The Josef Underground Laboratory and New Challenges

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ABSTRACT: The Josef Underground Laboratory is an academic facility primarily engaged in research activities. Launched in 2007 by the Centre of Experimental Geotechnics at the Faculty of Civil Engineering of the Czech Technical University in Prague, the laboratory has received support from Metrostav a.s., among others. Most of its research and development activities focus on the safe and sustainable storage of radioactive waste. With the support of the Radioactive Waste Repository Authority, among others, this research continues in cooperation with ÚJV Řež a.s. The long-term experience gained from these projects led to the signing of a memorandum of bilateral cooperation with the Korea Atomic Energy Research Institute in 2025. In collaboration with Korean partners, the project "Optimization of Materials and Technologies for Radioactive Waste Disposal in Deep Repositories" (TAČR SIGMA program TQ16000084) is underway. This project has three main objectives: developing bentonite granules, testing the spread of substances in bentonite experimentally, and constructing a 1:1 scale in-situ experiment.

Other current in situ projects include researching the use of old mines and waste materials for seasonal energy storage. Another emerging topic is researching the safe storage of hydrogen. In 2024, the Josef Underground Laboratory became a testbed for underground structures within the National Centre for Construction 4.0. This collaboration has introduced new challenges in underground construction, especially regarding digitization and robotization.

In the field of digitization, activities primarily focus on creating a georeferenced BIM model of underground spaces. This model incorporates safety features and experimental results. Since mid-2025, an autonomous loader for underground structures, including its digital twin, has been under development. This loader moves around in the digital model of the Josef UL underground. One project in development is the JULBOT (Josef Underground Laboratory Bot), a university robot designed to inspect and monitor underground structures. It is equipped with sensors and can perform comprehensive environmental analysis and create its own BIM model. Postgraduate students are not the only ones involved in the experimental activities. Currently, international students are working on topics such as gas diffusion in bentonite, the acoustics of underground structures, pond sealing, and underground excavation technology. The Josef Underground Laboratory has been in operation for 18 years and continues to successfully address new topics relevant to teaching and research.

1. INTRODUCTION

The Josef Underground Laboratory (Josef UL) is a teaching, research, and experimental facility operated by the Faculty of Civil Engineering at the Czech Technical University in Prague. The Josef UL complex includes the Josef Tunnel, an exploratory tunnel. It is located near the Slapská Dam, not far from the village of Chotilsko. From an academic standpoint, the facility's primary function is to provide students with hands-on training in an authentic underground setting, support the execution of experimental projects, and fortify the connection between academic learning and professional practice.

The Josef mine was excavated in the 1980s as part of a geological survey of the Mokrsko and Čelina gold deposits. Almost eight kilometers of underground space were excavated. The adit (mine) was abandoned in the 1990s. In 2007, it was opened as part of the "Josef Underground Laboratory" project, which is still developing. In the first phase, 600 meters were put into operation, and teaching and research activities began. By 2026, an additional 6 km of underground space will be operational, and the 1.2-hectare surface area of the Josef Underground Laboratory will be used for teaching, scientific research, and other projects.

The Josef Underground Laboratory primarily conducts research that impacts current social and industrial issues. Long-term experiments related to the safe storage of radioactive waste and energy storage are conducted here. Additionally, new technologies related to the construction and operation of underground structures are tested here. Given the developing possibilities of Industry 5.0, activities related to digitization and automation are underway. For example, developing BIM as an efficiency-increasing tool is certainly suitable for testing in Josef UL. For this reason, a unique BIM environment is currently being developed at Josef UL to showcase ongoing experimental work, including underground projects. As part of Industry 5.0 activities at Josef UL, robotic and autonomous systems are being tested as well. Topics related to building inspection and monitoring, as well as critical situation resolution, are gradually being developed. Other Czech Technical University in Prague institutes, including the Czech Institute of Informatics, Robotics and Cybernetics, are involved in these activities as well. Within the framework of the JULBOT platform, the first projects are being implemented in cooperation with industry. For example, a project for an autonomous loader for underground structures is being developed.

