Rock slope stability assessment toward elimination of accidents

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Abstract. The authors assess the effect of seismic vibrations induced by blasting in Biyanka gravel quarry and by movement of trains. The research was initiated in view of the accident in summer of 2017, which resulted in off-trip of two cars. The jointing structure of the rock slope is inspected, and the slope stability is assessed in some sites of the slope within the limits of the Asha railway haul. The recorded seismic vibrations in the rockfall-hazardous sites of the slope are less hazardous for the slope stability than the geological features of the slope, which are the cause of all rock falls. The recommendations on prevention of rock falls on the track are given.

1. Introduction
On July 19, 2017, in the Minyar–Biyanka haul nearby the town of Asha, two rear cars of a freight train composed of 74 cars run off the track. Commuter trains were canceled and long distance trains were delayed because of salvage work. The cause of the accident was the slope failure of the mountain shoulder adjoining the south pit pit wall of Biyanka gravel quarry.

Neither accident site inspection nor study of paperwork revealed an unambiguous cause of the slope failure due to a variety of natural and induced influences disclosed. Opening of fractures, abundant rain in June–July 2017, blasting-induced displacements of rock blocks on the slope for more than 50 years, as well as vibrations due to train movements could jointly initiate the disastrous event.

2. Methods and materials of research
With a view to detecting possible failure sites and preventing catastrophic rock falls, mountain shoulders along the Asha track haul were inspected.

The scope of the survey included:
—inspection of the fractured structure of shoulders of the mountains at the railway facilities and Biyanka gravel quarry along the Biyanka–Simskaya haul at the average slope width of 250 m;
—instrumental measurements of factual PPV on the avalanchine slopes adjoining Biyanka quarry:
  • Measurement of seismic vibrations from train movements;
  • Measurement of seismic vibrations from large-scale blasts;
—Slope stability estimation along the Biyanka–Simskaya haul at Bianka quarry.

Within Kuibyshev Management’s infrastructure, the roadbed instability records specify 45 sites as rockslides over the length of 18.775 km. Rock falls are regularly observed in the most attackable sites of the Asha railway haul. These sites are assessed as hazardous. Rock traps largely prevent fall of stones on the railway but are incapable to hold back voluminous landslides such as the landslide on
July 19, 2017 at the distance marker post of 1751 km of Biyanka station. The rock slope at that post of the Biyanka–Simskaya haul is composed of limestone (see Table 1) with some pockets of other rocks.

Table 1. Physical and mechanical properties of limestone

| Property                          | Average value | Range       |
|----------------------------------|---------------|-------------|
| Protodyakov’s hardness factor $f$ | 6.6           | 1.6–14.3    |
| Ultimate compression strength $\sigma_c$, MPa | 99.0         | 6.0–260.0   |
| Ultimate tension strength $\sigma_t$, MPa  | 11.0          | 2.0–38.0    |
| Cohesion $C$, MPa                | 30.0          | 7.0–64.0    |
| Porosity $\Pi$, %               | 9.6           | 0.4–37.4    |
| Young’s modulus $E$, GPa         | 61.0          | 18.0–93.0   |
| Shear modulus $G$, GPa           | 26.0          | 7.0–31.0    |
| Poisson’s ratio $\mu$            | 0.26          | 0.13–0.45   |
| Density $\rho$, g/cm$^3$         | 2.64          | 2.1–2.99    |
| P-wave velocity $c_p$, km/s      | 4.63          | 1.3–6.9     |
| S-wave velocity $c_s$, km/s      | 3.01          | 2.22–3.08   |

Slope stability is for the first turn governed by its jointing and movement of joint blocks due to the presence of water and filler. Essential influence on movement of joint blocks is exerted by seismic vibrations which can even be a trigger for geodynamic events. With a view to reducing the risk of rock falls on railway track, it is necessary to undertake an integrated research including rock mass jointing and seismic effects of blasting in a quarry of Biyanka Aggregate Preparation Plant, as well as due to vibrations caused by trains. Assessment procedure of seismic effects from trains and blasts is based on recording of PPV values in soil using seismic transducers and seismic acquisition system [1–5]. Seismic vibration velocities were measured using URAN seismic acquisition system at the Rock Fracture Laboratory of the Institute of Mining, UB RAS.

For getting a representative bulk of information on seismic effects exerted on rock mass by railway train, additional measurements were taken along a distance of 150 km split into two intervals of 60–70 m. URAN systems were installed on the test slope, in two lines of two points in perpendicular to the railway bed (Figure 1a). Blast-induced vibrations were measured similarly, with two URAN systems installed at the test slope at a spacing of 50 to 100 m (Figure 1b).

![Figure 1. Layout of instrumentation installation in measurement of effects induced by (a) railway trains and (b) blasts in Biyanka quarry.](image-url)
The research was carried out the procedure developed at the Institute of Mining, UB RAS [6–9]. Seismic vibrations from blasting in the quarry of Biyanka Aggregate Preparation Plant were measured on October 10 and November 3, 2017. Allowable PPV was determined using the common approach [10–16]. In dolomitic limestone of slope at 1751 km distance post of the Biyanka–Simskaya haul, the seismic vibration velocity was 0.2 m/s. During large-scale blasting in Biyanka quarry, over the interval of 240 m from the blasting block to the quarry boundary, the PPV values obtained were:

- at a distance of 5 m along the slope from the quarry boundary—0.0144 m/s;
- at a distance of 37 m along the slope from the quarry boundary—0.0116 m/s;
- at the quarry boundary, near the top base of the rockfall netting mesh—0.0085 m/s;
- at a distance of 40 m along the slope from the quarry boundary, in the west—0.006 m/s;
- at a distance of 50 m along the slope from the quarry boundary, in the east—0.0015 m/s.

