illuMINEation
THE FUTURE OF MINING

D4.4 The Safe Zone Concept

Improved safety and environmental performance

This report describes all elements of the Safe Zone Concept. That includes emissions and groundwater quality monitoring services, tracking/positioning of equipment and personnel as well as instrumented rock bolts with low-cost and data transmission capabilities, with a focus on safety and environmental performance.

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Abstract:	The safe zone concept combines knowledge about different aspects of mining and implements it into an IoT platform. This specific deliverable D4.4 discusses how to develop and integrate a sensoring concept, a data streaming concept and data analysis. The whole concept is divided into 4 safe zones: [Safe Zone 1] Intelligent rock bolts for geotechnical & atmospherical monitoring, [Safe Zone 2] Positioning/tracking of equipment & personnel, [Safe Zone 3] Environment monitoring (incl. acid mine drainage), [Safe Zone 4] Tailings dam stability. They are all different but going in the same direction – to make mining a safer space for both people and machines.

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Executive Summary

The illuMINEation project aims to rethink the traditional mining process and digitalize it with available and still developing technologies to make the mining industry safer and more economical. To accomplish that, knowledge and gathered data must be combined into one platform - the safe zone concept aims to create a tool that helps to assess the safety status of mining areas based on multiple sensors from different monitoring systems. The collected data is analysed and transferred into safety status information related to mining areas. Continuous monitoring enables not only permanent assessment of safety status but also serves as a warning system in case of rapidly changing conditions. Knowledge of the staff and machinery position is therefore crucial in managing and avoiding hazardous situations. As a result, low-cost approaches will be employed in conjunction with current systems to track people and machinery. A key tool for the reasonable application of the safe zone concept lies in the preparation and visualization of gathered information required on a multi-stage level for personnel with different scopes of work.

[Safe Zone 1] Intelligent rock bolts for geotechnical & atmospheric monitoring
The safe zone concept connects findings from many different disciplines where safe zone concept 1 contributes to the assessment of underground environment-related atmosphere and geotechnical conditions in the mine. The foundation for safe zone 1 is a dense installed monitoring system consisting of a large number of intelligent rock bolts attached to deformation and atmospheric sensors. The safe zone concept 1 will contribute as a useful tool for supporting engineers in assessing health and safety risks for personnel related to environmental hazards in an underground mine. And serves to analyse methodologies for judging management actions in environmental controlling measures. Similar to an observational approach, the safe zone concept is designed as an iterative system for various reasons.

[Safe Zone 2] Positioning/tracking of equipment & personnel
This task's work focuses on the safety of mine trucks and other heavy vehicles in mining environments, as well as the presence of mining people and other mobile equipment. Reliable and comprehensive tracking of the position of equipment and workers in mines adds to overall workplace safety and enables the optimization of various mining operations for maximum operational efficiency. The known location of employees and equipment also enables the categorization of mining sites under the Safe Zone Concept, as well as intelligent rock bolting, environmental monitoring, tailings dam stability, and drone inspections.

[Safe Zone 3] Environment monitoring (incl. acid mine drainage)
To effectively protect the natural environment, it is necessary to carry out systematic monitoring and to react quickly to any threat of pollution. Safe Zone 3 focuses on comprehensive and frequent environmental monitoring supported by a rapid alert system. In addition, the concept of using relatively low-cost sensors reduces the overall cost of monitoring, which may increase observation spatial resolution to help more accurately identify sources of potential pollution. Environmental monitoring under Safe Zone 3 focuses on the observation of basic physicochemical parameters of waters, both underground and surface, as well as air quality. The proposed solution should therefore positively impact environmental protection in mining areas, but it can also be used by other industries.

[Safe Zone 4] Tailings dam stability
"Tailings storage facilities (TSFs) are recognized as high-risk structures, requiring comprehensive engineering solutions to effectively mitigate potential risks. In this deliverable, we present a specialized engineering framework tailored to analyse and interpret data from TSFs, with a specific focus on its successful application at the Zelazny Most TSF. By

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harnessing advanced data analysis techniques and leveraging machine learning algorithms, this framework enables engineers to accurately assess critical parameters, including displacement, pore water pressure, geotechnical layers, and factor of safety.
The demonstrated capabilities of this specialized engineering solution highlight its pivotal role in proactive monitoring, evaluation, and the establishment of safe zones within TSFs. Through in-depth data analysis and interpretation, engineers can detect potential instabilities, identify areas of concern, and prioritize targeted risk mitigation strategies. By implementing this framework, engineering professionals can enhance the safety and stability of TSFs, safeguarding not only the surrounding environment but also the well-being of nearby communities.
The successful application of this specialized engineering solution at the Zelazny Most TSF serves as a testament to its effectiveness in providing critical insights and enabling informed decision-making. By employing cutting-edge technologies and methodologies, engineers can proactively address potential risks, reduce the likelihood of accidents or failures, and uphold the integrity of TSFs. This deliverable underscores the significant contribution of data analysis and machine learning approaches in ensuring the long-term sustainability and safety of TSFs worldwide."

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1 Introduction

Europe must reduce its reliance on raw material imports. To do so, the mining industry must redesign traditional mining processes, as well as adopt pioneering innovations and data analytics. The EU-funded illuMINEation project highlights important aspects of digitalisation in underground mining activities to achieve the highest levels of safety, environmental, and economic performance possible. The project also builds a multi-level distributed IoT platform that is based on large sensor networks with wireless communication capabilities (see previous deliverables 2.1, 3.1, 3.2, 4.1, (Nöger et al. 2021; Paterek et al. 2022)).

With technological advancements come new opportunities to improve the rock bolting system. Nowadays, when there are numerous different sensors on the market, some of which are used every day, particularly in our mobile phones, they are becoming more developed and affordable. This opens up the possibility of using the same sensors in the mining industry by incorporating them into rock bolts.

First and foremost, when running a mining operation, responsibility should be taken to secure people's safety. According to (Oxford Language) safety is defined as: "the condition of being protected from or unlikely to cause danger, risk, or injury". In general, dangerous situations should be avoided and cleared in advance, and the risk of hazardous events should be decreased to safeguard personnel from physiological and psychological harm. Looking back on mining history, ensuring the worker's safety has always been a difficult task, and its absence had catastrophic consequences. Despite many significant changes over the last century, the mining industry nevertheless has a bad reputation that is not necessarily justified when comparing accident numbers to other industries. However, no excuse should be accepted for increasing the health & safety situation.

The essence of mining has always been and continues to be a risky industry. An artificial environment must be constructed in a complex natural setting to extract minerals from the earth's crust. Health and safety concerns occur due to existing elements in the environment such as hazardous gases and water, as well as changing geological and structural conditions and their unpredictable impact on underground excavations. Moreover, man-made influences like machinery and blasting have a major impact on the overall situation. Prevailing environmental conditions, and therefore health & safety situations, are mainly governed by natural and artificial impact and their attempt to control those environmental conditions in case of atmosphere and rock mass stability with ventilation and rock engineering measures.

Reducing the risk of a hazardous scenario developing should be the primary goal of guaranteeing safety in a confined workspace since immediate escape options are frequently limited. For that reason, risk management methodologies have been successfully developed and applied in underground mining. The requirement for risk assessment and management is driven not only by the enormous number of uncertainties and limited knowledge of the rock mass, but also by the complexity of the interaction between humans, machinery, explosives, and the rock mass. To allow any action to take place a certain risk level always has to be accepted. Dealing with risk entails first assessing it and, if accepted, planning how it will be managed. Risk assessment methodologies attempt to estimate the likelihood of an event happening as well as the severity of its impact. However, such an estimation is not straightforward and should be a dynamic process due to continuously changing conditions. Risk assessment is reliant on experience, continuous and relevant monitoring, and worker sensibility to changing conditions. To deal with a certain level of risk it has to be managed either active or reactive. Where active reduces the risk in advance by appropriate design measures and reactive manages the risk if unwanted event happens.

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1.1 Purpose of this Document

The purpose of this document is to report on the progress of work package 4 and introduce the overall development and implementation of the safe zone concept in the mining industry, and describe its most important elements. To present ideas on how to further develop the overall idea of the safe zone concept while identifying challenges and potential risks in the process. A more detailed description is given in the next chapter.

1.2 Scope of this document

This document describes the safe zone concept and its elements. Moreover, it identifies possible risks that could occur in the mining environment and the potential of the safe zone concept. Identifying safety risks and assessing them is an important part of any safety program. The first step in identifying safety risks is to conduct a risk analysis - identifying potential hazards and evaluating the likelihood and severity of each hazard. Once the hazards have been identified, the next step is to assess the risk associated with each hazard. This involves evaluating the likelihood and severity of each hazard and determining the level of risk associated with each hazard.

Monitoring data accumulation and data stream process is also important. This involves monitoring data collected from various sources to ensure that it is accurate and up-to-date. It also involves monitoring the data stream process to ensure that data is being collected promptly and that there are no gaps in the data.

Applied analysing and interpretation methodologies for safety status information involve analysing collected data to identify trends and patterns. It also involves developing methodologies for analysing and interpreting data to ensure that it is accurate and reliable.

An integration example of a use case scenario involves integrating various safety systems to provide a comprehensive view of safety status information. For example, an organization may integrate its safety management system with its environmental management system to provide a comprehensive view of safety and environmental performance.

In conclusion, this deliverable covers several important topics related to safety risks and assessment, including identification of safety risks, monitoring data accumulation and data stream process, applied analysing and interpretation methodologies for safety status information, and integration examples of use case scenarios.

1.3 Related Documents

This deliverable is building up on the previous deliverable of the same work package, deliverable D4.1. and later will be complemented with D2.3 from WP2 – the final validation report, describing the technologies deployed and their implementation.
"D4.3 – Advanced data analysis for TSF dam monitoring & stability control" partly contains overlapping information, as the underlying principles for both parts are similar.

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2 The Safe Zone Concept

2.1 Instrumented rock bolts for environmental & geotechnical monitoring [Safe Zone 1]

illuMINEation is developing a low-cost intelligent bolt that will be wirelessly connected to the network cloud and collect data on rock bolt movements and deformation over time. This information will be used to track and position movements in rock bolts and environment data, which will then be calculated and processed to gain a better understanding of the movements in the rock mass and overall mine status. There are numerous possibilities and benefits for mining companies with this type of system. An overview of non-destructive testing methods used to assess the condition of rock bolts and the effectiveness of investigated methods is already investigated (Lama, Momayez 2023).
Similar to the NATM approach in tunnelling or medical healthcare treatment, the observational approach strategy has proven applicable when dealing with various changing conditions. The basis forms an iterative procedure including measuring, diagnosis and treatment. As already pointed out, also in the case of the safe zone concept this approach is reasonable due to a high number of uncertainty parameters and changing conditions. Because the safe zone concept will contribute to improving health & safety related to environmental hazards, these hazards must be assessed qualitatively, to be aware of them as a very first step. This identification sets the requirements for the overall design of the system. Followed by the identification of the corresponding symptoms. Similar to diseases in medical healthcare, before a hazard event occurs accelerating condition changes happen and pre-indication signs usually show up. Therefore, an appropriate monitoring system forms the backbone to measure and track these changes and identify the symptoms. A monitoring system just gives the possibility to identify symptoms in an early stage, but it doesn't mean that those adequately be recognized. Not every unexpected change necessarily means running into safety problems and normal judged condition changes doesn't mean always stability and safety. Especially in the field of mining where, for instance, only limited knowledge of rock mass is available. Judgement of the symptoms requires careful interpretation of gathered data.

