In mountainous regions with intensive economic development and mineral mining operations, problems can arise as a result of interaction of human activities and mountain development processes. These phenomena are especially dangerous and active in the north of Siberia (Grebenets et al., 1992) and include: intensive gelifluction and landslide processes; anthropogenic salinization of soils and seasonally thawing layers of the ground, snow and ice; intensive degradation of permafrost and glacial complexes; and a generally deteriorating ecological situation.

The Norilsk industrial region is one of the largest mining and metallurgical centers in the world, and is located in a mountainous region in northern Siberia above the Arctic Circle (latitude 69°N), near the Putorana Plateau. Within 60 years of the city's existence, industrial operations radically changed the engineering and geological conditions of the territory (Grebenets et al., 1994). This resulted in a decrease in the load-supporting ability of the ground, the destruction of foundation material, and an increase in structure deformation.

Processes and phenomena occurring on slopes, as a result of their industrial development, are especially dangerous. Numerous pits and mining sites increase the effect of instability of existing natural slopes. The costs for special protective engineering and geological efforts aimed at stabilization of the situation in the region, have increased almost 15 times within the last 30 years.

The development of the open pit mine “Medvezhy Ruchey” by drilling and blasting methods resulted in formation of a huge pit (Rudnaya Mountain, about 250 m deep and 3 km wide), as well as rock fracturing and the appearance of waste dumps, also known as slag heaps.

On the northern slope of Rudnaya Mountain, one of the world's largest waste dumps is located; it was formed as a result of open pit mining. At present, the rock dump volume is about 60,000,000 m³ or about 110 million tons (Figure 1).

The dumping process of this rock mass lasted 25 years and was completed in 1984. The actual height is 105-120 m and the slope angle is 30°-36°. The dumping was arranged layer by layer along the slope, with an angle of 12°-15°. Rocks were covered by Quaternary till sediments and loamy soil with thicknesses from 0.5 to 6-7 m. In many places (25% of the slope area) lenses of ice occur, with the thicknesses of 0.5-4 m close to the surface. In other areas, where the capacity of ice and loam exceeded 3-4 m, slow gelifluction has occurred. The natural slope was quite stable and the ground temperature at 8-10 m depth in 1945 was -4 to -6 °C.

In a geological sense, the dump is a mixture of various rocks from the mine “Medvezhy Ruchey”, 43% of extrusive origin, 56% of intrusive origin and 1% of sedimentary origin. More than 5% of the material is represented by “rejections” (blocks of 80 cm to 2.5-3 m size), 60% is crushed rock to boulders (2 - 80 cm), and the remainder is small-sized material, including particles of dust and clay. In the process of dump formation, snow and ice
fell into it (subsequently transformed under pressure into firn), and this also reduced the stability of the dump as a whole. The high infiltration ability of the material caused penetration of rain and flood waters that froze as a result of low temperatures and permafrost.

To analyze the situation, from 1993 to 1997 a number of complex studies – including engineering-geological, geodetic and geothermal observations – were undertaken at the site.

Findings of observations

The waste dump on the slope “Rudnaya” mountain can be classified as a body with a complex structure, containing soil and ice. It is, in many respects, similar to rock glaciers that have been observed in many mountain regions (for example, in Austria, Sweden etc.).

Deformation of the mine dump was observed in the summer of 1992. On the top platform of the dump, vertical subsidence and fractures were observed, with depths of 5 - 7 m, widths up to 0.5 m, and lengths up to 200 - 300 m (Figure 2). At the base, along the road, a ridge of 600 m length occurs that contains a fine-
grained structure. Similar morphology is typical for rock glaciers (Höllerman, 1983). Due to the bulging of the excavated ground layers, and as the underlying layers shift, the ridges reach about 6-8 m high. During summer time, there are water streams from both sides of the ridge and during flood periods some collapse take place. All this makes the road operation and transportation of the ore very difficult. In 1995, this dump destroyed the ridges and the road. The shift of the dump also destroyed the drinking-water pipeline.