All measured values appeared to be much lower than the allowable threshold of 0.2 m/s.

Accordingly, given appropriate arrangement of blasting operations, blasts can induce no critical seismic vibrations and no slope instability.

Measurement of seismic vibrations from railway trains was carried out on October 25, 2017 (Figure 2).

![Figure 2](image-url)

**Figure 2.** Layout of seismic acquisition systems MiniMatePlus and URAN at the bottom of test slope for recording seismic vibrations induced by trains at spacings of 140, 70, 45, 25 and 20 m from railway bed.

During movement of trains on October 25, 2017 from 12.30 p.m to 04.06 p.m. at 1752 km post of the Biyanka–Simskaya haul, the maximal resultant velocity of seismic vibration at the bottom of the slope, at a distance of 25 m and 20 m from the track upward the slope made 0.002 m/s in the west and 0.0007 m/s in the east, respectively. The recorded maximal PPV values at the bottom of the slope were less than the allowable threshold. Trains have no adverse impact on the slope bottom and cause no slope instability, or rock falls and landslides.

Stability of exposures was also estimated. The railway runs along a steep (to 45°) hard rock slope composed of limestone of various degree fracturing. For the analysis of rock falls, Gin Geo company accomplished large-scale measurement of elements of jointing in 6 sites along the railway (Figure 3).
All in all, 615 measurements of joints were taken. The azimuths of the test slope sites were: 115° in sites 1 and 2, 105° in site 3, 130° in sites 4 and 5, and 53° in site 6.

The survey revealed a few types of jointing: blocks—irregular polyhedrons from a few centimeters to 10–20 m in size; slabs—sheet jointing in parallel to bedding, from 0.02–0.03 to 0.15–0.20 m in size, and pillars—elongated polyhedrons from by three equal systems of joints, from 0.15–0.20 m to a few meters in size.

On the whole, the types of block structure occur regularly in the rock mass slope: plates at the bottom of exposed surfaces and blocks, and seldom, pillars at the top. The pillar blocks are the most hazardous, when the pillars are to a few meters in size, which is observed in sites 1, 2, 4 and 5. In the same sites, blocks to 20 m in size are detected, which are also hazardous if they have a vertically elongated shape and are formed by the same systems of joints as the pillars.

Figure 3. Orientation of main systems of joints relative to slope.

3. Results and discussion
Mapping of the main joint systems of the test slope (Figure 3) allowed drawing some conclusions below:

1. The main systems of joints have the similar orientation in all test sites, i.e., the risk of rock falls depends on the mutual orientation of the joints and the slope surface.

2. The orientation of jointing in site 1 and 2 is unfavorable for initiation of large rock falls: subvertical joints are oriented at an angle of 25–27° to the slope surface, which impedes tripping and rockfalling. The other two systems of joints are perpendicular to the slope surface. The gentle dip (on average 25°) of joints of one the joint systems prevents movement of blocks. Small rock falls can be initiated due to the change of the jointing orientation in the periods of heavy rainfalls or snow melting.

3. Site 3 has the same conditions as sites 1 and 3, except for the gently dipping system of joints toward the valley. The dip angles of the joints (7–25°) predetermine small movements of blocks only in case of water inflows. The displacements can accumulate with time, but without external effects (blasting, intense physical weathering, etc.), the site is unhazardous in terms of large rock falls.

4. Site 4 is assessed as hazardous in terms of rock falls: the systems of subvertical joints are almost parallel to the slope surface, and the angle between the strike of the joints and the slope is 3°,
i.e., formation of large rock falls due to tripping of blocks cut by counter joints with dip angles of 30 and 67° is highly probable.

5. Sites 4 and 6 are similarly rockfall-hazardous as site 4: the angle between the slope surface and the subvertical system of joints is larger (6–5°) but here we have a distinct joint system with gentle dip (15–20°) toward the slope. In the meanwhile, the strike of these joints is parallel to the slope surface as against site 3 where this dip angle is 18°.

6. The downward rockfall hazard rating of the test sites is: 4, 6, 5, 3, 2 and 1.

4. Conclusions
The instrumentation measurement of actual velocities of seismic vibrations on rockfall slopes adjacent to Biyanka quarry proved zero seismic impact. The recorded seismic vibrations at the slope bottom due to trains are insignificant, belong to high frequency range and have no adverse effect on the rock mass. Thus, the cause of rock falls on the track is the geological specificity of the slope.

The recommended measures to prevent rock falls on railway include:
—construction of rock trap screens (effectively operated in iron ore mines since the 1970 and joining success in open pit pit mines of Zhezkazgantsvetmet since the 2000s);
—rockbolting with subsequent cable netting (practice of open pit mines of ALROSA;
—terracing of the hazardous slope areas;
—throw of rock overhangs using directional blasting;
—cutting-back and benching meant to trap rock falls instead of rock trap screens.

Acknowledgements
The authors express their gratitude to O. V. Zoteev, P. V. Menshikov and A. S. Flyagin from the Institute of Mining, Ural Branch, Russian Academy of Sciences, for the valuable advice in the course of preparation of this paper.

The study was supported by State Contract No. 075-00581-19-00, Topic No. 0405-2019-0005 (2019–2021), and partly by economic contracts.

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