Design of Underground Laboratory Prototype complying requirements and best practices in deep copper mine conditions

Baltic Sea Underground Innovation Network (BSUIN)

Interreg Baltic Sea Region
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KGHM CUPRUM Research and Development Centre

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Abstract	Underground laboratories provide a unique environment for various industries and are the perfect place for developing new technologies for mining, geophysical surveys, radiation detection, as well as many other studies and measurements. Unfortunately, working in underground excavations is associated with exposure to many hazards not necessarily encountered in surface laboratories. In result, most of the underground working, which was left i.e. after mining activities, has been abandoned or flooded with water. Nevertheless, fruitful cooperation within BSUIN project proved that there are many possibilities of further reuse of post-mining underground excavations. Such activities may be implemented especially in Polish Copper mines where both infrastructure and environmental conditions are suitable for setting up of non-mining activities. In the present document, the development of Underground Laboratory Prototype complying requirements and best practices were presented.

List of Abbreviations	
H&S	Health and Safety
UL	Underground Laboratory
FEM	Finite Element Method
LEM	Limit Equilibrium Method
FDM	Finite Difference Method
SF	Safety Factor
PPE	Personal Protective Equipment
AED	Automated External Defibrillator
3-D	Three dimensional
WP	Work Package

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1. CONTENT OF PRESENT DOCUMENT

1.1. Document justification

The present document is a part of the project BSUIN work package four (4) outputs related to Health and Safety in laboratories. The conceptual models of Underground Laboratory, with respect to safety requirements (A.4.2) and best practices (A.4.1.) are presented, what is one of the promised outputs of WP4.

1.2. Content description

Underground environment is a very specific and, from the science and research point of view, very valuable place. Mostly due to unique conditions which cannot be met in other branches of industry, and rather cannot be simulated due scale of loads, variables of parameters etc.

Still, most of the underground mines, due to local reclamation regulations are filled by the earth, water or even forced to collapse, to minimise the post-impact of mining activities.

Within the scope of WP4 of BSUIN project, two prototypes of the underground laboratory were taken into consideration. The first type, called as the small-scale laboratory, describes the feasibility study of the construction of a single chamber for the purposes of Geophysical research, astrophysical research etc. The second type called a large-scale laboratory describes the possibility of setting up the trial mining panel, in the area of waste rock or rock with a small content of valuable minerals. Such an object will allow developing new mining technologies, testing new monitoring systems in in-situ conditions, and will be a good place for the training of students and new employees.

2. BSUIN PROJECT

The BSUIN project aims to make the underground laboratories (UL) in the Baltic Sea Region more accessible for innovation, business development, and science by improving the information about the underground facilities, the operation, user experiences and safety.

Baltic Sea Underground Innovation Network (BSUIN) is a collaboration project between 14 partners from 8 Baltic Sea Region (BSR) countries. In addition to the project partners, 17 associated partners contribute to achieving project goals. BSUIN includes five existing underground laboratories around the BSR. Moreover, one UL prototype will be developed within BSUIN activities. During the project, the ULs will be characterized both from infrastructural and operational points of view. As a result, the UL's within the network will be more appealing to potential customers, providing important practical and preliminary information on the location and services. The UL's are looking to attract customers, to develop innovative activities and increase the usage of these underground laboratories.

The main outcome of the project is to create a sustainable network organization, which will collect, describe, and distribute knowledge on designing, building, and maintaining of these kinds of facilities.

Project is funded by Interreg Baltic Sea funding cooperation. Its duration is 36 months, with a total budget of 3.4 M€.

3. SITE DESCRIPTION

Design of Underground Laboratory Prototype was prepared under the conditions of the underground copper mines in Poland. Concept of the UL assumes its location in the underground space within active copper mine with all applicable implications connected with the exploitation process and local geotechnical conditions.

KGHM is one of the biggest copper producers in the world with assets located in Europe, North and South America (Figure 3.1). In Poland, KGHM operates in three underground copper mines (Polkowice-Sieroszowice, Rudna and Lubin) located in Lower Silesia Voivodeship in South-West part of the country. Annual copper ore production exceeds 30 mln tons which allow producing ca. 500,000 tons of pure copper.

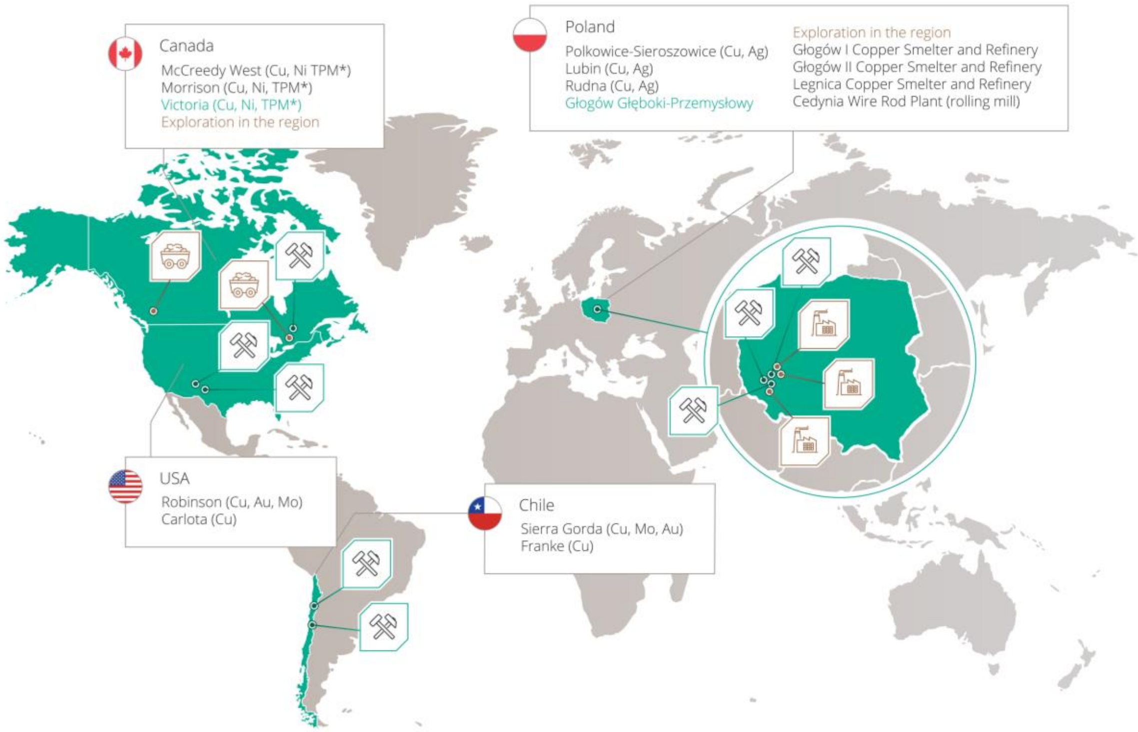


Figure 3.1. KGHM operations in the world (www.kghm.com)

Due to geological ore structure, there is used room-and-pillar mining method with blasting (Figure 3.2). Process of extraction is fully mechanized by suitable machines that dimensions are adjusted to the workings. In some areas machines with 1.4 m height are used.

Nowadays depth of exploitation reached 1,200 m below surface level. The mine is still under the development of the mining method at greater depth. Continuously geotechnical observations and analysis helped gather detailed knowledge of rockmass behaviour and allowed to select the best place for potential laboratory. It's worth to mention that besides of main mining process which is focused on copper extraction, there is also small exploitation of rock salt. Salt deposit is located above the copper ore layer.

For this study, the Polkowice-Sieroszowice mine, owned by the KGHM Polska Miedź S.A., was chosen as a most suitable location.

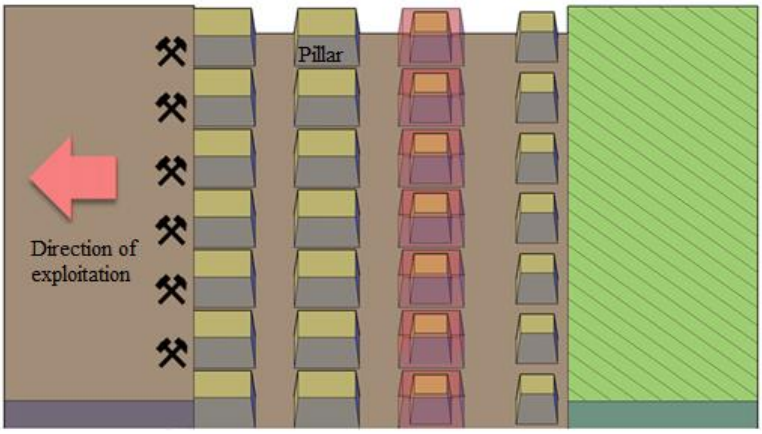


Figure 3.2. The basic scheme of Room-and-Pillar mining method

3.1. Polkowice-Sieroszowice mine

Polkowice-Sieroszowice Mine has been operated above 30 years. There are more than 4 000 employees. Total surface area is more than 175 km^2. Annual ore production reaches 11 mln tonnes. Polkowice-Sieroszowice Mine is located about 100 km North-West from Wrocław, which is the capital city of Lower Silesia area Voivodeship (Figure 3.3). This is an important centre of education and research institutes with ca. 700,000 habitants. There are also lots of innovative industries. In the city is located the international airport and railway station. An important advantage of the Polkowice-Sieroszowice mine location is a relatively small distance to the border of Germany and the Czech Republic. The nearest town named Polkowice is 3 km from the mine. In the closed neighbourhood (30 km) there are also three cities with hotels, hospitals and other infrastructure which can be potentially useful for cooperation with laboratory.

Figure 3.3. Location of Polkowice-Sieroszowice Mine

The Polkowice-Sieroszowice mine operates in four mining districts: Polkowice II, Radwanice Wschód, Sieroszowice I and Głogów Głęboki-Przemysłowy (Figure 3.4).

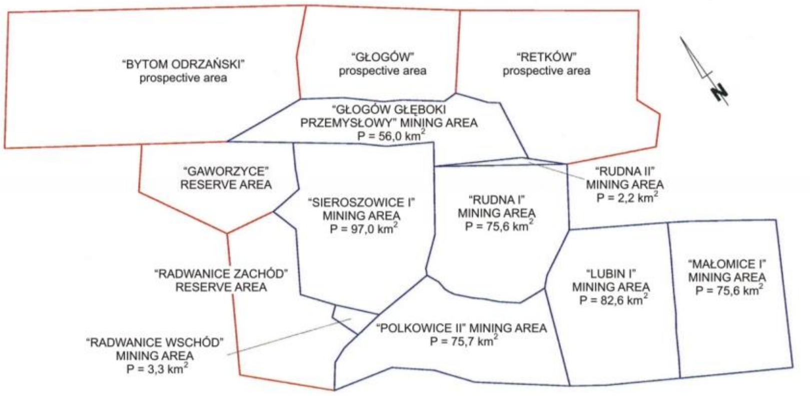


Figure 3.4. Mining districts boundaries

3.1.1. General geological conditions

The copper ore deposit in Poland was formed as stratoidal accumulations in sediments from the Fore-Sudetic Monocline. The geological profile includes the following types of rocks (Figure 3.5):

- fine-grain sandstone,
- clayey shale series,
- anhydrite series,
- rock salt,
- dolomite,
- carbonate series (dolomite, limestone, shale)
- copper ore seam,
- grey and red sandstone.

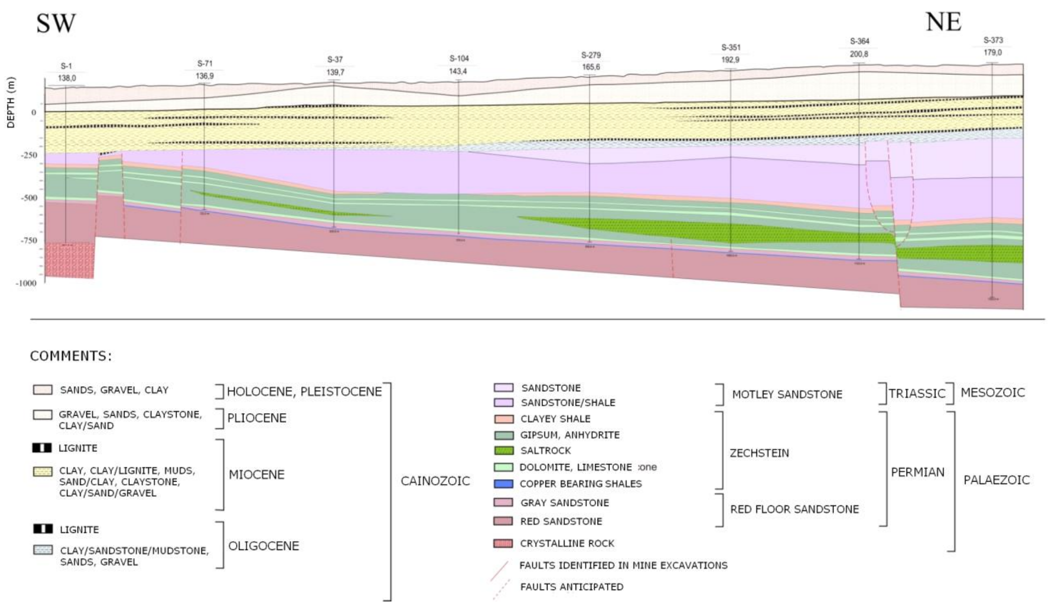


Figure 3.5. Geologic cross-section in Polkowice-Sieroszowice mine

Overburden strata above copper ore deposit including three main zones of different geological features which have a significant impact on the stress-strain state of the rockmass. Zones are characterized in Table 3.1. Location of zones at mining districts is shown in Figure 3.6.

Table 3.1. Characteristic of overburden strata

Zone name	Description
Central Zone	Zechstein formation of stiff dolomite-anhydrite strata of 160 – 220 m of thickness overlaid by 200-400 m Triassic sandstone
Northern Zone	Dolomite-anhydrite strata of 30 – 90 m with rock salt deposit and thick Triassic sandstone
Southern Zone	Glacial deposits on Zechstein formation, no Triassic sandstone

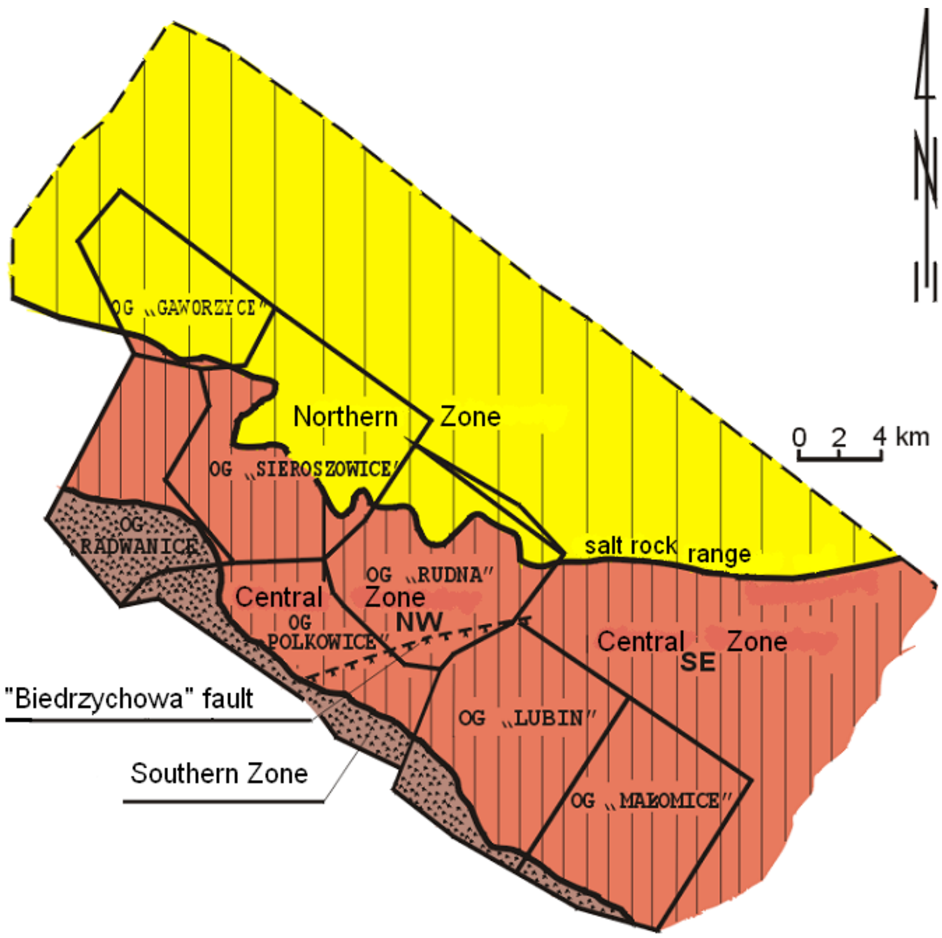


Figure 3.5. Overburden zones within mining districts

The copper-bearing deposit consists of sandstones, shales and carbonate rocks, especial dolomites (Figure 3.6). The thickness of the ore strata varies from 0.4 up to 26 meters. There are many different ore structures like nests, lenses, dissemination and others. Disseminated mineralization is the most popular and is typical for all varieties of ore. In the case of dolomites with copper mineralization, nest structure is the most common. At the current stage of ore exploitation, average copper strata thickness is less than 1.7 m with copper content ca. 2%. In total ore production carbonate rocks and shales represents ca. 77%, rest of ore (23%) it is sandstone.

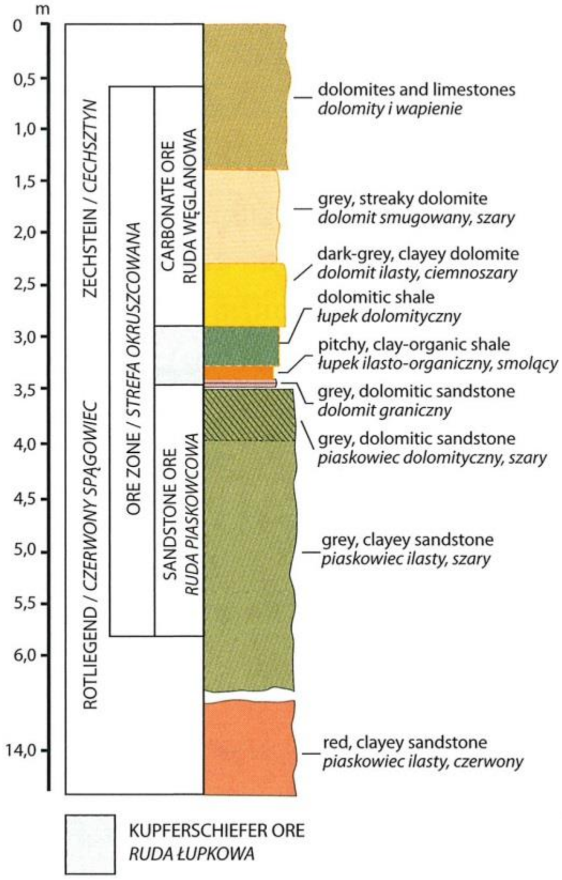
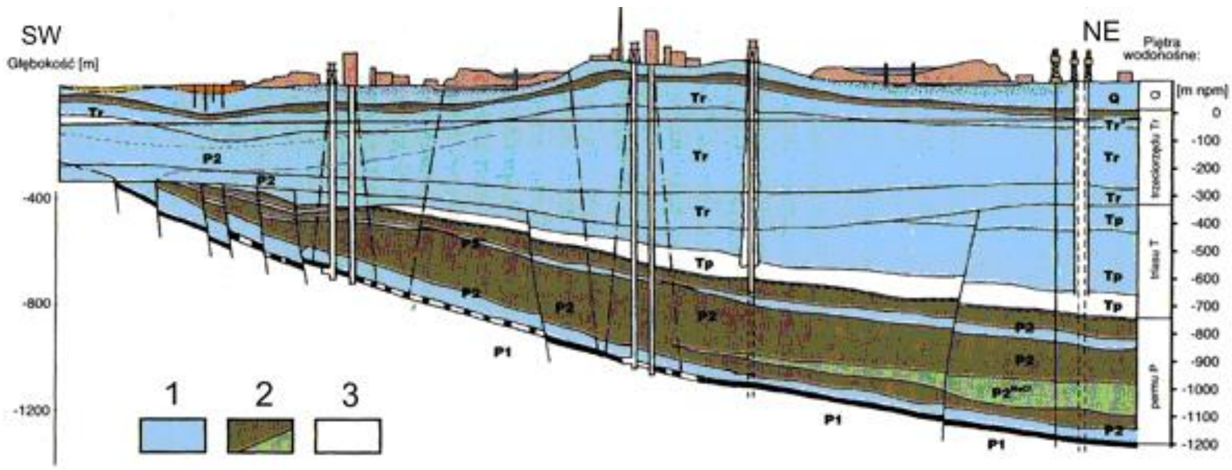


Figure 3.6. Copper deposit lithostratigraphy

3.1.2. Hydrogeology of the site

Hydrogeological strictures of Polkowice-Sieroszowice area are shown in Figure 3.7.



(1 – water deposits, 2 – impermeable deposits, 3 – impermeable but slightly saturated deposit)

Figure 3.7. Hydrogeological cross-section of copper ore

From the perspective of the potential location of the laboratories, there are dry areas isolated from the amplifier. This is important from the safety point of view. An example of this kind of area is a salt and anhydrite rock mass.

3.1.3. Existing infrastructures

3.1.3.1. Underground excavations

Long-time mining operation processes and size of mining areas results in hundreds of kilometres of excavations which are accessible and drive-able. An example of part of Polkowice-Sieroszowice mine geometry with transportation, ventilation and communication galleries are shown in Figure 3.8.

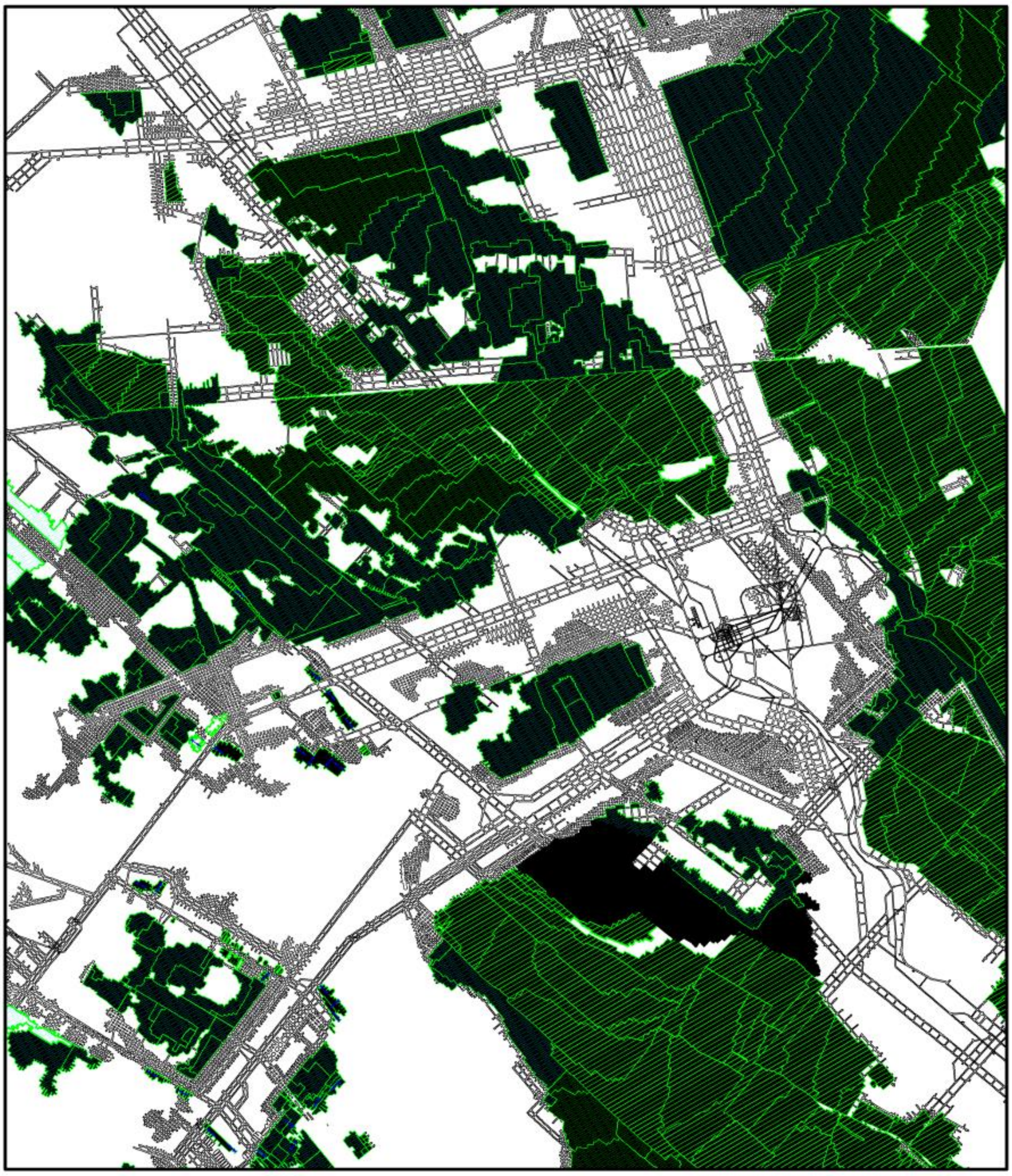


Figure 3.8. Map of a part of Polkowice-Sieroszowice mine

In most cases, galleries and roads have trapezoid shape, however, functional chambers like workshops may have different (in most cases rectangle) shape and size (Figure 3.9 and 3.10).

