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Natural risks and monitoring systems: Case study of the mining-industrial heritage objects of Karelia (Ruskeala Mining Park), Russia

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Abstract

Mine workings (open and underground) abandoned during the production process become part of the environment. These objects begin to degrade in accordance with ordinary processes occurring in nature. However, such developments are often of historical value and therefore become tourist sites. They pose a serious threat to the health and life of people visiting these tourist sites, if such workings were not initially processed to safe conditions. The paper considers an example of such an object – a marble quarry with elements of underground caves – the Ruskeala marble deposit, located in Karelia. In the middle of the XX century, it was abandoned, today the "Main" quarry is a monument of the historical and cultural (mining-industrial) heritage of the Republic of Karelia. Ruskeala Mining Park has collected all the risks of degradation inherent in such a natural site. The paper has proposed solutions for monitoring the sustainability of underground objects used as museum exhibits to ensure the safety of tourists visiting them.

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Природные риски и системы мониторинга: на примере объектов горнопромышленного наследия Карелии (Рускеальский горный парк), Россия

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Реферат

Горные выработки (открытые и подземные), заброшенные в процессе производства, являются тем не менее частью окружающей среды. Эти объекты начинают приходить в упадок (деградировать) в соответствии с обычными процессами, происходящими в природе. Однако достаточно часто такие выработки имеют историческую ценность и поэтому становятся туристическими объектами. Они представляют серьезную угрозу для здоровья и жизни людей, посещающих данные туристические объекты, если такие выработки изначально не были приведены в безопасное состояние. В статье рассматривается пример такого объекта – мраморный карьер с элементами подземных пещер – Рускеальское мраморное месторождение, расположенное в Карелии. В середине XX в. он был заброшен, на сегодняшний день карьер является памятником историко-культурного (горнопромышленного) наследия Республики Карелия. Рускеальский горный парк собрал все риски деградации, присущие такому природному объекту. Предлагаются решения по мониторингу устойчивости подземных объектов, используемых в качестве музейных экспонатов, для обеспечения безопасности посещающих их туристов.

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Introduction

The history of developing different types of marble discovered in the Ruskeala field is widely highlighted in literature, and is repeated in many publications and on several dozen websites[1] (*Севергин, 1805*; *Sobolevsky, 1839; Борисов, 1949*; *Сементовский, 1998*; *Беликов и др., 1998; Зискинд, 1989; Осколков, 1991*).

The place with the outcrops of beautiful marbles was discovered by Samuel Alopeus, and then in 1765, at the beginning of the reign of Catherine II, began to be developed as an industrial quarry.

In those days, five quarries were laid on the chosen area, where marble of several varieties was quarried with the help of gunpowder charges in small workings. It was divided according to its colors – ash gray, gray-green, white with gray veins and white-blue-gray. Up to five hundred inhabitants of the surrounding villages were engaged in the excavation and transportation of stone.

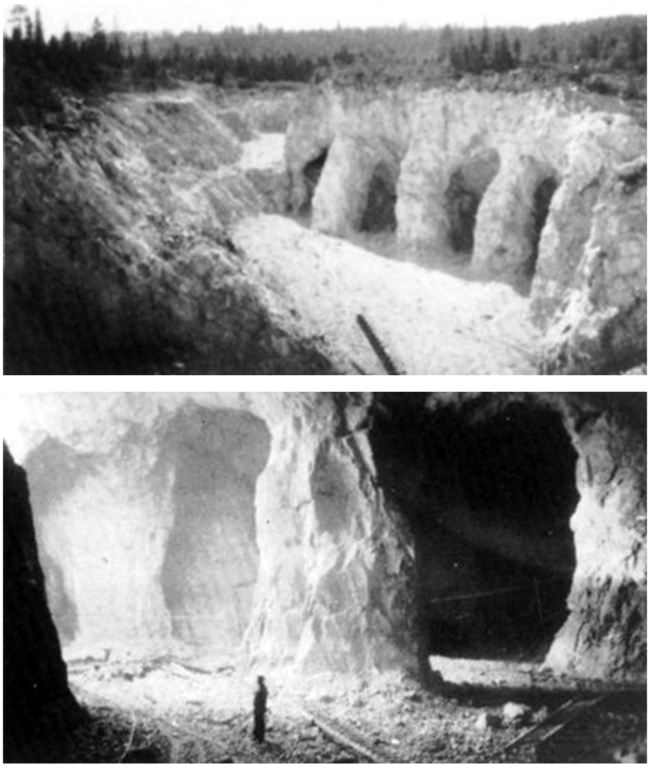

Fig. 1. View of the nineteenth century quarry – the upper photo. Below – an underground marble development in Ruskeala in the middle of the XX century is represented (*Mining Road, 2014*)
Рис. 1. Фото вверху – вид на карьер XIX в., внизу – подземная мраморная выработка в Рускеале середины XX в. (*Mining Road, 2014*)

The widespread use of Ruskeala marble in the historic buildings of Saint Petersburg and its suburbs has brought this stone great fame. Isaac's Cathedral, revered by some experts as a museum of stone, has been completely faced with Ruskeala marble; it was also used to line the floors of the Kazan Cathedral, to make the windowsills of the Hermitage and frame the windows of the Marble Palace and the frontage of the Mikhailovsky Castle.

