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Evaluation of the mill tailings disposal site at the Zirovski vrh uranium mine in Slovenia

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Abstract. Uranium mine Zirovski vrh in Slovenia was closed due to economic reasons. After that extensive work on decommission was done. The results of the comparison between three potential sites for mill tailings are presented. The results of the probabilistic approach to the factors of safety and confidence, seismic hazard analysis, hydrogeological models and in the economic evaluation are given. For the common evaluation they were interpreted in the way of UMTRA decision matrix. On the basis of the engineering judgemen calculations for the recent status and the status after 1000 years was preformed.

1. INTRODUCTION

Strong progress has been made in the field of peaceful and safe nuclear energy use in Europe since the end of the Second World War. As the consequence of this process, extensive research for the possibilities of nuclear energy use began in Slovenia around the year 1950. Following several years of prospecting work, high natural radioactivity was detected in the area of Zirovski vrh and soon after that the first mining works began. Development of the Zirovski vrh uranium mine ran simultaneously with the design and construction of the Krsko nuclear power plant. While the Krsko nuclear power plant still operates today at its full power, the ore extraction at the Zirovski vrh uranium mine was stopped in 1990. The omission of the extraction at the mine has been followed by extensive decommissioning works in the mine itself as well as and in its surroundings. One of the main activities was design of decommissioning of the disposals and closure of the underground mine. Immediately after the extraction process ceased, extensive sliding of the mill tailings material occurred and alternate sites for mill tailings deposition had to be considered. The methodology and results of this study are presented in the paper.

2. GENERAL SETTINGS

The Zirovski vrh uranium mine is located in the western part of Slovenia, at the distance of approximately 50 kilometres from the capital city Ljubljana (Fig. 1). It is situated in the area named Polhograjsko hribovje in the valley near the junction of two creeks that are the tributaries of the river Poljanska Sora. Geomorphologicaly the area can be described as a hilly area with steep slopes and relatively dense drainage networks where several ravines appear. The altitude difference is between 400 to 700 m a.s.l.. Water springs are very common phenomena in the valleys and ravines. The slopes are covered with dense vegetation of coniferous and deciduous trees.

The climate in the area is temperate with 1800 mm/year average rainfall and yearly real evapotranspiration of around 550 mm. Air temperatures are between –28°C to 37°C with the yearly average of 7°C. The maximum thickness of snow cover is up to 1.8 m. The direction and speed of wind in the area depend on the relief, however, weak south-northern winds prevail. Temperature inversion occur autumns and winters at about 500 m a.s.l. in the valley where the mine entrance is located.

The uranium ore in the area was first discovered in the late fifties and the first underground investigation works began in the year 1960. The first yellow cake was produced in the processing plant in 1984. In the year 1990, the mine was closed. Altogether 3 307 000 tones of material were removed during the extraction period. The ore was represented by 633 000 tones and low-grade ore with 206 000 tones.