To improve and support the interpretation process, massive sets of accumulated data must be analysed and processed in a way that meaningful information could be gained out of it. One of the main objectives in successfully lowering health and safety risks is the interpretation or diagnosis process, which is fundamentally different from geotechnical and atmospheric hazard monitoring. Solid and correct data interpretation requires knowledge and experience. Medical research and long-term experience with the effects of poor atmospheric conditions have compelled authorities to define specific threshold limit values in the case of atmospheric monitoring. Therefore the "interpretation" is already externally outsourced. In the case of geotechnical-related data, interpretation is not that straightforward. Rock mass conditions in every single mine can completely differ from each other.

It has taken a lot of research to develop general, reliable laws for rock mass behaviour based on observations and measurements and basic principles of trends and correlation can be observed. However, due to the strong variability of the rock mass, the limited knowledge of its behaviour and the number of influencing factors, no general threshold limit values can be derived to determine the stability of excavation. In the end, it is up to engineers with relevant experience to judge the rock mass condition based on provided analysis of the gathered data. In the end, general data analysis and interpretation can be performed based on the knowledge of current scientific and technical developments. When a restricted understanding of rock mass is accepted, a limited application of such data analysis and interpretation must be acknowledged. As a result, a significant benefit of the safe zone concept will be a continuous

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learning process that applies to all three main principles: measurement, diagnosis, and therapy. That means, learning about the possibilities and limitations of used monitoring systems, their combined usage and efficient installation. This includes learning how to read and analyse data to identify symptoms and warning signals that could lead to a hazardous scenario. But also, learning to increase understanding of system behaviour, to avoid dangerous situations in advance.

Finally, the idea is to learn and improve the overall understanding of active and reactive treatment measures to control and deal with safety hazards to avoid making the same mistake twice. Overall, the goal of the integrated learning process is to transfer the experience gained by engineers and miners over the course of their careers to an objective platform that can be contributed to and accessible by anybody who needs it. The developed IIoT platform will be critical in constructing this experience by storing reported events, corresponding monitoring data, and its back analysis. On this basis, new and improved algorithms for data analysis can be developed and an improved understanding of the response behaviour of the rock mass due to excavation activities can be derived. The final goal should be supporting the responsible person in decision-making. The whole process and safe zone concept parameters are described in figure 1. To define all possible parameters of the safe zone concept full picture of the mining must be considered, therefore internal and external factors are identified, so on one side there are external factors like political, social and financial factors, and on the other side internal factors that include machinery, human factor and the mining environment. The scope of this deliverable analysis focus is on internal mining factors which are divided into 3 main categories human factor, machinery position and mine environment. All three of those are connected with where exactly in the mine is something happening to avoid collisions, additionally, mine environment is divided into two more categories: geotechnical aspects and air quality. In the end, all those internal factors were connected into a face zone concept.

To ensure the successful application of the safe zone concept in practice, the whole system established under the illuMINEation project, which includes an IIoT and visualization platform, must be robust and simple. This covers simple monitoring system installation, data transmission, data storage, data analysis, data visualization, protocol storage for occurring events, set measures, and back analysis.

The majority of the mine rock support systems don´t have monitoring capabilities, and monitoring /measurements are performed separately from rock bolts. This type of monitoring is discontinuous, costly, and requires specialized equipment such as laser scanners and extensometers. Furthermore, visual inspections can only check surface irregularities but do not reveal much about the inside of the rock mass. The only advantage of today's used systems for rock bolt inspection - it does not require the special production of intelligent rock bolts, nor does it require a centralized information system to gather and analyse all data that bolts collect.

There are currently few options for monitoring rock bolts, but none of them is very affordable for the large-scale mining industry. There is always the possibility of damaging sensors with blasts and other mining operations, hence implementing expensive measuring instruments is not very sustainable. Hence, these systems are usually only applied in cases where significant deformations are expected and need to be monitored or where special monitoring requirements need to be fulfilled. There is still a need for a low-cost, long-term solution, that enables more widespread monitoring of the entire mine.

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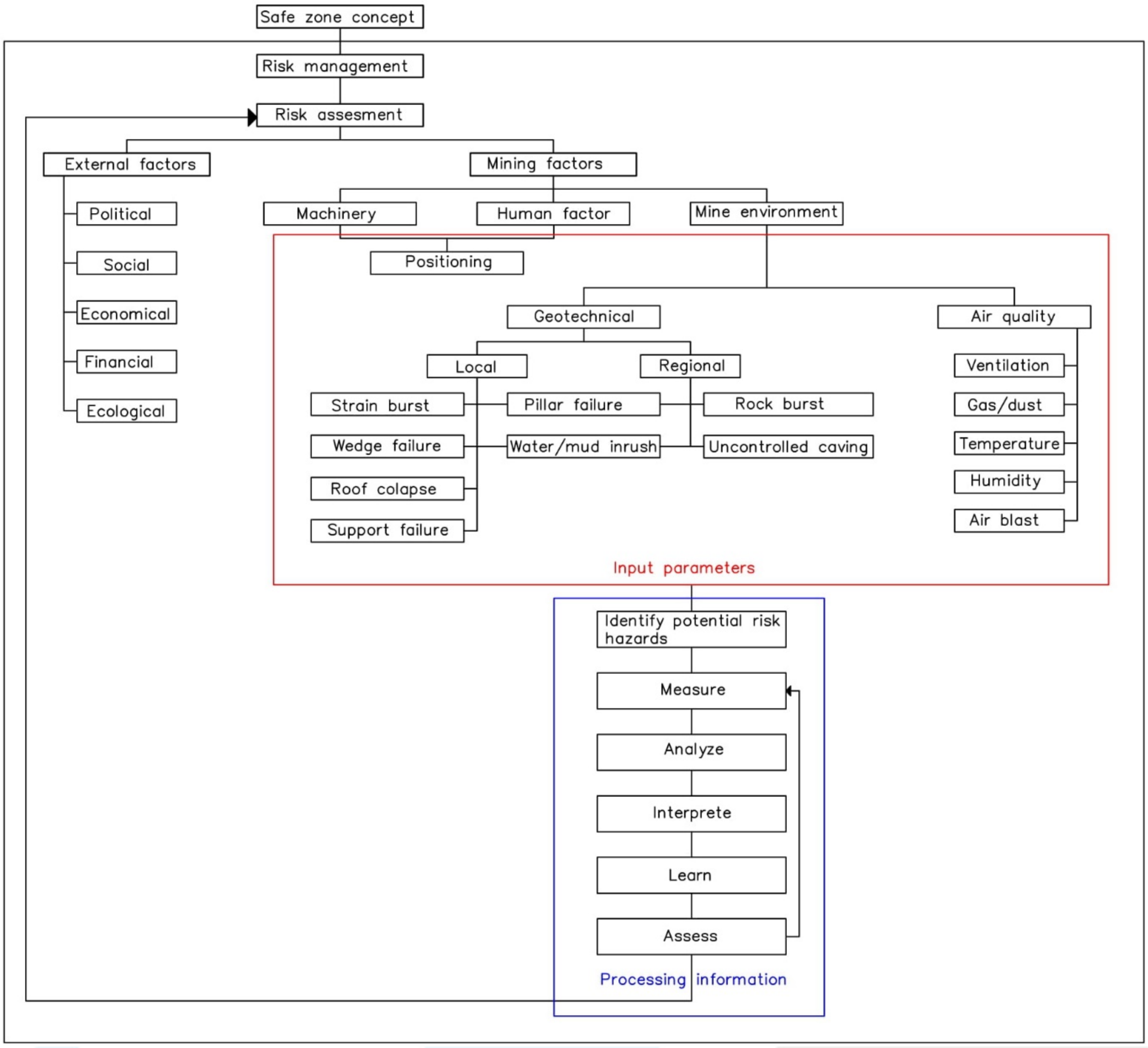

Figure 1 Overview of the safe zone concept components

Rock mass behaviour can be assessed using observations from digital rock bolts. Geological structural information, as well as deformation distribution along the tendon, enable the identification of discrete discontinuities based on strain concentrations. For example, if geological data is combined with bolt deformation data the result could be used to predict rock mass behaviour and detect potential local or regional instabilities. As input data for evaluating rock mass stability, joint orientation and positioning with deformation value measured by rock bolts in the mine area show possible weak spots in the rock mass. Bolt measurements can detect movement in addition to value. When enough data is available, machine learning techniques and big data analysis systems will be able to predict movements in the rock mass. This calculation would also have to include the positioning of blasting areas and working machinery. It is critical to understand what caused bolt movements. The effect of blasting events on the monitored rock mass and deformations can be determined over time by continuously monitoring bolt deformations and knowing when and where blasting is taking place. Data collected is valuable for the entire mining process and mine safety because predicting the position of instabilities; where they are most likely to occur and when; can make the entire mining process safer and more predictable. When bolts detect more movement than expected, it is recommended to evacuate the area and thoroughly examine the rock mass stability.

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The safe zone concept has the advantage of making the mining environment safer and more reliable for workers and machines, as well as increasing overall mine productivity and saving time and money, and in the future with more technological advances more predictable.
Instead of costly investigations, intelligent bolts will provide information about their deformations, which will then be translated into rock mass movements using geological data.

2.1.1 Literature background of rock support systems

Instabilities in the rock mass are causing problems in the vicinity of mechanical excavations. For providing safe ground conditions on a local scale appropriate rock support including rock bolts are installed. There are several approaches to selecting the appropriate type of support; however, because rock mass is a complex and natural material, it is difficult to generalize the solution. Researchers and geotechnical engineers developed various methods for selecting the appropriate type of support systems based on the number of different aspects and rock mass properties. Hoek (2006) provides an overview and description of various rock bolt types. Hoek E. et al. (1995) provides detailed descriptions of rock support design, acceptable risks, geology data evaluation, rock mass classification, shear strength of discontinuities, structurally controlled instabilities, in-situ and induced stress, the strength of rock and rock mass, design and applications of rock bolts and dowels, and shotcrete supports. Li (2006) investigated the instability of a mine roof due to fracturing and proposed a solution in the failed rock mass with the concept of a pressure arch (the first use of this design was mentioned in IME 1936). Cao et al. (2012) proposed a rock bolting system classification based on the fundamental theory of load transfer mechanism and discussed rock bolting system failure modes. More research has been conducted in testing various types of rock bolts and attempting to improve them or equip them with sensors to provide additional information about the rock bolt's state. Bharti et al. (2014) evaluates the performance of grouted rock bolts in the rock mass and gives an overview of different types of load transfers. Johnson et al. (1999) shows how to use strain-gauged rock bolts to measure rock mass strain during drift development. Guo et al. (2020) are investigating the application of the micro-clamped Fibre Bragg Grating (FBG) sensor in rock bolt support quality monitoring. They proposed that micro clamped FBG sensor replace the encapsulated bare FBG sensor and establish a theoretical formula of strain sensitivity. Høien et al. (2021) investigated the pull-out and critical embedment length of grouted rebar rock bolts-mechanisms when approaching and reaching the ultimate load. Lin et al. (2020) tested bolted joints under shearing to reveal the mechanical behaviour of the bolt and failure mechanism. They conducted a direct shear test by changing the state of grouting, the number of bolts, and the inclination angle of the bolt. This paper concludes that increase in the number of joints the shear strength of the joint will increase, grouting in the joint improves the stress condition of the bolt. Cai et al. (2004) developed an analytical model for rock bolts based on Shear-Lag Model. The developed model is based on the description of the interaction behaviour of the rock bolt, the grout medium and the rock mass. They showed the effects of the coupling and decoupling behaviour in pull-out tests and uniform deformation of the rock mass and intersecting joints. Skrzypkowski (2021) investigated stress-strain characteristics under static and quasi-static loading for partially embedded rock bolts. Waclawik et al. (2017) investigates rock bolting at the room and pillar method.