In the middle of the twentieth century, Ruskeala marble was used to face the underground stations of the St. Petersburg Metro "Primorskaya" and "Ladozhskaya", where it is now available for careful study, because, unlike the open areas, where marble was used for exterior decoration and has largely decayed and lost its polishing over the past time, in these stations the walls have been preserved, demonstrating the beautiful stone texture.

In 1846, sawing and grinding plants using water-powered devices were put into operation; after that, the number of workers employed in breakdowns reached eight hundred people.

From 1939 to 1947 the quarry did not work. Production at the marble and lime plant was resumed in 1947 and operated on a small scale until the early 1990s. In 1998, the main quarry of Ruskeala marble was accepted into state protection as a cultural heritage site.

In 2004, Kolmas Karelia LTD carried out measures to develop and improve the "Main" quarry: fences, stairs and bridges were installed, trails were erected, a parking lot was organized, the territory of the park and the Marble Lake area was cleared of debris.

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[1] "Рускеала". Горный парк : сайт. URL: https://ruskeala.ru/about ; Карьер мраморных ломок в пос. Рускеала // Объекты историко-культурного наследия Карелии : сайт. URL: http://monuments.karelia.ru/napravlenija-dejatel-nosti/populjarizacija/est-takoj-pamjatnik/kar-er-mramornyh-lomok-v-pos-ruskeala/.

In 2005, the Ruskeala Mining Park was established, which is a unique man-made natural and landscape-tourist site (Fig. 2).

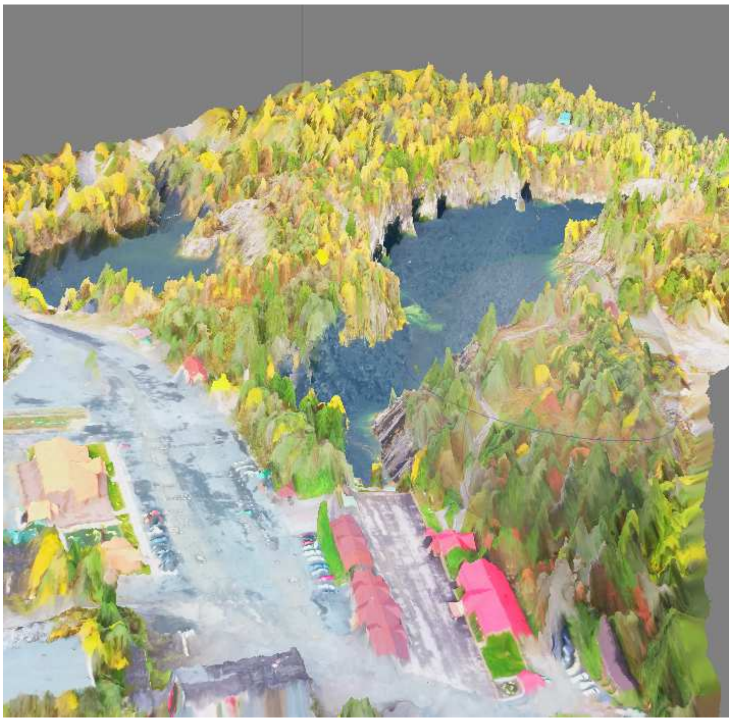

Fig. 2. The main quarry of the Ruskeala Mining Park today. View from the quadcopter (model created by V. Shekov)
Рис. 2. Главный карьер Рускеальского горного парка сегодня. Вид с квадрокоптера (модель В. Шекова)

The total length of the main quarry is 460 meters with a width of 100 meters.

From a geological point of view, the Ruskeala marble deposit is timed to the metamorphosed sedimentary-volcanogenic formations of the Pitkjaranta suite of the lower Proterozoic, represented by marbles that form the southwest wing of the anticline fold (Fig. 3).