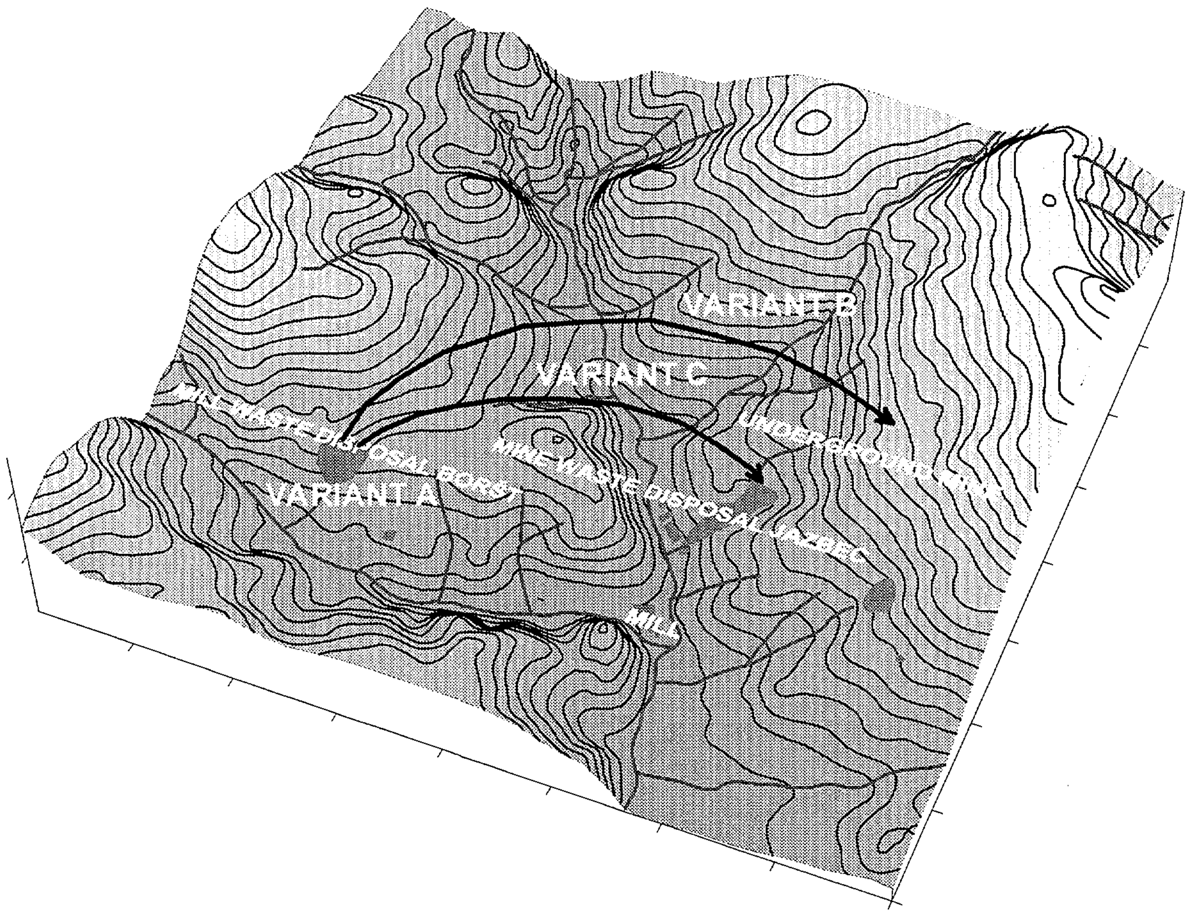

FIG. 1. Arial view on Zirovski vrh area with main characteristics of possible relocations of mill waste (area 4x4 km, sight to south).

The underground mine is perpendicular to the valley and is positioned in the hill between 430 and 610 m a.s.l. Access to the main underground works was through nearly horizontal adits positioned in the different altitudes from the valley bottom at 430 m a.s.l. to the 530 m a.s.l.. After the finishing of the exploitation works several breakdowns occurred. The influence area of this phenomenon extends to the surface above the mine. The mine is developed in the clastic groeden beds of Permian age. The ore was excavated from grey quartz sandstone and conglomerate that were deposited in the fluvial environment. In the surrounding of the mine clastic Carboniferous and Triassic rocks are also present. They are represented with various dolomites and limestones, piroclastic rocks and siltstone. The geologic structure consists of several napes thrusted from the northern direction. They are dissected by the Dinaric faults in the direction NW-SE. The ore minerals are uranium oxides in the tar and several secondary ore minerals such as uranosferit, torbernit, autunit etc. [1, 2]

During the excavation period, the mine mill tailings and mine waste were deposited in the surrounding of the mine. The mill tailings site Borst is positioned around 1.5 km from the mine entrance. It covers 4.2 ha between two ravines in the altitudes between 520 and 580 m. The total amount of 673 000 tones of tailings were deposited. Deposition of tailings began in 1983 and was ended when the mine production stopped in 1990. The tailings consist of silty to sandy aggregate formed during the hydrometallurgical process. Chemically it is silica, gypsum and sulphate salts. In the bedrock of the tailings disposal, Triassic clay stones and piroclastic sedimentary rocks with poor geomechanical characteristics are present. The weathered zone of the rocks is relatively thick. In the year 1990, the landslide of 2.9 million cubic meters of uranium mill tailings and underlying rock occurred. The sliding was stopped by extensive drainage works with underground drainage gallery. During the construction works, a strong fault crossing the gallery was found with the evidences of past sliding. Natural conditions on the slope itself also assisted in the movement stopping.