2. BASIC INFORMATION ABOUT THE JOSEF UNDERGROUND LABORATORY

The Josef UL complex is divided into three sections. The underground section consists of the reopened Josef Adit. The second part is the surface section, and the third part is the administrative building of the Josef Underground Research Centre (URC Josef). This building houses offices, a meeting room, and accredited laboratories.

The underground section (adit) passes through two different geological formations in a north-south direction across the Veselý vrch rock massif in the Psí hora ore district. One part consists of sedimentary rocks of the Jílové Belt (mostly Proterozoic), and the other consists of magmatic granitoids of the Central Bohemian Pluton (see Figure 1). During geological exploration, the underground section was divided according to deposits into the Čelina and Mokrsko parts (see Figure 1). The adit is further divided into the Mokrsko-west, Mokrsko-east, Čelina-west, and Čelina-east sections. The Čelina and Mokrsko deposits are connected by a 1,835-meter-long main drift with a cross-section of 14 to 16 square meters that ends with a 136-meter-deep mine shaft. This mine shaft ensures a natural draft of mine winds in the main tunnel. The Čelina-East section is naturally ventilated due to the temperature difference underground and on the surface. An escape portal to the slope is located at a level of +40 m in this section. The other parts are forcibly ventilated. The tunnel is connected to other linear exploration works via numerous crosscuts that follow the ore structures. At the Čelina East section, the tunnels connect to two other levels: +20 m and +40 m. The total length of the tunnels is thus almost 8 km. Between 1989 and 1991, a 40-meter-high cavern was excavated at the Čelina-East deposit. Approximately 6,000 m^3 of excavated rock was transported away, underwent extensive processing, and yielded 21.5 kg of gold. It should be noted that the richest part of the deposit was selected for this experimental mining. Average gold contents at the site range up to 3 g per ton of waste rock.

Figure 1 – Horizontal layout of the Josef mine (left: representation in geological maps, (SVOBODA, Jiří, Jan SMUTEK a Jiří ŠŤÁSTKA. 2012; MORÁVEK, Petr a et al. 1992) right: entrance portals to the Josef mine).

