | -    | -    | 11.5 | 0.9–4.4 | 9.9 | 1.3–2.1 | 11.5 | 1.1–7.5 |
| Neryungri     | 5.6 | 1.4 | -    | 1.23 | -    | 1.4 | 3–8.5 | 1–3.4 |

Table 4. Content of sand-and-clay particles -2 mm in peat and gold sand of placers in Yakutia

| Mining region | Clay-and-sand particles -2 mm, % |
|---------------|----------------------------------|
| North         | 32.5                             |
| East          | 17.7                             |
| Aldan         | 47.2                             |
The main methods of stripping in all test regions are dozer cutting and combinations of dozers, loaders, different shovels and dump trucks.

It is seen in Table 5 that dozer cutting is the most popular method of stripping. The amount of dozer cutting reaches 78–92% and 17–50% in stripping and actual mining in Neryungri, and is 47–60% in stripping in the North and East regions where it is not used in actual mineral mining.

Table 5. Percentage of stripping/actual mining methods at placers in Yakutia

| Mining region | Stripping/actual mining | Combinations of methods |
|---------------|-------------------------|-------------------------|
|               | Dozer                   | Dozer–loader–dump truck | Dozer–loader | Dozer–shovel–dump truck | Dozer–shovel |
| East          | 47/0*                   | 17/64                   | 5/13         | 26/23                    | 5/0          |
| North         | 60/0                    | 20/55                   | 0/18         | 20/27                    | 0/0          |
| Aldan         | 91/17                   | 0/17                    | 0/8          | 5/25                     | 5/29         |
| Neryungri     | 78/50                   | 0/6                     | 6/11         | 17/28                    | 0/6          |

The most widely used dozer is Komatsu D-375. The other dozer models operated in stripping and actual mining are: Fiat-Allis 31, D-275, T-35.01, T-25.01, D-355, D-475, SD-32, SD-22, SD-16, T-170, T-40.01, D-10N, T-500, Liebherr PR-764, PR-754, CAT-D6, CAT-D9 and CAT-D10.

Production cycle also involves loaders and shovels. The loader models in stripping and actual mining are L-34, WA-500, WA-600, K-702; the shovels are diesel Doosan DX520LS, Solar 500LC-V, PC-750-7, Volvo EC460, RS-400, as well as electric EKG-5A.

When haulage distances exceed 5 km, the process flow chart is added with dump trucks of such models as BelAZ-7548, BelAZ-548, BelAZ-540, BelAZ-7540, Ural-4320, Scania and Volvo.

Combinations of mining methods with loaders dominate in the North and East regions, the Aldan and Neryungri placer mines use mainly shovels. In placers more than 8 m thick in all test mining regions in Yakutia, shovel-based combinations of mining methods prevail.

Complexity of a process flow chart is governed by the number of rock mass travel chain toward a dump or a sluice. Regarding the test placers, there are three variants of process flow charts: one chain (dozer); two chains (dozer–loader, dozer–shovel) and three chains (dozer–loader–dump truck, dozer–shovel–dump truck). The analysis shows that the number of stripping and actual mining chains is higher in the North region than in Aldan and Neryungri regions. This is connected both with geological conditions and climate of the mining areas (Figure 1).

![Figure 1. Average number of process flow chains in stripping and actual mining at placers in Yakutia](image-url)
Regarding permafrost rock preparation before cutting, peat and gold sand placers are softened in natural thawing, ripping and shattering by drilling and blasting (Table 6).

**Table 6.** Percentage of rock mass in various preparation to cutting

| Mining region | Percentage of rock mass preparation, % |
|---------------|---------------------------------------|
|               | Natural thawing | Ripping | Shattering |
| North         | 73             | 27      | -          |
| East          | 71             | 8.5     | 20.5       |
| Aldan         | 76             | 21      | 3          |
| Neryungri     | 44             | 66      | -          |

Natural thawing prevails in placers in the Aldan, North and East mining regions in Yakutia: it embraces 71–76% of rock volume. In Neryungri, the natural thawing percentage is much lower (by 1.7 times). Shattering by drilling and blasting is applied at 22% of placers in the East region; this approach covers 20.5% of rock mass and 43% of mineral. The same method is used to soften 4.5% of Aldan placers, with percentage of dirt rock and mineral as 3 and 23, respectively, which is almost half as much as in the East region.

Peat deposits to 10 m thick in the North region are cut with dozers and combinations of digging (Table 7). The cost of dozer stripping at peat placers to 5 m and 5–10 m thick is 2.4 and 1.5 times higher, respectively, than in stripping using a combination of machines. Peat placers thicker than 10 m are mined using a combination of dozers, shovels and loaders. The cost of the latter method is 99 Rub per cubic meter, which is 1.2 times higher than in 5–10 m thick cutting with shovels.

**Table 7.** Cost of stripping by different mining methods versus peat thickness at different placers in the North and East regions in Yakutia

| Stripping method | Peat thickness, m | Stripping cost in the North region, Rub/m³ | Stripping cost in the East region, Rub/m³ |
|------------------|-------------------|-------------------------------------------|------------------------------------------|
| Dozer            | 0–5               | 104.1                                     | 58.2                                     |
|                  | 5–10              | 126.7                                     |                                          |
|                  | more than 10 m    |                                           |                                          |
| Shovel-based combination | 0–5         | 43.1                                      | 57.0                                     |
|                  | 5–10              | 85.7                                      | 54.6                                     |
|                  | more than 10 m    |                                           | 87.2                                     |
| Loader-based combination | 0–5          | 47.5                                      | 109.0                                    |
|                  | 5–10              |                                           |                                          |
|                  | more than 10 m    |                                           |                                          |

The East placers of any thickness are mined using a shovel-based combination of machines as well as using dozers in case of peat thickness to 10 m. The stripping cost at peat placers to 5 m thick using machine assembly with loaders is 1.2 times lower than using machine assembly with shovels. In the range of peat thickness of 5–10 m, the cost of shovel stripping is slightly (1.07 times) less than the dozer stripping has and half as much as the loader-based stripping has. In case of peat placers more than 10 m thick as compared with placers 5–10 m thick, the cost of shovel-based combination is 87.2 Rub/m³, or 1.6 times higher.

3. Conclusions
1. At most gold and peat placers in operation in Yakutia, average thickness is 1.5–1.6 and 5.2 m, respectively. In mining with dozers, the highest average thickness of peat placers reaches 15.2 m in the East region and lowers to 5.0–9.3 m in the other mining regions. The content of sand-and-clay particles increases 2.7 times from the northern to southern placers.

2. In preparation of permafrost placers to mining, natural thawing method prevails in the Aldan, North and East regions (71–76%). The most widely applied method of stripping is dozer. Percentage of dozer stripping grows from 47 to 91% from the northern to southern placers. Minerals mostly extracted by combinations of equipment using loaders and dump trucks, with the related percentage drop from 64 to 6% from the northern to southern placers. The Aldan and Neryungri mining regions use simple process flow charts of mining.

3. The commonly used method of stripping in peats to 10 m thick in the North regions is digging with shovels. The stripping cost with shovels is 1.5–1.3 times lower than with dozers. Moreover, the cost of stripping with shovels decreases with an increasing thickness of peat. In the East region, the cost of stripping with shovels is 2 and 1.07 times lower than with loaders and dozers.

4. The implemented analytical review allows a more reasoned approach to mining improvement with regard to the existing trends, theoretical knowledge and practical skills.

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