Figure 3.9. An example of a personnel transport station

Figure 3.10. An example of an underground workshop

Due to geotechnical condition, the ground support system is based on the rock bolts. More than 2 mln sets are used each year. In most cases, rock bolts are installed with a square grid of 1.5 x 1.5 m. The most popular length of rock bolts is 1.8 m.

3.1.3.2. Vertical transport

In the case of KGHM mines access to the underground workings is possible by shafts only. They have different functions and sizes like ventilation, transportation etc. Currently, all mines belong to the KGHM in Poland use 27 shafts (one is under construction) including 10 shafts in Polkowice-Sieroszowice mine. The diameter of the shafts are 6.5 m (older shafts) and 7.5 m (newer) and depth are varies from 650 up to 1,200 m. Depend on depth shaft consists of iron cast shells (soft and water-bearing layers), deeper parts have concrete lining usually (Figure 3.11).

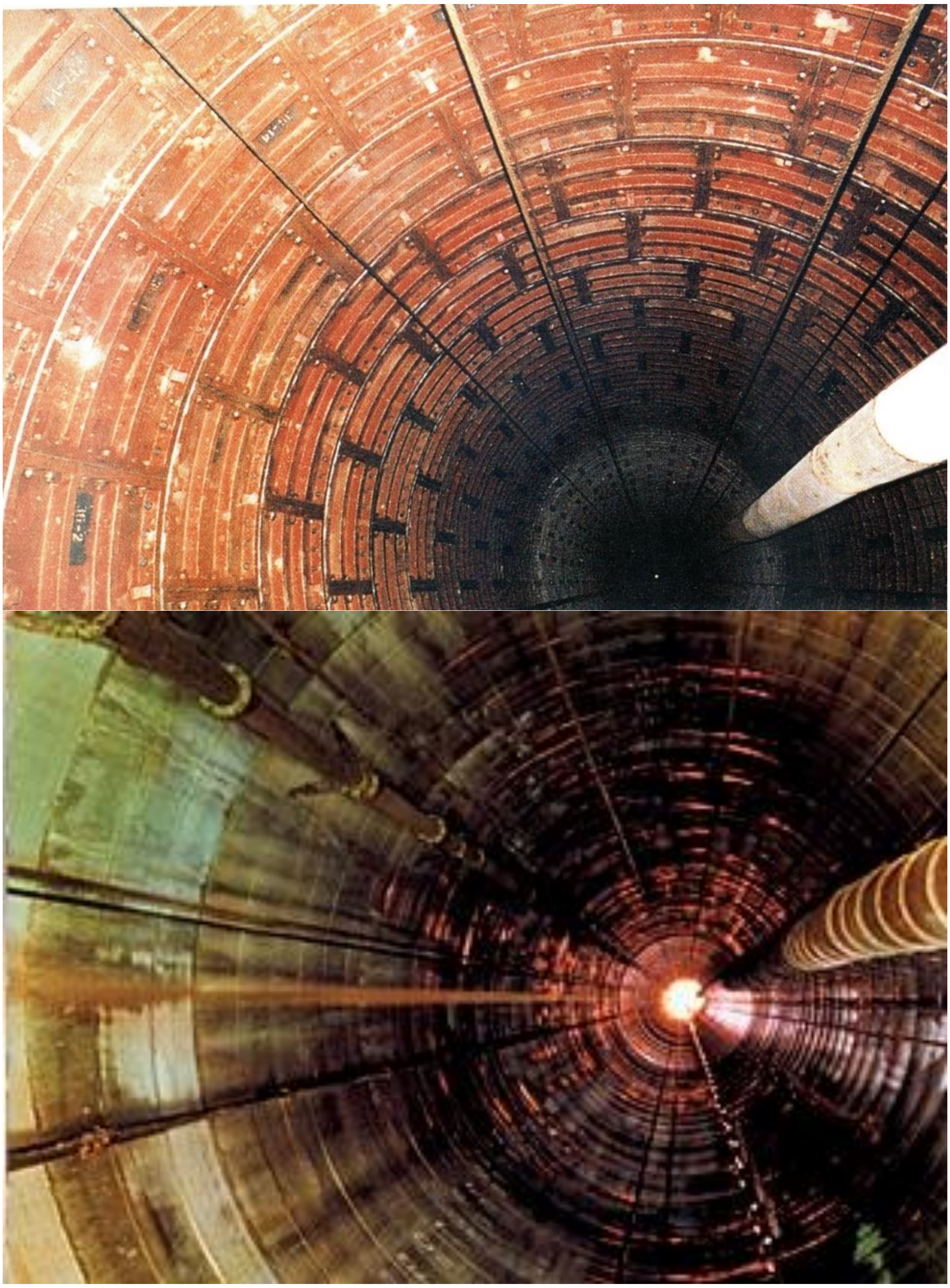


Figure 3.11. An example of the shaft with the iron cast (above) and concrete lining (down)

3.1.3.3. Ventilation and cooling

One of the crucial elements that must be fulfilled to provide safe ore exploitation in an underground mine is proper air quality, which must be breathable and with acceptable temperature. That is the main task for the ventilation and cooling system. This system has to provide the proper amount of fresh air that must be distributed into all staff accessible workplaces and remove all toxic gases comes from rock mass, machines and operation processes. The system is built with ventilation shafts, fans, ventilation galleries and dams. Scheme of the ventilation system in KGHM mines is shown in Figure 3.12. One of the ventilation units is shown in Figure 3.13.

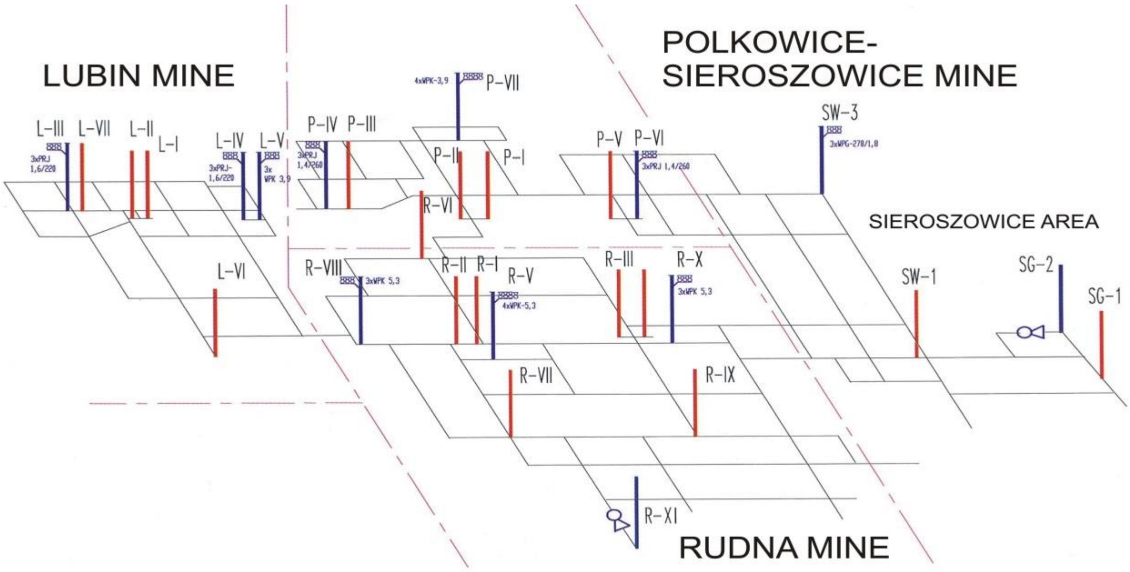


Figure 3.12. Simplified scheme of the ventilation system in KGHM mines

Figure 3.13. An example of a ventilation unit in Polkowice-Sieroszowice mine

The geothermal gradient in this area is about 35 m / 1 ˚C and at the depth of 1,200 m, below the surface, rock temperature is about 50–60˚C. The heat that comes from the rock mass and diesel machines heats up the air. It causes that in some cases air temperature is too high and must be lowered by means of an air condition system. The geothermal cross-section in the mine's overburden is shown in Figure 3.14.

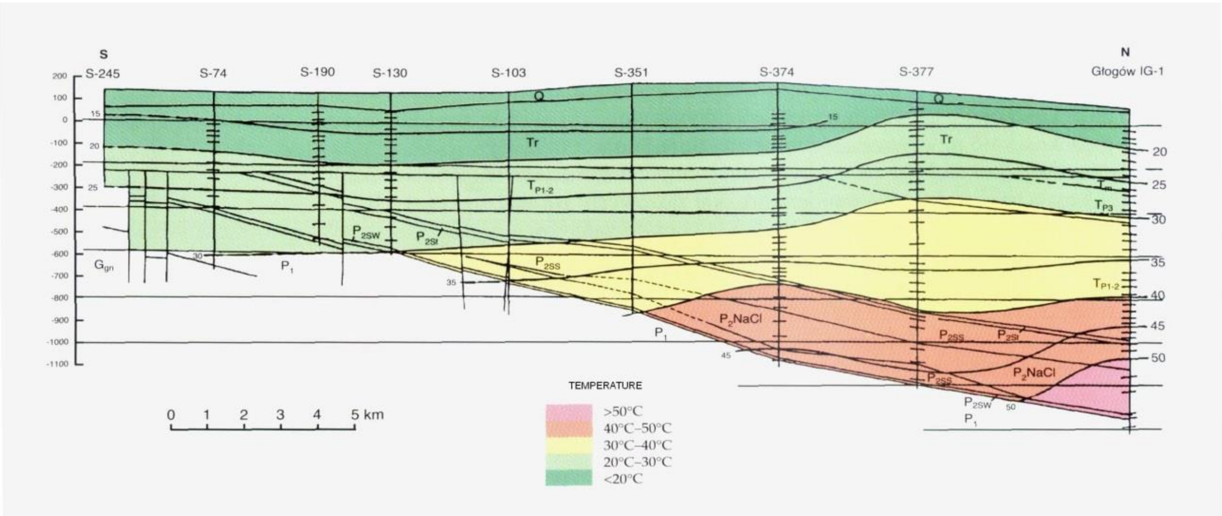


Figure 3.14. Geothermal cross-section of overburden in Polkowice-Sieroszowice area

3.1.3.4. Electricity and water supply

The mine has two independent sources of electric power supply with the automatic switch-on system. It ensures the reliability of the electric system and limits the risk of failure. There are typical voltages available underground from 6 kV to 230 V. By means of electrical devices electric parameters can be easily adjusted to the needs. An example of underground electric distribution station is shown in Figure 3.15.

Figure 3.15. Example of electric distribution station

The main parts of the electric system are electric power transmission lines, transformers and control systems with safety devices. There are available of undrinkable technological water in underground workings. Due to of hydrogeological condition in most cases this is saltwater. This water comes from the drainage water system.

Currently, drinkable water is available in form of bottled water supply from the surface. If there would be a need to supply drinking water in large amount there is the possibility to build a water treatment station or pipeline from the surface.

3.1.3.5. Rescue chambers

Safety system concerning the unbreathable atmosphere is based on the self-rescuer which all underground staff is equipped. This system is under development and rescue chambers are being implemented successively. Each of the chambers is prepared for 40 people and provides fresh air for 6 hours. Chambers are also equipped with a communication system and additional self-rescuers.

3.1.3.6. Mining drainage

Mining drainage system aims to remove water comes from rock mass and other processes. It is one of the crucial element in the underground safety system. The water drainage system consists of:

- water pipelines,
- drainage holes,
- pumps,
- water storages,
- water dams.

The capacity of the system must be adjustable to the standard local condition and additional be prepared to remove additional water in case of emergency. An example of pumps station is presented in Figure 3.16.

Figure 3.16. An example of an underground pump station

3.2. Technological Cycle

Copper ore exploitation using the room-and-pillar method with explosives requires at least five mining operations, namely: drilling of blastholes, loading of blastholes, blasting, ore transport and ground support building (Figure 3.17).

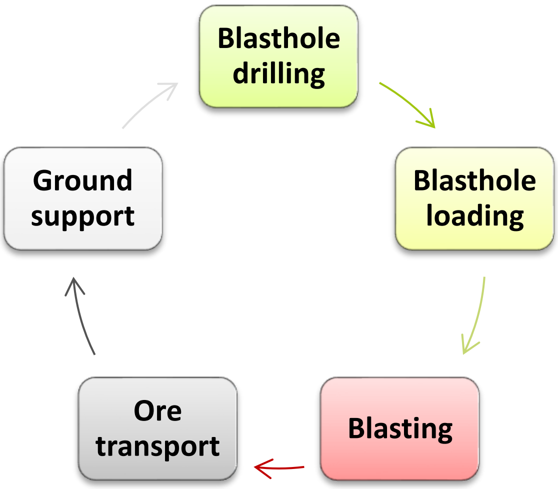


Figure 3.17. Technological cycle

Nowadays, all processes are mechanized using special machines. For example drilling of blastholes is done by means of a drilling rig (Figure 3.18).

Figure 3.18. An example of a drilling rig (Mine Master, 2020)

The most popular explosive is a bulk emulsion which is produced by moveable production unit in-situ (Figure 3.19).

Figure 3.19. An example of a bulk emulsion production unit (KGHM Zanam, 2020)

The rest of the operations are done by other special machines like loaders, trucks, rock bolting rigs. All these machines are developed to ensure safety for operators and a suitable level of productivity.

4. ANALYSED SCENARIOS OF UL CONCEPTUAL PROTOTYPE

Within the present document, two concepts of the underground laboratory were prepared and analysed (Figure 4.1). The first scenario consists of a case study of underground chamber development. This facility from the geomechanical point of view will disturb the geomechanical conditions mostly during the excavation process. Later on, after roof and wall support it is expected that stresses and strains will stabilise and geomechanical hazard won't change significantly over time.

The second type of facility is large scale laboratory for the development of new mining and tunnelling technologies, and suitable for conducting scientific activities in in-situ conditions. This type of facility is a unique one because it is assumed that the geometry of the trial mining panel may change over time. This will allow to analyse new blasting technologies, destress methods and bolting techniques, but at the same time, it may be expected that geomechanical hazard will vary over time. In such a case, the periodical risk assessment has to be implemented.

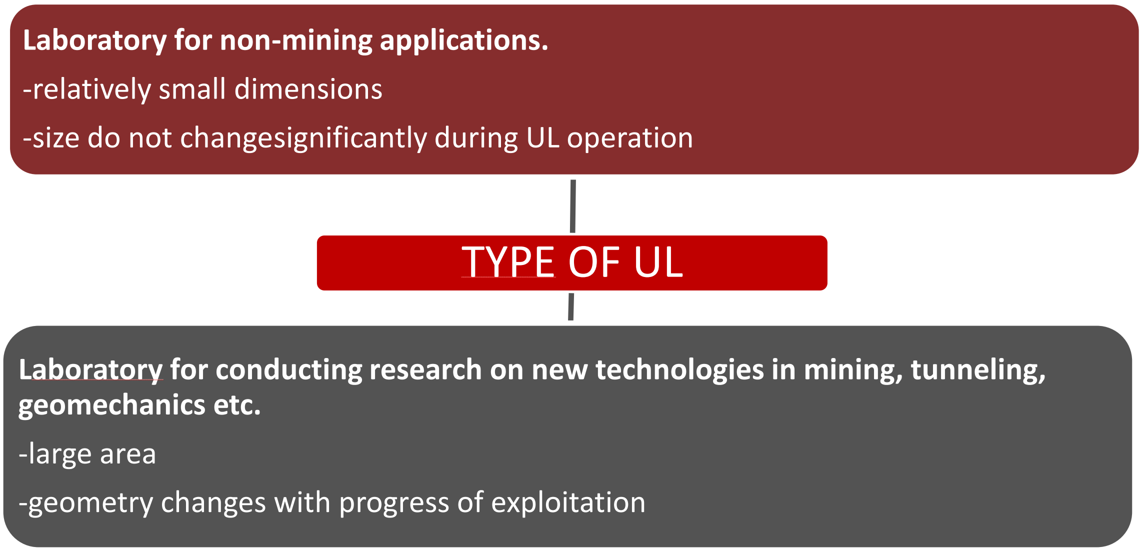


Figure 4.1. General assumptions related to both types of Underground Laboratory

4.1. Underground Chamber

4.1.1. Location and general layout

Potential location of underground laboratory took into consideration the following aspects:

- access to the site (shafts, existing workings, transportation routes, ventilation etc.),
- a rock layer with appropriate thickness and geotechnical parameters,
- hydrogeological conditions,
- low seismic activity,
- the acceptable temperature of the rock mass.

According to the assessment of all abovementioned issues selection of the location was done. The laboratory may be placed within anhydrite deposit at the depth 636 m close to the shaft (Figure 4.2).

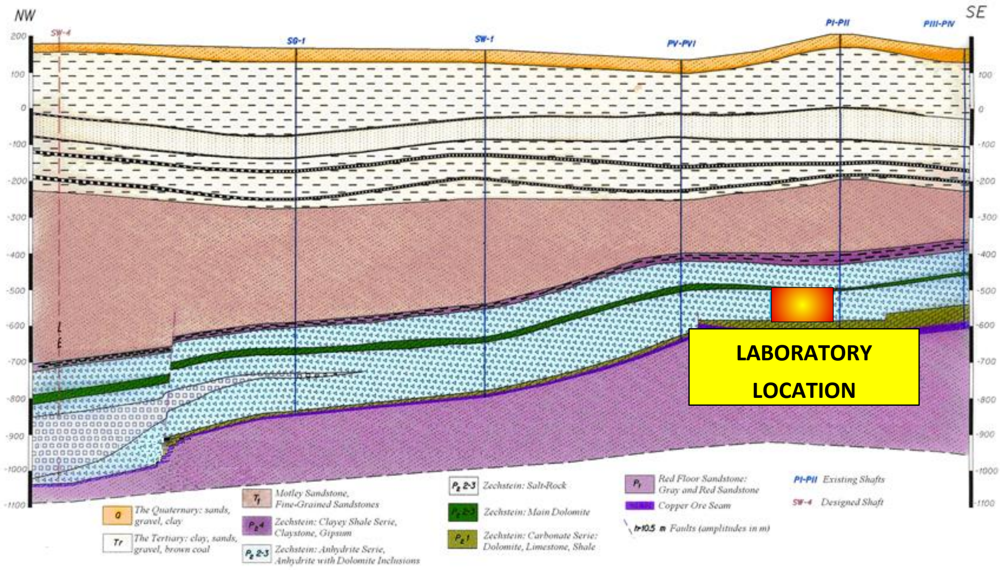


Figure 4.2. Overburden cross-section with the selected location of the underground laboratory

The laboratory will have a good connection to the ventilation shaft with a diameter of 7.5 m, which provide very good transport capacity and access to the other infrastructure (Figure 4.3). Shaft vicinity ensures a large area of unmined ore what is very favourable from the stability of the rock mass in this region.

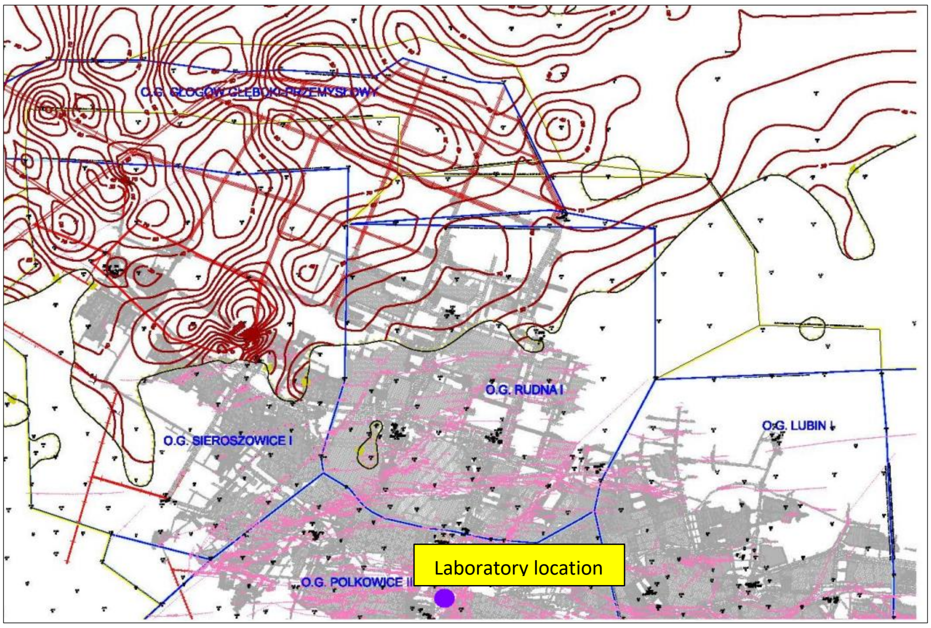


Figure 4.3. Selected laboratory location with anhydrite deposit thickness (brown lines)

The main chamber of the laboratory has a cylindrical shape with a diameter of 79 m and a height of 47 m (Figure 4.4).