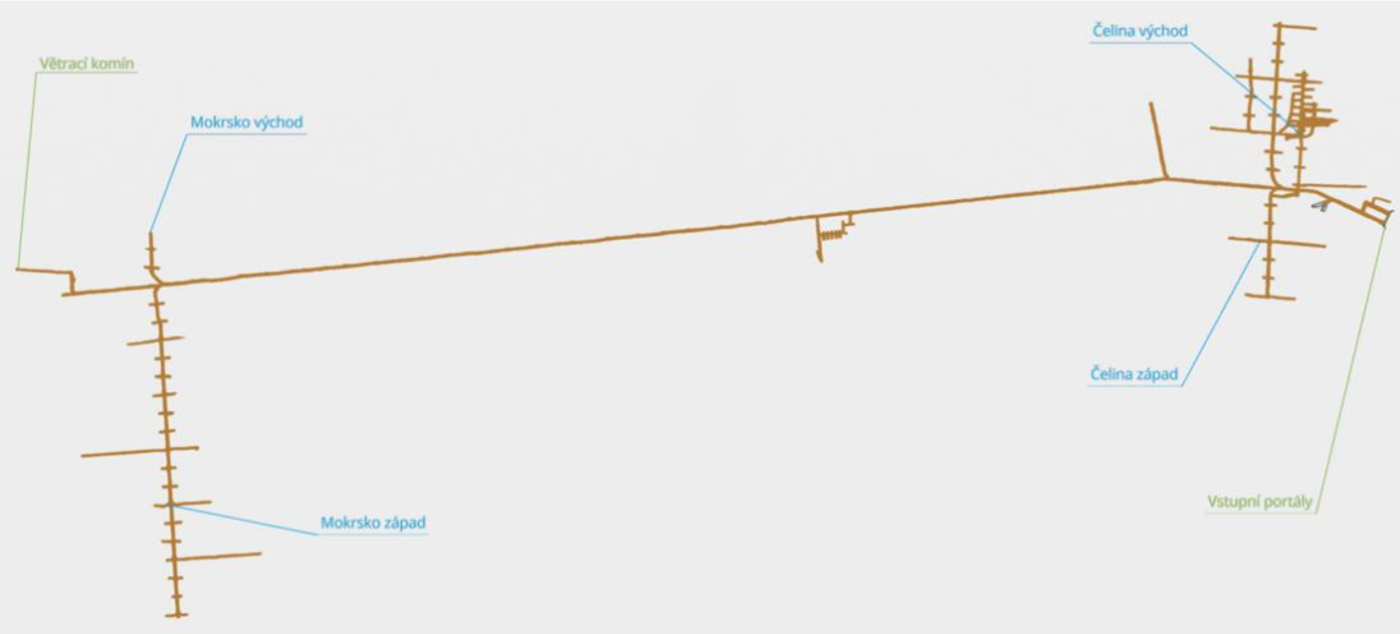

Figure 2 – Floor plan section from the new georeferenced 3D model of the Josef adit. Of the 8 km, approximately 6 km of underground space is in operation. This means that approximately 2 km of the original mine workings in the Mokrsko East deposit area are not in operation.

3. RESEARCH AND DEVELOPMENT IN THE JOSEF UNDERGROUND LABORATORY

3.1 DEEP GEOLOGICAL REPOSITORY OF RADIOACTIVE WASTE

As one of its main energy sources, the Czech Republic supports nuclear energy. Therefore, it is necessary to address the end of the fuel cycle and ensure the safe isolation of radioactive waste produced by nuclear power plants for up to one million years. This isolation period is determined by safety calculations that consider various future geological repository development scenarios. High-quality data is necessary for these assessments, and the Josef Underground Laboratory is well-suited for this purpose.

In terms of tectonic, geotechnical, and petrophysical properties, the Josef UL rock environment is similar to that of certain sites currently being considered for a deep geological repository in the Czech Republic. Although the Josef UL site is not at the anticipated depth of the future repository, this laboratory can perform tests that will provide valuable data for developing a safe repository.

For example, the amount of oxygen in groundwater inflows primarily depends on their yield and how far they are from the main tunnels, which are the source of oxygen. From this perspective, there is no fundamental difference between a depth of 100 meters and 600 meters below the surface. A similar statement applies to chemical composition — differences caused by depth alone are minimal. The tunnels in Josef UL have been open for several decades; the environment has stabilized and is now in equilibrium. There are no significant differences among the inflows, which is advantageous for some areas of long-term corrosion research on storage containers for spent nuclear fuel, for example. However, for some types of research, the mechanical parameters of the rock environment are also important, as they are related to the height of the overburden. The maximum height of the overburden in Josef UL is approximately 150 meters.

In the Czech Republic, research related to deep geological repositories is primarily conducted at the Bukov Underground Research Facility, which is located 550 meters underground. This depth corresponds to that of the future deep geological repository. The Bukov and Josef Underground Research Facilities complement each other well. As they are existing underground facilities, they are a cost-effective option before the characterization facility is constructed at the final deep geological repository site. The Czech Republic is committed to meeting European requirements for managing spent nuclear fuel and radioactive waste, including ensuring a safe solution for their final disposal. Due to the planned construction of new nuclear power plants and EU taxonomy requirements, the strategic goal is to commission a deep geological repository by 2050. Achieving this goal requires a high level of technical readiness, so it is necessary to leverage available expertise, research facilities, and infrastructure, including both underground laboratories: Josef UL and Bukov URF.