The mine waste disposal site Jazbec covers the area in the vicinity of the mine. It consists mainly of mine waste and red precipitate from the processing plant. The deposition began in 1984 and was stopped in 1990. In the total 3 900 000 tones of mine waste was deposited between 420 and 460 m.a.s.l.. The disposal site Jazbec is positioned on rocks of various ages. Clastic rocks prevail over the carbonate ones. The area, where the Jazbec disposal site is positioned, is relatively near of water. Surface waters are drained off through underground concrete channels and plastic pipes. The later divert springs in the bedrock of the disposal site.

In the year 1990, when sliding of Borst mill tailings began, extensive studies and design of remediation works were performed. During this work, several alternatives for mill tailings redeposition were studied. Three main possible variants were established:

- Variant A: Mill tailings stays on the Borst location. The site must be improved as much as it is possible with all remediation and environmental protection measures.
- Variant B: Mill tailings and contaminated subsoil would be removed with transport to the underground openings of the abandoned mine.
- Variant C: Mill tailings and contaminated subsoil would be removed with transport onto the mine waste disposal site Jazbec.

In the each of the variants all waste sites and mine are decommissioned. All three variants have some serious drawbacks that are the consequence of geological conditions in the area:

- Variant A is problematical due to the great land sliding potential. The movements stopped with the excavation of underground dewatering tunnel could be reactivated.
- In the variant B the breakdown of roof in the mine could occur and as the consequence leaching off of the tailings material would be present.
- In the variant C the main disadvantage is great recharge area and as a consequence of this great erosion potential of the site.

3. METHODOLOGY

According to IAEA [3] recommendations the site selection should be preformed with rating matrix of Uranium Mill Tailings Remedial Action Project of United States Department of Energy [4, 5]. The UMTRA rating matrix is proposed for the site selection. In the Zirovski vrh uranium mine the sites are already present. This is the reason why the parameters of UMTRA decision matrix were slightly modified or even excluded from the analysis.

There are 35 different parameters of the UMTRA matrix divided into four different groups:

- geotechnical group (land slope, surfical materials lithology, surfical materials thickness, distance to nearest seismic risk capable fault, susceptibility to slope failures, present erosion, geomorphic stability, conflict with mineral resources, relative strength and compressibility of foundation soil or rock)
- hydrological group (well yields, background water quality, widespread ambient contamination, upgradient groundwater contamination, geologic strata where there is no existing groundwater, volumetric flux of uppermost aquifer through cross-sectional area under

disposal site, geochemical properties of aquifer and subsoil, potential for upward hydraulic gradients below a low hydraulic conductivity stratum, proximity to point of groundwater discharge, depth to groundwater in shallowest aquifer)

- environmental group (distance to the nearest point of groundwater withdrawal from potentially affected aquifer, precipitation frequency, total annual precipitation, annual pan evaporation, population density, transportation network, presence of cultural or historical sites, endangered or economically important species, scenic values, current land use, potential land use, land ownership)
- economic group (distance from existing site, distance to potential borrow sites, existing road network, roads with positive grade from mill site and tailings to disposal site)

Each parameter is ranked from 0 to 4 and weighted by factor score. For some parameters ranks are omitted. Parameter erosion in the geotechnical group presents the example of ranking. Intense gullying is ranked with 0, moderate gullying is ranked with 1, minor gullying is ranked with 2, sheet or rill wash is ranked with 3 and absence of erosion is ranked with 4. This parameter is weighted by factor score 4. The parameter well yield is the example of parameters where only two ranks are given. Well yields less than 2 m^3 is ranked by 0 and above 2 m^3 is ranked by 4. The parameter is weighted by factor score 10.

All three evaluated sites for mill tailings disposal are positioned close to each other. This is the reason why some parameters from UMTRA decision matrix are not discernible and they don't influence the final calculation of the matrix. Among them are precipitation frequency, total annual precipitation, annual pan evaporation, population density, and endangered or economically important species and land ownership.

4. RESULTS AND INTERPRETATION

According to ranking demands all the present research data should be carefully studied and incorporate in the matrix. In the present paper the most important implementations are presented.