Many studies have been conducted because of the complexity of rock mass, particularly in the interaction with rock support systems. Based on laboratory findings and in-situ observations, various rock bolt systems have been created. They have been designed for many application situations and requirements of quasi-static or dynamic events. Using measurement bolts would provide the opportunity for the detection of in-situ rock mass rock bolt interaction behaviour. Advances in rock support design based on earlier results should be of great importance for a safe and cost-effective mine process.

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2.1.2 Geotechnical monitoring

Rock bolts are important in underground mining as they provide support to the rock mass around the excavation. They are the most common reinforcement method in mining and civil engineering excavations. The length of the bolts, types and spacing between them can be varied, depending on the reinforcement requirements and the use case (Kolapo et al. 2022).
The main idea behind a rock bolt is that it should provide safety and stability for the rock mass in the excavation area. Bolt systems can be mechanically anchored, grouted, and friction anchored. They usually don't have a measurement option, there is a possibility that it failed without showing visible signs on the surface, especially in grouted rebar bolts where they can still have some residual strength. Therefore, support functionality can be lost without even recognising it.

To overcome that, sensors can be installed on all three previously mentioned bolt systems. Intelligent bolts with implemented measuring systems have a function of showing changes and indicating if there is some damage on the bolt. So, it can be said that intelligent rock bolts are regular bolts equipped with additional instruments which are helping us in detecting potential instabilities and damages inside of the rock mass.
Changes in rock mass can be tracked, by measuring rock bolt reaction concerning the excavation response. Rock mass damage and instabilities are therefore measured in terms of rock mass deformation. Moreover, other additional information depending on the type of the sensor device could be collected. Based on such measurements, information about rock mass state can be derived.

Different rock bolt types work at different reaction principles. Therefore, limitations on sensor application and information that can be extracted must be considered. Expansion shell bolts, for instance, would measure deformation along the tendon and in the case of grouted dowels localized strain mobilization would be preferable to measure.

Various monitoring techniques have been implemented to assess the state of the rock mass. MWD (measure while drilling) could provide information about the jointing and rock strength. Extensometers or lidar scans would also be able to offer areal or localized data on rock mass deformation. To determine the state of the rock mass, however, visual inspection based on classification methods and the engineer's knowledge remain crucial components. Thus, each of the methods listed has advantages and disadvantages regarding installation costs, monitoring accuracy, monitoring frequency, usability of results, and staff intensity.

The good thing about these methods is that they are well-known and established in practice, but they are not a very good long-term solution. That is where the intelligent rock bolt would fit in with the ability to monitor long-term and wirelessly transmit data. So, it does not require a person to go to the mine to measure or gather data. The only time when someone needs to go in person to check on them is when installing, changing the battery, and if something is wrong with the connection, so only in some special cases.

Measurements have a big potential for implementation because they can indicate certain conditions in the mine or prevent dangerous situations. Moreover, information about current rock mass conditions as well as the integrity of the rock support system could be gained. The detection of indicators, pre-coursers, and causal circumstances is what drives the need for a mine-wide geotechnical monitoring system. Based on deformation measurements, rock mass response and support function are measured objectively. Early detection of dangerous situations is possible, but knowledge should also be accumulated to enable better modelling and design. Where, in the long run last, a better safety environment should be created.

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Asking questions about the gathered data is important because it can help to understand how to improve the safety of miners and mining operations. By understanding the potential of instrumented rock bolts for monitoring support function, more cost-effective solutions can be developed and ensure the possibility of early warning for miners about increasing roof fall risk. Analysing data from instrumented rock bolts can help to identify potential problems and improve safety measures.

A mine is a complex environment and there are numerous processes taking place simultaneously including both workers and machinery. It is all taking place in a partially unknown environment – rock mass.
Stress environment and resulting movements are to be expected all the time, especially around excavation areas which are subjected to potential instabilities. Depending on the scale, instabilities can happen locally and regionally. Local and regional rock mass behaviour is interlinked as well. Signs of local instabilities also could be pre-coursers of regional problems. An increase in geotechnical events in certain areas could be a result of larger situated problems. The purpose of a monitoring system using intelligent rock bolts should have two tasks within this example: The first, providing the information for judging the rock support system integrity ensuring safe conditions on a local scale. And second, gain basic information supporting the engineer in the detection of deeper going issues. There is still a need for engineers to determine whether certain areas are safe or not because rock mass is such a complex material and there is still no uniform way to predict exactly what will happen with high precision. As a result, the project is providing data and analysis based on deformation in specific areas where the measuring bolts are installed.

There are various potential rock mass failure mechanisms in underground mines, some of them are as follows (Brady, Brown 1999; Hoek, Brown 1997, 1980):

Rock bursts are unexpected and serious failures of underground mine rock masses that release stored energy and cause the rock to violently release from the mine's walls or top (figure 2). These occurrences are hazardous to miners and can result in injuries, fatalities, and extensive damage to mining equipment and infrastructure. Detecting them is crucial for protecting miners and avoiding mine damage. Rock bursts can be detected using a variety of approaches, including microseismic monitoring, acoustic emission monitoring, and strain measurement. Microseismic monitoring involves identifying and finding the source of seismic events induced by rock fracture, whereas acoustic emission monitoring detects energy release when cracks open in the rock mass. By monitoring the deformation of the rock mass, strain measurement can also be utilized. Predicting rock bursts is more difficult and less credible than detecting them, although preliminary research has yielded favourable findings. An increase in seismic activity, a rapid increase in gas concentration, or an increase in rock stress are all symptoms of a probable rock burst. It may be feasible to predict the occurrence of a rock explosion by monitoring these indications and analysing the data. However, because of the complicated nature of rock behaviour, predicting rock bursts with certainty remains a tough endeavour, and further research is needed to enhance prediction approaches (Brady, Brown 2006; Yuanyuan et al. 2019; Faisal et al. 2023; Li et al. 2019).

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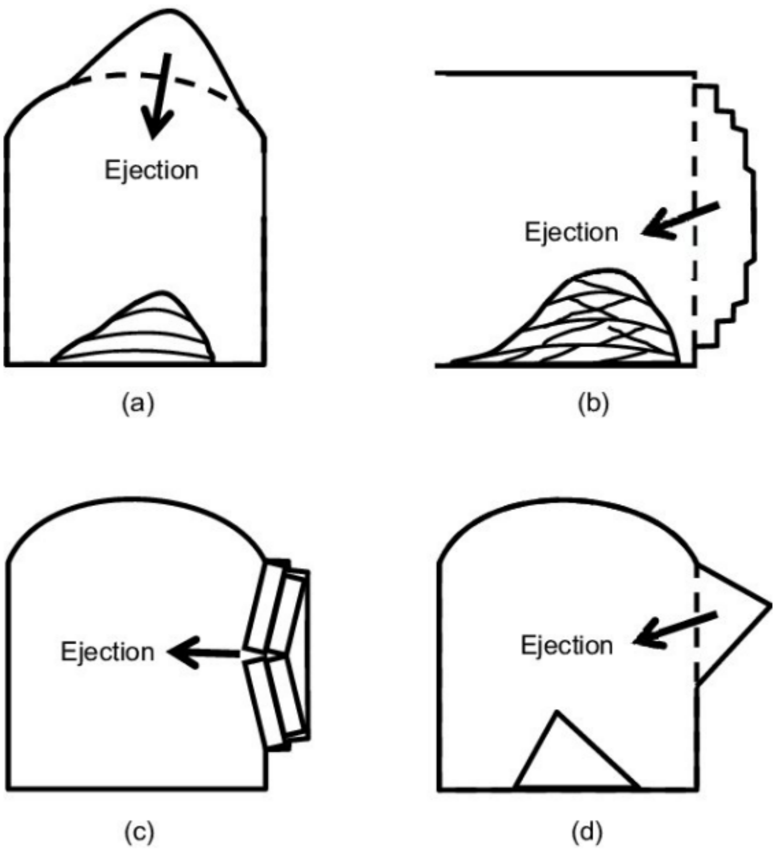

Figure 2 Different types of rock bursts: a) intact rock – roof, b) face bursting, c) buckling, d) Rock block ejection (Li et al. 2019).

Pillar failure is the collapse or deformation of the pillars that support a mine's roof or walls (figure 3). This might happen as a result of poor pillar design or high loading from overlaying rock. Pillar failure is an issue, particularly in deep mining operations where mineral resources must be extracted by removing the surrounding rock. In underground mining, pillars are left to support the mine's roof or walls, and their failure can result in a variety of safety problems and economic losses. Pillar failure can be caused by several circumstances, including high mining-induced loads, geological and geotechnical conditions, and poor pillar design. When a pillar collapses, the surrounding rock mass can collapse, resulting in roof falls, and floor heaves that can destroy equipment and infrastructure and put miners in danger. Mining engineers employ numerous ways to design and optimize pillar size, form, and spacing based on the geology and geotechnical conditions of the mine to prevent pillar failure. Empirical approaches, numerical modelling, and observational methods are examples of these techniques. Monitoring techniques such as convergence measurement, strain gauges, and rock mass monitoring are also employed to detect stress or deformation in the pillars and surrounding rock mass. Despite all of this, pillar failure can still occur as a result of unforeseeable reasons such as geological faults or fractures that are not always observable. To ensure the safety and economic feasibility of mining operations, continual monitoring and periodical assessments of pillar stability are required (Bieniawski 1984; Kaiser, Cai 2012).

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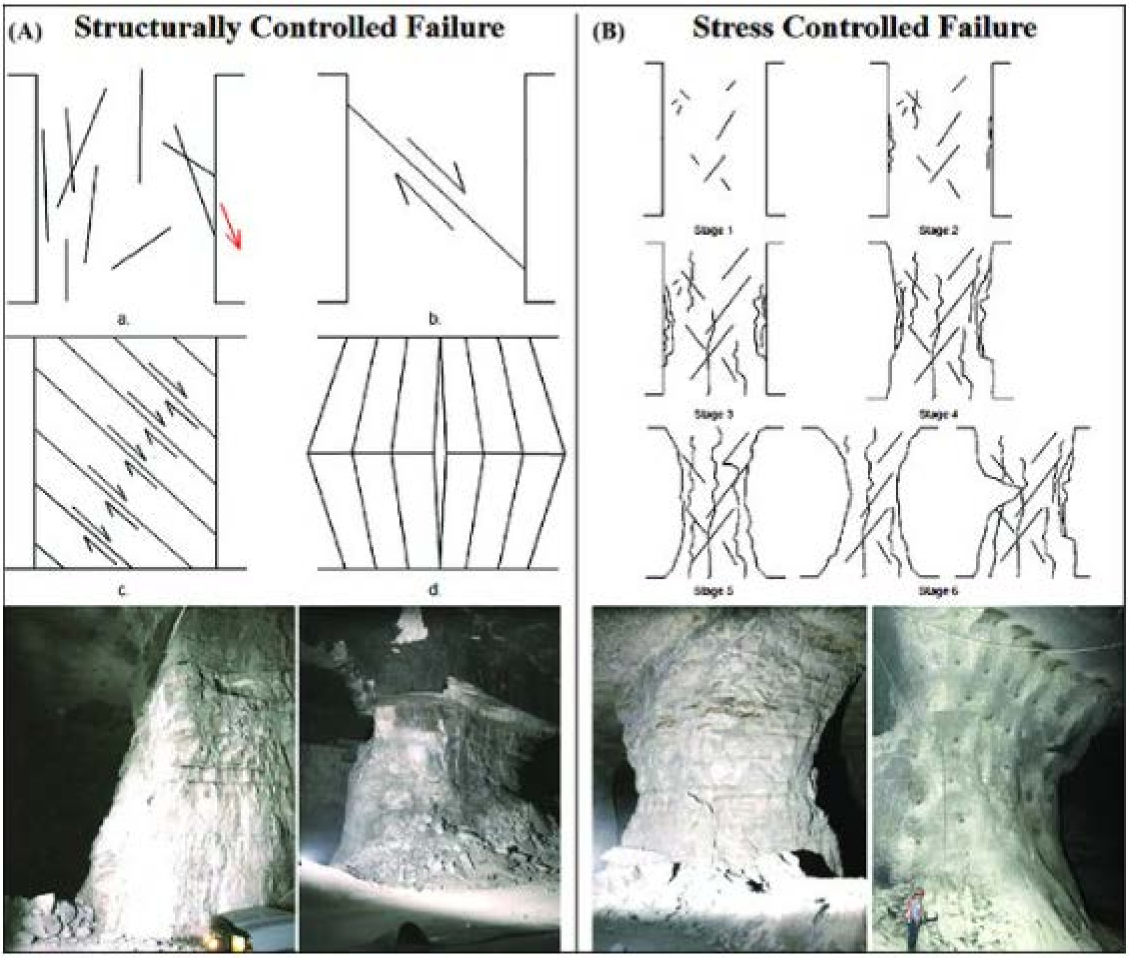

Figure 3 Pilar failures: a) structurally controlled failure, b) Stress controlled failure (Monsalve et al. 2020).