3.1.1 *MATEO project*

The main project, titled "Optimization of Materials and Technologies for Radioactive Waste Disposal in Deep Repositories" (TAČR-SIGMA Program, TQ16000084), extends the bilateral cooperation between the Czech Republic and the Republic of Korea. This project involves sharing knowledge and experience regarding the final disposal of spent nuclear fuel, particularly the use of granular bentonite for sealing and filling layers in deep repositories. To achieve the program's objectives, a consortium was formed with ÚJV a.s., KEARI, and HBC. In the Czech Republic, the research focuses on verifying the construction of a new bentonite layer around a container of spent nuclear fuel. A 1:1 scale experiment is being prepared, and drilling work is currently underway, including the creation of a large-profile borehole with a diameter of 1650 mm and a depth of 5300 mm. A test borehole was first drilled and now serves to demonstrate the method of spent nuclear fuel disposal to the public. At the same time, technologies for monitoring the progress of the experiment are being tested here (see Figure 3 on the left). The three-year project has three main objectives: developing bentonite granules, testing the spread of substances in bentonite experimentally, and constructing a 1:1 scale in-situ experiment. Figure 3 on the right shows the conceptual design of the experiment.

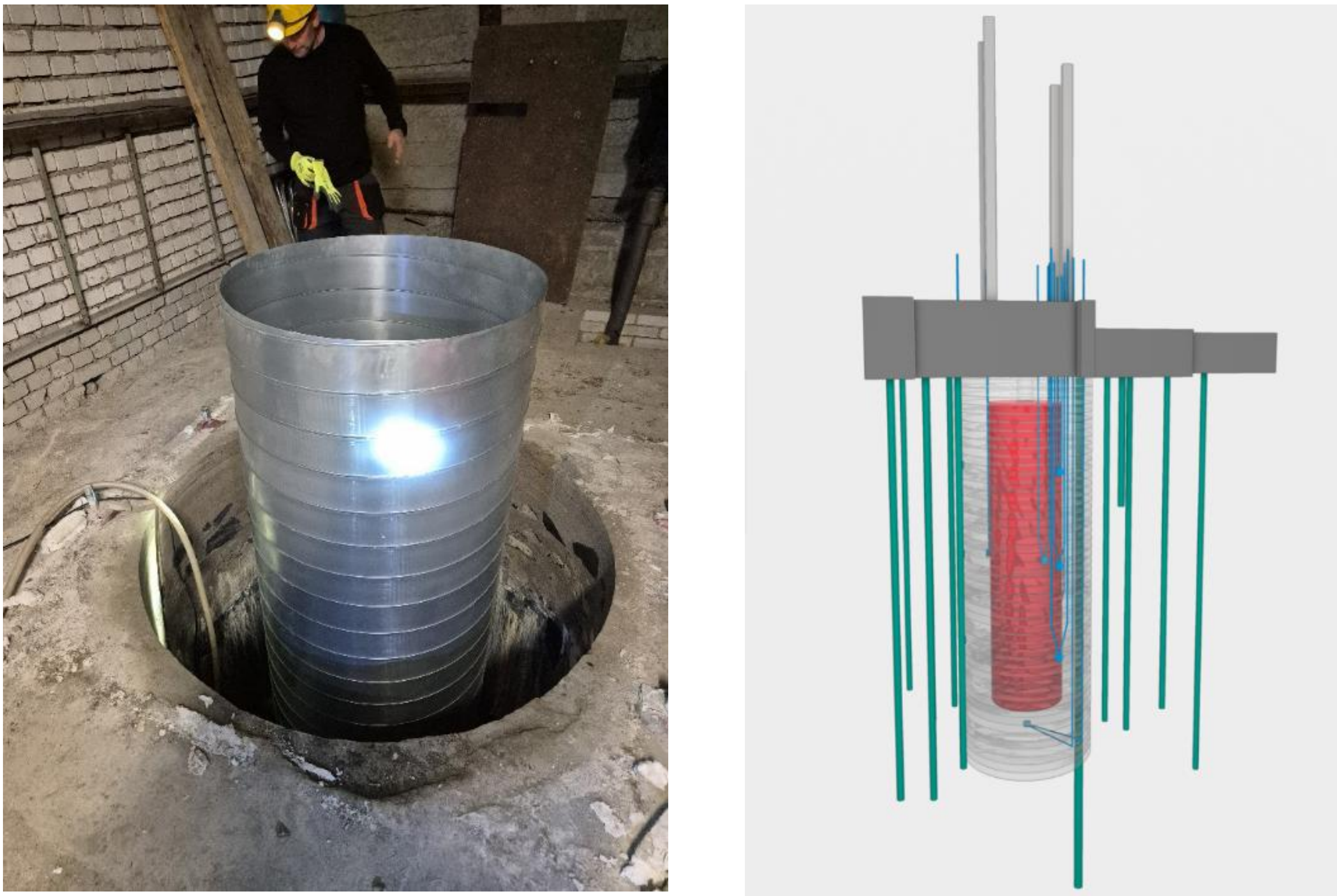

Figure 3: On the left is a large-profile underground drilling test for the MATEO project. The borehole has a diameter of 1650 mm and a depth of approximately 2000 mm. A pipe indicates the vertical storage of a container with spent nuclear fuel. On the right is a 3D conceptual design of the MATEO project experiment. Green narrow boreholes indicate rock monitoring. Dark gray indicates the concrete platform on the ground. Red indicates the heating element that will simulate the storage of spent nuclear fuel in a borehole with a diameter of 1650 mm and a depth of 5300 mm.