4.1. Engineering geology

Stability of an engineering object is usually expressed with the factor of safety i.e. ratio between allowable value of some quantity to the calculated value of that quantity. For evaluation of the stability of engineering system, various methods of evaluation of safety factor are used. Calculation is carried out with several input parameters, usually with their averages that are determined in laboratories. The results of these tests and the factor of safety are distributed according to statistical distribution. The statistical measure which express ratio between mean factor of safety and its standard deviation is defined as reliability index. It describes the stability of a slope by the number of standard deviations separating the mean factor of safety. For normal distribution the relationship between reliability index (β) and probability (p(f)) of failure follows the equation [6]:

$$p(f) \approx 1 \times 10^{-\beta}$$

For conventional structural practice the reliability index must be greater than 3 [7]. In most cases the factor of safety that is greater than 1,5 overcome the inherent variability of the material.

For Borst and Jazbec waste sites stability analysis was done. The Borst landslide calculated safety factor is 1,3 and required safety factor that should overcome measured variability is not lower than 1,6. For the Jazbec waste site only static stability analysis were performed. For the recent status of Jazbec 1,4 safety factor was determined. In the case where the material from Borst mill tailings would be redeposit onto Jazbec waste site 1,33 safety factor was calculated. Considering the earthquake acceleration safety factor will be lowered to near 1.

4.2. Seismotectonics

Seismic hazard was studied by carefully examination of older reports and articles about the seismicity of the area. The intention of seismic hazard analysis is to predict the influence of a likelihood future earthquake with the certain magnitude on the site of interest. For this purpose we have to study surrounding seismic zones of potential seismic source and the site itself in aspect of influence of the earthquake intensity. The parameters that define seismic hazard are: magnitude of design earthquake, peak horizontal acceleration, distance of the site of the potential active fault, length of the active fault, fault characterization and visible dislocation of the ground surface as a result of a strong earthquake.

The influence of the earthquake to the site could be direct and indirect. In the case of Zirovski vrh uranium mine we verified the following consequences: land sliding, liquefaction of the mill tailings and impact to the underground excavations. In the vicinity of Zirovski vrh uranium mine there are five seismogenic zones (Ribaric, 1976, cf. Zadnik, 1992). These are:

- Ljubljana seismic zone (the magnitude 6.5, the distance 28 km)
- Idrija seismic zone (the magnitude 7, the distance 16 km),
- Villach-Dobratsch seismic zone (the magnitude between 6.5 to 7, the distance 60 km),
- Friuli seismic zone (the magnitude 6.5, the distance 80 km)
- Polhograjski dolomiti seismic zone (the magnitude 5, the distance from 10 to 15 km).

In the investigation of the neotectonics in the area of Zirovski vrh uranium mine we determined four systems of faults:

- Faults in the Dinaric (NW–SE) direction with vertical dislocation between 50–300 m and horizontal dislocation 100–3000 m. They were active in the Würm glacial and in the beginning of the Holocene,
- Faults in the cross Dinaric (NE–SW) direction are well defined. They were active in the Günz glacial,
- Faults in the Alpidic (W–E) direction. They were active in the Mindel glacial,
- Faults in the direction N–S. They are still active.

According to UMTRA decision matrix criteria designed earthquake should be considered as the earthquake with the greatest impact and with the maximum horizontal acceleration. Due to the small distance between sites the same data from Idrija seismic zone for all of three variants were used:

Distance	16 km
Maximal magnitude	7
Maximal intensity	9–10 MSK
Maximal ground acceleration	0,48 g
Design acceleration	0,27 g
Maximum amplitude	26 mm

Liquefaction potentials for sites were not treated into detail. Due to the geo-mechanical characteristics of waste and mill tailings material we assume that that the liquefaction potentials are very low. The influence of the earthquake onto underground openings in the mine was estimated according to the literature [8]. The estimated damage in the mine is smaller than on the surface.

To determine the landslide hazard of Borst the simplified pseudodynamic analysis was performed [9]. Considering the maximum likelihood earthquake the shift of 2,85 m of mill tailings mass was established. In the case where the weakening of share resistance of mill tailings material is treated the estimated shift of the deposited material is 30 m. According to the stability analysis Borst area will be stable during the institutional control. After that time, due to the share resistance reduction sliding of Borst could occur.

4.3. Hydrological characteristics

In the hydrological characterization of the sites all required parameters from UMTA matrix were evaluated. Climatic factors of the sites are nearly the same. In the contrary hydrogeological characteristics of the underlying rocks and sediments in the sites are very different and variable.