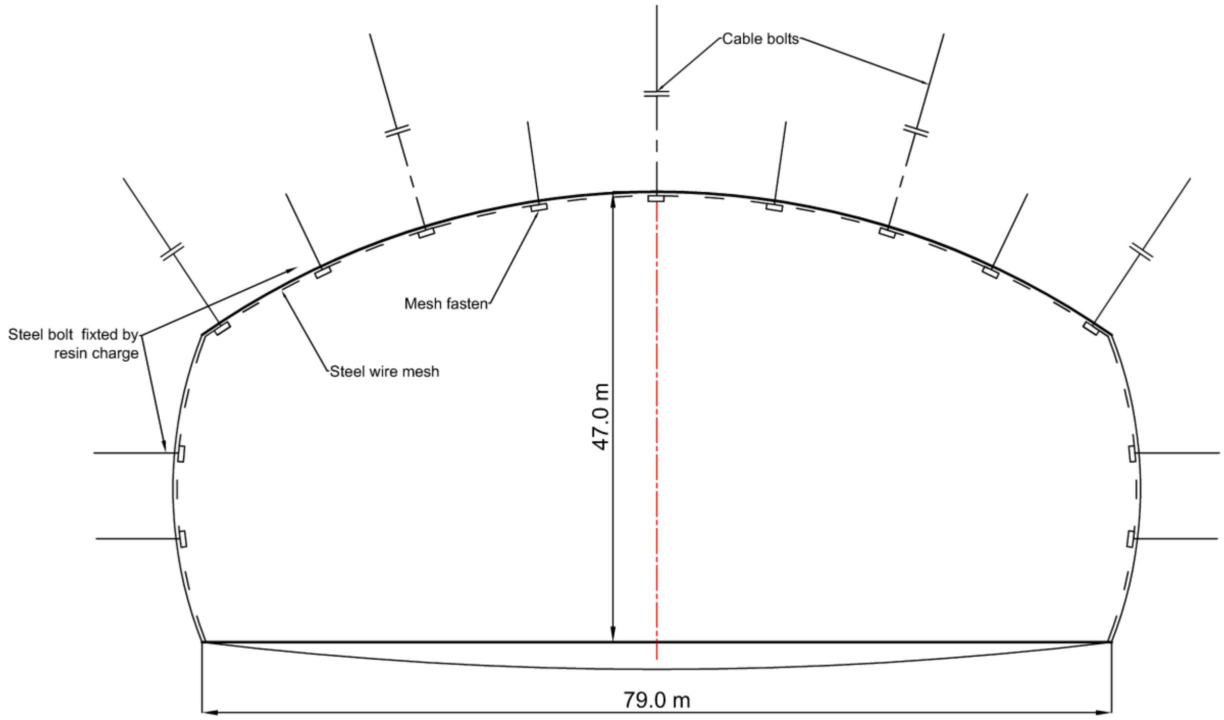


Figure 4.4. The dimension of the main laboratory chamber

4.1.2. Geology and main geomechanical parameters

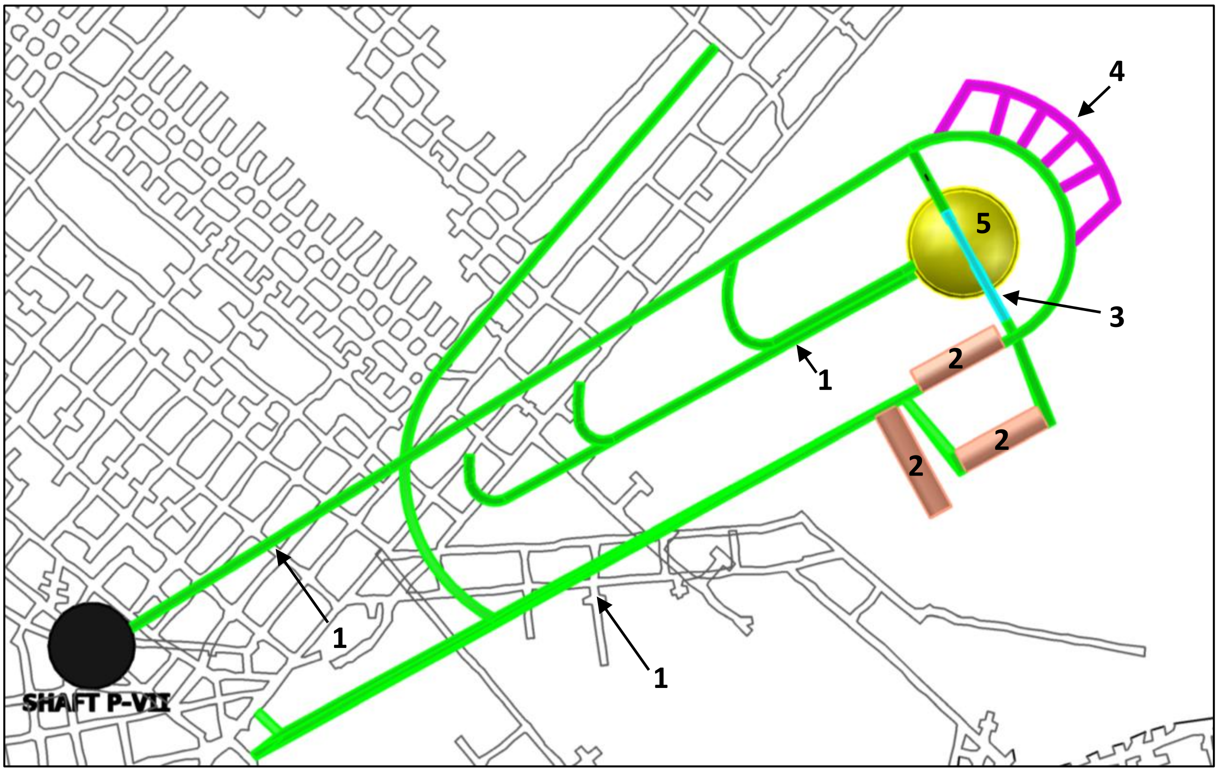
As was mentioned before, the main chamber of the laboratory may be placed in anhydrite deposit at the depth ok 636 m below the surface in the vicinity of the ventilation shaft. Detailed map with geology cross-section is shown in Figure 4.5.

Rock characteristic data is shown in Table 4.1.

Table 4.1. Rock characteristic data

Type of rock	σ_{ci} (MPa)	ϕ (°)	c (MPa)	σ_{cm} (MPa)	σ_{tm} (MPa)	E_m (MPa)	ν	Dil angle (°)
1	2	3	4	5	6	7	8	9
Quartz Sandstone	62.1	30.1	2.12	6.43	0.06	4734	0.26	2.57
Claystone	25.3	24.7	0.62	1.47	0.003	1302	0.29	0.26
Basic Anhydrite	93.3	35.26	4.8	19.64	0.24	13270	0.24	5.19
Main Dolomite	157.6	47.57	14.42	72.92	1.02	47146	0.2	12.5
Upper Anhydrite	87.4	34.25	4.2	16.51	0.2	11260	0.24	4.65
Lower Anhydrite	106.25	37.56	6.3	27.55	0.36	18329	0.23	6.45
Limestone and Dolomite	184.1	53.31	20.0	105.0	1.49	67489	0.18	16.3
Floor Red Sandstone	10.075	22.7	0.52	2.77	0.03	1983	0.3	0
Salt Rock (no reduction acc. to H-B, Maxwell's viscous parameter – 1.569e11 MPa sec	-	62	3.0	-	1.38	3440	0.3	0

2 – unconfined compressive strength obtained in laboratory tests
3 – angle of internal friction
4 – cohesion
5 – compressive strength in the rock mass
6 – tensile strength in the rock mass
8 –Poisson's ratio
9 – dilation angle
7 – modulus of deformation in rock mass conditions



1 - ventilation/access ramp; 2 - functional chamber; 3 -office; 4 - Additional chambers (different usage possible); 5 - Main chamber

Figure 4.5. The geometry of Conceptual Underground Laboratory

4.1.3. Stability calculation - Feasibility study

Stability calculation of the main chamber has been performed using FLAC3D – the finite difference approach (Itasca, 2020). As was mentioned before the chamber was placed in anhydrite at the depth of – 636 m, the horizontal maximum stress component equal to 44.4 MPa.

The calculation results are generally confined to:

1. Stress and strain (displacement) contours, instantly after excavation (for all materials) and after 40 years (for salt rock and anhydrite under the salt rock layer exclusively).
2. Plastic areas location (unstable parts of surrounding rocks - spalling).

Calculation results for the final shape of the UL chamber using elastic-plastic with the strain-softening model for anhydrite and elastic-plastic model for the remaining rocks. Chamber subjected to tectonic stress. An example of results of calculation was shown in figure 4.6 (stress), 4.7 (displacement) and 4.8 (spalling) for the intermediate and final stage of excavation.

INTERMEDIATE STAGE FINAL STAGE

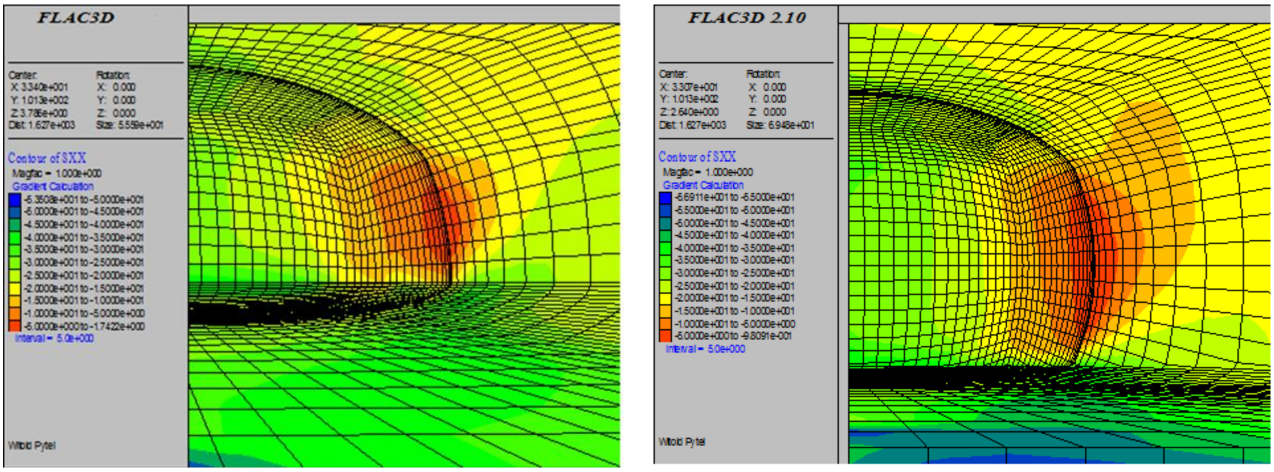


Figure 4.6. The contour of σ_{xx} stress (MPa)

INTERMEDIATE STAGE FINAL STAGE

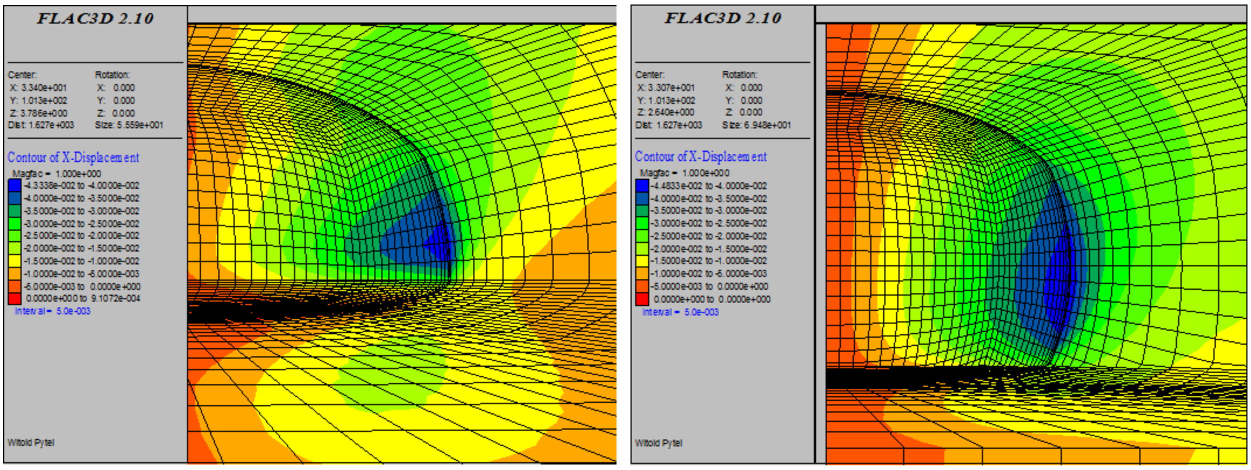


Figure 4.7. The contour of w_{xx} displacement (m)

INTERMEDIATE STAGE FINAL STAGE

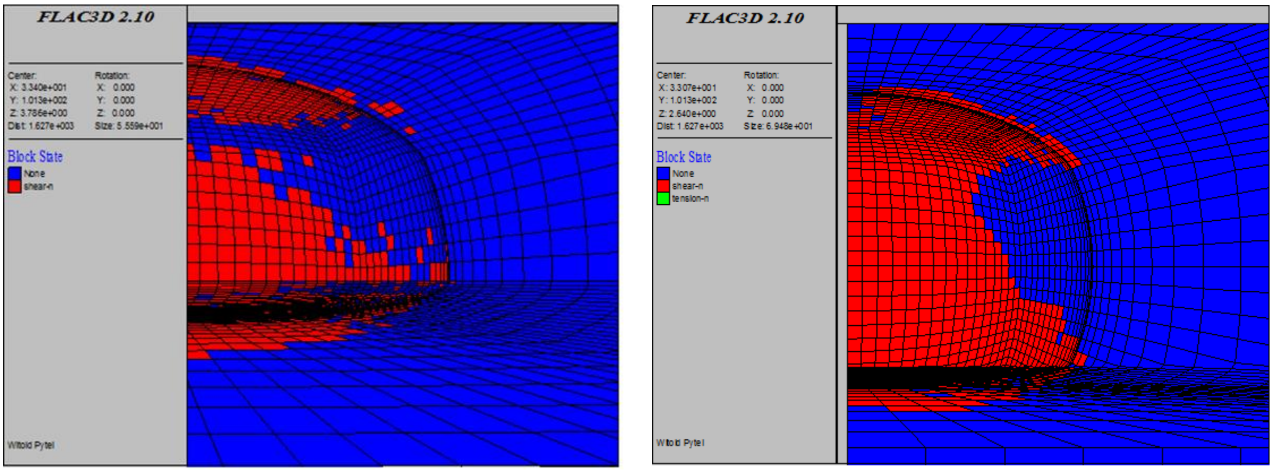


Figure 4.8. Spalling of chamber surface – location of the yielding (unstable) blocks (x-z cross-section)

4.1.4. Safety factor assessment

Finite Difference Method

The factor of safety, which may serve as a basic hazard measure, has been assessed for the whole chamber using the anhydrite strength parameters reduction procedure created a series of several models. It is assumed that the model failure is associated with safety factor equal to one and therefore the actual safety factor may be calculated as the ratio of the appropriate strength parameters. Results of calculations showed that the overall safety factor is greater than 2.5. Additional, the safety factor was assessed also including the effect of mining-related seismicity. An example of the results of one of the model is presented in figure 4.9 (with and without seismicity).

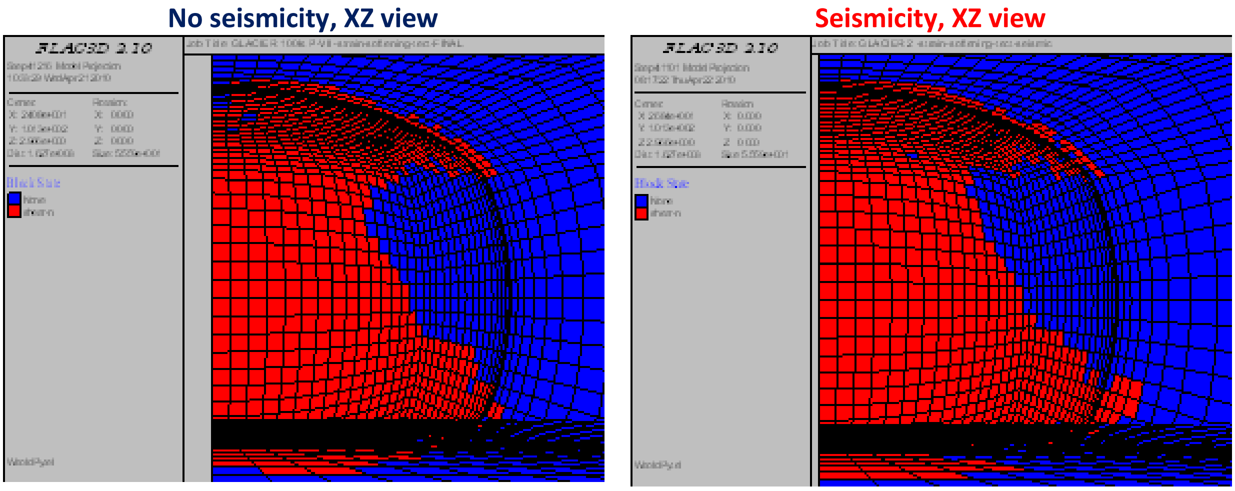


Figure 4.9. Selected results of calculations - spalling of the chamber (x-z cross-section)

All these analyses have shown that chamber that is planned as conceptual underground laboratory located in the anhydrite layer will be stable in long term, and the only type of rock failure is spalling of face layers after the excavation.

Limit Equilibrium Method

The limit equilibrium analysis allows calculating the possibility of a special type of rock failure which involves creating wedges in roof walls or floor of created m chamber. These wedges are formed by crossing systems of joints separating the rock mass into large, heavy and mutually interlocked pieces of rock. The failure is expected when calculated Safety Factors have a value below 1. The problem was examined using UNWEDGE 3.0 software developed by RocScience, addressed to this kind of failure process (RocScience, 2020).

Due to the lack of information about significant discontinuity sets (dip, direction) within anhydrite mass in the selected area, the following, some rigorous assumptions have been made. Firstly the significant dips in the roof, walls and floor of the chamber were assumed. The average dip and dip direction of discontinuity sets are presented in figures 4.10, 4.11 and 4.12. Then potential wedges which could be created and then fall or slide into the opening have been identified. Of course, wedges tend to fail without any support. Therefore to simulate the real conditions

Threadbars Anchors of the length of 25 m, the capacity of 175 tons, spaced by 1.5x1.5 m have been applied to the model. In result following safety factors were obtained.

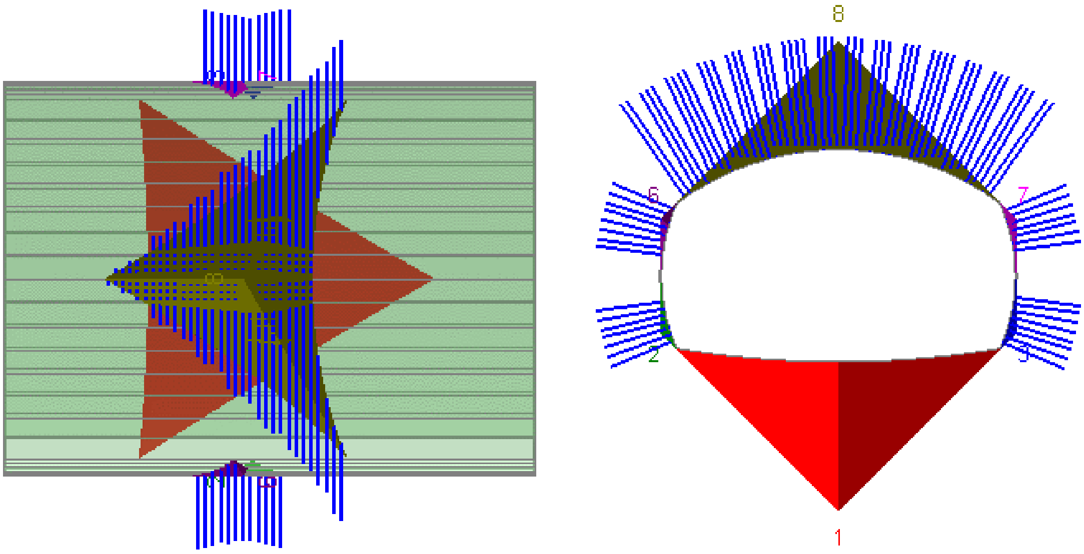


Figure 4.10. Top (left) and front (right) view of the prepared model geometry

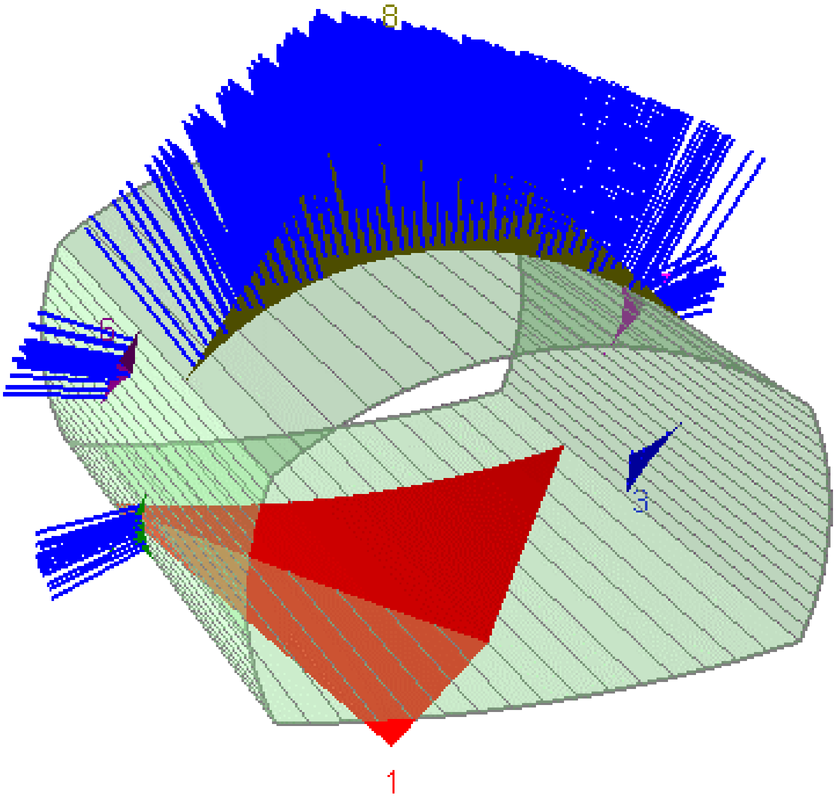


Figure 4.11. Top (left) and front (right) view of the prepared model geometry

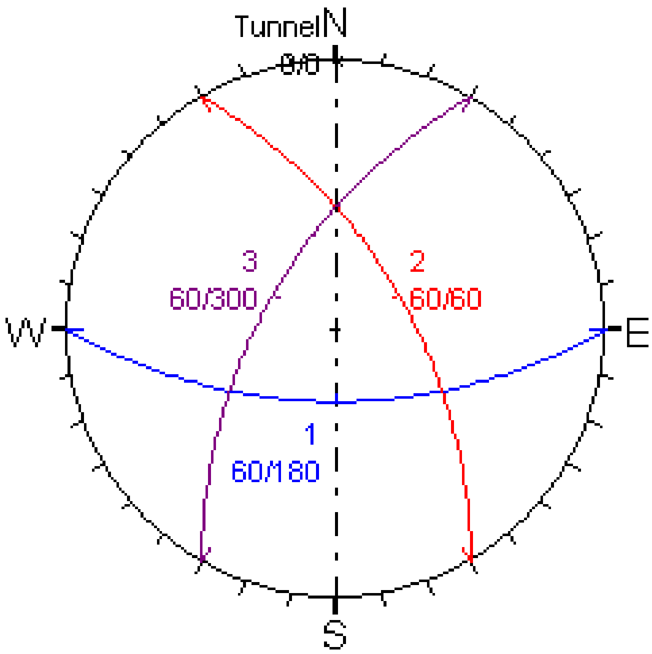


Figure 1

Figure 4.12. The dip set assumed in LEM based model

Table 4.2. The obtained safety factors for wedges presented at figure X

Wedge ID	1 (Floor)	2 (Left bottom wall)	3 (Right bottom wall)	6 (Left Top wall)	7 (Right Top wall)	8 (Roof)
Safety Factor	Stable	4.626	4.896	3.457	3.106	3.098

As one may notice the calculated safety factor in all six cases has the value over the 1. In case of floor wedge, there is no place to move of wedge downward, and therefore UnWedge software does not calculate safety factor and marked it as a stale. In the rest of wedges, the SF always exceed the value of 3 what gives a good safety margin in case of seismic activity occurrence. The lowest safety factor for the roof rock wedge (No. 8) has been established as Fs = 3.098.

It should be emphasized that in the structurally controlled instability analysis has been performed for very conservative assumptions since

- field stress positive effect has not been included in long term safety factor assessment,
- the dip of joint sets has been significantly overestimated and was assumed to be very steep (60°),
- 2D excavation geometry created larger wedges than it could be expected in a case of 3D conditions.

<u>TAKING ABOVE-MENTIONED INTO CONSIDERATION IT WAS CONCLUDED THAT UNDERGROUND LABORATORY WITH PROPOSED GEOMETRY WILL BE STABLE IN CURRENT GEOMECHANICAL CONDITIONS.</u>

4.2. Large-scale UL (Mining Trial Panel)

From the mining technology development point of view, the Underground Laboratory in form of the trial mining panel is highly desired. Possibility of conducting an in-situ test of mining equipment will turn into an increase of safety and efficiency of conducted works. This is due to unique conditions which may be observed exclusively in deep underground excavations. Of course, setting up of such kind of Laboratory is possible in most of the active underground mines. Still, the development of new roof support systems, excavation methods and monitoring devices are related to changes in the geometry of unground laboratory. Also, significant changes in stress/strain conditions in surrounding rock mass may be expected. Therefore to ensure the safe conditions during the whole life cycle of facility, proper project and risk evaluation of whole construction need to be conducted. It is strongly recommended to utilise a rigorous approach and take into account also scenarios which are based on extreme values, e.g. dynamic load.

4.2.1. Location and general layout

As it was pointed out in chapter X Polkowice-Sieroszowice copper mine, which belongs to KGHM Polska Miedź S.A. company is one of the most developed underground copper mines in the world. Every year over 200 km of underground workings is excavated and over 12 Mt of copper is extracted. What more, science 2015, The Głogów Głęboki – Przemysłowy mining region adjacent to the Polkowice-Sieroszowice mine from the north is a prospective area for further development of the Polkowice-Sieroszowice mine. Given the size of the copper ore resources in the area, accessing this deposit is currently the largest deep mining project in Europe.

Setting up UL for research, education, and new technologies development will be a great value for further development of Polkowice-Sieroszowice mine.

Bearing in mind that the new facility must not disturb the production process, the location of the trial panel should fulfil the following requirements:

- Be close to the mining shaft to minimise travel time,
- At the same time distance from strategic objects like shafts, etc. should be long enough to ensure that every kind of dynamic impact (induced tremors, blasting works) will be at the safe level, without affecting these objects
- Be located in are where rocks are classified as the waste rock of or ore unprofitable to extraction,
- Trial mining panel must not be located in the area directly surrounded by the backfilled area.
- The laboratory should be located far away from the faults

In turn, when considering the safety issues, the following requirements should be fulfilled:

- At least two evacuation roads should be available,
- Rock in the direct surrounding of the trial panel must be characterised by high strength parameters, ensuring the safe geomechanical condition

- Trial mining panel have to be supplied by fresh air
- Evacuation has to be possible by walk and by cars

Bearing abovementioned in mind it was decided that the concept of the trial panel for underground research will be located near SW-I mining shaft. It was assumed that the distance over 1 km will ensure the safe conditions in surrounding of the shaft even in case of use of hundreds of kg of explosives. The planned location of the trial panel is presented in Figure 4.13.