Rock falls from a mine's roof or walls as a result of rock mass instability or structural failure. This might be created by natural geological features or by stress caused by mining. They occur when rock fragments detach from a mine's ceiling or walls and fall to the floor. Blasting operations, seismic occurrences, and geological instability are all potential causes of rock falls. Mining engineers employ numerous strategies to construct and maintain the mine infrastructure to prevent rock falls, such as adding rock bolts, wire mesh, and shotcrete to support the rock mass. They also develop monitoring procedures to detect symptoms of rock mass instability. The danger of rock falls can be assessed using a variety of methodologies, including empirical methods, numerical modelling, and observational methods. These methods can be used to anticipate the likelihood and severity of rock falls, as well as to build appropriate risk-mitigation procedures. Rock falls can be a serious safety concern for miners, causing injuries or fatalities if employees are struck by falling rock and can cause equipment and infrastructure damage, resulting in costly repairs and downtime (Fortsakis et al. 2012; Hoek E. et al. 1995; Fuławka et al. 2022).

Flooding is the intrusion of water into a mine through geological faults, and mining-induced cracks, which can lead to rock mass destabilization and potential collapse. It can be caused by a variety of circumstances, including significant rainfall, groundwater intrusion, or equipment failure. Water entering an underground mine can cause major infrastructure damage and represent a safety hazard to miners. As a result, preventing and managing flooding is a crucial part of mine safety. Mining engineers utilize monitoring techniques to detect symptoms of water entry, such as water levels, flow rates, and water quality, in addition to preventative measures. These monitoring approaches can aid in detecting early warning indications of flooding and

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allowing necessary measures to be made to minimize or mitigate its impacts. Flooding occurrences can be difficult to predict since they can occur quickly and with little warning. Monitoring techniques, on the other hand, can help detect early indicators of water infiltration and allow suitable steps to be taken to prevent or minimize floods. Furthermore, based on weather forecasts and other parameters, hydrological models can be used to predict probable flooding episodes (Wolkersdorfer 2006).

Thermal-induced cracks and fracturing can occur in rock as a result of high temperatures and changes in thermal gradient. Thermal-induced rock failure occurs when high temperatures create changes in the rock mass and can occur in underground mining. When exposed to high temperatures, rocks can experience thermal expansion, which can result in cracking and fracturing. This can weaken the rock mass, making it more prone to collapse or other types of failure. It can occur in numerous ways in underground mining. For example, high temperatures caused by nearby magma or other geothermal sources can cause thermal expansion and weakening of the rock mass. Similarly, generating heat through mining activities such as drilling or blasting can produce thermal expansion and rock failure (Collins et al. 2020; Kant et al. 2017).

The presence of chemicals in the rock mass can cause chemical degradation, resulting in rock structure weakness and instability.

Earthquakes can cause a variety of failures in underground mines, putting miners in danger and damaging mining infrastructure. Rock bursts, pillar collapse, and ground failures are the most common forms of failures that can occur in underground mines during earthquakes (Potvin et al. 2000).

2.1.3 Intelligent rock bolt

For mine operators, it is essential to identify and monitor potential failure mechanisms to prevent or minimize their impact on mine safety and production. In the case of monitoring rock mass with intelligent rock bolts, further investigation and data collection are necessary. Although it will be a lengthy learning process, advances in technology and deformation measurement throughout the entire bolt tendon will lead to better comprehension and potential prediction of failures.

The ”intelligent rock bolt” is instrumented bolt with different types of sensors (figure 4). There are many possible additions and combinations of installing sensors, depending on the needs of the specific mining site. Rock bolts could have deformation monitoring system that tracks the deformation of the bolt in time and reports its capacity and performance to the central unit. This kind of sensor would provide better insight into the rock mass and behaviour of the excavation stability.

During the development, there were a few setbacks regarding different parts of this system. The first idea was to print the sensor on the flexible strap and glue it on the bolt, but that idea has been discarded due to the decoupling of the sensor strap. To fix that problem sensors are now printed directly on the bolt. Printing the sensor on the bolt requires a base coat that isolates the sensor and also serves as the surface preparation. The next layer is the sensor itself which is on the base of conductive ink. For the sensor protection there also needs to be a top coat to protect sensors from scratches during the installation. The whole concept works in a way that the sensor deforms together with the bolt and the readout unit is detecting that deformation in the form of a resistance change of the sensor. For that to be possible, the sensor needs to be fixated on the bolt without any decoupling. Then there was a problem with the base coat similar to the glue, it was decoupling from the bolt too early and thus breaking the sensor. That problem was solved by using a different type of basecoat that was more ductile. The most

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critical part of the basecoat was in the position where the nut gets fixated on the bolt. Since the readout unit for deformation sits in the same case as the other sensors, battery life is very important. For that reason, there are two different readout units, one (red nut) has fewer sensors and is cheaper and more battery efficient, and another one (blue nut) is a bit more expensive, but it contains more sensors for environment monitoring (D2.3 will provide more technical details on the sensors and read-out units)). This system has been tested with expansion shell rock bolts.

The main advantage of our bolt is the price and possibility to measure environmental aspects like gasses, temperature and humidity. However, it currently offers only one measurement per bolt.

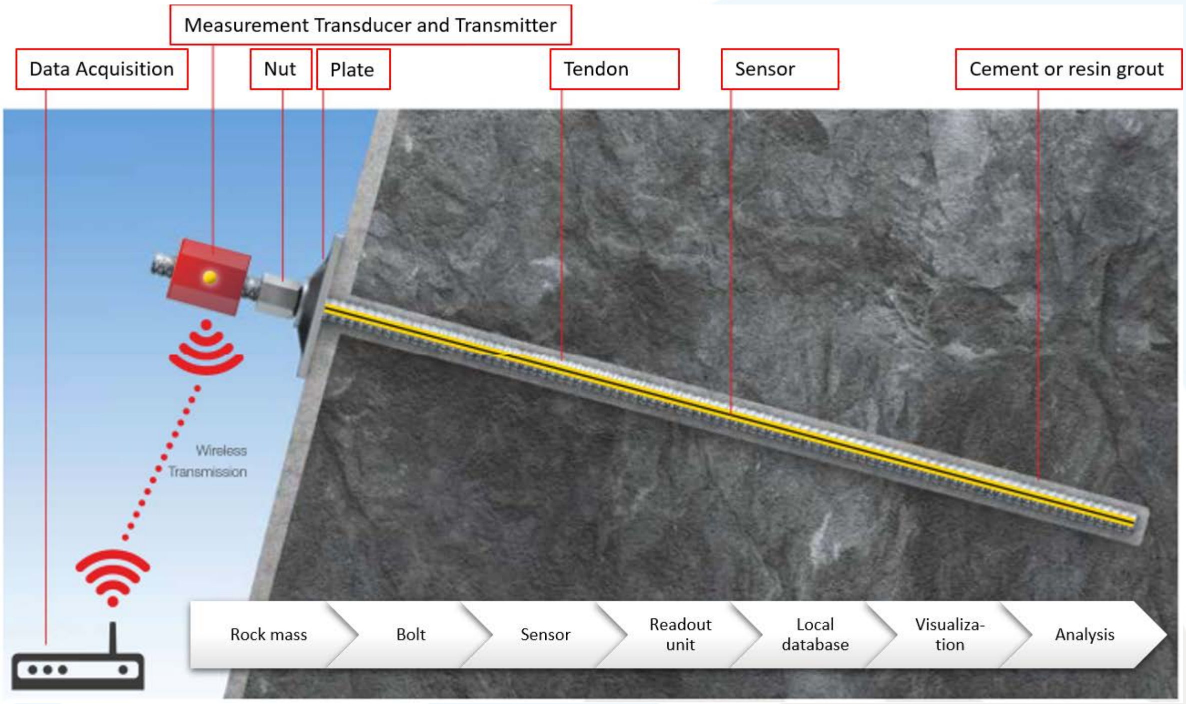

Figure 4 Components of the intelligent rock bolt and a data transmission path.

In the future, depending on the type of the sensor these bolts can remain very simple and have only one resistance sensor that monitors only the elongation of the whole bolt as one unit, or they could be more complex and measure the distribution of the deformation along the bolt with high spatial resolution. Figure 5 shows the difference in resolution or number of sensors/measurement points per bolt. 3 possible scenarios are presented: a) Only one measurement point, b) four measurement points per bolt, and c) forty measurement points per bolt.

1.) One measurement per bolt (Green - Figure 6): This could already give us very helpful information about the bolt status. For example, if the bolt failed or not (figure 5), when many instrumented bolts are installed it could point us to the potential instability if multiple bolts are reaching their maximum deformation capacity in the same area.

2.) Four measurements per bolt (Red - Figure 6): More detailed measurements can give us the utilization capacity of the bolt and from that one can calculate the elastic or plastic state of the bolt in total. Also, it could already indicate in which region of the bolt the problem is located

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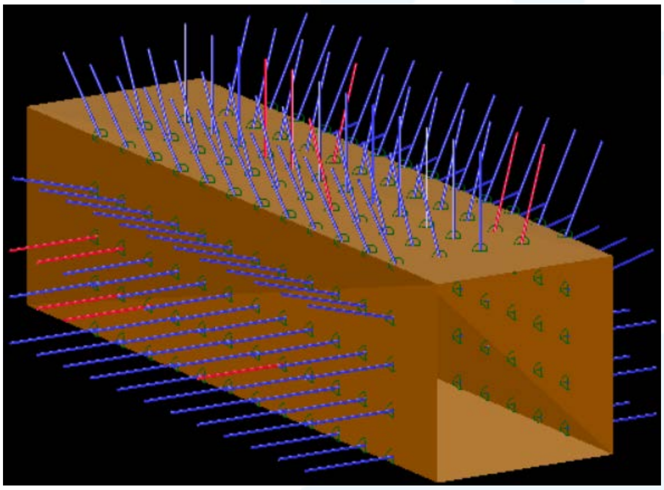

Figure 5 Visualization of the simulated data in the case bolts can only show if they failed or not (red bolts failed and blue are still working).

3.) Forty measurements per bolt (Blue - Figure 6): The most detailed measurement gives us the whole distribution of the deformation of the bolt with reasonable precision. Analysis of this case is the most complex since there is the most data and the most possibilities. One of them is the structure of the rock mass analysis, since it can be determined exactly where the bolt deformation is happening, hence moving joints can be positioned, and connecting this kind of information with more bolts in the profile gives the movement of the whole slice- depth. Of course, the precision depends on the length of the bolt. If there are many of those profiles along the whole mine, whole mine deformations could be observed in detail. From this kind of system, there are multiple possibilities for parameter calculations and back analysis. However, it would require decision making capabilities from the engineering side for data analysis and interpretation.