In the mill tailings Borst location bedrock is classified as very low to non-permeable rocks. The weathered zone above bedrock has hydraulic permeability between 10^{-7} to 10^{-8} m/s, clay stones and piroclastic tuffs have permeability less than 10^{-9} m/s. The hydraulic permeability of the landslide sliding plane is estimated on 10^{-5} m/s. The hydrometallurgical waste has permeability between 2×10^{-9} to 3×10^{-10} m/s. In low water conditions the outflow from underground drainage gallery was on the interval between 0.5 to 7 l/s. In the area of mill tailings two groundwater horizons are present. The first horizon is in the waste zone with intergranular porosity and the second in the bedrock of double porosity of joints and pores.

By the demand of Public Health Inspectorate after the final decommission of the Borst site average yearly Ra emission into the surface water must not be higher than 60 Bq/m^3 and total yearly emission must be lower than 50 MBq. In the year 1994 77% of ^{226}Ra and 11% of uranium from Zirovski vrh uranium mine sources was emanated from Borst site.

In the area of Jazbec waste disposal only dolomites and limestone in the bedrock are classified as aquifer. The body of ore waste is very heterogeneous and various perched groundwater horizons have been formed. The hydraulic permeability of ore waste is estimated on the interval between $2{,}4 \times 10^{-4}$ to 3×10^{-5} m/s. Red precipitate is very wet and with relatively low hydraulic permeability that is estimated on the interval between 10^{-7} to 10^{-8} m/s. The piping of small debris from ore waste was established during the investigation works. Due to this reason lower parts of the waste site have lower permeability. During the construction of Jazbec waste site several small creeks was covered by waste and diverted into the underground channels and drainage pipes. Nowadays some channels are damaged and broken Total discharge of water through the waste body is on the interval between 2,5 to 38 l/s. Infiltration of rainfall represents 20 %, waters from the recharge area 27%, springs on the edge of waste body 4% and 33% springs covered by the waste [10].

Waste site Jazbec contributes 6% of ^{226}Ra and 38% of uranium from Zirovski vrh uranium mine sources. Currently in average 600 mg/m^3 of $U_3O_8^-$ and 40 Bq/m^3 of Ra is released from the Jazbec area. By the demand of Public Health Inspectorate after the decommission the total yearly amount of $U_3O_8^-$ should not be higher than 100 kg and Ra emission 25 MBq.

In the mine area several sandstones with fissure porosity are classified as aquifers. The hydraulic permeability is very variable and depends on density and apertures of fractures. It is estimated on the interval between 9×10^{-3} to 1×10^{-7} m/s. Near the mine upper Triassic dolomite that is important regional aquifer is present. From the mine in average flows out 20 l/s. From the climatological data it was estimated that the recharge area of the water in the mine is 1,2 to 2,0 km^2 which is approximately the same as the ground plan of the mine openings.

The outflow from the mine contributes 11% of ^{226}Ra and 51% of uranium from Zirovski vrh uranium mine sources. Currently in average 300 mg/m3 of $U_3O_8^-$ and 60 Bq/m^3 of Ra is released from the mine openings. By the demand of Public Health Inspectorate after the sanitation works the total yearly amount of $U_3O_8^-$ should not be higher than 200 kg and Ra emission 50 MBq.

For each of the evaluated sites groundwater potential for future likelihood drinking water supply and well yield was estimated. The area of the site and all potential locations in down gradient direction were evaluated.

4.4. Economic factors

The total costs were estimated according to the available projects and other documents. The cost for each of the variant are shown below:

Variant A	13 million ECU
Variant B	28 million ECU
Variant C	17 million ECU

In all three variants the main expense is mine openings remedial measures. In the Fig. 2 the structure of the cost for all variants is represented.