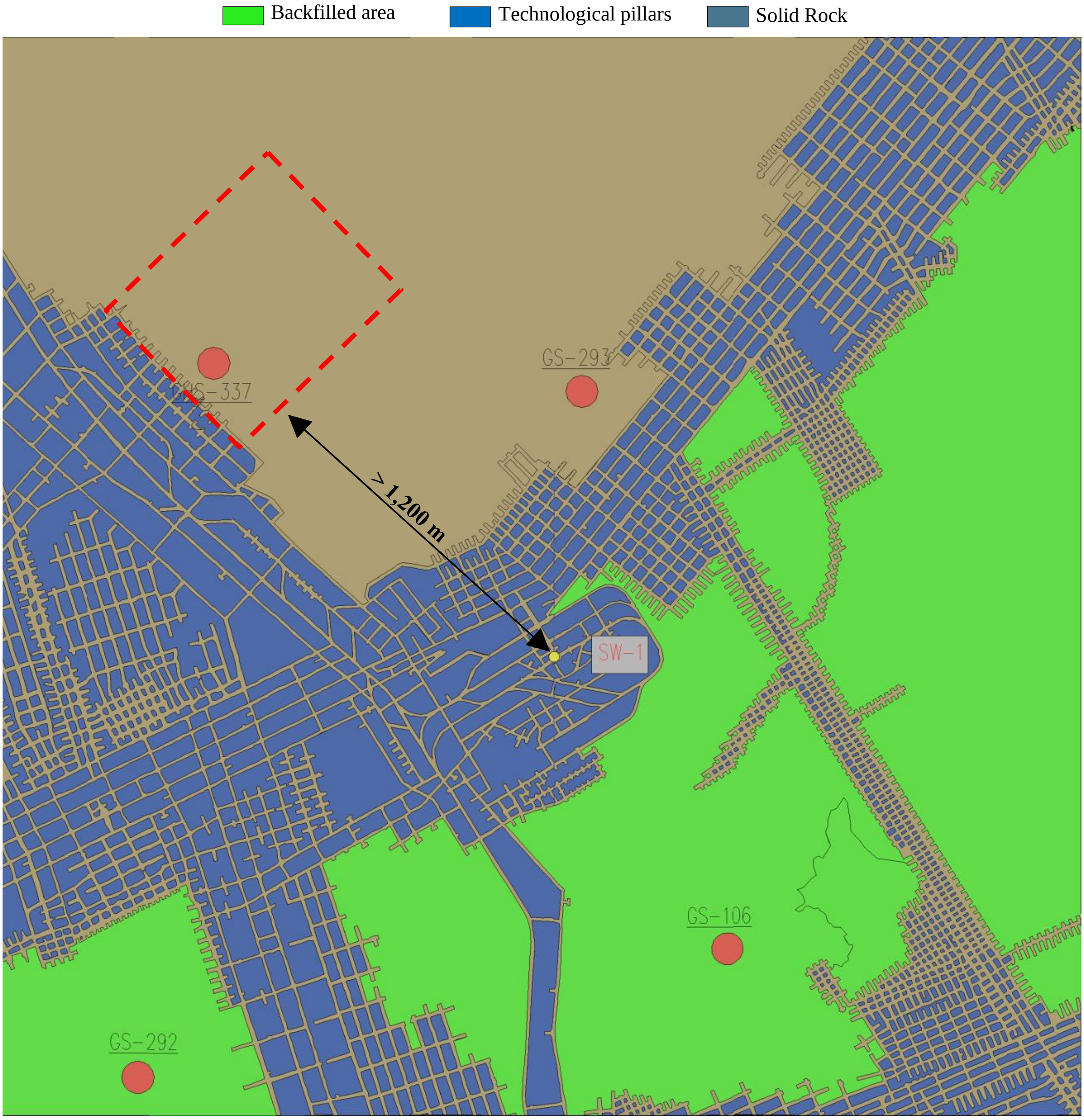


Figure 4.13. Map of the current situation in the vicinity of SW-I shaft

When planning the geometry of excavations and whole mining panels it was assumed that total length of workings should exceed the value of few kilometres what should be enough for few up to dozen years of research depending on the degree and type of laboratory use. Also, the geometry of pillars should be big enough to ensure the safe condition in terms of roof fall and rockburst hazard. According to authors experience the length of pillars equal to 30 metres and their width of 15 metres should be sufficient to withstand the load of overlying rocks. The geomechanical safety for the whole mining panel will be presented later in this report.

It was decided that rooms will be rectangular with a width of 6 meters and a height of 3.6 metres (Figure 4.14). Such geometry will enable to conduct underground tests of mining machines and at the same time will be enough for testing i.e. new drilling and blasting patterns.

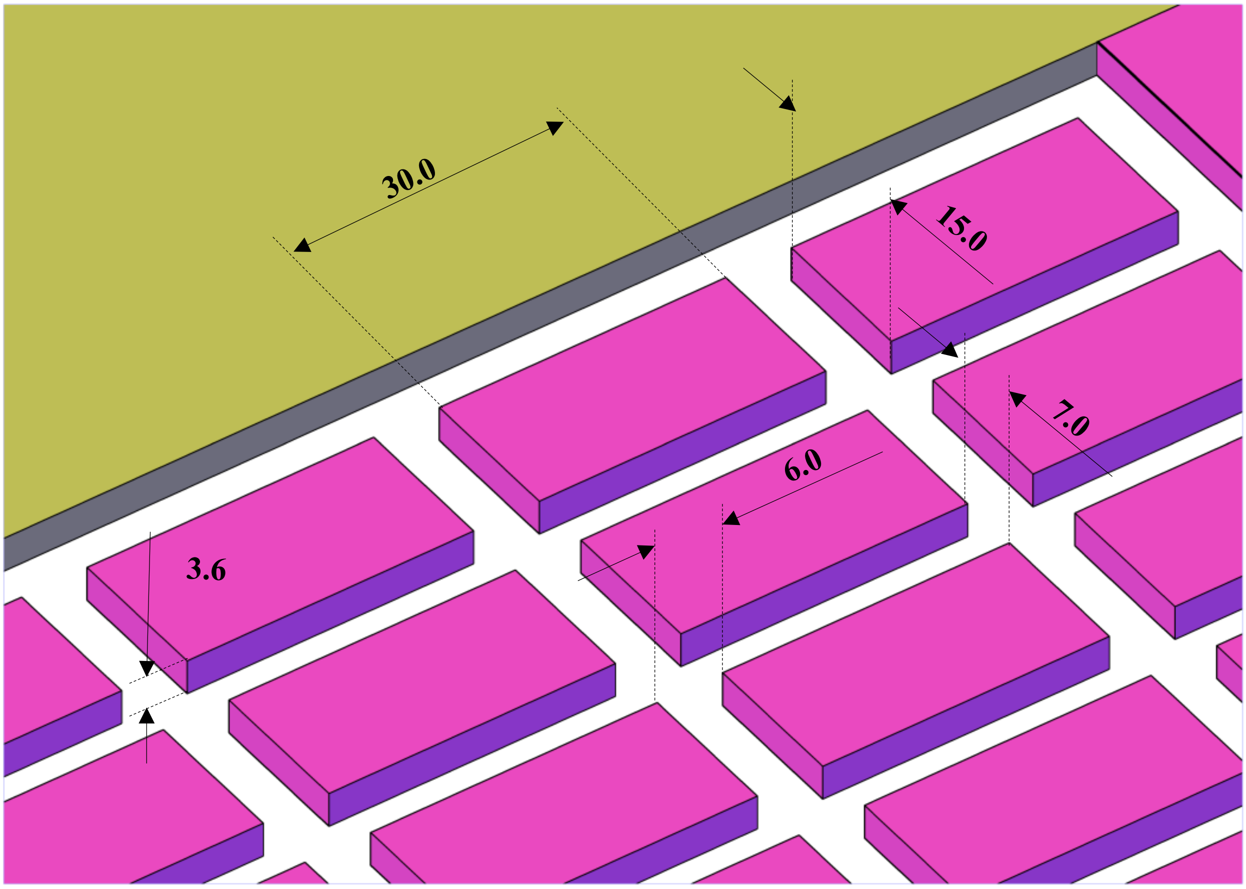


Figure 4.14. The geometry of pillars and working within the projected trial mining panel

It was assumed that in the first few years of Underground Laboratory life cycle the fourteen rooms will be excavated. The length of a single excavation will be 250 m. In such case the total length of workings in analysed mining panels may be calculated according to the formula:

$$\sum L_E = L_r \cdot N_r + B_p \cdot N_p \qquad (4.1)$$

Where:

$\sum L_E$ - total length of underground workings in prototype UL, m,
L_r – length of a single room (excavation parallel to pillars direction), m,
N_r - number of rooms in projected mining panel, -,
B_p – width of a single pillar, m,
N_p – number of pillars, -,

In addition to mining excavations also evacuation and transportation roads are planned. To make an underground facility self-sufficient (Figure 4.15).

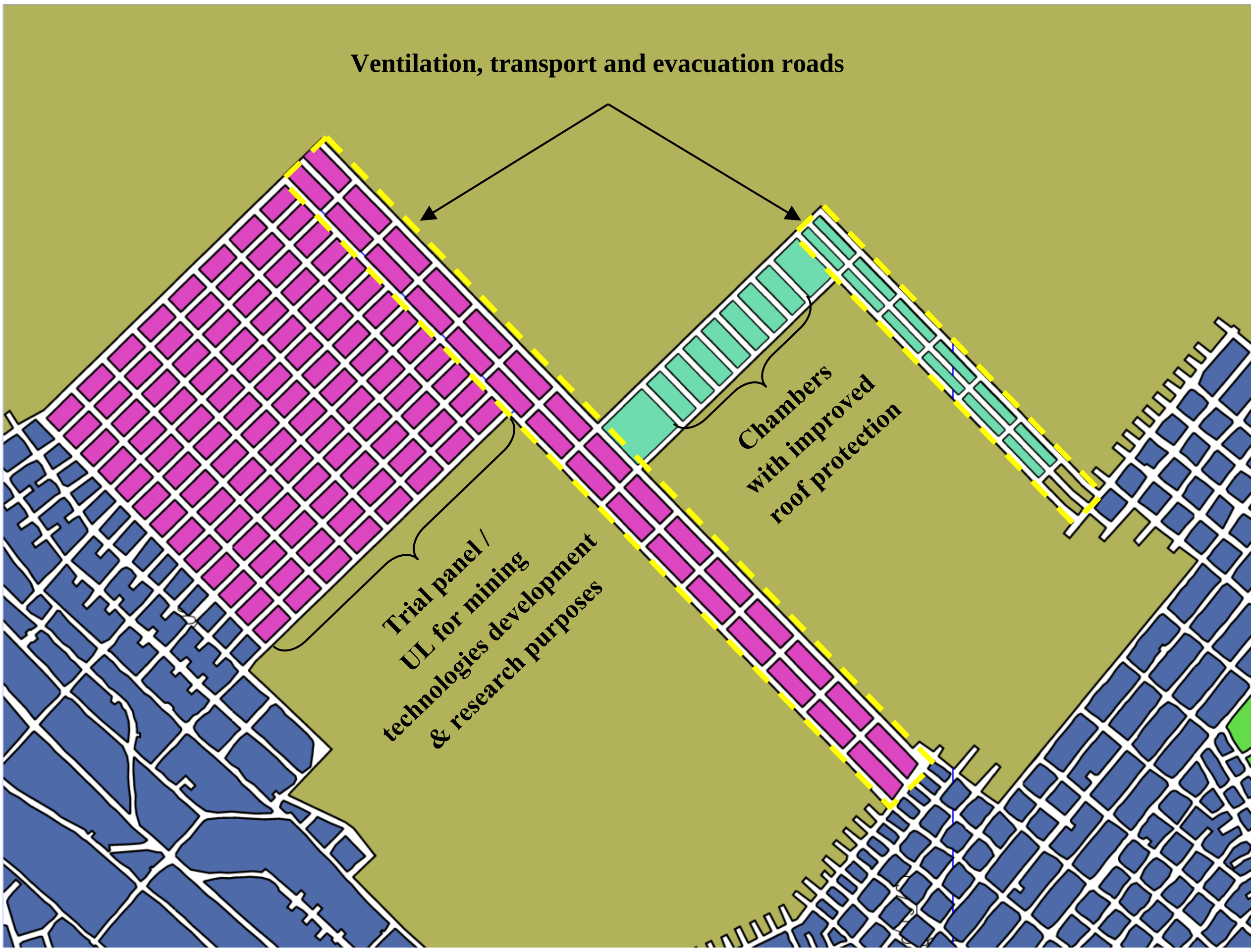


Figure 4.15. The geometry of the projected trial panel

Preparing the geometry of trial panel as shown in the figure will require 4,300 meters of excavations. Moreover, additional 4,500 meters of workings need to be excavated to prepare transport and evacuation roads and eight special chambers which may be used as a parking place for mining machines (Figure 4.16), crew assembly points or research equipment storage chambers. All eight chambers will be additionally supported and equipped into furniture, entrance and exit gates, extinguisher, self-rescuers and electricity and water supply as well.

Figure 4.16. Example of mining chamber for parking of mining machines and transportation cars

The distance of closest working in the trial panel in relation to SW-I shaft was 1,200 meters what fulfil the requirements of mine management.

4.2.2. Geology and main geomechanical parameters

In the direct vicinity of SW-1 mining shaft, there are several exploration boreholes. Most of them are drilled from the ground surface to the level located below the mine workings. For the purposes of this case study, four boreholes were used (Figure 4.17). The location of boreholes in the surrounding of SW-1 mining shaft used for the purposes of conceptual analysis is presented in figure 4.18.

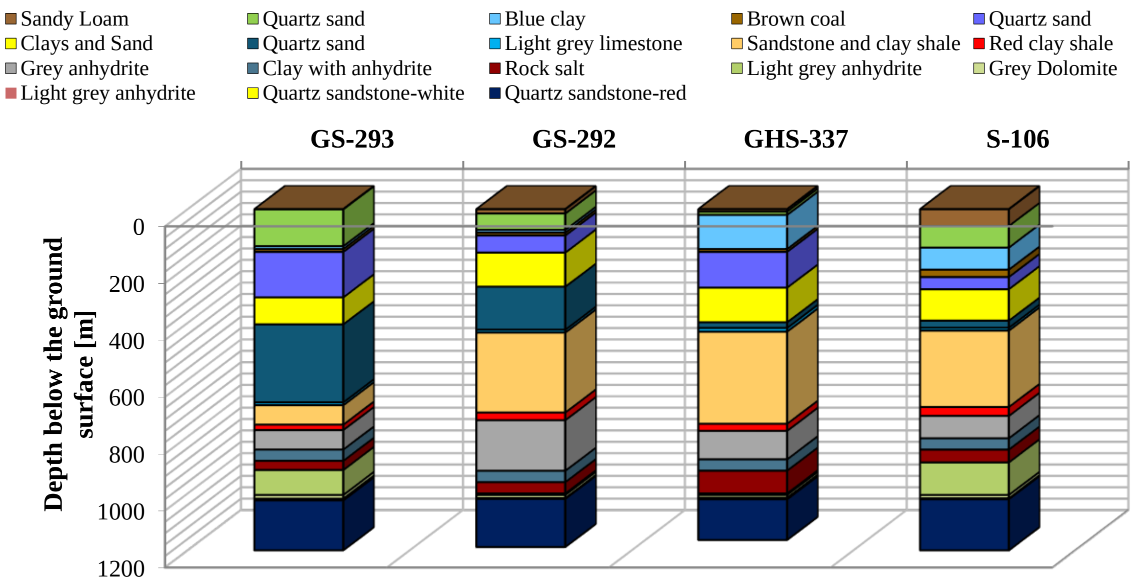


Figure 4.17. The layering of strata in analyzed boreholes

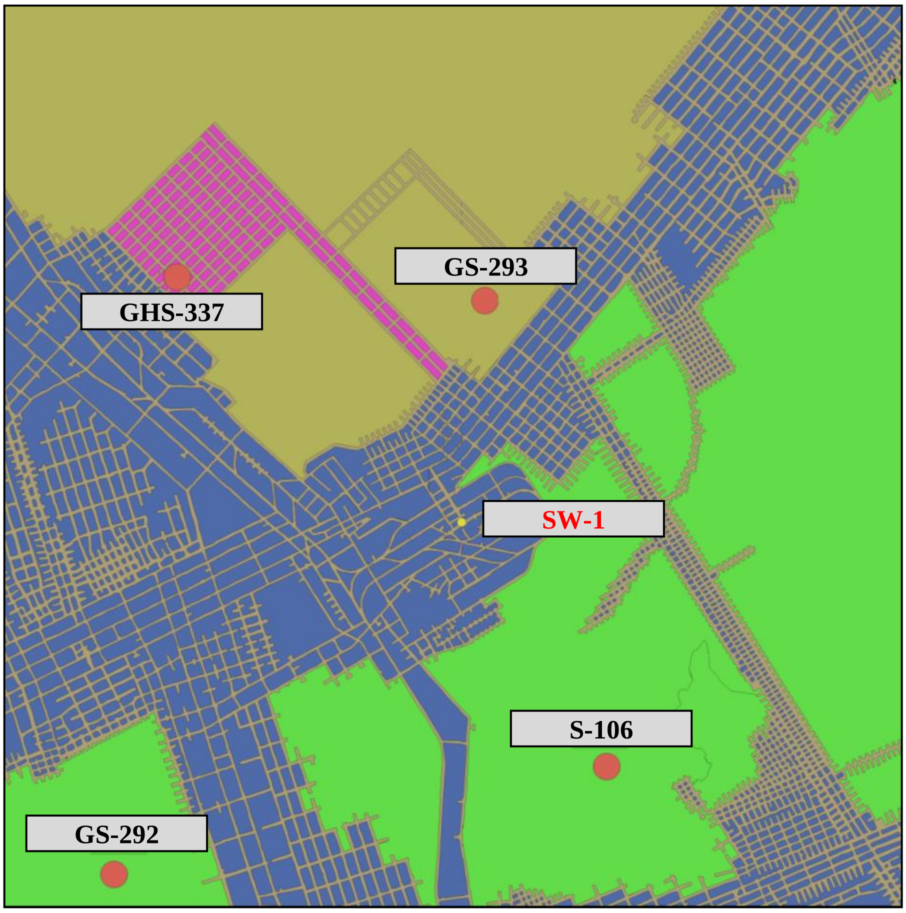


Figure 4.18. Location of the boreholes in the vicinity of the projected mining panel

4.2.3. Stability calculation - Feasibility study

Stability calculations were conducted with the use of GTS NX FEM-based numerical software. During the analysis, the Mohr-Coulomb failure criterion was used.

The Mohr-Coulomb model is defined by an elasto-plastic behaviour as shown in figure 4.19. Such an assumption of material behaviour shows reliable results for general nonlinear analysis of the ground and is widely used in geomechanical analyses.

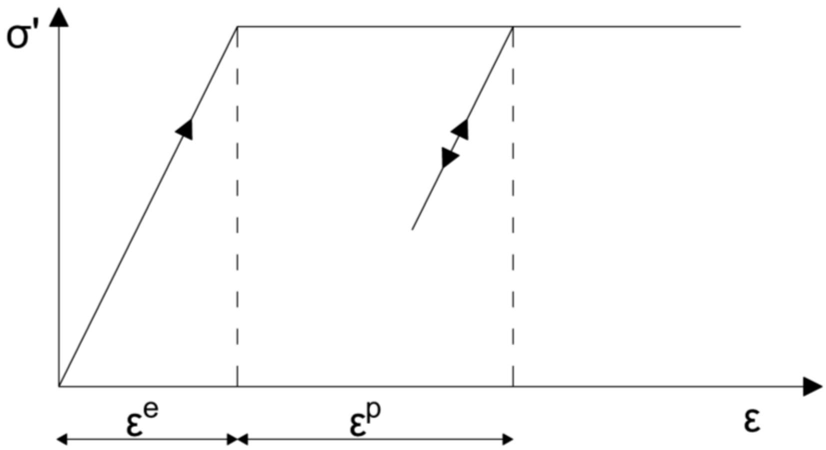


Figure 4.19. The material behavior of the Mohr-Coulomb model

Strength parameters for each layer were chosen on the basis of laboratory tests. The boundary conditions and mesh of the model are presented in figure 4.20. The whole model was prepared with the use of hybrid mesh based on Triangles and Quadrilaterals. In general the area of interest, due to high complexity of shape were prepared with triangular mesh type, while layer lying above the mining panel have been meshed with 3-dimensional hexahedron-based elements.

Theoretically, all pillars are excavated in the same type of material. Nevertheless, it was assumed that backfilled areas, where pillars were turned in post-critical strength, will be characterised by significantly lowers strength parameters. In the case of the analysed region, the mined-out area was filled with hydraulic backfilling with sand. Therefore, within this area, sand material was used for the purposes of the simulation. Such an assumption is in accordance with the fact that all pillars in the backfilled area should be yielded. The geometry of large-scale conceptual mining pannel, prepared with the use of GTS NX software is presented in figure 4.21.

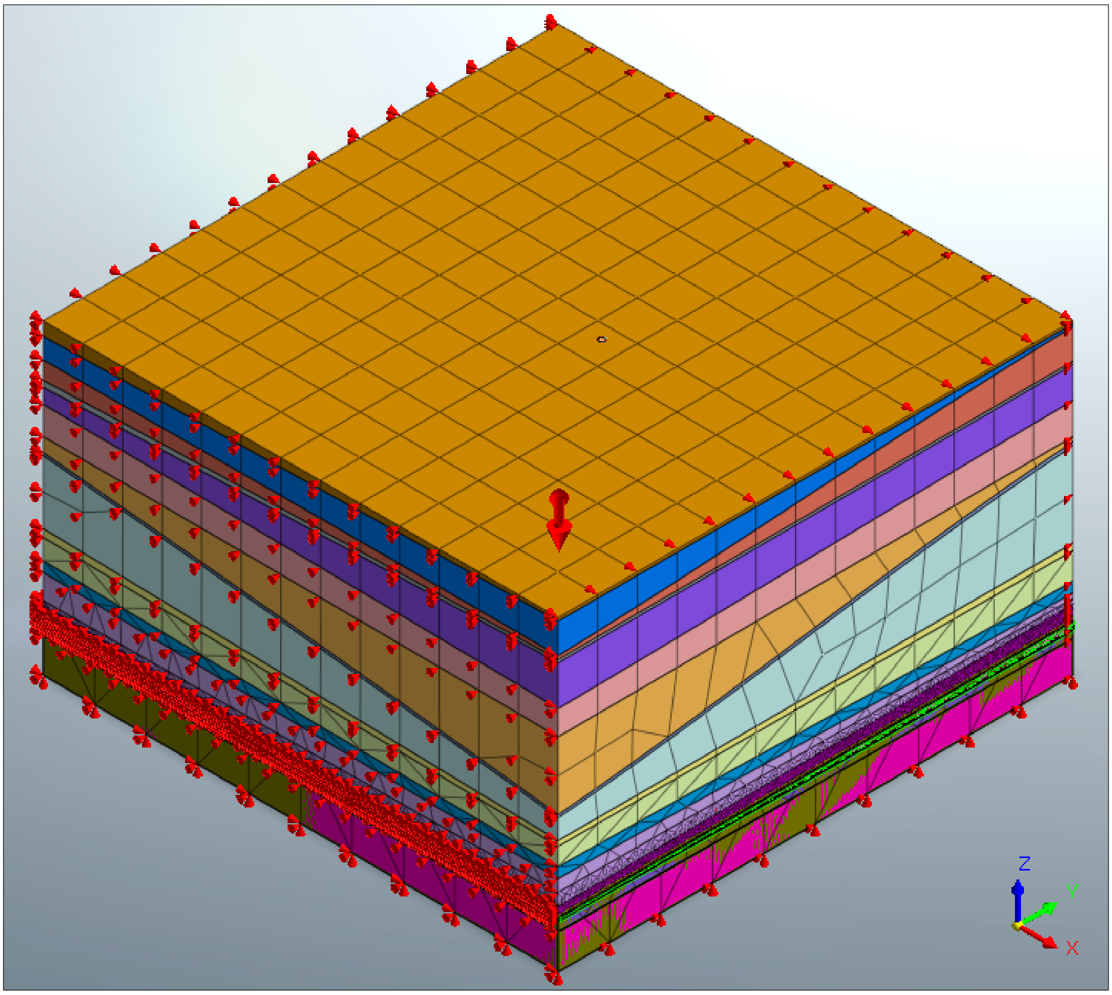


Figure 4.20. The external geometry with mesh and boundary conditions of the 3D UL model

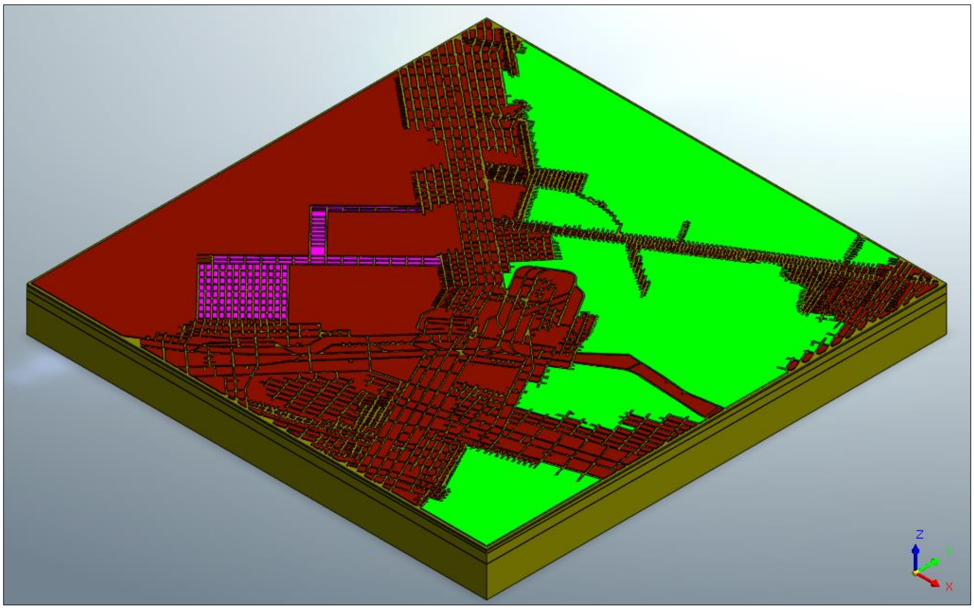


Figure 4.21. The geometry of the trial mining panel

Great attention was paid to the accuracy of the conducted analysis, therefore the mesh was denser in the area of any significant shape changes. In the case of solid rock and backfilled area, the bigger element was utilised to reduce computing time (Figure 4.22).