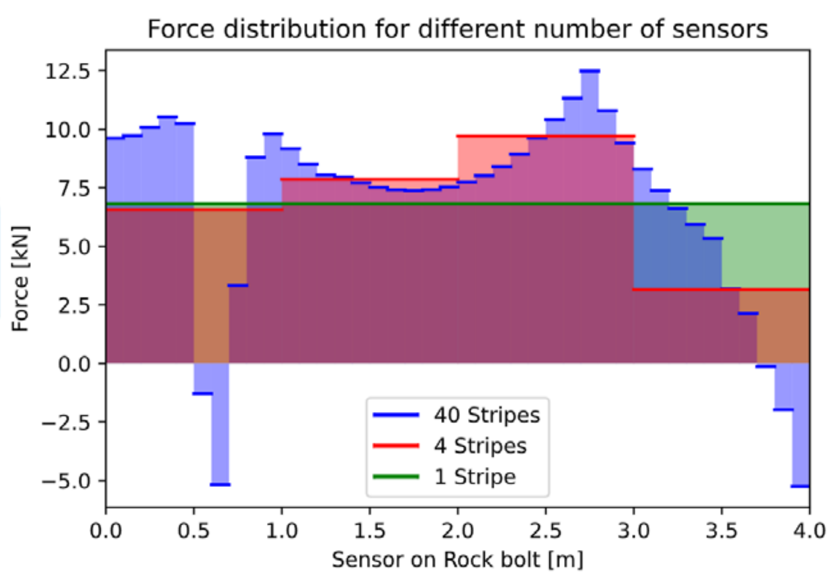

Figure 6 Force distribution along the tendon of the rock bolt for 1, 4 and 40 measurement points along the tendon, respectively.

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2.1.4 Environment monitoring

The underground atmosphere includes everything related to climatic conditions like humidity, temperature, air pressure and air content (mixture of required inert and harmful gases and particles). The air quality on the other side is also influenced by a variety of factors like ventilation parameters, gas and dust concentrations, temperature, humidity, and air blasts. It is simpler to measure air quality and determine whether it is safe or not because of the laws and safety regulations that specify boundary levels of a particular gas or dust. Temperature and humidity levels are easily monitored and there are boundaries when it starts being uncomfortable or even dangerous for human life. Safety assessment is a continuous process of gathering information and it consists of identifying potential risks, measuring, analysing, interpreting, learning and assessing the outcomes. Deviations from standard atmospheric conditions can cause short- or long-term damage. Because of the absence of apparent symptoms, the impact of long-term damage is sometimes overestimated. Furthermore, also sudden events can happen to improper atmosphere conditions. The famous quote “the dose makes the poison” is especially valid for threads related to the underground atmosphere, where the term “dose” can be described with concentration level and exposure time. Sudden events are linked to combustible air–gas mixtures and or air – combustible dust mixtures. Methane explosions and resulting coal dust explosions have to be named as important representatives, which has killed many miners in the past. In case of long-term exposure, even rather low or moderate concentrations of toxic gases and dust can cause severe health damage if people are exposed over a long period. For example, miners still face a higher risk of black lung disease because of everyday exposure to certain types of dust. Or exposure to nitrogen oxides can lead to cardiovascular diseases. Also, short-term exposure of staff to suffocating or toxic atmospheric conditions at high concentration levels can rapidly cause fatalities, if the situation is not cleared quickly. Fire events should be named in this context, where a large volume of toxic gases is being released. Working under high temperatures and humid conditions can lead to heat stroke diseases.

Gas sources are either man-made or linked to certain geological conditions; nonetheless, their impact on the subsurface atmosphere might be just as harmful to humans. Many medical studies have been conducted on the effects of hazardous substances in the environment on the human body. Based on such findings and experience from the past, most countries provide legislative threshold limit values for exposure time and concentration which must be retained. In the case of an underground atmosphere, there is a direct lever between gas/dust concentration plus exposure time to the severity of health damage. However, not every mine faces the same problem, depending on the installed machinery or deposit type, therefore only potentially relevant substances should be measured. Figure 7 summarizes typical atmospheric parameters which must/should be measured to avoid health issues.

For transferring atmospheric measurements into safety status not only the concentration level itself, but also the areal distribution and the exposure time of personnel in those areas are relevant. In addition, parameters like air pressure should be measured, which does not directly influence the health and safety risk but can be a pre-indication for excessive gas release in coal mining. In terms of atmospheric monitoring, the fundamental component of the safe zone concept is to determine the present risk level related to harmful compounds and climatic circumstances, but also analytical tools, and indirect monitoring control methods, such as ventilation, will be offered. Such monitoring allows engineers to manage health and safety risks in advance by proper design and control measures.

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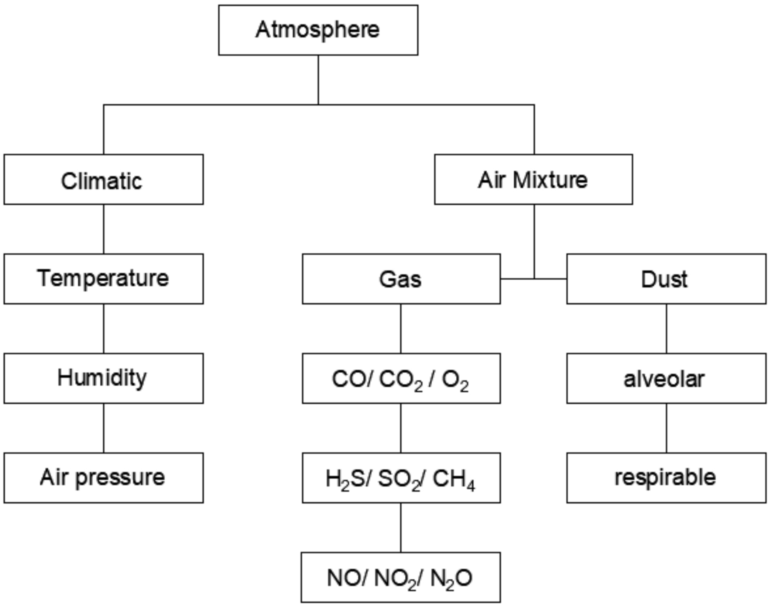

Figure 7 Substances to be measured to reduce the risk of severe health damage on personal

Already installed monitoring systems used in the mine measuring the atmospheric and climatic conditions will be integrated into the newly developed system of intelligent rock bolts. The main data which could be delivered using intelligent rock bolts are presented in table 1.

Table 1 Main data that could be delivered with sensors in the scope of the illuMINEation project.

Climatic Condition	**Air Mixture**
Dry Bulb Temperature [°C] Measurable	O_2 [%] Measurable
Relative Humidity [%] Measurable	CO [ppm] Measurable
Absolut barometric Pressure [hPa] Measurable	CO_2 [%] Measurable
	SO_2 [ppm] Measurable
Wet Bulb Temperature [°C] Calculated	NO [ppm] Measurable
Percentage of Humidity [%] Calculated	N_2O [ppm] Measurable
Moisture content [kg/kg dry air] Calculated	NO_2 [ppm] Measurable
Density (apparent) [kg dry air/m³] Calculated	CH_4 [%] Measurable
Density (actual) [kg moist air/m³] Calculated	H_2 [%] Measurable
Enthalpy of air [J/kg dry air] Calculated	H_2S [ppm] Measurable
Sigma heat [j/kg dry air] Calculated	Alveolar Dust [mg/m³] Not measurable
	Respirable Dust [mg/m³] Not measurable

This qualitative identification of measurable parameters sets the basic framework for monitoring underground air composition and climatic conditions. Except for dust concentration level, all required data for assessing atmospheric-related risk can be delivered. However, just having the possibility to measure a wide spread of different substances will not reach the goal of the safe zone concept. As a first step, used sensors must be chosen to meet the accuracy requirements of threshold limit values in measuring gas concentration levels. Furthermore, installation density and distribution in the underground building must be designed to provide areal information on environmental conditions, as is required in the case of the safe zone concept. Finally, setting the appropriate reporting time interval of the sensors is also of major importance. The design of installation density and reporting frequency will strongly depend on the speed of changing parameters either in space or in time. Regarding sensor accuracy, installation density and reporting frequency a minimum requirement, depending on the

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analysing methods, has to be set to achieve the goals of the safe zone concept. The more monitoring units installed and the higher the reporting frequency the clearer a real-time picture of the prevailing conditions can be taken. However, in reality, compromises must be made. High reporting frequency will result in higher energy consumption per time, reducing the available measurement period and therefore increasing the maintenance work for keeping the sensor online. This is also scaling with the number of rock bolts installed. Although the system is designed to be low-cost, the costs of the overall system the additional installation effort as well as the maintenance work must be considered in the end. A main point, in the design of an appropriate monitoring system is to meet the legislative regulations and should be kept in mind every time.

2.1.5 Identification of safety risks and assessment

The first stage in any risk assessment strategy is to identify potential risk sources. As previously stated, safe zone concept 1 will primarily focus on environmental dangers, particularly those that can be mitigated by the employment of intelligent rock bolts. This will be accomplished by monitoring the mine's geotechnical and atmospheric conditions.

Risks can also be categorized by the forms of rock mass failure. In this stage of development, they cannot be properly evaluated utilizing intelligent rock bolts and cannot be measured directly. Regarding the collapse of the rock mass, conclusions that may be drawn include the location of the potential failure based on the bolts' utilization capacity, and the precise placing of that utilization inside the drift could be seen as a sign that something is going on there. There is also a chance of determining whether the walls or the roof have deformations. Figure 8 shows the possible visualization outcome of the rock bolt deformation. In this case, it is assumed that there is a possibility to track deformation along the tendon, which is so far not possible with the available technologies. However, in the future with more developments has a lot of potential.

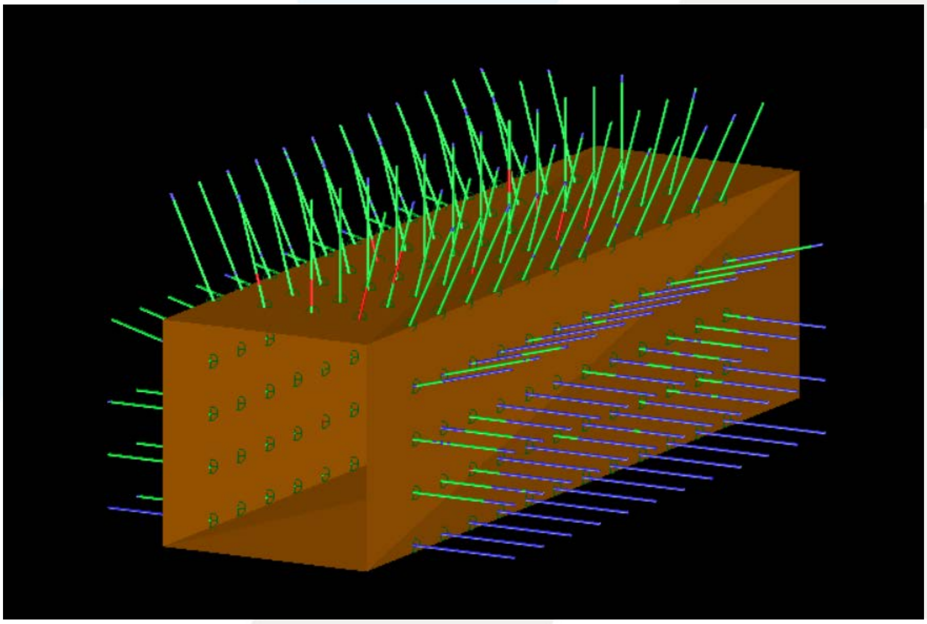

Figure 8 Concept data visualization outcome, deformation displayed along every bolt in one part of the mine.