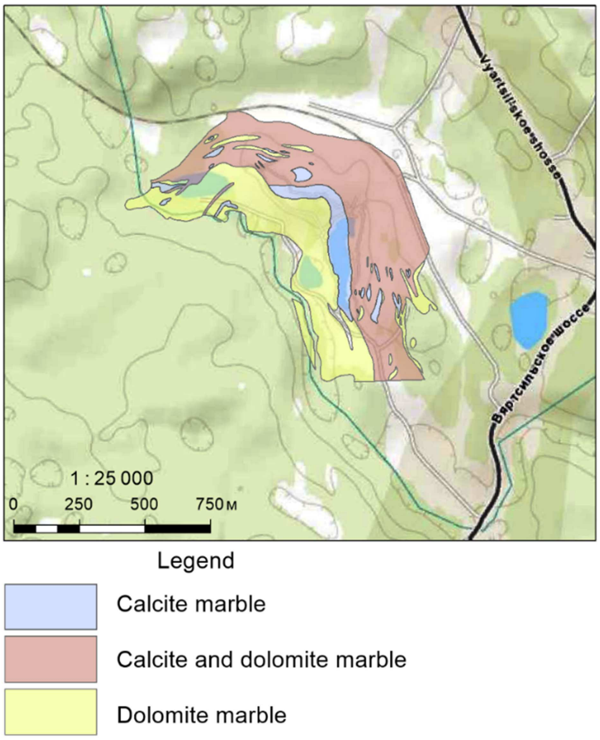

Fig. 3. Geological map of the Ruskeala field (*after A. Ivanov, 2019*)
Рис. 3. Геологическая карта Рускеальского месторождения (*выполнена А. А. Ивановым, 2019*)

Carbonate rocks form a lens-shaped deposit of 1.7 km long, with a width of up to 0.5 km in the southwest wing of the anticlinal fold. Carbonate thickness is divided into three packs: the lower pack with a width of 200–300 m of layered white and gray calcite and calcite-dolomite marbles; an average part of up to 80 m pure white calcite marbles; a top pack with a width of up to 200 m of gray and dark gray dolomite and calcite-dolomite marbles. In some places marbles are in varying degrees skarnished and contain silicate minerals: tremolite, actinolite, serpentine, pyroxene, quartz, and mica.

The coloration of marbles varies from dark gray and black due to the inclusions of the corner coallike matter to the snow-white, sometimes with bright green and yellow spots and stripes width from a few millimeters to 10–50 mm. The prevailing structure is thin- and fine-grained, the texture is layered, striped, sometimes spotted and flowing.

The mineral composition of marbles is heterogeneous and complex. Composition of calcite marbles: calcite – 80–100 %, dolomite – up to 10 %, quartz – up to 1 %. Dolomite and calcite-dolomite marbles contain dolomite – 65–100 %, calcite – up to 35 %, quartz – up to 10 %, silicate minerals – up to 15 %.

The field development system is completely correlated with the shape of the bodies of calcite marbles. If in the southern part of the deposit the extraction of marble was conducted in an open way, in the northern part, where the body bends sharply to the west, the development of the ore body was conducted underground.

Both open quarry and the underground part of the deposit are currently places of tourist interest. In recent years, the attendance of the Ruskeala Mountain Park has steadily increased, exceeding 300,000 people per year in 2019.

At the same time, there are risks on the territory of the park associated with an unprofessional assessment of the threats arising from the extraction of minerals, since the quarry and underground workings were not rehabilitated in due time and were not transferred to a safe state.

Materials and methods

The activities for the maintenance and control of the behavior of underground workings in parks and museums, in which they are used as "exhibits", are significantly different from the same activities that are carried out in existing mines and open pits. First of all, this is due to the absence of various kinds of dynamic operations (explosions, drilling) that affect the rock massif, the presence of professional personnel who are prepared for mining operations in workings and the financial capabilities that are higher for a mining enterprise has in comparison with a museum.

In this regard, the problem arises of ensuring supervision over the safe behavior of the massif in conditions when professional mining engineers and similar professional specialists cannot be used in the museum business due to their insufficient workload by profession and, accordingly, the impossibility of compensating for their work according to their qualifications.

The solution to this issue is the preparation of special regulations for monitoring the sustainability of workings based on simplified methods, which are within the power of non-professional staff in a museum environment under the control of a professional outsourcing company.

As such a regulation, it has been proposed to use a sequence of measures to ensure control over the safety of mine workings, based on visual, optical (laser), photogrammetric (lidar) control over deformations of the roof and walls in underground workings, and deformations of the walls of the quarries.

The aim of the work is to determine the periodicity of monitoring the stability of mine workings at different stages using various technical solutions.

The study of hazardous areas has been carried out mainly by a visual method with the study of cracks in massif, extracted from polygonal models (not considered in this paper).

The surveyed territories are recorded in photographs and presented in the form of polygonal models. The western side of the quarry (indicated by number 1 in Fig. 4) is a vertical cliff up to 30 meters high, part of which is hidden under water. Considering the instability of this kind of walls and its collapse prism, traces of previous collapse, it can be assumed that it is in a state where its collapse can occur at any time. Therefore, photographs were taken along the western side for further processing of materials by photogrammetry methods – to obtain models of the wall.

The western side of the quarry being a vertical cliff is the most popular place visited by tourists while walking through the park and at the same time it is the most dangerous one.

Figs. 5, 6, 7 show the conditions in which the rocks of this area are situated.

The east side is in a safe condition: the angle of inclination is 45–60 degrees and does not exceed the critical value. This ensures a steady and stable condition for most of the quarry east wall, where the risks of injury are eliminated by erecting fencing.