Finally, the whole FEM based model was built with the use of 2,500,000 of the 3-dimensional element. The distribution of elements in the surrounding of conceptual UL is presented in figure 4.22.

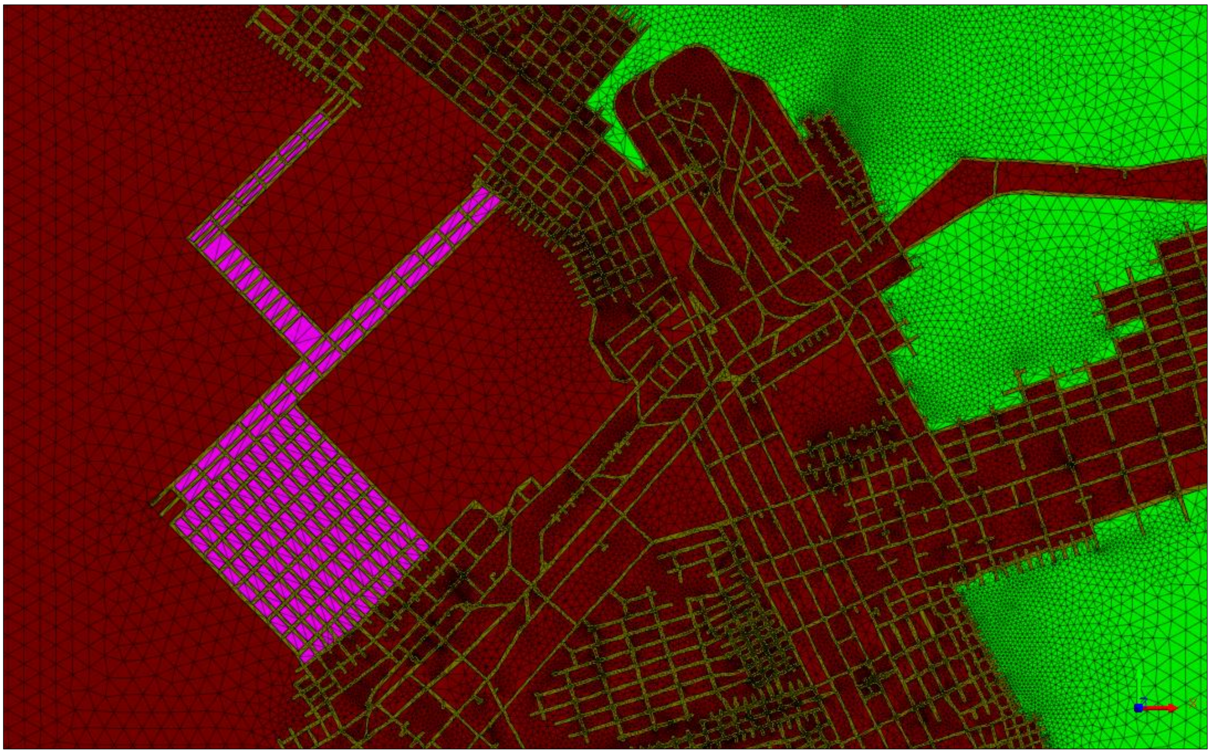


Figure 4.22. Top view of meshing of the area in the surrounding of the conceptual trial mining panel

The analysis in MIDAS GTS NX software allows determining changes in stress, strains, displacements and safety factors as well. To make the results of the analysis accessible even to readers who do not specialize in rock mechanics, the current state of all working within the model were presented with the use of so-called Safety Factor (SF). The principle of calculation of Factor of Safety Using Mohr-Coulomb Failure Envelope is presented in figure 4.23.

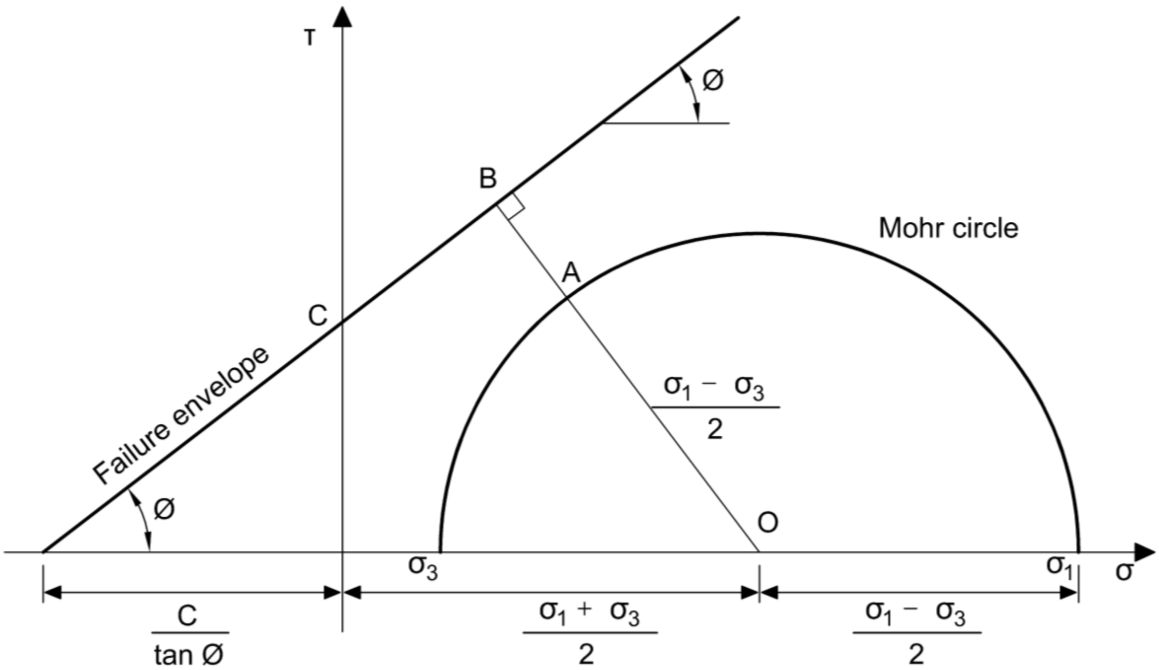


Figure 4.23. Mohr-Coulomb Failure envelope

If the principal stresses are known at a certain location, the factor of safety at that location can be calculated according to the following formula:

$$SF = \frac{\left[\frac{\sigma_1+\sigma_3}{2}+\frac{C}{tan\varphi}\right]\cdot sin\varphi}{\frac{\sigma_1-\sigma_3}{2}} \tag{4.2}$$

where, σ_1 and σ_3 are the major and minor principal stresses, C is cohesion, and φ is the angle of international friction.

Values of Safety Factor smaller than 1 indicate the areas prone to instability occurrence. The results of the calculation are presented in figure 4.24.

On the basis of 3-dimensional FEM-based numerical simulations, one may conclude that the trial mining panel will be stable from the geomechanical point of view. Safety factors within the area of conceptual UL are not less than 2. In the surrounding of 8 chambers, which are crucial from the safety point of varies, the safety factors vary around SF=2.5 (Figure 4.25). The instability or in other words yielded areas are observed only in the backfilled regions (Red areas in figure 4.24).

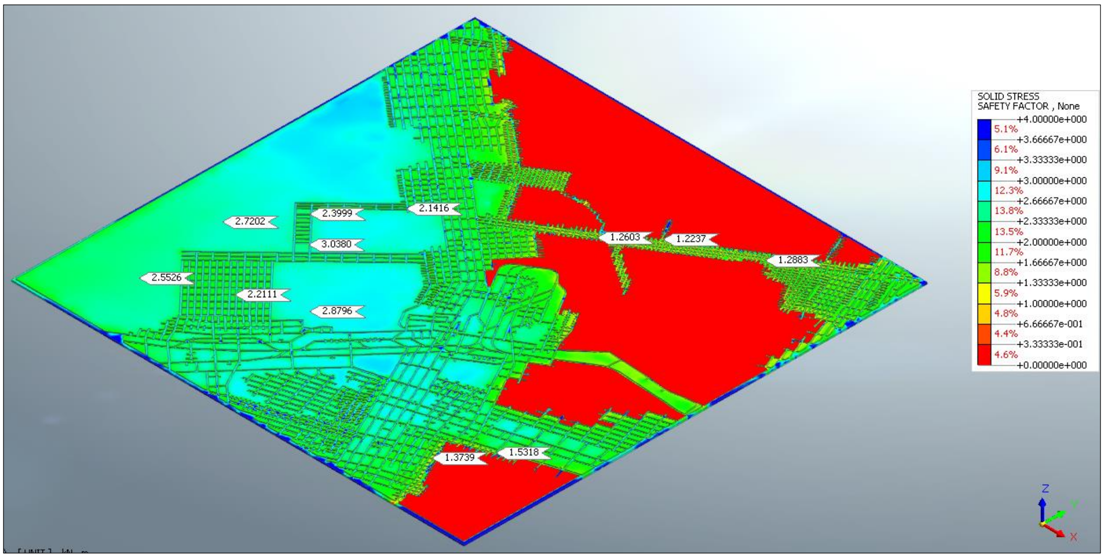


Figure 4.24. Contours of SF values at the level of conceptual mining pannel

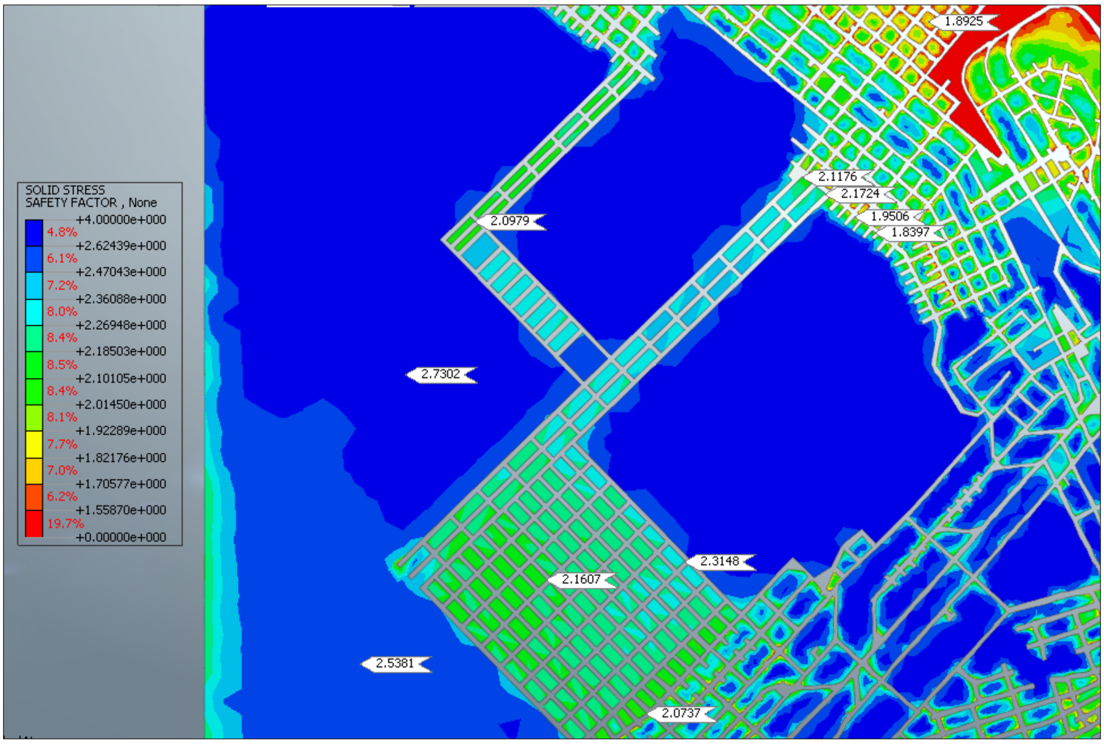


Figure 4.25. The distribution of safety factor in Conceptual Large-Scale Underground Laboratory (yellow frame)

Of course one of the key factors determining the stability of the whole area is not only the strength of pillars in the analyzed region but also the strength of rock stratum above them. The cross-sections at the base of the trial panel and the boundaries of the numerical model are presented in figure 4.26 while in figure 4.27 the cross-sections representing the roof layers stability above the trial panel were shown. As one may notice the layers of dolomite, anhydrite and sandstone located above the analyzed area have Safety factor Significantly higher than 2. Only loose sands at the top of the model are characterized by safety factor less than 1 what is which coincides with the actual state.

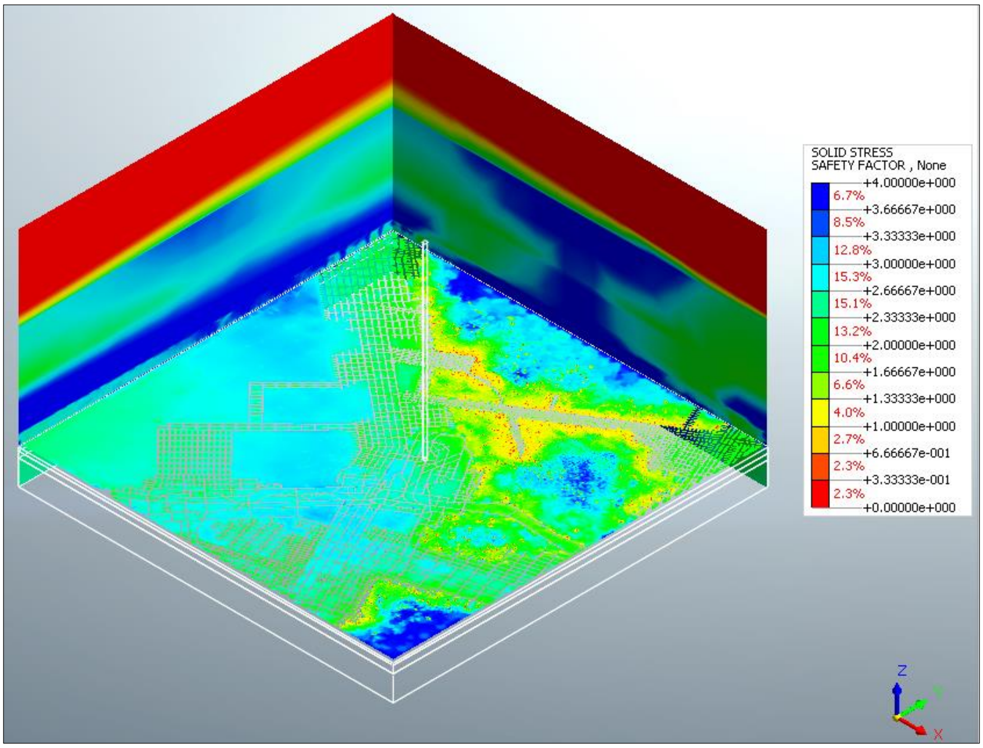


Figure 4.26. Cross-sections through the base of the trial panel (horizontal) and boundaries of a numerical model (vertical)

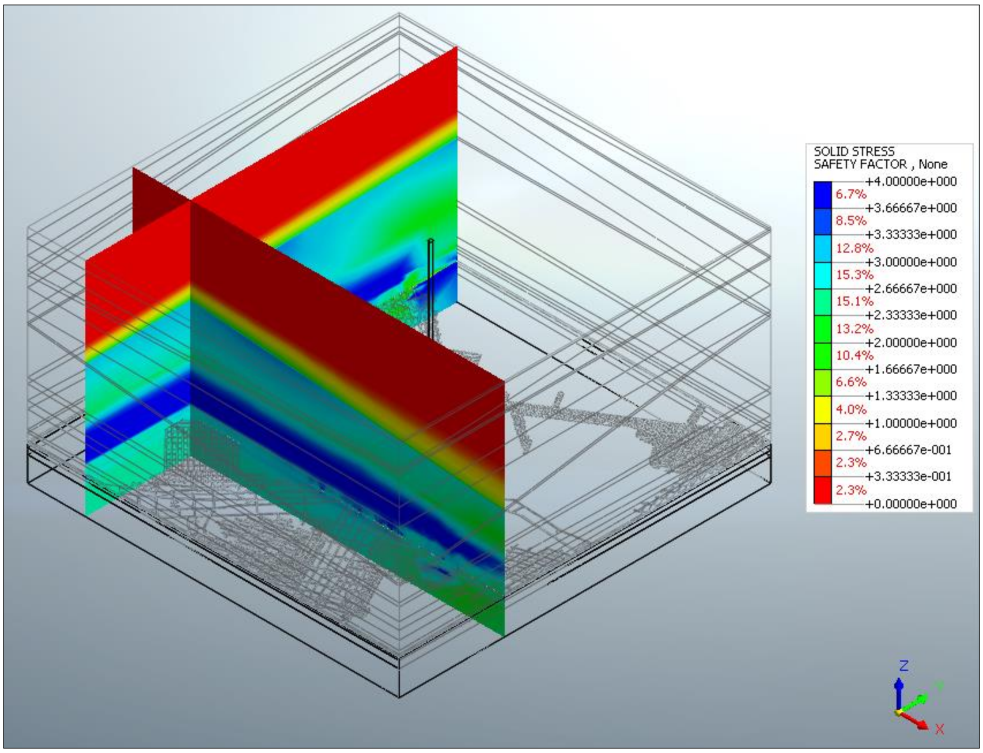


Figure 4.27. Verticals through the base of the trial panel (horizontal) and boundaries of a numerical model (vertical)

<u>TAKING ABOVE-MENTIONED INTO CONSIDERATION IT WAS CONCLUDED THAT UNDERGROUND LABORATORY WITH PROPOSED GEOMETRY WILL BE STABLE IN CURRENT GEOMECHANICAL CONDITIONS.</u>

5. RISK MANAGEMENT

5.1. Best Practices

This guide provides general safe work practices when work or visit potential underground laboratory placed in Polish copper mine conditions. Therefore, besides the requirements regulated by Polish Mining and Geologic Law, we recommend utilising additional measures according to best practices of UL management in BSR region. A target group of this guide will be workers that operate in the UL and all visitors. The goal of these instructions is to ensure safe workspace for all people's presence in this area. The information contained herein is based on the analysis wide range of hazard that is present in this kind of underground objects. Some of best practices may be found in one of the BSUIN reports *"Best practices from the Uls to Uls"* prepared by University of OULU.

5.1.1. Accessibility and outside visitors

The conceptual prototypes of UL (I - large chamber and functional galleries, II - the large scale trial panel) due to the planned business model, has to be accessible to outside entities, but because of safety regulations, the number of conditions must be met. Minimum requirements are as follows:

- all researchers and workers must be in good health what which should be confirmed by a medical certificate,
- all visitors, researchers and workers must have completed health and safety training and training in the use of self-rescuers,
- new workers must be accompanied by a staff member as a guide and supervisor during the first two weeks,
- students and visitors must be accompanied by a staff member as a guide and supervisor during all the time,
- one supervisor can be responsible for a maximum of 10 people,
- each of people visiting UL needs to have the self-rescuer and map of workings with highlighted escape routes,
- each of the visitors must have helmet lamps provided by Polkowice-Sieroszowice mine, which have a built-in location tracking system.

5.1.2. Organisational regulations

5.1.3. Training

Awareness of existing in workplace hazards and knowing how to handle that is a key issue with the effectiveness of the safety management system. That is the reason that safety training has to be conducted in a regular manner and cover all aspects of underground operations in the light of safety. Therefore training is the fundamental part of Best Practices. In KGHM mines, the periodical training is conducted every year. Besides that, one of the good practices utilised in Polish copper mines is every week, several-minute-long crew training, where basic H&S rules are recalled, and in case of any injury occurrence, the reasons are described. Also, actions allowing to avoid such an event are discussed with employees. In the case of running a trial panel, such best practice will be implemented as well. The training program must provide information about threats, safety regulations and working methodology in the underground environment. On completion of the training participant will be able to at least:

- list of the hazards to be encountered in Underground Laboratory,
- state typical PPE requirements used in working place,
- list the actions to take in case of emergency (e.g. fire),
- state the appropriate course of actions to take in case of an accident (e.g. interact with machines),
- state the evacuation procedure with the indication of meeting points,
- demonstrate knowledge about working equipment,
- demonstrate knowledge about safety required safety procedure.

The training program must be revised regularly to ensure it is actual and adjusted to the current condition and operation performed in Underground Laboratory. Working in the UL should be available for trained personnel only. Visitors have to be trained in hazards and emergency procedures and be guided by competent workers during their visit to UL.

5.1.4. Communication and internet

The whole trial panel, same as the underground chamber, will be supplied with antennas of DOTRA system, which allow to contact in underground conditions and to call to the surface as well. DOTRA system has been developed by INOVA company and has been used in KGHM mines for many years. Considering the internet connection it is planned to organise 2 chambers where computers with an internet connection will be available. The example of rugged computer station is presented in figure 5.1.

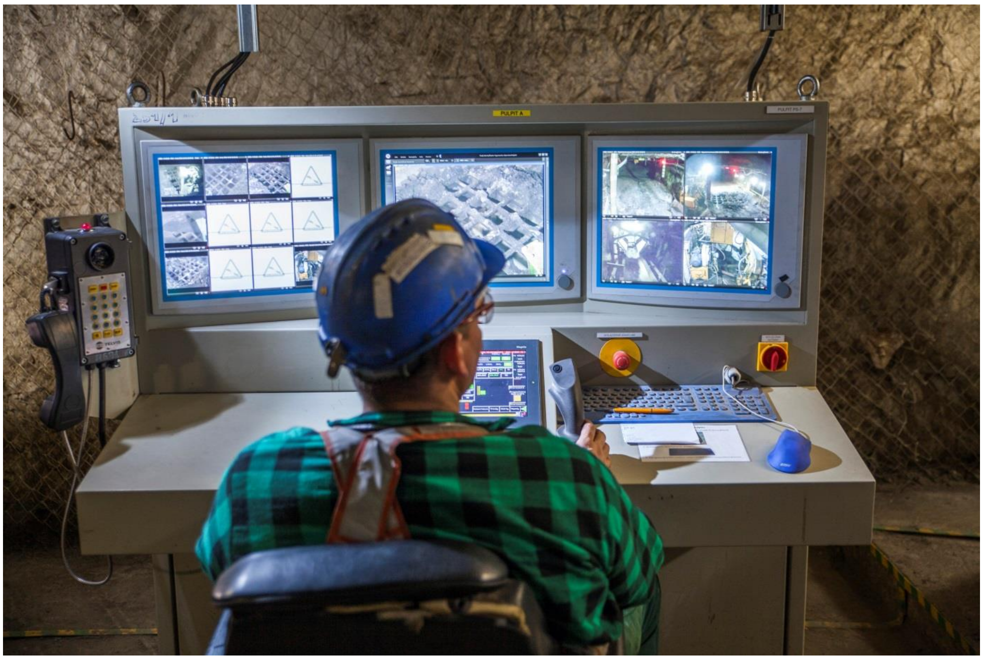


Figure 5.1. Example of underground computer station (KGHM, 2020)

5.1.5. Lightening, power and water supply.

Based on the experience of other BSUIN laboratories it is planned to install intelligent lighting systems within the projected underground laboratories. However sophisticated lightening control system will be only available in chosen chambers. The details and assumptions concerning intelligent lightning are presented in one of the master thesis prepared within the framework of BSUIN project (Pujol, 2019). This master thesis is available online in open access.