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2.1.5.1 Failure types of rock bolts

A *mechanically anchored bolt* is structural support inserted into a drill hole and anchored, it doesn't have any other fillings. Determining state change from elastic to plastic in expansion shell bolts depends on steel properties and length of the bolt, which is relatively easy to determine from the steel properties curve. During a linear phase in the graph, steel is in an elastic state, and after reaching yield strength it starts changing to a plastic state. If exact steel properties are known and combined with constant deformation measurement in real-time, we can know when the bolt reaches its plastic state, and in the end, calculate the utilisation capacity of each of the states and overall capacity. Failure in mechanically anchored bolts depends mainly on the steel properties and length of the bolt. It is simple to determine failure with a sensor that is connected to it since the sensor will also fail because after failure bolt will not have residual strength left and it will easily detect it - that is not the case with grouted bolts.

A *grouted bolt* is structural support inserted into a drill hole in the rock mass and then grouted (Cao et al. 2012). In grouted rock bolts many aspects are affecting the state of overall stability: steel properties, length of the bolt and embedment, grout properties, friction between 3 different materials (steel-grout-rock surface), and profile of the drill hole. The situation with grouted bolts is much more complex than with mechanically anchored bolts. There are also different types of fillings; resin and grout. Failure patterns can occur in bolts, grout or a combination of them. After the failure of the bolt or grout, there can still be some residual strength left. There are three different types of pull-out failure in grouted bolts (Høien et al. 2021). Pull-out failure can be difficult to detect with the strain gauge sensor that is attached to the bolt and monitoring only bolt deformations. When the failure and main deformations are happening in the grout the sensor detects that the bolt is still in the elastic state and that would not raise alarms. Only when there is a significant deformation in the bolt it can be detected with the attached sensor. There are 3 different components included in bonding forces: chemical adhesion, friction and mechanical interaction between concrete and steel. First, there is a chemical adhesion in work, before the slip occurs, and after small movement friction and mechanical interaction take place. Slip can happen in two different ways: the ribs can split the concrete or it can crush it and that powder gets compressed and lodged in front of the ribs (Lutz 1970).
One of the issues that can occur is the improper installation of rock bolts, particularly for grouted dowels. Additionally, it is difficult to identify since bondage between rock bolt and rock mass cannot be accurately measured.

2.1.6 Monitoring data accumulation & data stream process

The degree of automation achieved by the safe zone idea is depicted in Figure 9. The project should include automation for measuring information, analysis using pre-developed algorithms, and visualization of the results. However, the situation is not that simple for information interpretation, learning processes, converting information into safety status, and deciding on measures. The question is not just if it is technically doable, but also whether it is valuable. This means that measurement is the simplest and most automatable aspect of the entire process. That is something that can be automated and repeated. However, process goes further, an engineer must be involved, someone with more expertise and knowledge of the mine, as well as someone who can look at the big picture and make an intelligent decision. In this part, an automated algorithm can give some recommendations and help an engineer to learn and study the situation, but the decision in the end needs to be made by a human. The following part lists the processes from identifying a potential hazard towards a final assessment of the risk as a combination of automated measurements and human interpretation:

Identifying potential risk hazards: This stage entails methodically examining the mine environment for any dangers that might compromise safety. It enables preventive measures

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to be carried out to avoid accidents or incidents from happening. The procedure establishes the foundation for a complete safety approach by identifying these dangers.

Measuring is the process of gathering relevant data and information about many areas of mine operations, such as equipment performance, environment, rock bolt deformation and utilization, and position of personnel. This data provides useful insights into overall safety performance and aids in risk quantification.

Analysing data: After gathering the data, it must be evaluated to find patterns, trends, and correlations. This analysis assists the mine management team in determining the root causes of probable risks and hazards. By identifying these fundamental causes, appropriate preventive measures can be implemented to effectively limit the risks.

Learning from the situation: Continuous progress requires learning from past incidents and near misses. Valuable lessons can be acquired by thoroughly investigating the origins and repercussions of previous accidents. This stage emphasizes the necessity of creating a learning culture and supports the implementation of corrective actions to prevent similar occurrences from happening in the future.

The final stage is to **interpret all of the collected data and knowledge** to make informed judgments about safety practices, rules, and procedures. Mine management can design effective plans to limit risks, improve safety measures, and allocate resources efficiently by combining the information from the preceding processes.

Benefits of this process include:

1.) Proactive risk management: The procedure enables a proactive approach to risk management by recognizing potential dangers early on and adopting suitable control measures. This lowers the possibility of accidents and enhances overall safety performance.

2.) Continuous improvement: By incorporating lessons acquired from accidents and near misses, the process develops a culture of continuous development. It encourages the gradual deployment of corrective actions and the development of more effective safety practices.

3.) Data-driven decision-making: The method promotes data-driven decision-making by gathering, analysing, and interpreting relevant data. This guarantees that safety measures are founded on accurate and up-to-date data, improving the possibility of making educated decisions that improve mine safety.

4.) Enhanced safety awareness and accountability: Because it emphasizes the identification and comprehension of potential dangers, the procedure creates a higher degree of safety awareness among mine personnel. It also promotes accountability at all organizational levels, ensuring that everyone is accountable for safety.

5.) Regulatory compliance: Implementing an effective strategy for identifying and managing risks to comply with regulatory conditions and industry standards. This assists the mine in meeting safety rules and develops a positive relationship with regulatory agencies.

Overall, the described process contributes to the development of a proactive, data-driven approach to mine safety. It enables the detection of possible risks, permits continuous

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improvement, enables informed decision-making, raises safety awareness, and assures regulatory compliance. Mines may considerably reduce the occurrence of accidents, safeguard the well-being of their employees, and maintain a safe working environment by applying this approach.

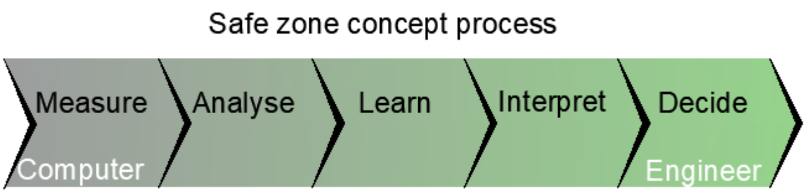

Figure 9: Flow chart of the safe zone concept showing possible degree of automatization.

While the process described for ensuring mine safety has numerous benefits, there are a few potential disadvantages to consider:

1.) Time and resource-intensive:
This method necessitates quite a bit of time, effort, and resources. It entails obtaining and analysing data, conducting extensive assessments, and putting corrective measures in place. Extensive data collection and analysis can be time-consuming and may necessitate specialized skills or technology, posing issues for mines with limited resources.

2.) Complexity:
There are several steps in the process, including risk identification, data collecting, analysis, and decision-making. Because of the complexities of each phase, effective implementation may necessitate further training and experience. This complexity can also raise the risk of data errors or misinterpretation, which can affect the accuracy of judgments made.

3.) Implementation challenges:
Implementing this approach successfully necessitates strong leadership, corporate dedication, and excellent communication. If there is reluctance to change or a lack of cooperation from personnel, the process's effectiveness may suffer. It can be difficult to ensure that all stakeholders actively participate and follow the agreed safety measures, especially in larger mining operations.

4.) Data quality and availability:
The accuracy and reliability of the data collected are crucial for effective decision-making. However, data quality can vary depending on factors such as the reliability of measurement equipment, the diligence of data collection practices, and the availability of historical data. Inaccurate or incomplete data may lead to faulty analysis and flawed decision-making.

5.) Limited predictability:
Regardless of how thorough the analysis and risk assessments are, it is critical to remember that not all potential risks and hazards can be predicted or eliminated. Unexpected situations or new hazards may occur, putting the process's effectiveness in jeopardy. To address growing threats, it is essential to maintain a flexible and adaptive approach.

6.) Implementation barriers:
Cultural resistance or a lack of information about safety standards may impede the process's success.

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2.1.7 Applied analysing and interpretation methodologies for safety status information

The term "applied analysing and interpretation methodologies for safety status information" refers to the specific techniques and procedures utilized to analyse and evaluate mine safety data. It entails using various analytical approaches and tools to extract useful insights from acquired data, which can subsequently be used to make educated decisions and conduct appropriate safety actions (Adriaensen et al. 2019). Different methods can be used in dealing with analysing and interpreting data for safety status information going from more traditional ones like statistical analysis to more modern ones like predictive analytics. To gain relevant information, data must be prepared and examined for processing. The main task is to analyse data using appropriate methods to conclude current situations. Furthermore, long-term and short-term changes in ground conditions should be provided for further interpretation based on this data analysis. Aside from identifying condition changes, another important responsibility is forecasting future trends.

The main objective is to use existing information to derive forecasts for future developments and behaviour patterns based on present knowledge. Safe Zone Concepts, as seen in Figure 1, derives in part from the iterative analysis, interpreting, and learning process, which allows for the accumulation of further knowledge about specific sub-areas and interconnected systems through time.

To enable this continuous learning process, it is required to check and verify existing predictions of employed models on the one hand and to increase basic knowledge by back-analysing specific instances on the other. Weak points in the utilized models must be identified and realizations about system behaviour must be enhanced based on the data back analysis.

A better understanding of key system parameters allows for fundamental scientific improvements to make model prediction more precise. Moreover, optimized design criteria for future planning can be generated.

The purpose of the data analysis and back analysis depends in each case on its objective. The aim is to provide information for assessing the current risk, to identify emerging changes at an early stage and to provide a broad information base for optimizing the risk assessment. The data required for the analysis methods must be mapped via the monitoring system.

The information required for assessment narrows the selection of analysing approaches and assumes proper implementation or, if necessary, further improvements. The decision for a certain method also defines the frequency with which it has to be performed. As a result, the analytical methods specify the criteria for the supplied data and establish the fundamental requirements for the monitoring system. In reality, always a compromise between data which is nice to have, good to have or essential must be made to accomplish analysis. Limitations in the data generation as well as resulting limitations in the evaluation must also be considered in their interpretation.

Applied analysing and interpretation methodologies for safety status information can be:

Statistical analysis is the process of analysing data using mathematical and statistical tools to detect patterns, trends, and correlations. It aids in comprehending the correlations between various factors and determining the value of safety-related data. To gain insights and form conclusions, techniques like regression analysis, correlation analysis, and hypothesis testing can be used (Reimann et al. 2013).

Data visualization is the use of graphics to visually summarize and communicate complex information. It makes it easier to interpret safety status data by presenting it in a more accessible and intuitive format. Charts, graphs, heatmaps, and dashboards are popular visualization techniques for identifying trends, abnormalities, and potential safety hazards (Wilke 2019). Tools for visualization should be created to make it simple and quick to understand the information needed. As a result, prepared and reduced data must be displayed

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at specific user levels. On the one hand, the management decides to visualize data for various user levels, but it is also an iterative process during the implementation stage.

Root cause analysis (RCA) is a method for determining the underlying causes of safety accidents or hazards. It entails studying and assessing the circumstances, events, and situations that contributed to an incident. RCA techniques such as the "5 Whys" technique, fault tree analysis, and the fishbone diagram aid in understanding the underlying causes and establishing appropriate preventive actions (Okes 2019).

The comparative analysis involves analysing information on mine safety status across different periods, regions, or operational units. This method identifies differences, deviations, or performance gaps, emphasizing areas that require attention or improvement. Comparative analysis provides a benchmark for evaluating safety performance and allows for the exchange of best practices across mine locations (Becker et al. 2019).

The process of **evaluating historical safety data** over time to detect patterns and trends is known as trend analysis. It aids in determining the amount and direction of changes in safety performance indicators, incident rates, or risk levels. Trend analysis provides insights into the efficacy of safety actions, enables early detection of new risks, and promotes proactive decision-making to avert incidents (Esterby 1993).