3.1.2 *EPSP sealing plug for deep geological repository*

In September 2012, the Josef Underground Laboratory launched the international DOPAS (Full-Scale Demonstration of Plugs and Seals) project. A 14-member consortium of European institutions carried out the project, including three Czech entities: SÚRAO, ÚJV Řež, and the Faculty of Civil Engineering at the Czech Technical University in Prague. The project involved designing, constructing, operating, and evaluating a physical model of a "plug" for sealing access tunnels to a deep geological repository for radioactive waste. As part of the project, an EPSP (Experimental Pressure and Sealing Plug) was built (SVOBODA, Jiri, Lucie HAUSMANNOVA, Radek VAŠÍČEK, et al. 2016). In 2025, SURAO prepared a project to dismantle the EPSP plug. The project aims to comprehensively evaluate the EPSP plug. The sub-goals are: a. determining the condition of the outer plug's structure and concrete; b. assessing the homogeneity and degree of saturation of the bentonite seal; c. evaluating changes in the properties of the materials used in the contact zone between the bentonite and the inner plug's concrete; d. evaluating the usability of logging and geotechnical measurements; e. analysing the transport of bentonite into cracks in the event of erosion. The dismantling of this unique project is planned for August 2026.

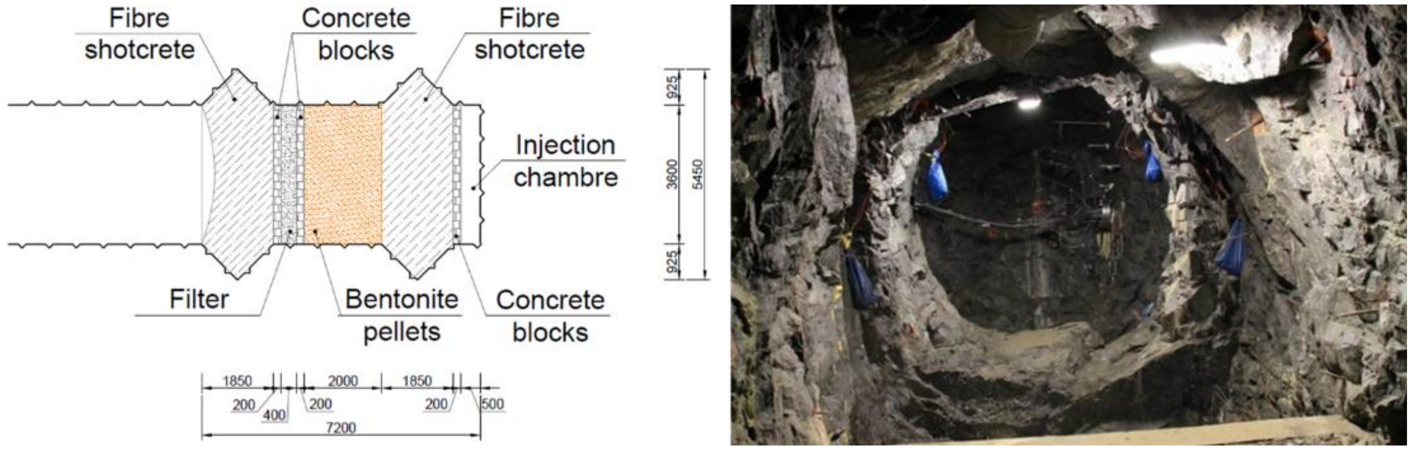

Figure 4 – On the left is a vertical cross-section of the experimental EPSP plug, and on the right is a view of the drift before the construction of the EPSP.