Concerning power and water supply, it is assumed that Underground Laboratory will be supplied with undrinkable water in taps, and drinkable water in bottles. In all mining chambers also electrical switchboard will be installed with the current of 400 V, 230 V, 24 V and 12 V.

5.2. Hazard Identification

Hazard identification is the first step of risk assessment, which is crucial in whole risk management and mitigation process. The details about risk identification and evaluation are presented in one of the BSUIN reports titled “Health & Safety in Underground Environment” (Fuławka et al., 2020)

5.2.1. Fire Hazard

Fire in underground conditions is way more dangerous than on the surface. This is mostly due to the lack of fresh air in underground workings. In such conditions, even small fire may consume an enormous amount of oxygen what may lead to a number of causalities. Although, there is no risk of endogenous fire in KGHM conditions, still, there is a possibility of exogenous fire than may be caused by the following sources:

- High-temperature works (e.g. welding, grinding etc.),
- machines and other operation equipment (e.g. diesel engines, conveyor belts, fans),
- electric devices (e.g. transformers, electric engines etc.),
- blasting works,
- open fire.

The fire management system is implemented in the mine. This system consists among others: automatic firefighting systems, fume sensors, manual fire extinguishers, firefighting procedures, combustible material management etc. similar firefighting systems can be installed in UL.

5.2.2. Dust and Noise

There is an occurrence of dust with different particle size. Exposure level depends on the location of the working. In many locations, there is an anti-dust system in form of water sprinkles. PPE is required in specified locations. Dust level is measured regularly. A similar system can be used in UL. The problem of noise is possible in some areas. The main sources of the high noise level are:

- mobile machines (drilling rigs, bolting rigs, loaders, trucks etc.),
- blasting works,
- ventilation fans.

Noise level is measured in a regular manner. In specified places, there is a need for using proper PPE or other types of limitation of noise level is used (e.g. soundproof cabins). Depending on the type of operations in UL and their noise emission suitable protection systems can be used, similar to these are currently used in the mine.

5.2.3. Seismic Activity

There is a possibility of occurrence induced seismic events. Therefore designed, potential UL will be located in a protected area close to the shaft where seismic activity is low. Despite this, this area in mine is equipped in the system of seismographs which monitor seismic events. Seismicity of this area is observed a long time and trends can be determined with high probability. Even though seismicity of this area is low, to ensure that the underground facility will be very safe, potential seismic activity was taken into consideration during the designing process of UL. It means that shape and ground support will be adjusted to the seismic activity. The additional underground facility which will be belonging to the laboratory will be also equipped with seismic monitors.

5.2.4. Electricity

There is an underground electric network with different voltages (mainly 230 V – 6 kV) and many electric devices, hence there are threats related to electric power. The most dangerous hazards related to electric power are:

- electrocution,
- fire ignition caused by electric devices,
- power failure.

Nowadays in the mine are implemented many safety systems to protect workers. To avoid power failure, the mine has two independent sources of electric power. There are also many automatic safety systems that switch off electric power in case of an emergency. High voltage systems are also protected by barriers. Similar safety equipment will be installed in UL. Systems that eliminate these kinds of hazards will be prioritized.

5.2.5. Ground Control

Due to the geological structure and depth of mining operations, there are geomechanical hazards in the analysed area. Under such conditions, mining activity generates high pressures within the rock mass which in turn are the cause of damage to workings. The most dangerous hazards are roof falls and rock bursts. Therefore suitable ground support is one of the most important issues to ensure a safe workplace. The factors that have a significant impact on rockfall and rockburst hazards are:

- exploitation depth,
- mine-out area,
- seismic events,
- strong rocks in the roof,
- occurrences of geologic discontinues.

There are many active and passive preventive methods to limit these kinds of hazards. One of the most effective is blasting method which is used to provoke intentionally seismic events which release stress in the rock mass in specified time where the crew is safe outside the danger area. Additional in some areas backfilling is used. There is also a special work organisation in danger areas where the number of workers is limited. Due to this fact conceptual prototype is located in a protected area close to the shaft.

5.2.6. Ventilation

Prototype lab will be located in the deep underground mine. It means that ventilation aspects are crucial from the safety point of view. Underground space is limited and air quality can be changed rapidly due to natural process, technological processes or accidents like fire. It means that it is possible that unbreathable or toxic atmosphere can be a presence in underground space. Due to connection with mining ventilation system mining ventilation hazards have an impact on the underground laboratory. Taking this into consideration there are three main hazards:

- low level of oxygen,
- occurrences of danger gases (toxic, asphyxiate),
- air temperature.

Therefore, the main target of the ventilation system is to provide a suitable amount of fresh air to supply oxygen and dilute/remove danger gases from mining atmosphere. The following toxic and/or asphyxiate gases can be a presence in Polkowice-Sieroszowice mine:

- CO and CO_2 (carbon monoxide or dioxide),
- NO_x (nitrogen oxides),
- SO_2 (sulphur dioxide),
- H_2S (hydrogen sulphide),
- CH_4 (methane).

To control these hazards parameters of the ventilation system must be constantly monitored. Additional each of workers and visitors must be equipped with self-rescuer which can be used in case of emergency.

5.2.7. Radiation

Within the activities of BSUIN project, the natural background radiation in Polkowice-Sieroszowice mine was evaluated. The measurements were conducted in the direct vicinity of SW-1 mining shaft (Figure 5.2). The detailed results will be published, but in general, our measurements lead to the conclusion that naturally occurring radiation level is very low and there is no risk related to this. Still, it must be highlighted that this kind of hazard can be increased by man-made radiation related to potential research studies. In the case of conducting such activities, radiation measurement needs to be conducted in a periodical manner.

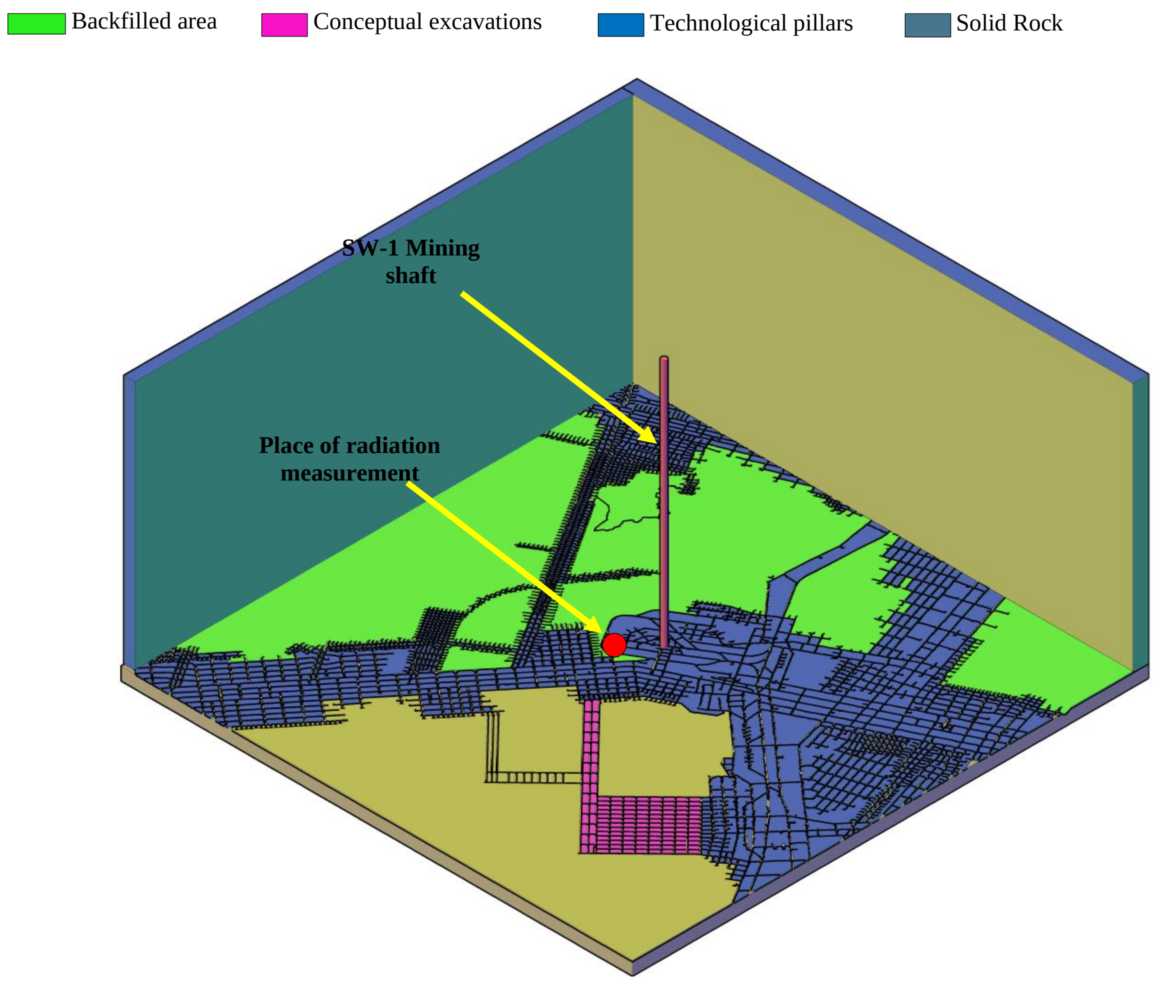


Figure 5.2. The location of radiation measurements

5.2.7. Flood

There is a hazard of water inrush hazard in some mining panels of Polkowice-Sieroszowice mine. Threats level is different depending on the location. To minimise this threat, both Concepts of Underground Laboratory are located over the level of the potential flood. This allowed to minimise or even eliminate the risk of flood due to the water inrush.

5.2.8. Transport

Access to the UL laboratory will be provided by transportation shaft (vertical transport) and transportation vehicles. Therefore hazard related to this kind of transportation operation can occur. The main hazards connected with transport operations are:

- lift breakdown,
- car accident,
- hit by vehicles,
- etc.

Prevention of such a threat will be based mostly on the training of employees and visitors.

5.3. Preliminary Risk Assessment

To assess the risk level for each of the hazards that were identified in Polkowice-Sieroszowice mine where UL is planned, risk assessment was carried out. Hazards were divided into four groups (Figure 5.3).

Enviromental	Workplace	Mining oparations	Other
•Ground control •Seismic activity •Water •Gases	•Noise •Vibration •Electric •Technological	•Machinery •Blasting works •Ventilation •Dust	•Economic •Social •Political

Figure 5.3. Group of hazards presence in underground mines

<u>**Environmental risk**</u>

In the case of environment group of hazards, the serious risk is focused on ground control issues. The most dangerous is the risk related to the following aspects:

- roof failures,
- workings instability,
- ground movement.

The manifestation of these threats is the movement of fragments of rock into workings free space, from the roof or walls. It causes serious hazards for workers, machines and mine’s infrastructure.

A part of ground control risk assessment is shown in Table 5.1.

Table 5.1. Risk assessment - environment

No.	Ground Control	Probability	Impact		Risk
1.	Geologic discontinuities occurrence	MODERATE	SEVERE		Medium
2.	Unsupported roof	LOW	CATASTROPHIC		Serious
3.	Spalling of wall	MODERATE	MODERATE		Medium
4.	Roof Failures	LOW	CATASTROPHIC		Serious
5.	Workings instability	LOW	CATASTROPHIC		Serious
6.	Overburden Caving	EXTREMELY SMALL	CATASTROPHIC		Medium
7.	Long term creep effect	MODERATE	MODERATE		Medium
8.	Too high In-Situ Stress	LOW	SEVERE		Medium
9.	Ground Movement	LOW	CATASTROPHIC		Serious
10.	Collapse of surface	EXTREMELY SMALL	CATASTROPHIC		Medium
11.	Mine collapse	EXTREMELY SMALL	CATASTROPHIC		Medium

Next part of hazards is associated with seismic activity what can cause fast and dynamic rock movement in form of rockburst. The source of rockburst can be pillars, roofs etc. Time and energy of occurrence of this kind of phenomenon are at the moment impossible to predict. It this kind of events large area can be affected and therefore it is one of the most dangerous hazards in mine.

Potential serious risk concern also gases, which can appear in the underground laboratory. This is due to the fact that fresh air is supplied by mining ventilation system danger gases that can be a presence in the mine maybe transfer to the laboratory. Sources of the dangerous gases can be rock mass, mining processes, machines, fires etc.

Hazard than must be taken into consideration during operation of the underground laboratory is also water ingress into underground workings. Sudden inrush of the significant amount of water can create severe threats for personnel and equipment.

Risk at the workplace

In the field of workplace hazard conducted risk assessment indicate that serious risk concern the following aspects:

- electrocution,
- lack or improper emergency procedures,
- lack of key sensors (oxygen concertation sensor, danger gases sensors, etc.).

Depending on the research type in the lab, other serious risks can appear e.g. noise, vibration, etc. A part of the risk assessment related to the electricity is presented in Table 5.2.

Table 5.2. Risk assessment - workplace

No.	Lightening and Electric	Probability	Impact		Risk
1.	Inadequate existing power supply	LOW	Severe		Medium
2.	No permanent power supply available	EXTREMELY SMALL	Catastrophic		Medium
3.	Frequent power failure	EXTREMELY SMALL	Catastrophic		Medium
4.	Electrocution	LOW	Catastrophic		Serious
5.	Short circuit	LOW	Severe		Medium
6.	Ignition of electrical devices	LOW	Severe		Medium

The analysis was shown that the most serious risk is associated with electricity, technology and lack or wrong emergency procedures.

Risk related to the mining operation

This kind of risk was analysed in the following group:

- machinery,
- blasting works,
- ventilation and air condition,
- dust.

Investigation in this issue shown that risk is very high in three main fields, namely:

- machinery (hit by machines, accidents with machines etc.),
- blasting works (uncontrolled explosion, post-blast fumes, misfires etc.),
- ventilation and air condition (fires, air temperature, air quality etc.).

Other

This group covered the following aspects:

- social risk (lack of qualified workers, problems with local community etc.),
- political risk (demonstrations, strike, etc.),
- economic (crisis, lockdown, etc.).

Study of this group presented that in this area risk level is relatively low.

5.4. Summaries

All these examinations at the stage of development of conceptual underground laboratory indicated that geomechanical risk is the most important. It means that a reliable assessment of this aspect was the key issue during the feasibility study. Verification of these projects was done on the base of numerical modelling and analysis, which confirmed, at this stage, that preliminary assumptions were correct and risk level is acceptable.

6. CONCEPTUAL DESIGN OF UNDERGROUND LABORATORY IN KGHM MINES

Within this chapter, final assumptions concerning the set-up of the underground laboratory will be described.

Knowing the potential risks the conceptual prototype of underground laboratories in deep copper mine conditions were prepared. Authors intention was to develop a solution which will fulfil not only safety requirements(National Centre for Nuclear Research) but also will provide a well-developed working environment with respect to the best practices. Because both concepts of Underground Laboratories will be located in an active mine, special attention will be paid to ventilation, induced seismicity and geomechanical hazard.

6.1. Underground Chamber

When considering the underground chamber, at the moment there is no exact idea of what kind of activities could be conducted there. In the past, the two detectors, namely GLACIER (liquid argon detector) and LENA (liquid scintillator detector) have been considered to be appropriate for kinds of rock mass encountered at Polkowice-Sieroszowice site. Unfortunately whole the entire venture has been abandoned, and science then there was no proposals of a new project. Still, Polkowice-Sieroszowice mine due to the unique rock properties are a suitable place for setting up of underground astrophysics laboratory.

Therefore, a geomechanical feasibility study was presented in chapter 4 of the present document. The exact shape, geometry of workings and required equipment of UL will be prepared in case of any project proposal.

6.1.1. Development of seismic network

The conceptual underground chamber is located in the area of the well-developed seismic monitoring system. Thus, there is no necessity of additional development of a seismic network for the purpose of UL monitoring. Moreover, according to current assumptions, the underground Chamber will be constructed for the purposes of physical or astrophysical measurements, and no activities generating additional dynamic load are planned to set up.

6.1.2. Geomechanical risk monitoring

Because of large dimensions the additional enforcement of roof and walls of UL are planned. To the stability of the chamber the special type of cable bolts and resign bolts will e utilised. Also, additional steel mesh will be installed at all free- faces of the underground chamber.

Moreover, the sophisticated monitoring system for continuous measurement of stress, strains and inclination within UL will be developed. The system will be based on joint measurements with the use of instrumented rock bolts and inclinometers.

Instrumented Rockbolts

The proposed solution allows for simultaneous recording at five measuring levels of the bolt's rod in four opposite directions in the vertical plane perpendicular to the bolt axis (Figure 6.1). High sensitivity of the installed strain gauges and changeable sampling frequency of in the range of 0.1-100 Hz determine high accuracy of continuous monitoring of axial stresses at each measuring level in the bolt's rod (Pytel et al., 2016; Pytel et al., 2019)

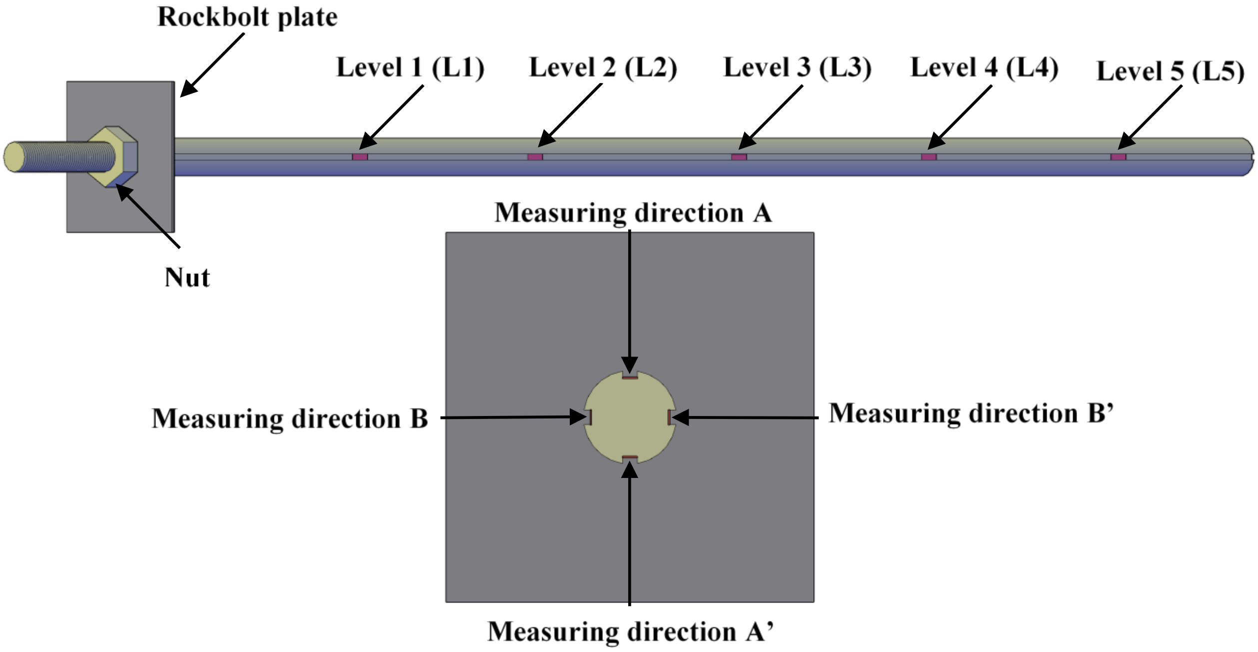


Figure 6.1. Scheme of instrumented rockbolt for continuous stress, strain measurements

Installation of stress-strain measuring posts allows determining scale of the hazard, both in its scale and its dynamics. Example of axial stress changes which had lead to the roof failure is presented in Figure 6.2.

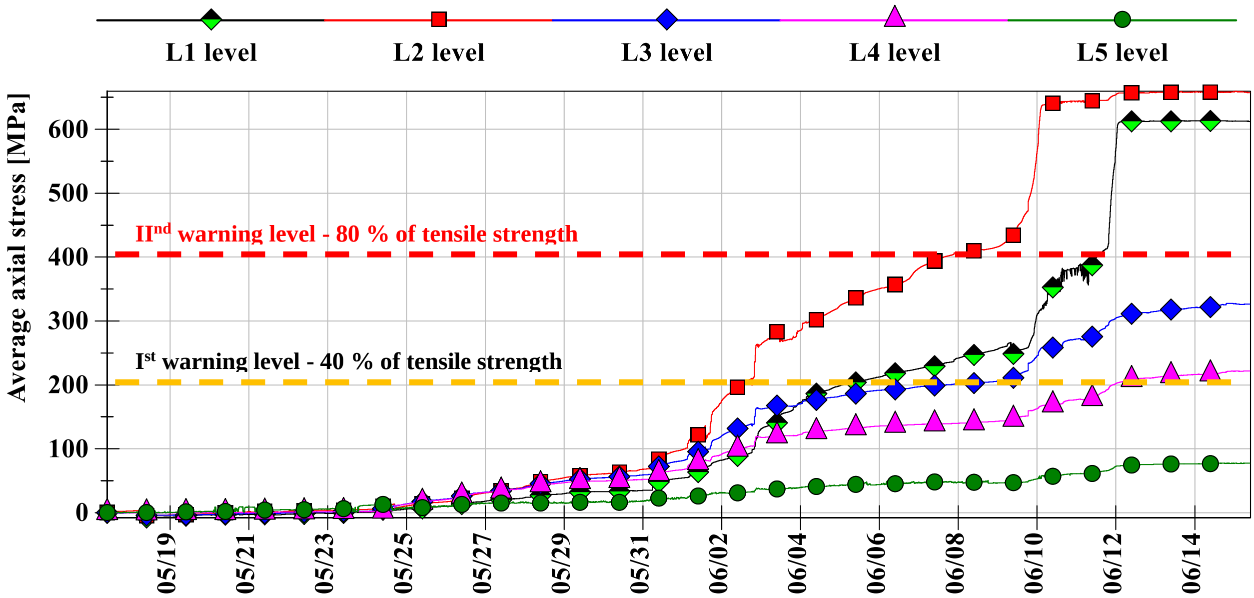


Figure 6.2. The principle of roof fall hazard warning with the use of instrumented rockbolts

Inclinometric measurements

As it was pointed out by Grzebyk and Stolecki. (2014) the rapid changes of inclination may indicate that technological pillars started to turns into the post-critical state, and local roof within mining panel may start to deflect, what will be strongly unwanted in case of the projected trial panel. Therefore inclinometric measurements will be utilised in the developed mining panel. The description of inclinometric sensors and principle of measurement is described in one of BSUIN reports WP4-H&S (Fuławka et al., 2020)

6.1.3. Gas monitoring

Rock mass in the surrounding of the Conceptual Underground Chamber is well recognised. According to research, there are no gas-filled caverns observed above and below the projected working. Therefore, there are no plans to install permanent gas detectors within the Underground Laboratory.

6.1.4. Temperature and Airflow regulation

The projected Underground Laboratory (Chamber) is located in the vicinity of the P-VII mining shaft. Therefore thermal condition and ventilation will fulfil all law requirements. It is expected that temperature within the Underground Laboratory will not exceed the value of 28°C degree. Thus, according to polish law, one shift within this laboratory can be 8 hours long. To ensure that research activities conducted within-trial panel will not affect the overall ventilation in Polkowice-Sieroszowice Mine, the Ventilation locks (Fig. 6.3) are projected at all access drifts to the Underground Laboratory (Figure 6.4).