Predictive analytics is based on predicting safety outcomes and identifying potential dangers by using historical data, statistical modelling, and machine learning algorithms. Predictive analytics can forecast the risk of specific events or hazards occurring by studying patterns and correlations in safety data. This allows for preventative measures to be done to avoid issues from occurring (Finlay 2014).

Different methodologies are not mutually exclusive and can be combined based on the needs of a specific mine to transform the data into a meaningful and valid safety status.

2.1.8 Integration example: Use case scenario

The management staff of a big underground mining company is dedicated to safeguarding the safety and well-being of the personnel. They've put in place a complete process that includes analysing and interpreting safety status data to identify hazards and make informed decisions. This is how the procedure would work in practice.

Identifying potential risk hazards: The mine undertakes vast hazard assessments regularly, relying on professional knowledge and historical data. Potential hazards such as unstable geological formations, equipment breakdowns, and dangerous gases are identified.

Measuring: A thorough data collection system is in place at the mine. Throughout the mining operation, sensors and monitoring systems gather data on a variety of characteristics like ventilation, gas concentrations, ground stability, and machine performance. This information is collected regularly and stored in a centralized database.

Analysing: Team of engineers or one engineer (depending on the scale of the operation) examines the collected data using statistical analysis tools and other data analysing methodologies. They look for trends, correlations, and anomalies to learn more about safety performance and potential threats. Statistical analysis assists in understanding the factors that influence events, such as gas concentrations or equipment failure rates, or in other words what happened before the hazardous event, or other correlations.

Learning from the experience: When a safety incident occurs, engineers and all other responsible personnel are conducting extensive investigations utilizing root cause analysis methodology. Using methodologies such as the "5 Whys" or fault tree analysis, they analyse the occurrence, collect data, and identify relevant reasons. Lessons from these occurrences

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are communicated with the workforce, and corrective efforts are taken to avoid such incidents in the future.

Data interpretation and decision-making: The responsible team visualizes the studied data with available tools to provide a clear overview of safety performance indicators. They examine data from various periods and operating units to detect trends and areas of concern. This data directs their decision-making processes, helping them to properly manage resources and prioritize safety measures.

For example, if the analysis reveals an increase in gas levels in a certain section of the mine, the supervisors can immediately act to improve ventilation systems, perform additional gas testing, and enforce safety standards in that area.

The mining operation benefits from a data-driven approach regarding security management by implementing these approaches. The constant analysis and interpretation of safety status information offers mine management to proactively identify risks, conduct targeted solutions, and build an organizational culture of safety awareness. Finally, this procedure leads to a safer workplace by lowering the likelihood of accidents and incidents.

2.2 Positioning/tracking of equipment & personal [Safe Zone 2]

The work performed in this task focused on the safety aspect during the operation of mine trucks and other heavy vehicles in mining environments and under the presence of mining personnel and other mobile equipment in the environment. Reliable and robust tracking of the position of equipment and personnel in mines contributes to improving all-around work place safety and allows for optimizing various mining processes for the best possible operational efficiency. The known position of personnel and equipment also allows for a safety classification of the mining areas under the Safe Zone Concept, together with intelligent rock bolts, environmental monitoring, tailings dam stability and inspections conducted via drones.

The evaluated detection and tracking technology described in this chapter is suitable for machinery that is operated manually, by tele-remote control, or autonomously. For all these types of machine operations, it is crucial to monitor the surrounding of the equipment in motion to prevent collisions with mine personnel or other vehicles. The evaluated detection and tracking system were selected for its ability to operate under the characteristic challenges of mining environments, that is, frequent exposure to dust and other particles as well as strongly varying illumination conditions, especially when operating both above ground and underground. The machine vision system can detect either reflective markers or infrared emitting light beacons and therefore be deployed for the detection and tracking of humans wearing reflective high-visibility clothing and specific equipment fitted with patterns of infrared LED markers.

The detection system is performing in a local context on the host machine/vehicle it is installed on and safety status information is derived from the position and velocity information estimated for detected personnel or objects and a defined layout of risk zones around the vehicle. Safety status information can then be used to warn a human operator of an immediate risk or by connecting the sensor system to the vehicle control system and allowing for automatic counter-active measures such as a controlled slow-down to avoid collisions between mobile machines and personnel or other machinery. Coordinates of detected personnel and equipment can further be transferred to a higher-level IOT platform where information from various vehicles is gathered and represented in a global mine context.

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Figure 10 Emitrace® sensor system mounted on an Epiroc mine truck.

2.2.1 Identification of safety risks and assessment

At present, a common way to create safe work zones in mines is the use of light curtains. Those devices prevent people and other vehicles to enter the safe zone where the mine truck and loaders are autonomously working. The light curtains are connected to a safety system controlling which vehicles have entered the safe zone. The safety system prevents unauthorized people or machines to enter the area, and if needed will automatically shut down the operation in the specific area. Machine positions are determined using laser scanners, odometers, IMU:s and articulation sensors in combination with a map of the mine environment. Wi-Fi is used as the communication link between machines and the safety system and to transfer the machine's location to the traffic management system.

In a mixed traffic scenario, with various machinery and personnel operating in a shared work space, it becomes crucial that machinery in motion is aware of humans and other mobile equipment in the surrounding area to prevent collisions and avoid injuries or fatalities to personnel and damage to equipment and infrastructure. Furthermore, it is important to obtain information about the nature of a detected object (person, vehicle, equipment) and in the case of another vehicle, the vehicle type (mine truck, personnel transport truck, etc.). All this knowledge contributes to adapting driving routes and speeds for the safe operation of mobile machinery. A truck, for example, can notice another mine truck ascending a ramp, causing the mine truck to drive to the side and allow the other vehicle to pass. Or a mining truck detects a personnel transport vehicle and slows down to allow them to pass safely. Alternatively, the mining truck detects a person and either slows down or comes to a complete stop to guarantee the individual's safety.

Position tracking systems for equipment and personnel can be divided into a global context and a local context. The global context shows the equipment and personnel in the entire mine, typically visualised in a 3D representation of the mine. Technologies such as UWB, BLE, LTE, NFC, RFID, 4G/5G or WIFI are commonly used for this aim, and allow for example for providing functions for work dispatch and blasting preparation by evacuating all personnel from the mine. In contrast, safety features implemented on mobile machinery usually build upon local on-board sensing and data processing directly on the vehicle to have as short of a reaction time

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between detection of a risk situation and the execution of a counter-active measure to avoid collisions or other incidents.

The sensor system evaluated in this task concerns the local sensing context and can detect both – humans on foot and equipment – under the prerequisite that humans are equipped with reflective high-visibility clothing and that the equipment of interest is fitted with a pre-specified pattern of infrared light beacons. The sensor system used infrared cameras and active infrared illumination to detect the objects of interest and computes object coordinates in 3D. Relevant safety status information is then extracted as described later in this chapter and relevant alarm signals are generated based on a pre-defined layout of risk zones around a vehicle. These zones follow the Safe Zone concept and are based on the classification of individual mining areas into safe (green), risky/critical (yellow) and dangerous/unsafe (red) zones. The warning signals can then be used to inform a human operator, to automatically trigger counter-active measures to prevent a collision or to be fed into a higher-level mine intelligence system incorporating information about the presence of machinery and personnel in a global context of the mine.

2.2.2 Monitoring data accumulation & data stream process

The sensor system evaluated for tracking personnel and machinery in this task is the emitrace® machine vision system. It is typically placed on the front or rear end of a mobile machine where it has a good overview of the highest risk zones in the vicinity when the vehicle is in motion. The sensor unit (see Figure 11) consists of a near-infrared stereo camera and active illumination in the near-infrared spectrum. It is suited to detecting both retro-reflective markers and infrared light-emitting diodes of a specific wavelength in the near-infrared domain. Table 2 summarizes the key specifications of the sensor system.

Figure 11 Emitrace® sensor unit.

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Table 2 Emitrace® sensor system specifications.

Parameter	Value
Supply Voltage	10-30 V
Power Consumption	~10 W
Field of View	Horizontal: 90°, Vertical: 67.5°
Operating Temperature	-30°C to +50°C
Update Rate	15 fps
Detection Range	1-20 m
Environmental Protection Level	IP67
Dimensions (W X H X D)	339 x 124 x 107 mm
Interface	Ethernet

Image pairs from the stereo camera are acquired and pre-processed by an inbuilt embedded system at a rate of 15 frames a second. Pre-processing tasks include basic image de-noising, contrast normalization, and image segmentation procedures. The data is then streamed over Ethernet to an in-vehicle computer installed on the mine truck that further analyses and interprets the image content. Figure 3 illustrates the typical image content when the sensor system observes workers wearing high-visibility clothing with retro-reflective markers, as well as when observing a pattern of infrared LEDs attached to an obstacle.

The stereo camera design of the sensor system allows for estimating the 3D locations of observed reflectors or infrared LEDs. As is typical for stereo imaging sensors, the accuracy of the depth component is not constant over the entire detection range and decreases with increasing distance between the observed object and the camera unit. Results from an experimental evaluation of the depth estimation accuracy can be seen in Table 3.

Table 3 Experimentally evaluated distance estimation accuracy of the infrared stereo camera system.

Distance Interval	Accuracy
0-5 m	±0.1 m
5-10 m	±0.25 m
10-15 m	±0.5 m
15-20 m	±1.25 m

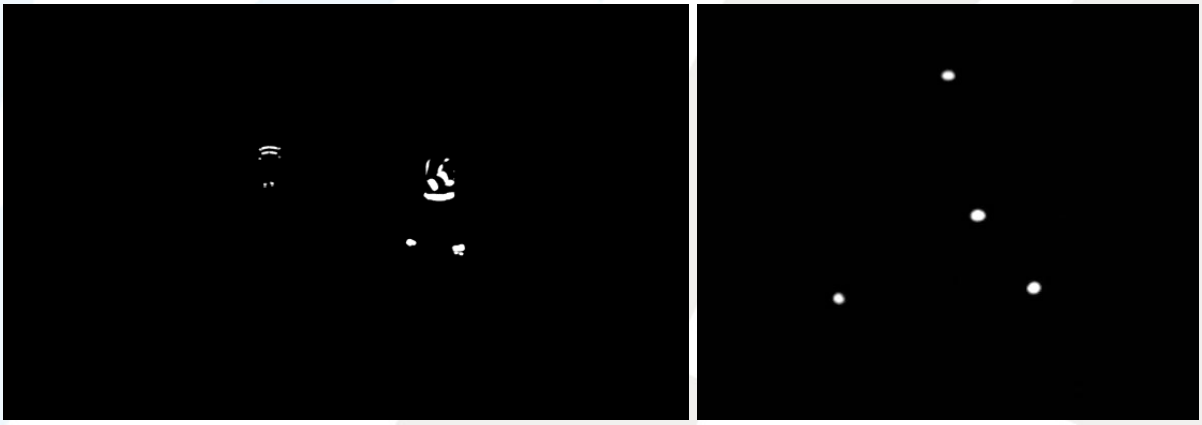

Figure 12 Near-infrared images captured by the emitrace sensor system, showing retro-reflective markers on high-visibility garments of two persons at 5 and 10 meters distance respectively (left), and a pattern of infrared LEDs observed at a distance of 5 meters.

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2.2.3 Applied analysing and interpretation methodologies for safety status information

The key data processing and interpretation steps can be divided into the following order:

1. **Image Segmentation**. Extract local interest regions from the raw images.
2. **Object Classification**. Analyse each interest region individually and classify them into high-visibility clothing reflectors, LED markers, and other reflectors.
3. **Human Detection**. Cluster regions are classified as high-visibility clothing and estimate the position and velocity of humans.
4. **LED Pattern Recognition**. Match regions classified as LED markers against a pre-programmed set of LED patterns to detect the position of equipment with LED lights.
5. **Safety Status Assessment**. Derive safety status information from the extracted object classes and coordinates.