Photogrammetry investigations were taken at intervals of 1 year to assess deformities at the selected site. The results of comparing models of different years (Fig. 7) showed the nature of the visual movement of the array towards the quarry.

Brown color characterizes qualitative changes in the sides due to various deformations.

Fig. 4. Geography of Ruskeala Park (*Google Earth Photo*). North at the top;
1 – the west side; 2 – the east side; 3 – underground workings
Рис. 4. География парка Рускеала (фото Google Earth): север вверху;
1 – западная сторона, 2 – восточная сторона, 3 – подземные выработки

Fig. 5. Plot marked in Fig. 4 as number 1. View from the side of the quarry (photo by V. Shekov)
Рис. 5. Участок, обозначенный на рис. 4 цифрой 1. Вид со стороны карьера (фото В. Шекова)

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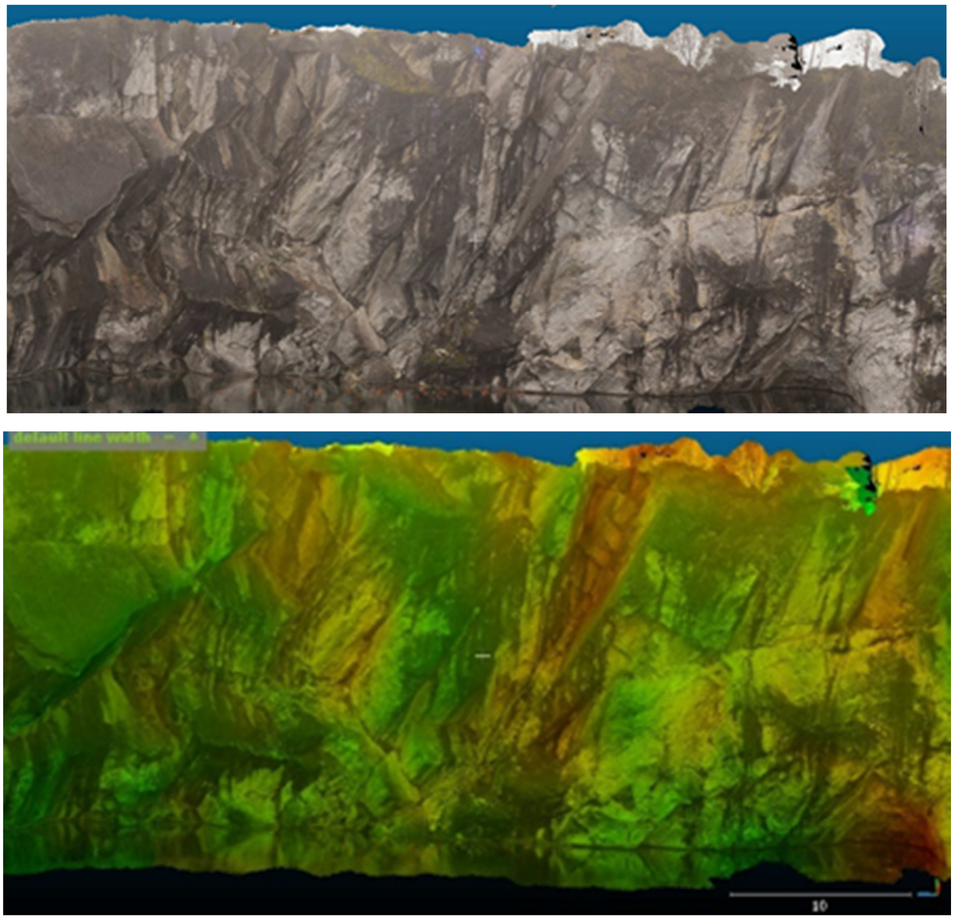


Fig. 6. Changes in the shape of the west side section of the quarry in one year.
In the top figure there is the result of the 2019 shooting, in the bottom – the result of comparisons between models obtained in 2018 and 2019 (model developed by V. Shekov)
Рис. 6. Изменение формы западной части карьера за год. Вверху – съемка 2019 г.,
снизу – результат сравнения моделей, полученных в 2018 и 2019 гг. (модель разработана В. Шековым)

A detailed survey of this site has shown that some of the rocks on board hang over the filled quarry and its stability is controlled by the strength of the rocks, as shown in Fig. 7, *a*, or due to the wall cracks shown in Fig. 7, *b*.

The areas shown in Fig. 7 are characterized by the fact that earlier in this place there were significant downfalls of pieces and blocks of different shapes and volumes. The remained shapeless pieces of varying volumes remain on the board of the quarry and their condition is currently undetermined. Some of them can collapse at any moment when significant loads appear on the upper edge, and some parts can be stable in the absence of loads (Fig. 8). The situation is aggravated by the presence of systemic cracks falling at the angle of 45–50 degrees towards the lake, along which some large pieces of the massif have already fallen earlier.