Figure 6.3. Example of ventilation lock used in KGHM mines

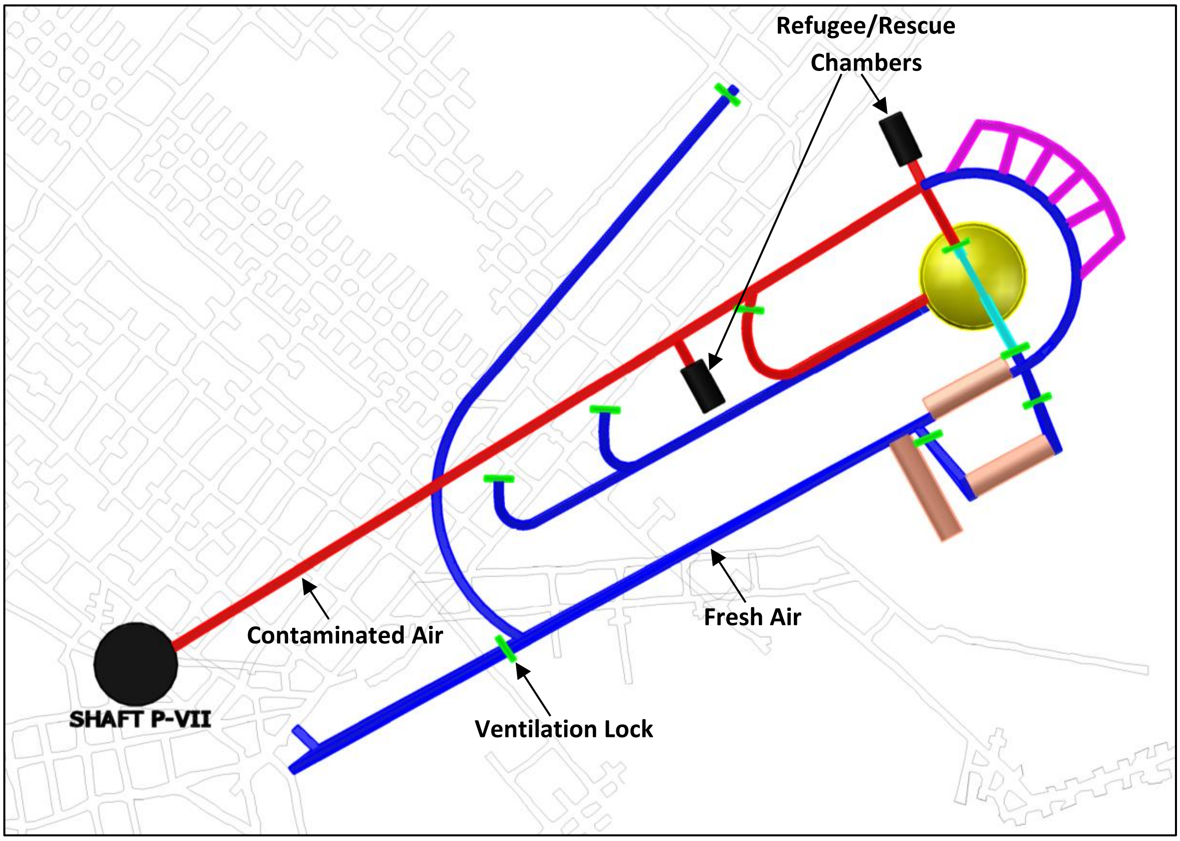


Figure 6.4. Scheme of air distribution through projected workings and location of ventilation locks

6.1.5. Safety Chambers

In case of any accident or fire, the accessibility to safety chamber has to be ensured. In the case of Underground Laboratory, the refugee chamber (figure 6.5) is planned to be in one of the evacuation routes, and near the functional chambers (Figure 6.4).

Figure 6.5. the example of a rescue chamber which may be installed in the vicinity of Conceptual UL (MineARC Systems, 2020)

6.2. Mining Panel

Ensuring safe condition in a facility like Large Scale Underground Laboratory or, in other words, trial mining panel is a highly complicated issue. Firstly, the thing is the fact that the geometry of the underground facility is changing during the time what effect continuously on local stress-strain condition. The second aspect what needs to be considered is the scope of activities conducted within the trial mining panel. Therefore it is necessary to plan reasonably not only geometry and infrastructure of the facility, but also develop monitoring systems and prevention methods to ensure safety for all visitors.

Considering ergonomic of developed chambers it is assumed that their geometry may vary depending on the purpose of use. Machine chambers in general will be bigger than chambers for staff or equipment. Proposals of geometry and arrangement of the machine chamber are presented in figure 6.6.

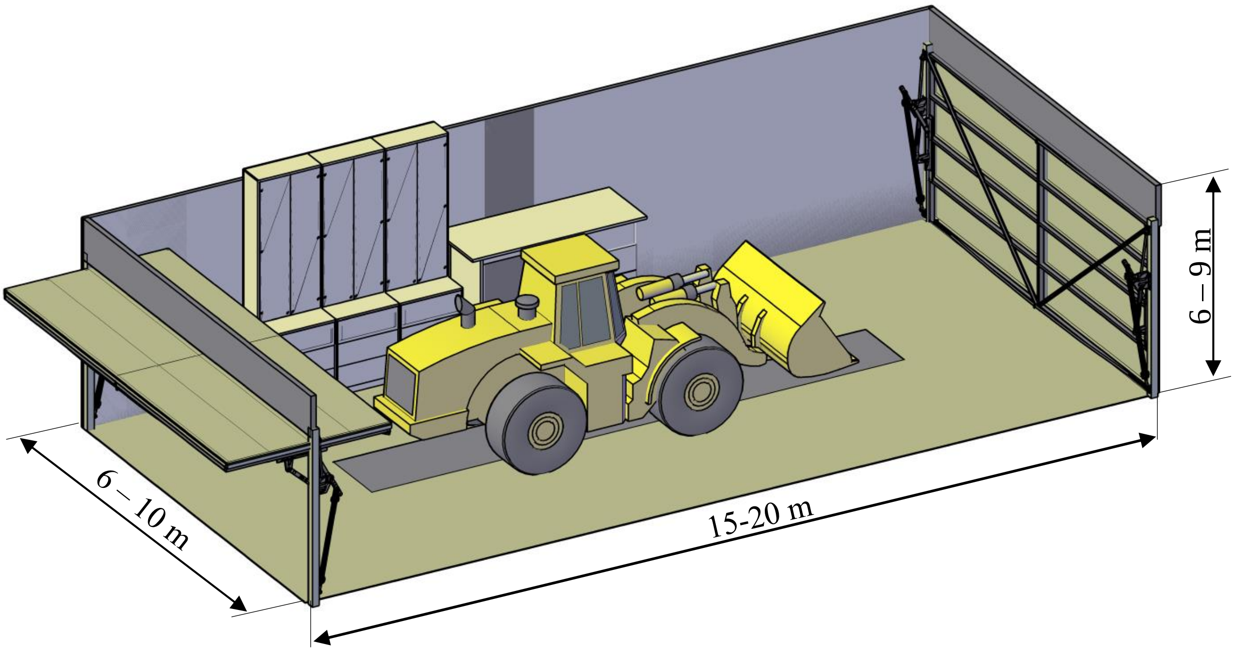


Figure 6.6. Conceptual shape and arrangement of a machine chamber located near the trial mining panel

Due to the fact that large scale laboratory will be developed for the purposes of research and development of mining technologies, it is planned to build also chambers for data collection and analysis. Such chambers need to be equipped with:

- AEDs,
- computers,
- freshwater,
- tables,
- fire extinguisher
- ventilation
- doors from both sides to regulate airflow and reduce dust
- bookshelf’s etc.

As it was pointed out in a report prepared by the University of California, Santa Cruz (2020) during the design of the job itself, work tools and the workstation location has a direct impact on the risk of injury. Incorporating ergonomic principles into the design of laboratory tools and workstations, and reviewing work processes to maximize productivities can help prevent work-related injuries. Periodic assessment of the work environment, tools and procedures help to ensure that necessary modifications are made as processes change.

Therefore the presented arrangement (Figure 6.7.) is the preliminary proposition. Further charges may be applied on the basis of surveys and checklists filled by workers.

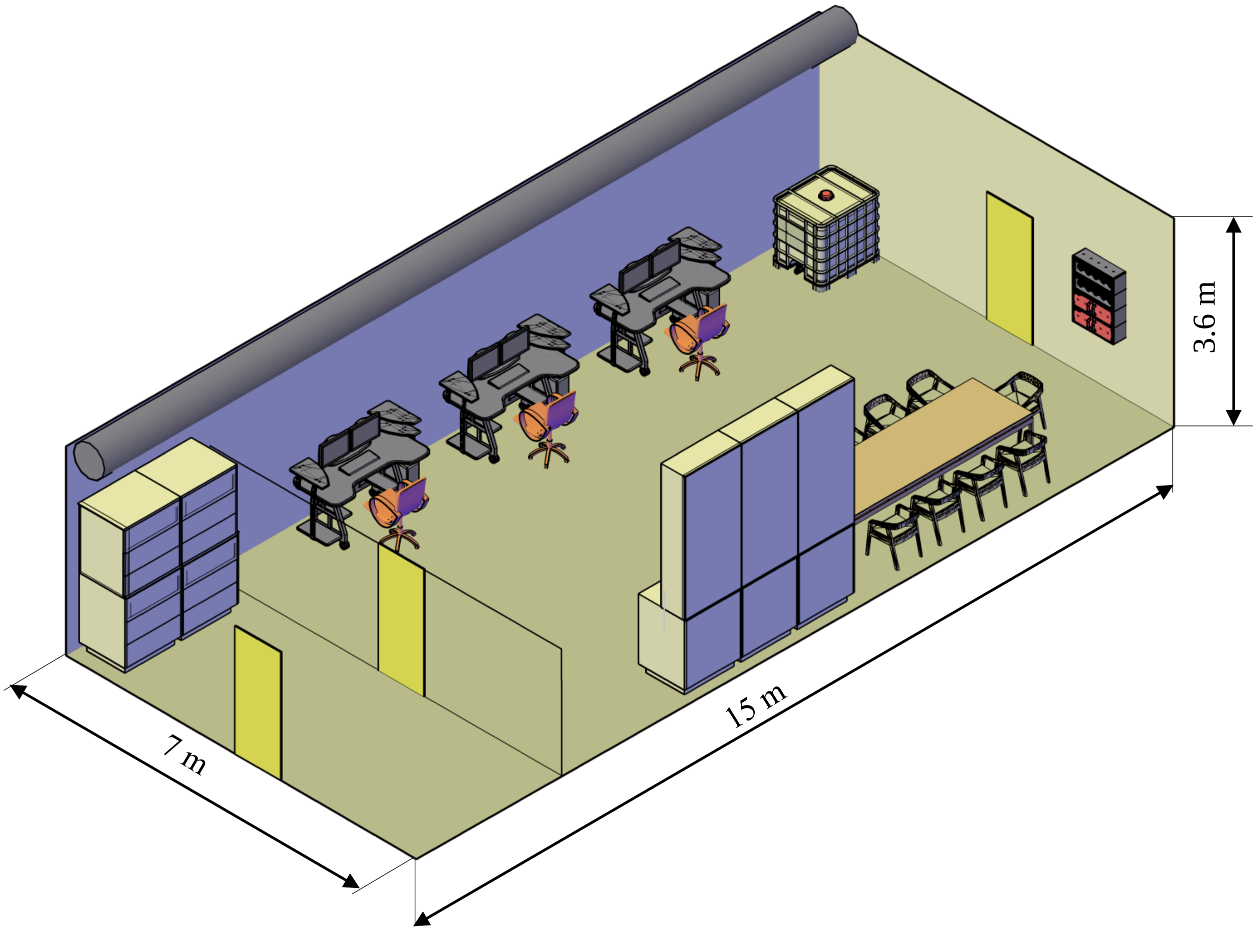


Figure 6.7. Proposal of one of mining chambers geometry arrangement

6.2.1. Development of seismic network

There are no active mining panels in the vicinity of the area where Underground Laboratory is projected. Therefore the stress-strain conditions in the surrounding of SW-1 mining shaft are stabilised at the moment, and the probability of seismic even occurrence in that area is relatively low. Still, the occurrence of the additional dynamic load, generated by far-field tremor is possible. What more in case of conduct research on blasting technology, the paraseismic load may be generated within the framework of the trial panel.

Thus, it may be expected that far-field tremors will generate low-frequency vibrations (f<10 Hz) but paraseismic activity in very close vicinity for mining source may be related to seismic wave with a dominant frequency exceeding 200 Hz. In such a case, it is recommended to conduct seismic measurements with the use of geophones or accelerometers with frequency bandwidth exceeding 200 Hz and the sampling rate over 1,000 Hz.The properly-developed seismic network allows to determine not only the amplitude and dominant frequency of seismic waves but also, based on gathered data allow to determine the location and energy of tremors.

There are many methods of determining hypocentres of mining-induced seismic events. However, regardless of the chosen method, the proper assessment requires using at least 3 seismic stations. With the rise of measuring stations, the quality of energy and location determination rise significantly. Therefore, in the surrounding of the projected trial panel, 4 seismic posts are planned to set up. A task aimed to determine the epicentral location can be given the form illustrated in Figure 6.8.

The location of the seismic source in the proposed method will be determined by the point lying at the intersection of the circles with radius D1, D2, D3 and D4. Obtaining reliable results requires a thorough recognition of the velocity field and a precise identification of the moment of arrival of the P wave and the S wave. In such case location, The location of the tremors determined based on measurements will be unambiguous even in the event of failure of one station will occur.

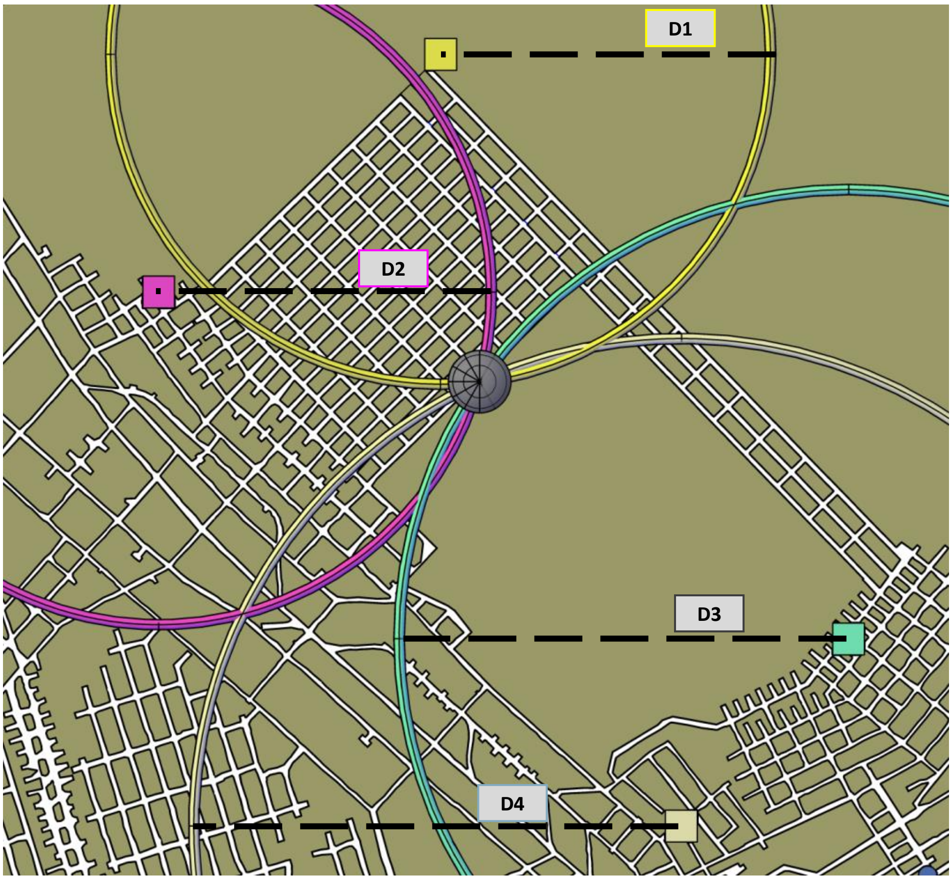


Figure 6.8. Spatial distribution of seismometers in the surrounding of the conceptual trial panel

Continuous monitoring is especially important in case of researching blasting technology. According to the author's experience (Mertuszka et al., 2018), proper synchronisation of detonation times in subsequent blast holes/mining faces is a key factor during the control of the seismic effect. Even with the use of the same type of material and the same quantity of explosives, the seismic effect may be significantly different, if delays and spatial location of blasted faces are selected properly. The example of amplified and damped paraseismic effect after blasting in one of KGHM mining panels is presented in figure 6.9.

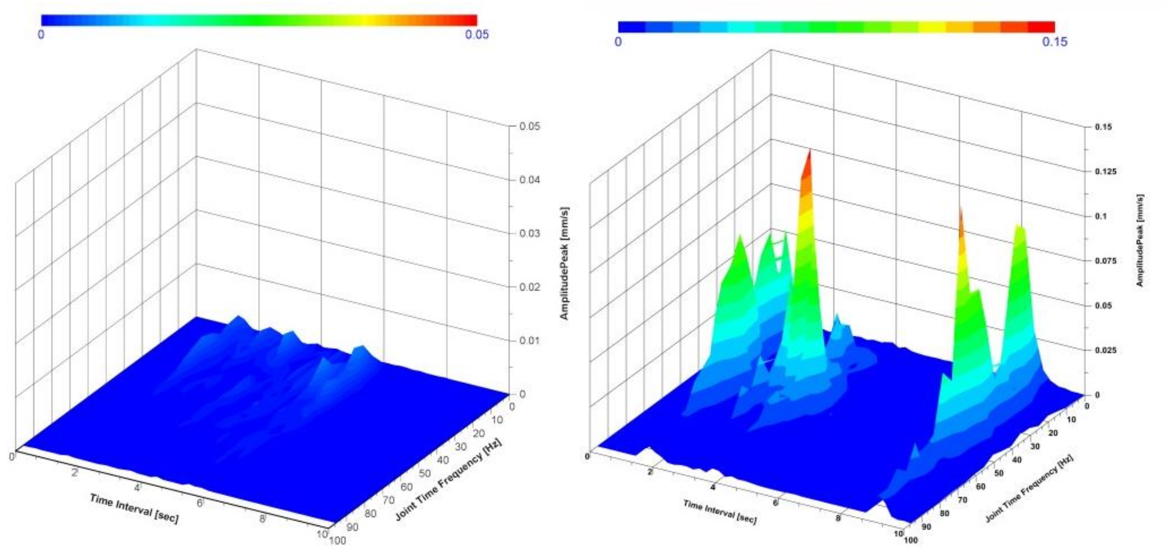


Figure 6.9. Relative seismic energy distribution after detonation of 25 faces- 1,465 kg left 22 faces- 1,470 kg

6.2.2. Geomechanical risk monitoring system

Stress-strain conditions; or rather their changes during the Underground Laboratory Life-cycle may indicate the actual risk of geomechanical hazard occurrence. Rapid rise or drop of e.g. axial stress within the immediate roof strata may indicate the possibility of roof fall occurrence. Therefore it is planned to install instrumented rock bolts in each one of eight chambers situated in close vicinity to mining panel.

In the proposed trial panel a sophisticated geomechanical risk monitoring system is planned to build in. Moreover, there will be two access/evacuation routes with a double line of workings what will be determined by ventilation requirements. Near the active mining panel, eight chambers for machines, people, equipment and datamining will be developed. In these chambers instrumented rockbolts with built-in early warning systems will be prepared. The details about monitoring devices locations, escape routes and locations of mining chambers are presented in figure 6.10.

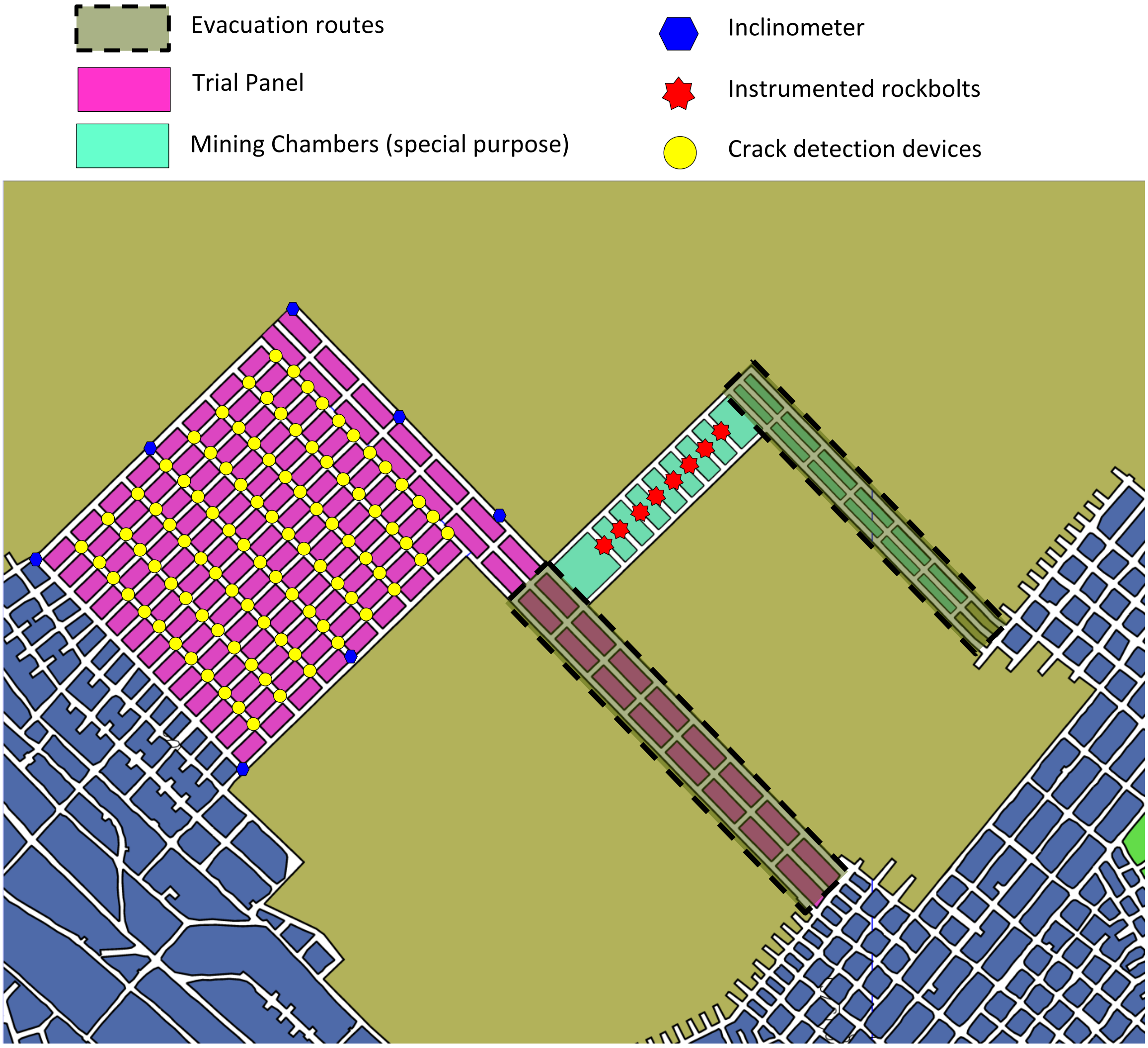


Figure 6.10. The geometry of the trial panel and location of monitoring devices

Instrumented rock bolts are planned to be installed mainly within the strategic workings of a conceptual underground laboratory. It is planned to mount at least one sensor in each of eight mining chambers. The principle of instrumented rock bolts measurements which is planned to utilise within the conceptual trial mining panel as well as their characteristic was presented in chapter 6.1.2.

Within the transport roads and chosen workings of the trial panel, clinometric sensors are planned to be installed. The measurements of roof layers deflection allow determining if pillars in the direct surrounding are prone to lose stability. The principle of inclinometric measurements and sensors which are planed to utilise within the conceptual trial mining panel were presented in chapter 6.1.2.

Crack detection devices

Due to the ease of interpretation of the results and the ease of installation, crack detection devices (SRS-Sensor of Roof Separation) are widely used in Polish copper mines. They are usually grouted in, and their length depends on hanging wall geology. Generally, the length of the SRS rods ranges from 3 to over 7 meters. The anchoring depth of the SRS should be twice the length of ordinary anchors to detect any loosening of the roof layers. It allows anchoring the SRS devices above the range of weak layers of the immediate roof rocks (Fulawka et al., 2018). Many variants are available with a different number of signalling plates, thickness and shape. However, the five-plate variant is most often used with a plate thickness of 5 mm (Figure 6.11).