3.2 ENERGY STORAGES

Current projects related to energy storage include Rock Accumulation of Seasonal Heat (RASH, TAČR – TS01030218) and Innovative System for Thermal Energy Storage Based on Recycled Waste Materials (INTES – TAČR - TS01030096).

3.2.1 Rock Accumulation of Seasonal Heat

The RASH project aims to develop innovative materials and technologies for storing heat in rock environments and designing efficient energy storage operations. Energy storage is a key pillar of the ongoing transformation of the energy sector, especially given the growing production of electricity from renewable sources in the summer and the critical need for heat in the winter. If the results are favourable, practical application can be expected in the medium term. Therefore, the project's ambition is to experimentally demonstrate selected technological processes and verify their feasibility under operating conditions. These conditions will be simulated underground at the Josef UL.

The successful implementation of the proposed solutions could contribute to transforming the Czech heating industry into a low-emission operation. These technologies have particular potential in specific environments, such as areas with accessible mining sites near urban areas where district heating systems (DHS) are in use. Using surplus, inexpensive electricity from photovoltaic power plants to "charge" heat storage facilities in the summer and use the stored heat in the winter could be a significant step toward meeting the Czech Republic's National Energy and Climate Plan objectives.

In 2025, there was a fundamental shift from the previous period, which had focused mainly on research, analytical work, and creating conceptual designs. In 2025, the project shifted its focus to transitioning from these initial considerations to detailed technical designs, preparing experimental infrastructure, and developing feasible technical solutions.

The focus was on two key components: the laboratory heat storage tank and the rock storage tank. The laboratory storage tank is located in the University Centre for Energy Efficient Buildings at the Czech Technical University in Prague. It underwent a major upgrade, including the design of elements that enable the energy balance of the entire system. Meanwhile, preparations began for long-term automated operation to ensure the stability and reproducibility of experiments.

Intensive development of structural solutions took place in the case of the rock storage tank (Figure 5). Key technological units were designed and partially manufactured, including a robust technological frame, pressure elements, and safety components. Installation work also began underground at the same time. Technical preparations for the construction of the Field Storage Facility were also underway underground.

Work continued on refining the mathematical models of the individual storage facility types. These models were continuously calibrated based on newly obtained experimental data, geotechnical measurements, and additional input parameters. Significant progress was made on the underground storage facility. The concept was finalized, and technology was planned for implementation in the next stages of the project.[6]

The research team is led by the University Centre for Energy Efficient Buildings at the Czech Technical University in Prague, and three companies (Watrad s.r.o., Progeo s.r.o., and SG Geotechnika a.s.) are participating in the project as well as the Faculty of Civil Engineering (Josef UL).

Figure 5 - Pressure seal of the rock reservoir. The reservoir will be used to monitor the behaviour of the underground system when using a liquid medium. In the centre, there is a prepared borehole with a diameter of 750 mm and a re-drilling of 1200 mm for the installation of the pressure seal, and on the right is the output from the prepared digital model of the experiment. (SVOBODA, Jiri, Lucie HAUSMANNOVA, Radek VAŠÍČEK, et al. 2016).

3.2.2 Innovative system for storing thermal energy based on recycled waste materials

The project's primary goal is to develop a thermal energy storage system that uses waste materials. Storing energy during production peaks and deferring consumption increases the efficiency of renewable energy sources (Dílčí odborná zpráva 2025).