The area represented in Fig. 7, *b* from the western side is the remnant of the downfallen block (the place is highlighted by a black rectangle), which is sandwiched between two cracks. The right crack at the top deflects slightly giving a wedge shape to the clamped block. In the lower part of the structure, breakaway pieces are visible, jamming the bulk of the stone hanging over them. The structure is in an extremely unstable condition and can collapse at any time if small pieces holding the overhanging block fall out.

The unstable part of stone is dangerous for visitors, especially for those who constantly approach it. From the side of the tourist trail, this part looks safe, and this can deceive visitors.

On our recommendation, it was strictly forbidden to approach this slope for visitors. Later, the castle stone was removed and the entire structure hung on it was collapsed managed with the removal of hanging blocks, as shown in Fig. 9. However, the collapsed mass revealed another problem – the crack along which this block is adjacent to the wall. In the block itself, you can see the cracks caused by stretching, which could be opened unpredictably. The hanging block should be dismantled and brought down into the lake as soon as possible.

a

b

Fig. 7. Overhanging parts of the rocks are in a threatening condition: *a* – the protruding ledge; *b* – a wedged part of the blocks being in an unstable state, the rectangle shows the locked part of the structure (*photo by V. Shekov*)

Рис. 7. Выступающие части скал, находящиеся в угрожающем состоянии: *a* – выступающий уступ; *b* – клиновидная часть блоков, находящихся в неустойчивом состоянии, прямоугольником выделена заблокированная часть конструкции (фото В. Шекова)

Fig. 8. The overhanging stretch of rock shown in Fig. 7, *b* from a different angle (photo by V. Shekov)

Рис. 8. Нависающая часть пород, приведенная на рис. 7, *b*, с другого ракурса (фото В. Шекова)

In the left side of Fig. 9, the overhanging "visors" of rock with unspecified stability are clearly visible.

Fig. 9. The result of the collapse of the hanging parts of the site (shown in Fig. 7) (photo by V. Shekov)
Рис. 9. Результат обрушения свисающей части площадки (рис. 7) (фото В. Шекова)

It has been found that within one year deformations accumulate in the workings of the Ruskeala Mining Park and some sections are moved, moreover they can collapse in the future. Nevertheless, during an year they are quite stable.

This approach based on modeling the walls, assessing their fracturing and deformations makes it possible to identify the most dangerous areas with an interval of at least 1 time per year. In the interval between these procedures, it is necessary to control the behavior of cracks by other methods.

Studying the condition of the quarries the underground part of the Ruskeala Mining Park has been examined as well.

The underground part of the Park includes two galleries with a total length of about 180 m leading to a large marble hall with powerful pillars (Fig. 1, the right picture) up to 20 m height which by two-thirds of their height are hidden under the water.

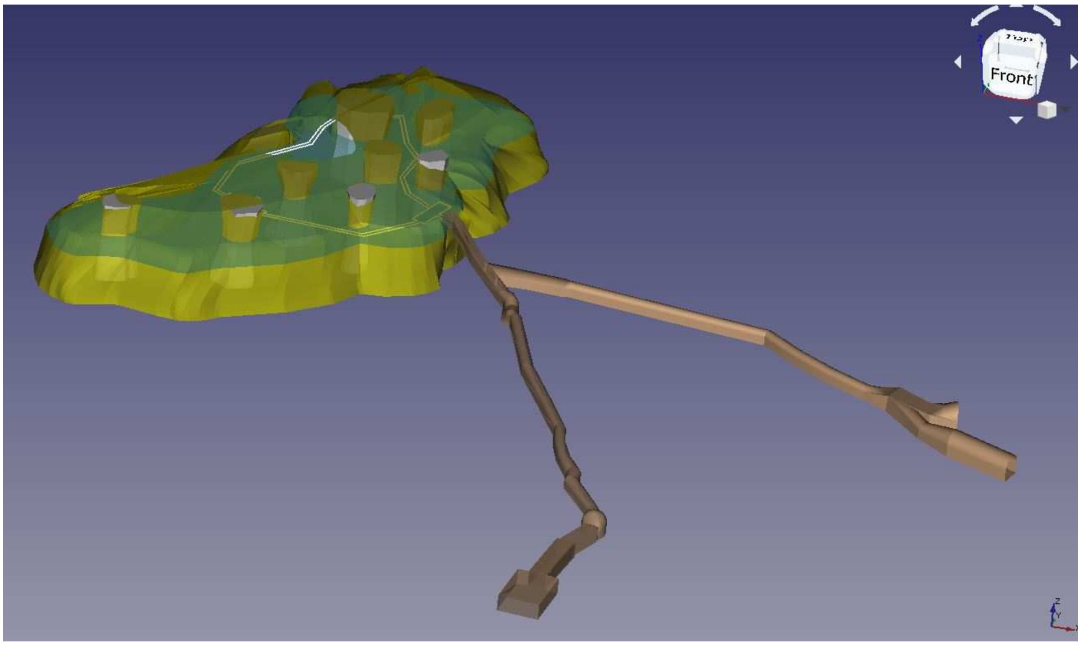


Fig. 10. Model of the underground space of the Ruskeala Mining Park (model prepared by V. Shekov)
Рис. 10. Макет подземного пространства Рускеальского горного парка (модель В. Шекова)

The route begins in the left gallery, then visitors follow to the marble hall with spectacular lighting and music; in winter time there is a collection of ice figures.