The extent of the frontal part of the dump is 1000-1200 m and the total displacement at the most dangerous site is 250-300 m. The average speed of movement grew from 5-10 mm/day in 1992 to 30-40 mm/day in 1996 (Figure 3). From 1995 to 1997, each of the parts started to move at varying speeds: in the zone of maximum movement, the speed was 60-80 mm/day, and in peripheral areas 15-20 mm/day. In the warm seasons from 1995 to 1997, in certain areas, speeds of 800-1000 mm/day were observed, as well as the falling of large rocks. The increase of displacement speed was promoted by penetration of water from communication lines into the dump, located in the upper part of the slope. The penetration of water led to the differential movement of separate parts of the dump. The deterioration of cryolithogenic conditions (decrease of bond strength between ice and ground) inside the embankment is caused by the general tendency of permafrost degradation (Grebenets et al., 1994). In 1996, three thermal measuring wells were drilled; in the upper part of the dump, to 30.5 m depth; next to the dump on the slope, to 25 m; and at the bottom part of the dump, to 125 m. The measurements showed that the temperature of the soil significantly increased. In the upper part of the dump to a depth of 20-30 m, the temperature was -2 to -2.5 °C. At the bottom, at a depth of 20-50 m, it varied from -1.2 to -1.5 °C to 0.2-0.4 °C (Figure 4).

Two main parts can be distinguished: 1) the active part or 60 % of the dump, which is the most dangerous; and 2) the rather stable part at the slope, where the thickness of the sedimentary rock with ice is not as great (2-3 m). On the whole, the dump is characterized by essential differences in surface movement speeds, in formation and in increase of fractures. The dimension of fractures (in the vertical parts) reaches 2-2.5 m with depths up to 3-4 m; it should be noted that the fractures are not filled by sediments, which testifies to the active movement of the dump embankments.

In our opinion, besides the dump moving as a complete body containing ice and rock (like a rock glacier), two other kinds of movements also occur: screes of broken material from the upper parts, and layered sliding of separate horizons.

This third kind of movement, the sliding of layers is most dangerous. As is known, the long-term resistance of ice to loads (including sliding) is very small or nearly zero and the ice has the ability to move under the influence of a load. It is obvious that the movement of separate layers of the dump body within more icy horizons, together with the general movement of this anthropogenic rock glacier, present a special danger because with a temperature change or increase of deformation, the creep may change into a rapid mass movement of all or part of the body. A special problem is caused by the water that fills the fractures, and its further drainage into the body through the channels formed after ice thawing.

In June 1996, the front part of the dump collapsed into the Medvezhy Ruchei River. The river flows through a narrow gorge, and at flood stage has a depth of 2-2.5 m, and a width of 15-20 m. At low flow, the depth does not exceed 1 m, and the width is from 5-10 m. With the collapse of the dump over the river, a tunnel was formed, composed of rocks cemented together with ice. For more than a year the river has flowed through this tunnel. The length of this tunnel is about 50 m (Figure 5).
However, in August 1997 the tunnel began to significantly deteriorate. With the future expected collapse of the tunnel, it is anticipated that a lake will be formed and the lake will eventually sweep away the dump and form debris flows. A debris flow along the valley of the Medvezhy Ruchei River could lead to the destruction of communications lines and industrial structures.

Conclusion

The calculations showed, that with an avalanche of 60 % of the dump body, the fragmented material could cover a distance of 1-1.2 km and destroy dozens of industrial buildings and structures. The probability of such an event within the next 2-2.5 years is about 70 %.

The main engineering protective efforts are aimed at evacuation of the most important objects from the hazard zone. At the distance of 300-500 m from the lower edge of the dump, a bulk dam 10-15 m high, was erected to support a significant part of the dump mass from collapse. Analysis of application of artificial ground freezing technologies at the top of the dump with the help of seasonally - cooling devices and natural cold is aimed at the improvement of the engineering-geological situation. Considerable experience in the application of similar devices, such as foundation engineering and hydraulic engineering structures occurs in the Norilsk industrial region (Grebenets, 1990). Many questions are unsolved, however, such as the forecasts of movement and the effective ways of stabilization of dumps.

The problems of anthropogenic dump movement in mountain and foothill regions are important ones for research in the field of soil and rock mechanics.

References