Particular emphasis is placed on effective, integrated solutions that combine thermal energy storage (TES) with renewable energy technologies (RET), operating at various temperatures. The project considers two variants with operating temperatures of 400°C and 900°C. The project aims to develop and verify TSE possibilities based on waste generated in foundry.

A research team composed of scientists from three universities—the Czech Technical University in Prague, the University of Technology and Economics in České Budějovice, and the Technical University in Ostrava—is implementing the project.

The Josef Underground Laboratory is currently constructing an in-situ experiment to test heat storage materials. This experiment will verify the functionality of the proposed energy storage solution and determine the thermal and durability characteristics in an underground environment. It will also collect data for modelling thermal and stress processes. In 2024, the Josef Underground Laboratory prepared the site selected for implementation and began developing the experiment, including designing and preparing monitoring procedures. A vertical, large-profile borehole with a diameter of 750 mm and a depth of 1,800 mm was prepared for the storage tank. Work then continued on finalizing the design of the physical in situ model, including its digitization and 3D modelling (Figure 6). The physical model is being prepared to be compatible with BIM tools, and the necessary data is being formatted accordingly.

Figure 6 – On the left is a photo taken during the drilling of a borehole for the INTES project experiment, and on the right is a conceptual design of the experiment, where waste materials from foundries will be tested for energy storage..

3.3 DIGITALIZATION, AUTOMATIZATION, AND ROBOTICS

Underground construction is one of the most technically demanding sectors of the building industry. Working in confined spaces, often in heterogeneous rock environments with difficult access, requires modern methods due to the high demands on safety and environmental quality. Digitalization, automation, and robotics are trends that are also emerging in underground construction. Therefore, it was necessary to start addressing these trends in teaching and projects at Josef UL. The following text provides examples of three such projects. These activities are mainly carried out in cooperation with the National Centre for Construction 4.0 (NCC 4.0). The Josef underground laboratory is an NCC 4.0 Testbed for underground construction.

3.3.1 Digitalization of the Josef Underground Laboratory

The Josef Underground Laboratory digitalization project aims to transform the laboratory into a digitally controlled facility. The project's goal is to create a digital twin with a two-way link. Reality, as measured in the laboratory — such as the temperature of the cutting machine or the amount of compacted bentonite in an experiment — is automatically transferred to the twin. Vice versa, turning off the lights in the twin automatically turns off the lights in the underground laboratory.

Creating a digital twin is not straightforward, especially since the underground laboratory is unique and extensive. The first step in the digitalization process was passportization, which involved revising and processing existing information sources. Point clouds and drawings created from the structure's construction to the present day were revised. While some parts of the underground have been repeatedly mapped over the years with varying degrees of quality, other areas have not been recorded at all, or only in archival 2D drawings. However, the mapped locations often lacked essential geospatial localization information. Therefore, additional laser scans were performed to fill in knowledge gaps throughout all drifts and tunnels. At the same time, the Trimble Connect CDE (common data environment) was implemented. This began controlling the information flow of the entire project. The second step was to create a BIM model of the entire tunnel, followed by individual experiments.

The key was identifying which elements to model and how. The result was a unique standard for BIM modelling of underground structures based on the internationally recognized IFC (Industry Foundation Classes, ISO 16739) data model. Common elements of conventional building construction, such as lights, switches, distribution boxes, portable fire extinguishers, piping systems, retaining walls, beams, and staircases, were modelled using Revit. The tunnels and crosscuts were modelled as polygonal meshes at three different levels of detail. To accomplish this, a combination of tools was used: Cloud Compare, MeshLab, AutoCAD, and Geomagic Wrap. The Josef UL BIM model is currently a "digital trunk" that branches out and is refined for various uses. A breakthrough is the digitalization project for planning in-situ experiments. These experiments often require a combination of drilling and construction techniques for implementation. In the BIM model, it is possible to analyse the experiment's approach and exact location in advance. Adding a fourth dimension, the timeline of the construction (and subsequent dismantling) of the experiment, gives the scientific team unique insight into the entire project's course. Additionally, the simulation graphically displays the differences between the planned and actual execution of the work. Lastly, the BIM model of the experiment serves as a starting data node that connects to various other data sources. One example is sensors that measure the temperature inside the bentonite. Each temperature sensor is represented by an image in the BIM model. Information from the sensors is stored in a database of measured values over time. Then, each BIM model element refers to a specific time series of values for the relevant sensor.