Visual examination of the walls and roof of the underground space has allowed reveal several areas which can pose a danger to visitors.

As an example, a visitor can distinguish the area located in the right gallery (Fig. 11) at the exit of the underground route. Here, the arched entrance is broken by various systems of cracks, which lead to the appearance of dangerously overhanging monoliths, weighing 300–400 kg, located directly above the route, as shown in Fig. 12.

Fig. 11. Fragment of the marble hall with the pillar and the path for tourists, the actual height of the pillars is shown in Fig. 1. The water is frozen (photo by V. Shekov)
Рис. 11. Фрагмент мраморного зала с колонной и тропой для туристов, фактическая высота столбов показана на рис. 1. Вода полностью замерзла (фото В. Шекова)

Fig. 12. The character of the cracking on the site adjacent to the exit of the gallery (photo by V. Shekov)
Рис. 12. Характер трещиноватости на участке, примыкающем к выходу из галереи (фото В. Шекова)

The movement of one monolith has been detected by a laser device, the network of which is used in the Ruskeala Mountain Park to monitor the stability of the array and the threat has been eliminated. The operation of laser devices will be described in more details below.

Results and discussion

As a result of the work carried out by the Institute of Geology of the KRC RAS in the Ruskeala Mining Park, several recommendations have been developed to reduce the risk for tourists visiting the park areas depending on the location of the places that pose danger.

The requirements for such a regulation have included improving the quality of control measures at various levels when using financially optimal solutions. As a result, the content of the measures includes: 1) daily visual control, 2) periodic instrumental control, and 3) annual full control based on polygonal models. The regulations are drawn up in the form of a schedule for performing regular measurements (examinations) with the appointment of persons responsible for this procedure.

1. **Daily control** includes regular visual inspection of the state of mine workings with documentation (photographing), if necessary, of individual sections that can be deformed in the course of various local influences and, above all, freezing – thawing processes that occur in the autumn and spring periods. Based on the results of the inspection, measures are taken to localize threats (e. g. to prevent tourist access), if any are found.

2. **Periodic instrumental control** – includes various systems for observing the behavior of workings. As part of such a control, the use of laser rangefinders was developed, patented and recommended to control inaccessible areas. This technique allows quickly identify the movements of individual parts of the workings and respond promptly and flexibly to various deformation processes in the rock mass.

The most important property of this method is the simplicity of the device itself and its use. This simplicity makes believe that the regular use of this device is possible by the staff of the museum (park) with a periodicity established empirically under the control of an outsourcing company. Problematic areas for monitoring the stability of rocks are established based on the results of regular photogrammetric surveys (with a frequency of no more than once a year for the conditions of Ruskeala Mountain Park), with a number of related geotechnical measures.

The Institute of Geology KRC RAS has proposed a patented device (*Shekov et al., 2018*). It is to install a laser rangefinder on a specific point (Fig. 13). Regular measurements of the distance from point 1 to controlled point 5, as shown in Fig. 13, make it possible to track possible surface movements and take measures to eliminate emerging threats.