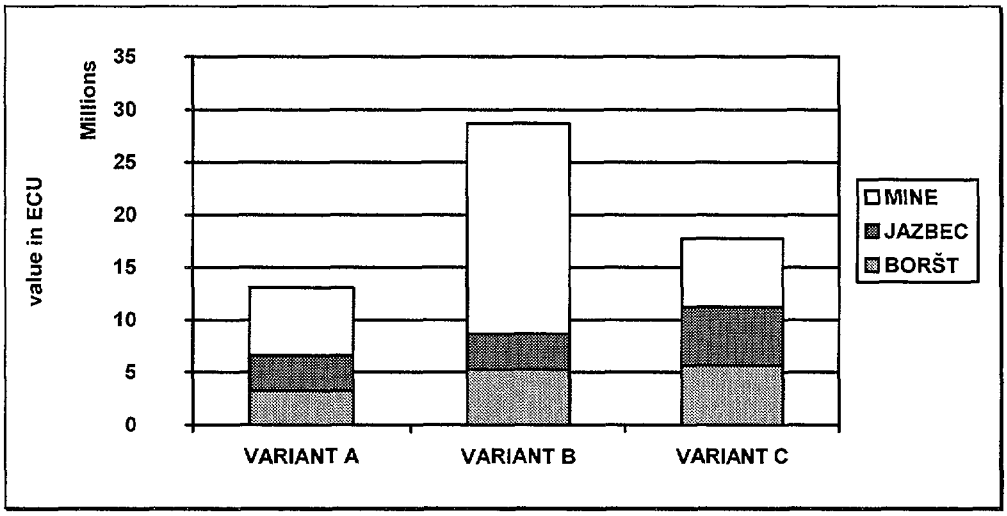

FIG. 2. Financial evaluation of variants according to available projects.

5. CALCULATION OF THE UMTRA MATRIX

For each of the variants UMTRA decision matrix were calculated. The calculations were done for the recent status and for the status after 1000 years. The results of the calculation for each site in the variants through A to C are represented.

The results of calculation for the recent status are represented in the following Table.

variant	A				B				C			
group	**I**	**II**	**III**	**Σ**	**I**	**II**	**III**	**Σ**	**I**	**II**	**III**	**Σ**
geotechnical	130	145	200	**475**	172	145	198	**515**	172	125	210	**507**
hydrological	12	4	12	**28**	16	4	12	**32**	16	4	12	**32**
environmental	109	109	112	**330**	107	109	112	**328**	107	109	100	**316**
economical	50	50	50	**150**	6	6	6	**18**	25	25	25	**75**
Σ	**301**	**308**	**374**	**983**	**301**	**264**	**328**	**893**	**320**	**363**	**347**	**930**

I – Borst mill tailings
II – Jazbec waste site
III – Mine

The results of calculation for the status after 1000 years are represented in the following Table.

variant	A				B				C			
group	I	II	III	Σ	I	II	III	Σ	I	II	III	Σ
geotechnical	112	82	159	**353**	146	105	159	**410**	146	99	131	**376**
hydrological	4	4	12	**20**	16	4	12	**32**	16	4	16	**32**
environmental	107	107	103	**317**	112	107	108	**327**	112	107	103	**322**
economical	12	12	12	**36**	50	50	50	**150**	31	31	31	**93**
Σ	**231**	**201**	**274**	**706**	**308**	**262**	**301**	**887**	**289**	**237**	**265**	**791**

I – Borst mill tailings
II – Jazbec waste site
III – Mine

6. CONCLUSIONS

In the re-deposition study of mill tailings disposal site of the abandoned Zirovski vrh uranium mine three variants were studied. In the variant A mill tailings stays on the present Borst location, in the variant B mill tailings and contaminated subsoil is removed to the underground openings of the abandoned mine and in the variant C mill tailings and contaminated soil is removed on to the mine waste disposal site Jazbec above the mine. With the UMTRA decision matrix all three variants were evaluated and compared.

In the Zirovski vrh uranium mine several studies about environmental impact and remediation measures were made after the closure of the mine. In our study the results of these previous studies were used in the probabilistic approach to the factors of safety and confidence, seismic hazard analysis, hydrogeological models and in the economic evaluation. These results were interpreted in the way of UMTRA decision matrix parameters.

The calculation of the UMTRA decision matrix showed that staying in the location of the present mill tailings disposal site Borst is the best solution for the present state. According to the calculations and on the basis of the engineering judgement for the future after 1000 years variant B where the relocation of the mill tailings site into the mine is assumed as the best solution.

At the present stage of the knowledge in the Zirovski vrh uranium mine the UMTRA decision matrix is additional aid in the engineering judgement for the selection of mill tailings disposal site. For the similar evaluations in the future the UMTRA matrix approach must be modified. The parameters that separate various sites according to the regional characteristics in the areas with relatively small surface similar to Zirovski vrh must be checked.

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