3.3.2 JULBOT University Platform

The robot is becoming a university platform that incorporates modern Industry 5.0 tools, emphasizing the integration of autonomous robotic technologies. One configuration is designed to perform challenging tasks related to the thorough exploration, inspection, and monitoring of buildings. This increases the safety and efficiency of work processes. Surveys and inspections can be conducted in environments that are difficult or dangerous for humans to access. JULBOT ver. 1.0 stands out from similar robotic systems due to its high robustness and resistance to extreme external conditions (Figure 7). Its flexible configuration allows the platform to be supplemented according to the specific activity being performed. The platform uses a digital model of the Josef Underground Laboratory for its pilot operation.

Figure 7 – JULBOT ver 1.0 – a robust machine designed for teaching, research, and development in the field of automated monitoring, not only of underground structures.

3.3.3 Development of an autonomous loader for underground construction

The project, with the project code CZ.01.01.01/01/24_063/0006805, is supported by the Ministry of Industry and Trade as part of the Operational Program Technology and Applications for Competitiveness (Call III – DEEP TECH). The project aims to develop an autonomous electric skid steer machine for underground construction capable of navigating environments without GPS. The project addresses the needs of the mining and construction industries by emphasizing increased work safety and operational efficiency while reducing the need for human resources in hazardous underground environments. The main objective is to create an autonomous control system that uses 3D environmental models obtained from machine sensors and advanced artificial intelligence algorithms. Key activities include developing localization algorithms, planning trajectories, integrating sensor modules, and testing the prototype in real conditions at the Josef Underground Laboratory. The project not only aims at technological innovation, but also at providing significant benefits to society. These benefits include improved work safety by eliminating the presence of people in hazardous environments, supporting sustainability through electric propulsion and reduced emissions, improving working conditions for operators, and developing workers' skills through new technologies (FSv ČVUT 2026). First Green Industries a.s. is the main contractor for the project, and the Faculty of Civil Engineering at the Czech Technical University in Prague is participating through its Experimental Centre and Centre of Experimental Geotechnics. The Czech Institute of Informatics, Robotics and Cybernetics, specifically its Department of Embedded Systems and

Testbed for Industry 4.0, is also participating. Figure 8 shows a remote-controlled loader from First Green Industries and an image from underground testing.

Figure 8 – The autonomous loader is being developed in cooperation with the Czech company First Green Industries, which supplies electrically powered machines worldwide.

4. CONCLUSIONS

Over the course of its eighteen years in operation, the Josef Underground Laboratory has solidified its position as a leading workplace in the fields of geotechnics, underground engineering, research into the deep geological disposal of radioactive waste, etc. Its growing importance in the field of disposal of radioactive wastes is confirmed by international cooperation, including a new partnership with the Korean Research Tunnel operated by Korea Atomic Energy Research Institute. Meanwhile, new areas of research are being successfully developed, including energy storage. Participation in the National Centre for Construction 4.0 has significantly advanced the development of topics related to the digitalization, automatization, and robotization of underground structures. The development of digital twins, autonomous machines, and the JULBOT university robot demonstrate the laboratory's commitment to future technologies. Education remains an important part of the laboratory's work, with students from the Czech Republic and abroad participating in specialized projects. Thus, the Josef Underground Laboratory continues to fulfil its role as a dynamic research and teaching centre that responds to the current needs of modern construction and energy, contributing to the development of new technologies in underground environments. Public involvement in the form of specialized tours is also important. In 2025, more than 3,000 people, including students, visited the facility. The Josef Underground Laboratory university project has received support from leaders in the Czech construction industry, such as Metrostav and Hochtief, as well as from the Ministry of Industry and Trade, the Ministry of the Environment, SÚRAO, Central Bohemian Region, etc.

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