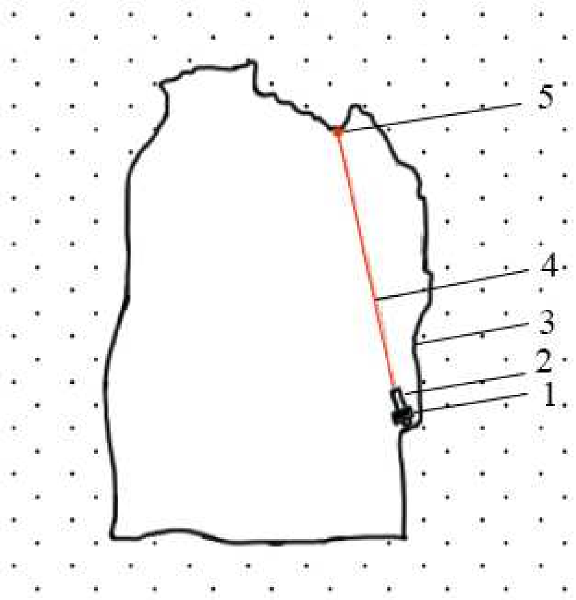
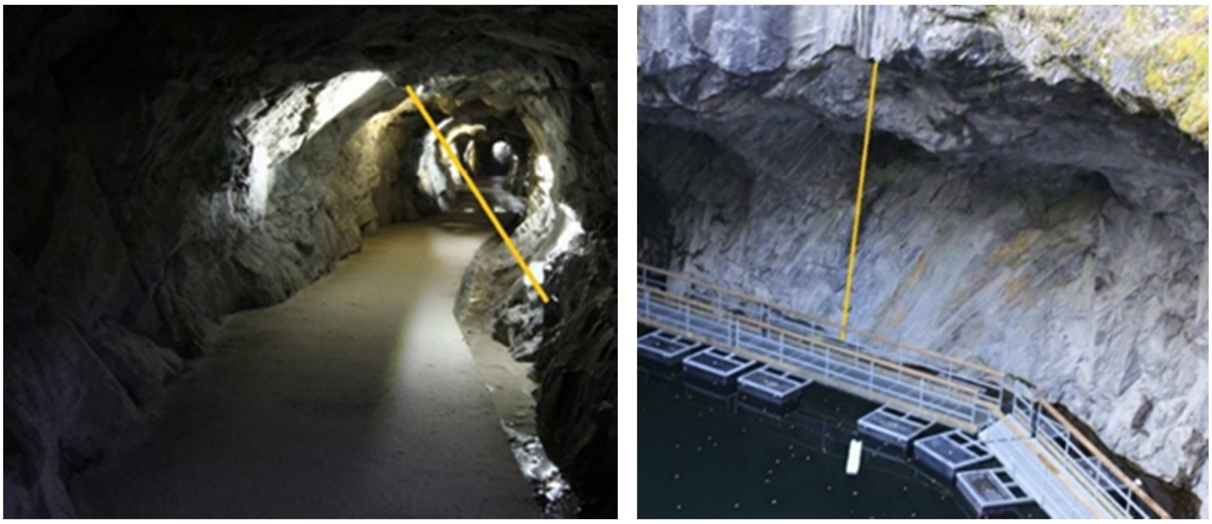


Fig. 13. Installation diagram of a laser rangefinder with subsequent measurement of the distance between specific point 1 and controlled point 5. 1 – the metal screw embedded in rock; 2 – the rangefinder; 3 – the wall of the underground tunnel; 4 – the laser beam; 5 – the controlled point

Рис. 13. Схема установки лазерного дальномера с последующим замером дальности между репером 1 и контрольной точкой 5: 1 – металлический винт, врезанный в породу (репер); 2 – дальномер; 3 – стена подземного тоннеля; 4 – лазерный луч; 5 – контрольная точка

A feature of the proposed method is the patent formula, which allows using one rangefinder with a special mechanism for installing it on the special base to provide tens and even hundreds of observation points. The device is designed in such a way that when it sets on a base, it always indicates the point whose mobility is controlled. This significantly reduces the cost of conducting observations, which can be performed by one person, even not very highly qualified (including conducting visual examinations) during the work shift. The frequency of measurements is selected based on current conditions and is determined over a long period of time. For Ruskeala Mountain Park it has been recommended to carry out such measurements once every 3–4 weeks.

In Fig. 14, *a* – the length of the laser beam is about 2 m, in Fig. 14, *b* – the laser beam length reaches 8 m. The distance to control is determined by the rangefinder range and the accuracy of the measurement. Modern laser rangefinders provide up to 1 mm accuracy in devices that cost less than $100 and applied for up to 100 meters.



a *b*

Fig. 14. Examples of measurements in various conditions in underground workings
Рис. 14. Примеры измерений в различных условиях в подземных выработках

For small distances in open areas, it is possible to use a modified measurement method, here it is uses two metal screws embedded in the rock, as shown in Fig. 15.