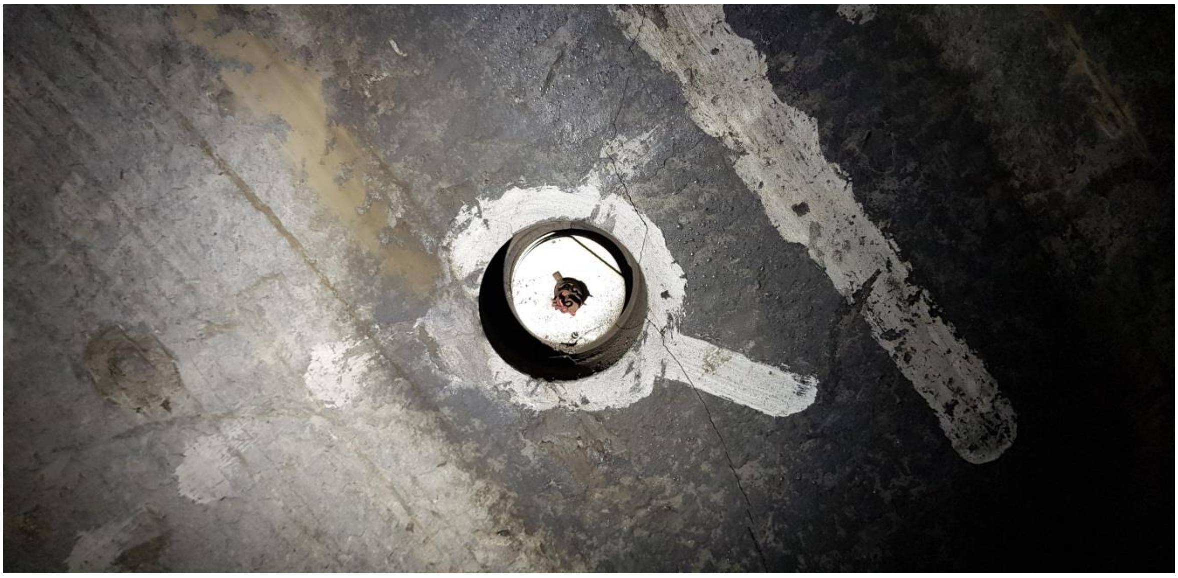


Figure 6.11. Device for Crack detection signaling

Crack detection devices will be installed within all cross-sections of trail panel. Crack detection devices are available in mechanical and electronic versions (Majcherczyk, 2005; Matusz & Szczerbiński, 2013), but there is no significant difference in the case of efficiency of both types of devices. Therefore, within the projected Trial-Panel mechanical version which is very cheap and effective at the same time, will be used. The principle of operation of the crack detection device is shown in figure 6.12.

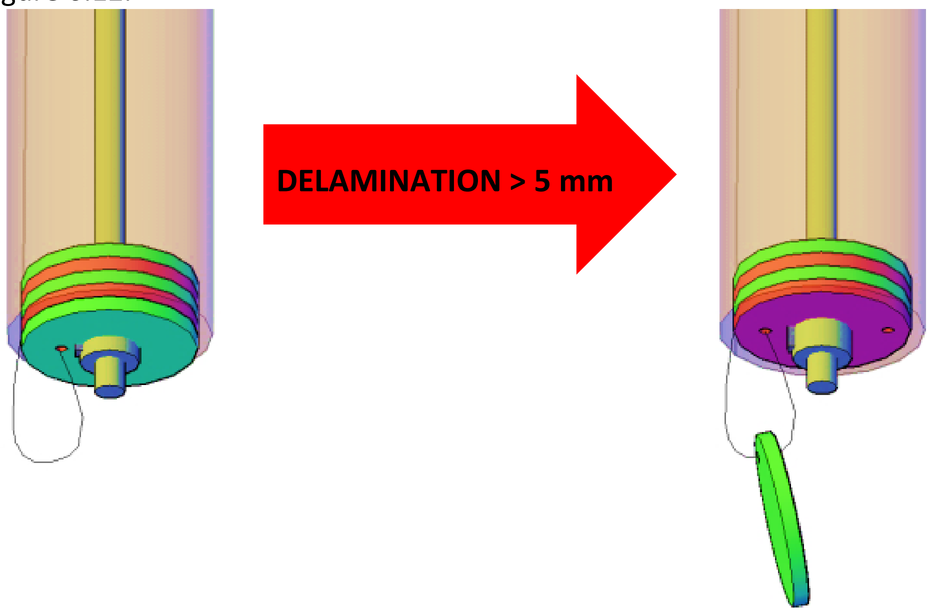


Figure 6.12. The principle of roof delamination warning

6.2.3. Gas monitoring

Rock mass in the surrounding of the trial panel is well recognised. According to research, there are no gas-filled caverns observed above and below the projected working. Therefore, there are no plans to install permanent gas detectors within the Underground Laboratory. Still, some fumes may be generated by blasting works, diesel machines or fire. Therefore a personal gas detection detectors are recommended.

6.2.4. Temperature and Airflow regulation

The projected trial panel is located in the vicinity of the SW-1 downcast mining shaft. Therefore thermal condition and ventilation will fulfil all law requirements. It is expected that temperature within the Underground Laboratory will not exceed the value of 28°C degree. Thus, according to polish law, one shift within this laboratory can be 8 hours long. To ensure that research activities conducted within-trial panel will not affect the overall ventilation in Polkowice-Sieroszowice Mine, the Ventilation lock are projected at the access drifts to the Underground Laboratory (Figure 6.13).

In the preliminary project, it is assumed that 2 of 8 chambers of the projected Underground laboratory will be separated by gates/doors. In these chambers, the humidity will be regulated, and therefore, scientific research devices and computers may be stored there. Rest 6 of 8 chambers will be the open one.

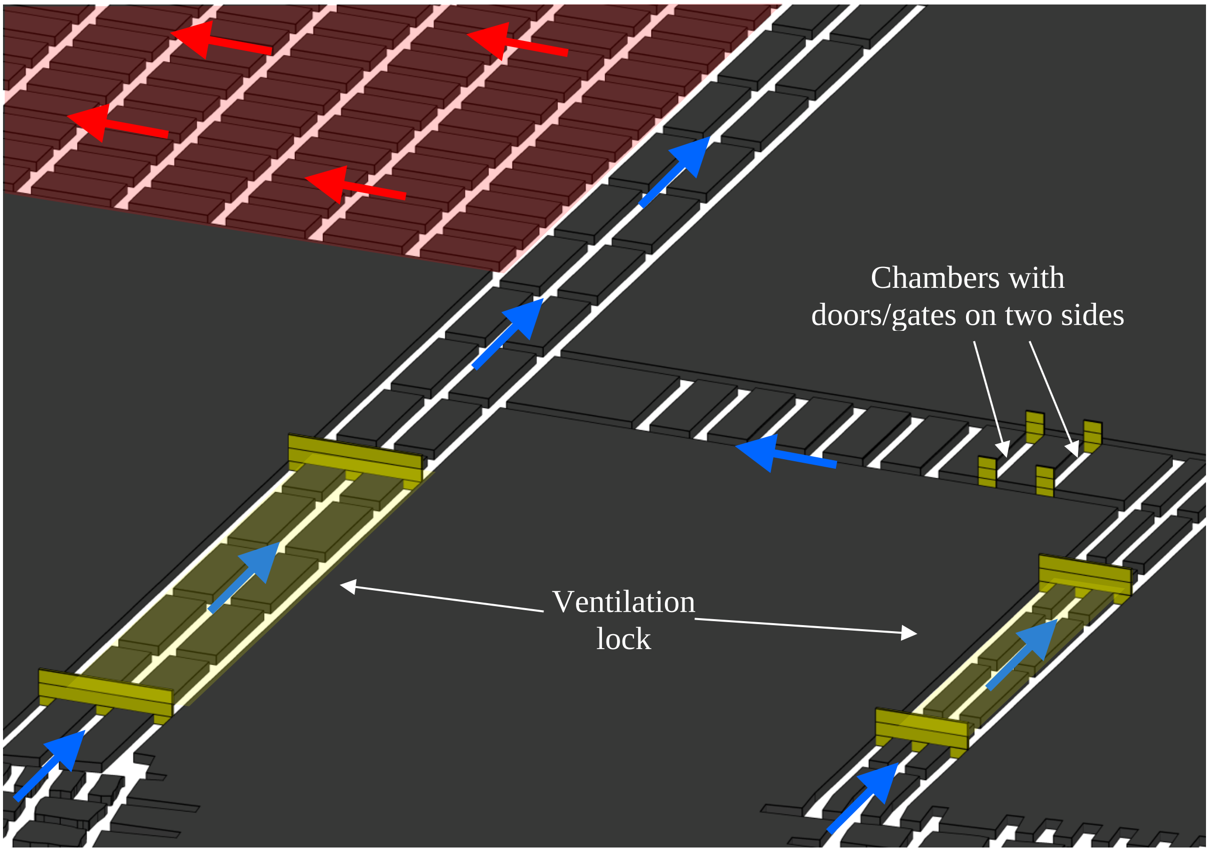


Figure 6.13. Scheme of air distribution through projected trial mining panel and location of ventilation locks

Concerning the types of ventilation locks at the entrance and exit of conceptual underground laboratory, it is planned to construct two types of gates. The first type is the dam of big size (5x3 metres) which will open automatically when a car/machine approaches it. Second, smaller gate (wall with doors) will be built next to it and will allow the pedestrian to access underground laboratory without opening the main gate.

6.2.5. Safety Chambers

Within the Trail Mining Panel, it is planned to install two rescue/refugee chambers. Due to the safety measures, It is recommended to install this chamber near the front line of the projected mining panel to minimise the distance of evacuation. The location of rescue chambers is presented In figure 6.14.

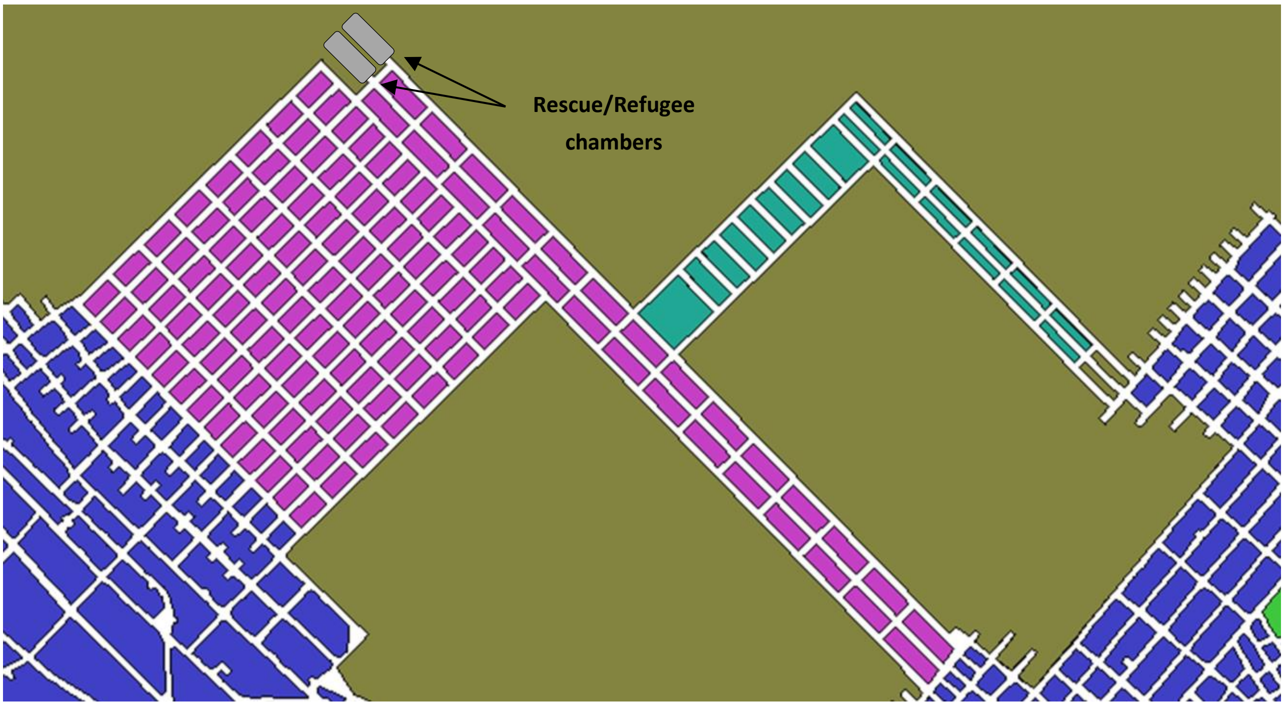


Figure 6.14. Location of safety chambers in vicinity of the front line of trial mining poannel

7. FACILITY IMPROVEMENT

Safety is a key priority in UL therefore additional monitoring devices should be implemented in the lab to ensure that control measures that are in place are working. In most cases, more than one control measures are necessary for sufficient managing a specific hazard. For example, the use of an oxygen detector, maintenance of the detection system, and training on using it might all be needed to avoid the hazard of low oxygen level.

Propose safety systems will be expanded in relation to the normal mining systems to guarantee a higher level of safety and reliability.

Table 7.1. Proposed solutions for facility improvement in the scope of environmental risk reduction

Hazard type	Control measures
Roof failures, working instability, ground movement.	1. Monitoring – instrumented rock bolts, convergence indicator, inclinometers. 2. Maintenance system and procedure. 3. Regular numerical modelling to check rock behaviour (validation on the base of monitoring measures). 4. Training, evacuation procedure.
Seismic activity	1. Monitoring – seismic sensors. 2. Maintenance system and procedure. 3. Training, evacuation procedure.
Water	1. Monitoring – water inflow. 2. Maintenance system and procedure. 3. Training, evacuation procedure.
Gases	1. Monitoring – oxygen level sensor, multi-gas detectors, anemometers, thermometers, fume detectors. 2. Maintenance system and procedure. 3. Training, evacuation procedure.

Table 7.2. Proposed solutions for facility improvement in the scope of minimizing the risk at the workplace

Hazard type	Control measures
Electric	1. Safety devices – automatic switch-off systems in case of emergency, overload protection systems, etc. 2. Backup electric power system. 3. Maintenance system and procedure. 4. Training, evacuation procedure.
Noise, vibration	1. Monitoring – noise indicator, vibration level indicator 2. Maintenance system and procedure. 3. Training, evacuation procedure.

Table 7.3. Proposed solutions for facility improvement in the scope of minimizing the risk related to mining operations

Hazard type	Control measures
Collision or hitting by machines	1. Localisation system for staff and machines – automatic brake systems in case of emergency, 2. Traffic management. 3. Maintenance system and procedure. 4. Trainings, evacuation procedure.
High temperature, Poor air quality	1. Monitoring – thermometers, oxygen level indicator, multi-gas detectors, anemometers. 2. Air condition system. 3. Emergency chamber with fresh air. 4. Maintenance system and procedure. 5. Trainings, evacuation procedure.
Fire	1. Monitoring – fume detectors, multi-gas detectors. 2. Automatic firefighting systems. 3. Maintenance system and procedure. 4. Trainings, evacuation procedure.

8. The process of UL planning and development

According to authors experience, the development of the new underground facility is a task which should consist of several key stages. Proposal for step-by-step UL development flowchart is presented in figure 8.1.

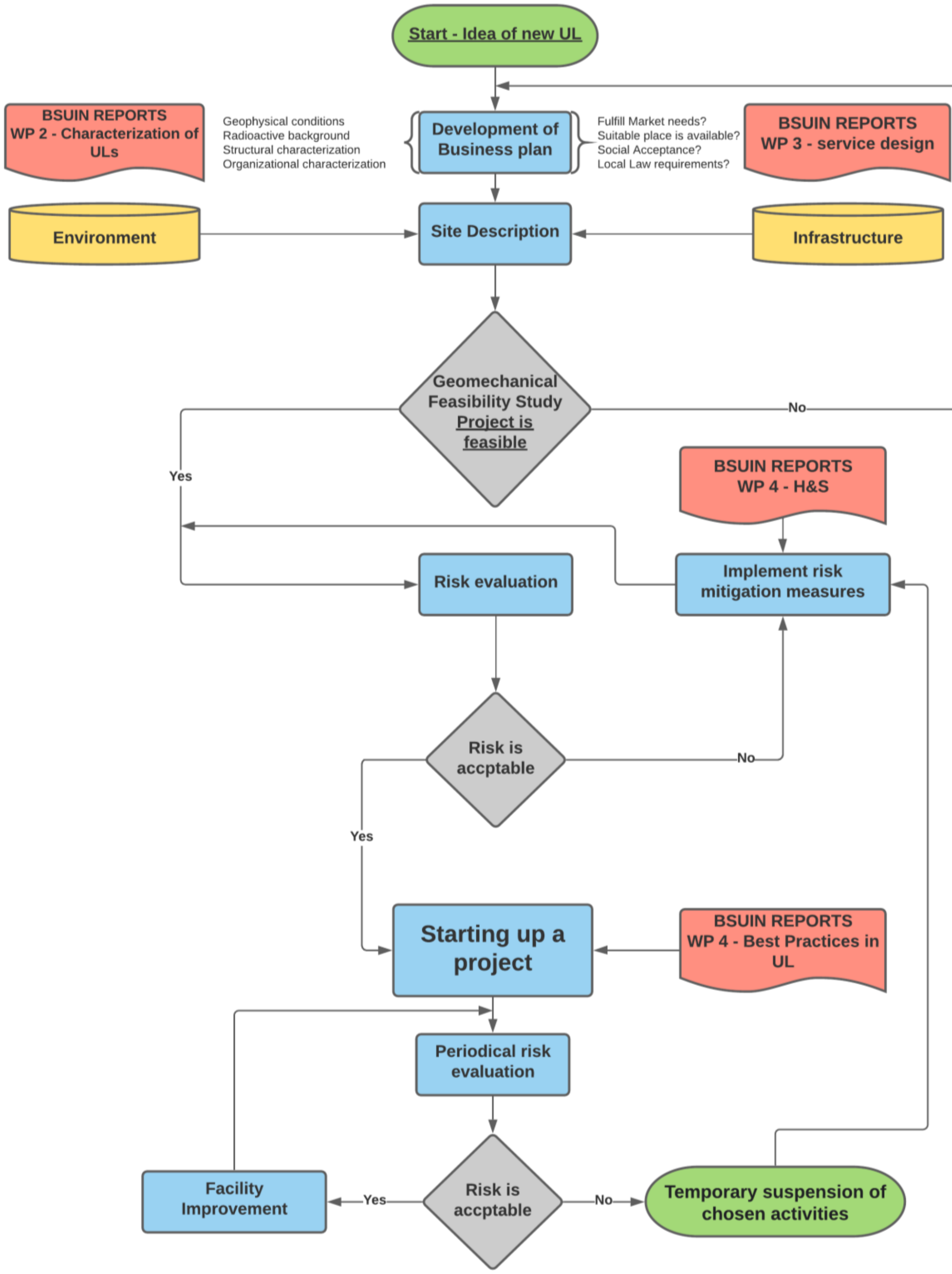


Figure 8.1. Flowchart representing the process of sustainable UL development

The whole process of developing a new facility, need to be based on the well-described concept. Some key information and hints concerning the development of the business plan may be found in BSUIN reports summarizing activities which have been held within WP 2 –Characterization of ULs and WP 3- Service design. Having a specified scope of activities it is important to analyze and describe in detail the environmental condition and available infrastructure. Such information is required for further processing of the geomechanical feasibility study. From the safety point of view, we strongly recommend conducting numerical analyses, with a rather rigorous approach. In the example, some variations in geomechanical parameters, or inaccuracy in whole facility geometry should be assumed. It will allow minimizing unwanted events in future. If analyses indicate that the project is not feasible then the whole idea concerning, the location and scope of activity should be reconsidered once again. Otherwise, an overall risk evaluation should have proceeded. The process of risk identification, classification, assessment and finally its evaluation is presented in one of the BSUIN reports WP4-H&S.

If there are no risks with the unacceptable level, which may jeopardize the whole project, then it is possible to run underground activities. If not, then risk mitigation measures need to be undertaken and the whole process of risk evaluation have to be repeated.

It should be highlighted that setting up of underground facility and starting of planned activities should be conducted with respect to best practices. It will make the whole project more safe, ergonomic and accessible for outside visitors and stakeholders.

The last group of activities, related with Underground Laboratory Lifecycle is periodical risk assessment and continuous facility improvement. If during the exploitation of underground facility some new hazard will occur, or hazard level will increase, then the temporary suspension of dangerous activities should be taking into account.

The procedures developed within Work Package 4 of BSUIN project may be used as a sort of guideline which may make the whole process of setting up of underground facility a much easier. Nevertheless, it must be kept in mind that, each underground location is characterized by different environmental conditions and different scope of activity. Therefore it crucial to remember that the whole process of project launch should be approached critically and the procedures presented above should be treated as a kind of guidance.

9. SUMMARY

Within the present documents, two conceptual prototypes of underground laboratories in deep copper mine have ben presented. One of the facilities (Underground Chamber) could be used i.e. for the astrophysical purposes, while the concept of the second facility (Trial Mining Panel) was developed mostly for the R&D purposes in the scope of applied geophysics, mining technologies, and safety analyses. In both cases, the geomechanical feasibility studies were performed. Moreover, both concepts have been prepared in accordance with the safety rules and best practices developed within BSUIN project

In the result of our analyses, we found out that Polkowice-Sieroszowice mine belonging to KGHM company is a suitable place for setting up of underground facilities for the non-mining purposes.

References

BSUIN WP4 Report: " Best practices from the ULs to Uls in the underground working environment" By A. Paat and J. Joutsenvaara, University of Oulu, Kerttu Saalasti Institute, (2020).

BSUIN WP4 Report: "Health & Safety in Underground Environment" By: Fuławka K., Pytel W., Szumny M., Mertuszka P., Joutsenvaara J., Shekov V. and Bubunova T., Wrocław, KGHM CUPRUM R&D, (2020)

Fuławka K, Mertuszka P, Pytel W. Monitoring of the stability of underground workings in Polish copper mines conditions. E3S Web Conf.; 29:00008, (2018).

Grzebyk W., Stolecki L., Inclinometric measurements as a tool of monitoring rock mass deformation in underground mines, Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN, no. 86, pp. 97-104, 2014

Itasca Consulting Group, Inc. FLAC3D — Fast Lagrangian Analysis of Continua in Three-Dimensions, Ver. 7.0. Minneapolis: Itasca, (2020).

KGHM Polska Miedź S.A., website: www.kghm.com (Access: 10 November 2020).

KGHM Zanam, website: www.kghmzanam.com (Access: 10 November 2020).

Majcherczyk T., Małkowski P., Niedbalski Z., Badania obciążeń obudowy w wybranych wyrobiskach korytarzowych. [Loading support research in the chosen dog-headings]. Górnictwoi Geoinżynieria, 29 (3/1). 289-298, (2005).

Matusz, C., Szczerbiński, K. Zwalczanie skutków zawałów skał oraz działania mające na celu zmniejszenie ilości zawałów i wypadków w kopalni „Polkowice-Sieroszowice'. [Suppression of the effects of rock falls and reduction of caving events and accidents number in 'Polkowice-Sieroszowice' copper ore mine]. Cuprum 1 (66): pp. 33-44, (2013).

Mertuszka P., Fuławka K., Stolecki L., Szumny M., Seismic effect of group winning blasting - case study from a Polish copper mine, Conference Proceedings 30th International Conference Blasting Techniques, pp. 126-135 (2018)

MIDASoft, 2020, MIDAS GTS NX 2020, http://www.midasGTSNX.com

Mine Master, website: www.minemaster.eu (Access: 10 November 2020).

MineARC Systems, website: https://minearc.com/ (Access: 10 November 2020).

Pujol M., Lighting at the End of the Tunnel-The Design of Adaptive and Intelligent Lighting for an Underground Workspace, Master Thesis, Oulu School of Architecture University of Oulu, (2019).

Pytel W., Mertuszka P., Fabiańczyk E., Fuławka K., System obserwacji stropu bezpośredniego oparty na wklejanej kotwi oprzyrządowanej, Wiadomości Górnicze, no. 12, pp. 654-664, 2016, Pytel W., Fuławka K., Mertuszka P., Effect of Near-Wave Field Mining Tremors on the Rock Bolt Support Behaviour within Stress Domain, E3S Web Conf., 105, 01007, (2019) DOI: https://doi.org/10.1051/e3sconf/201910501007

Pytel W., Fuławka K., Pałac-Walko B., Mertuszka P., Kisiel J., Jalas P., Joutsenvaara J., Shekov V. Universal Approach for Risk Identification and Evaluation in Underground Facilities, Minin Science, vol. 27, pp. 165-181, (2020), DOI: 10.37190/MSC202712

Rocscience Inc., Unwedge Version 3.0 - Underground Wedge Stability Analysis, (2020).

University of California, Santa Cruz, Reducing Ergonomic Risks in Laboratories, (2020)

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