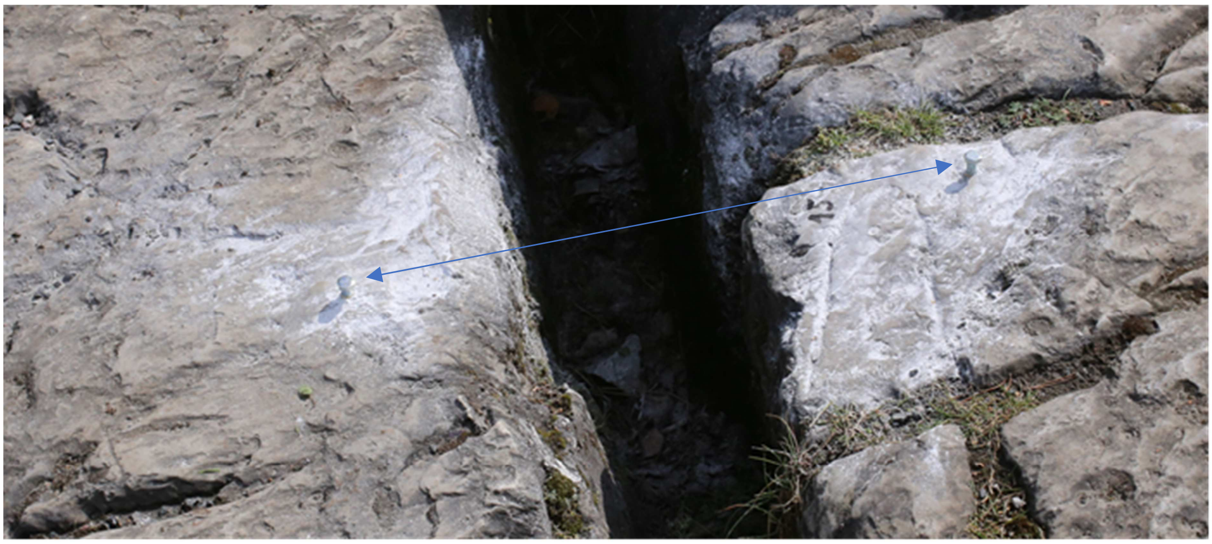


Fig. 15. Scheme to install metal screws embedded in the rock for measurements with laser devices
Рис. 15. Схема установки металлических саморезов (реперов) в скале
для измерений лазерными устройствами

To control the cracks, two metal screws are embedded in rock on both sides (two bolts with a hexagonal head are placed in the rock) and two side faces of the head are oriented on both bolts parallel to each other.

After that, the procedure for taking the distance readings between these metal screws will consist of using any (preferably of high accuracy) laser rangefinder, one end (heel) which will be mounted on the side of the head of one metal screw and will measure the distance to the side face of the head of another metal screw, thus fixing the expansion of the crack or if necessary – the ensembles of cracks, as it is shown in Fig. 16.

Fig. 16. Measuring the distance between two metal screws set to control crack expansion parameters
Рис. 16. Измерение расстояния между двумя металлическими винтами (реперами), установленными для контроля параметров расширения трещин

3. **Annual full control** can be carried out using photogrammetric survey once a year and is a cheap solution to control the shape of workings with the emphasizing of "mobile" zones prone to collapse. For the same purposes, it is possible to use lidar surveying with the same periodicity, which will be a more expensive solution. This method makes it possible to predict the appearance of areas that are in unstable conditions, as well as to evaluate the geotechnical parameters of the massif taking into account its fracturing.

For Ruskeala Mining Park, polygonal models of the walls of quarries and underground workings are documented and prepared. They allow use this method to control changes occurring in the massif surrounding the mine workings after a certain time.

Conclusion

The work on the selection of optimal solutions for monitoring the safety of mining objects operated as museum territories and exhibits has been permitted the author to offer a simple and effective method for monitoring hazardous phenomena: break downs, collapses, destruction of stone objects. This approach makes it possible to prevent threats arising during the stay of tourists at these territories in the most effective way.

Routine measures to prevent hazardous situations in mining museums include three stages of preparation:

1. Photogrammetric and engineering-geological survey of mining infrastructure facilities with the emphasizing of "suspicious" places by an outsourcing company at intervals of one year or more.

2. Installation of special reference points at the "dangerous" allocated places in order to monitor periodically their "mobility" (at intervals from 1–2 days to several weeks) with laser rangefinders. For Ruskeala Mining Park, the periodicity of 3–4 weeks has been established. When hazards arise, solutions to eliminate them are applied based on cooperation with an outsourcing organization.

3. In addition to the indicated instrumental observations, it is necessary to organize daily visual monitoring of controlling areas in the territory where both tourists and museum personnel can occur.

Compliance with such regulations at mining facilities used as museum objects will significantly reduce the threats to the stability of the mountain space even by the efforts of the company itself without using unjustified increased costs for this procedure.

Various natural disasters, whether they are related to the forces of nature or caused by any human activity, are united by only one factor: this is elementality. This means that if humanity does not pay attention to these events, then they can bring a lot of trouble.

The only correct solution in such situations is to monitor the causes of such natural events, study their mechanisms, and predict the likelihood of their happening. Thus, we will be able to transfer these events from the category of elemental to the category of controlled.

The paper proposes various methods and measures to reduce risks when using mining and industrial heritage sites for tourism purposes.

As part of the development of requirements for documenting underground workings used for tourism purposes, the idea of documenting underground and open mining workings based on creating full-scale polygonal models with the help of photogrammetry technology has been proposed. This will allow one to track the deformation changes in the surrounding areas over time.

For small distances not exceeding the first tens of meters, the technology of controlling the movement of the rock parts with the help of laser devices of small cost has been developed. This makes it possible to control large rock masses at a low cost.

Daily visual inspection is a standard requirement for inspection activities in all mine workings.

The paper provides methodical techniques and modes when assessing the possibility of applying underground mines to use it as tourist sites. The foundations for monitoring the sustainability using workings in the process of their application for non-mining purposes have been laid.

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Conflict of interests

The author declares no conflict of interest.

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