The different processing steps are summarized in the remainder of this section.

Image Segmentation. The first stage of data analysis involves extracting and describing image regions representing either reflective objects or objects emitting IR light. These two types of objects correspond to the white regions in the black-and-white images shown in Figure 3. Basic image processing algorithms such as locally adaptive thresholding is applied for this purpose. Subsequent contour extraction allows for further feature extraction and shape analysis of the extracted regions during the subsequent step.

Object Classification. The regions of interest extracted from the raw image are classified into multiple groups. Supervised machine learning is used for dividing the set of interest regions into 1.) regions showing reflectors that resemble the type typically appearing on high-visibility work garments, 2.) small-scale round interest regions as they appear when observing infrared LEDs, and 3.) other regions depicting objects that are of no particular interest for the application here (e.g. other reflectors in the environment). The machine learning algorithm is trained on pre-annotated geometrical features extracted from the interest regions such as area, circularity, convexity, aspect ratio, etc.

Human Detection and Tracking. Interest regions that during object classification were estimated to originate from a reflective garment are further analysed. A 3D centroid location is estimated for the reflector by applying stereo matching followed by triangulation using the simultaneously acquired image pair from both camera sensors. The 3D centroid locations are then grouped into local clusters. This clustering process is necessary as multiple reflectors are typically placed on both trousers, vest or jacket of the same person and the human tracking aims to track these clusters of reflectors representing one person. Each local cluster is then assigned a unique ID and tracked over time resulting in an estimated 3D position and a 3D velocity vector for each tracked person relative to the vehicle on which the camera system is located.

Equipment Detection and Tracking. Interesting regions that during classification showed a high resemblance with small, round, high-contrast objects are likely to originate from an IR LED pattern believed in the scene. The regions are therefore further analysed to see if any pre-programmed LED pattern can be detected among them. To do so, the geometric layout of the LED pattern attached to an object of interest (machinery, equipment, infrastructure, etc.) needs to be known beforehand, that is, the 3D coordinates of the LED markers on the object of interest need to be known. The 7-point algorithm is then used to assess whether the target pattern can be observed in the image and estimate the relative pose of the object of interest relative to the camera system. Each detected object is further assigned a unique ID and tracked over time resulting in 3D estimates for both centroid position and velocity.

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Safety Status Assessment. Relevant safety information can be extracted from the position and velocity estimates of both humans and equipment. Safety boundaries are defined around vehicles, to declare safe, medium-risk and high-risk zones as illustrated in Figure 4. The centroid positions of detected people and equipment are then compared to the safe zones to assess whether any of the tracked objects have entered a medium or high-risk zone. Furthermore, the estimated velocity vectors of each tracked objects make it possible to estimate if any object is likely to enter a risk zone in the near future and estimate the time until this event based on the current object velocities.

Figure 13 Epiroc MT42 with example visualization of near vehicle safe zones, with a green zone considered safe, a yellow zone of medium risk, and a high-risk red zone.

2.2.4 Integration example: Use case scenario

In a typical use case scenario, one or several camera units of the emitrace® machine vision system are placed in suitable locations on a heavy vehicle from where they have a good overview to monitor the specified risk zones in the vicinity of the vehicle. Figure 14 shows the placement of a camera unit on a wheel loader during a test session at an open-pit limestone quarry. The camera unit is powered by the vehicle battery. The output signals delivered by the system in case an object has been detected in one of the risk zones can be used in multiple ways. An audio-visual warning unit in the driver cabin can issue visible and audible warning signals. If the vehicle is equipped with a standard input signal interface, its output can further be connected to the vehicle control system and trigger an automatic breaking manoeuvre or limit vehicle speed in the presence of humans in the vicinity.

For successfully deploying the system in practice, mining personnel are required to wear high-visibility clothing with retro-reflective markers at all times. While a simple reflective vest is sufficient for the system to operate, the combination of multiple reflectors on trousers, vests, or jackets offer more robustness in scenarios where due to body posture or occluding obstacles some of the reflectors are not in line of sight of the camera system.

If the application requires mobile equipment such as other mining vehicles to be detected by the vision system, the target objects need to be fitted with a pattern of near-infrared light beacons (see example in Figure 14.) and the geometry of the pattern on the target vehicle needs to be known for successful detection in the acquired images.

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Figure 14 Evaluation of the emitrace® vision system on a wheel loader operating in an open-pit limestone quarry.

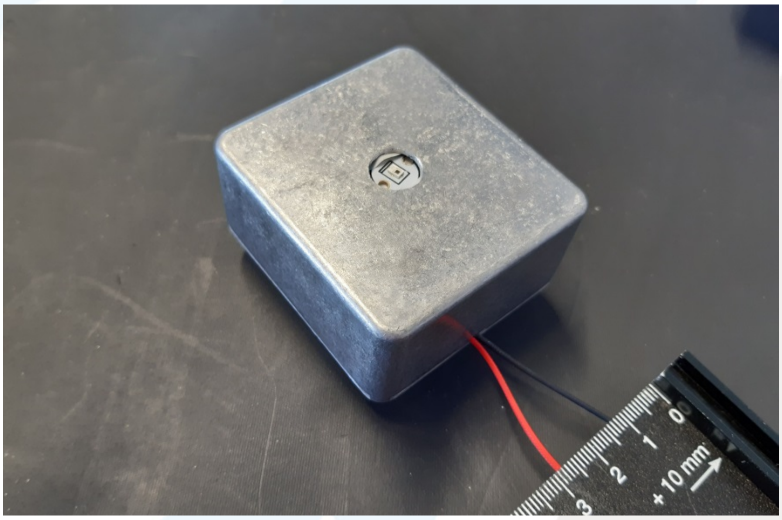

Figure 15 Example of IR light beacon used in the project.

The method was successfully shown to be effective in detecting humans in the vicinity of heavy mobile mining machinery up to a distance of 20 meters. Compared to technologies that provide the position of personnel in a global context of a mine, such as UWB, BLE, LTE, NFC, RFID, 4G/5G or WIFI, the investigated approach is designed for detecting humans near a mobile vehicle and therefore does not require any communication infrastructure to be installed in the mine. Given that suitable locations can be found on the host vehicle to place one or several camera devices that cover the risk zone of a vehicle, all sensing and data analysis tasks required to use the technology are handled directly on the machinery in operation.

Limitations of the technology include the inability of the underlying sensing approach to detect humans that are not equipped with reflective high-visibility clothing or equipment or infrastructure that has not been fitted with a pattern of infrared LEDs. An initial attempt to track a mining vehicle based solely on the attached patterns of reflective tape has proved difficult due to the rapid degradation of the reflective properties of the tape as soon as the vehicle is put in operation in a rough mining environment.

A further potential difficulty consists in finding suitable placements for camera units to monitor a 360-degree risk zone around the vehicle as illustrated in Figure 13, if the application requires

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such an all-around coverage. Movable parts such as the bucket as well as the exposure of certain locations to impact from rocks, tunnel walls, or other objects severely limits the possible placements for sensors.

2.2.5 Tracking and Positioning Using the Mobilaris System

When the illuMINEation project was put together, Mobilaris was a separate company and not owned by Epiroc. Mobilaris was a company that specialized in tracking humans and equipment in the underground mining industry and had some unique techniques to achieve this. After one year into the project, Epiroc acquired 33% of Mobilaris and the idea of creating / inventing 'another' mobile phone tracking hardware and software now seemed unreasonable as the project now had access to an already finished product. Then last year in 2022, Epiroc fully acquired Mobilaris and began integrating its underground mining products and solutions into Epiroc's portfolio. Epiroc and illuMINEation no longer needed to 'reinvent the wheel' at this stage.

Figure 16 Epiroc Test Mine; Kvarntorp and the Automation Area (enlarged block)

One of the tasks within the project is to complete a number of tests in the test mine, Kvarntorp, which is located close to the main Epiroc production facility. It was planned internally at Epiroc to eventually have Mobilaris Onboard and the Companion Tag installed and working at the test mine. As this was larger than illuMINEation, we in the project needed to wait until this work had been approved and begun by Epiroc at the test mine.
After much internal organization, as of 2023-05, Epiroc was ready to proceed with the installation(s).

The Mobilaris Companion Tag is a piece of hardware that can be installed on any vehicle or person to accurately track their position while on the mine site. The tag uses BLE (Bluetooth Low Energy) and Wi-Fi for increased positioning accuracy. Each unit includes a 3D Accelerometer and a 3D Gyroscope for movement detection. NFC (Near Field Communication) is used for easy configuration and tag provisioning. These tags will be stationed at the entrance to Kvarntorp, at the main check-in / check-out station Epiroc where each person is required to register when entering or exiting the test mine.

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Figure 17 Mobilaris Companion Tag

In addition to the Companion Tag, we will also use the Mobilaris Virtual Tag which is an application that runs on any android mobile phone. At the moment, there is no software for an iPhone. The Virtual Tag supports a mixed infrastructure including BLE, Wi-Fi, LTE and GPS positioning which allows for increased accuracy. There is also the possibility to display emergency messages and send an acknowledgement from the phone.
With these two Mobilaris products, we will be able to successfully and accurately track the humans and vehicles that are in the Kvarntorp test mine. The installation is planned, has begun and is expected to conclude by September 2023.

Figure 18 Mobilaris Virtual Tag

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2.3 Environmental monitoring [Safe Zone 3]

2.3.1 Identification of safety risks and assessment

Mining exploitation and operations affect the surrounding environment directly or indirectly. The impact on the land surface can take place both on surface waters, underground waters and in the air. Water pollution through high salinity or acidification, as in the case of Acid Mine Drainage, creates a high threat to crops, wild animals and aquatic organisms. Ultimately, they also pose a threat to people in case the drinking water levels are polluted. In addition, dust in the air, e.g. from opencast mines or mine dump, can also be unfavourable and dangerous. It causes bad health effects for the inhabitants of the surrounding areas, as well as for the employees of these mining plants. Therefore, it is necessary to monitor the entire natural environment for possible pollution and whole impacts to be able to react quickly enough, and, above all, to identify the place of specific impact - the pollution emitter - and prevent further emissions. The number of measuring instruments and monitoring stations plays a big role here. The more of them, arranged in a grid with greater density, we can conduct the better and the more proper, accurate analyses. The frequency of environmental monitoring measurements plays also an important role here. Getting results more often allows to react faster. The best solution seems to be using automatic monitoring, which can provide data with high sampling frequency, at any time of the day and the night. Unfortunately, the devices currently available on the market are relatively expensive, which limits the possibility of using them in big numbers. The second method of environmental monitoring is fieldworks by the measurement groups that can perform manual measurements. However, these time-consuming measurements and the distance between monitoring points often do not allow for conducting them in short periods with satisfactory coverage of the research area. In addition, the growing costs of labour and fuel determine the high cost of this kind of monitoring, which results in a reduction of the number of measurement sessions, and thus practically make it impossible to quick reaction to undesirable phenomena.

New publicly available electronic sensors used for DIY hobby applications can be helpful here because they are often sensors with measuring ranges and accuracy similar to laboratory sensors. They are adapted to programming platforms such as Arduino or Raspberry Pi. These sensors are relatively cheap and available, and their manufacturers often support users of these solutions by creating clear and transparent instructions on how to connect these sensors and program them to get the best possible effect. There is also a whole community of users on the Internet who help each other in creating and operating these devices. The partners of the illuMINEation project decided to use such sensors to create environmental monitoring devices to be able to reduce their production costs and thus be able to use such them on a wider scale (more measurement points) and create a dense monitoring network. Proper quality for both water and air is mostly defined in the relevant regulations established either at the national or international level. Such standards specify what values of physicochemical parameters constitute a deterioration in air and water quality and which are acceptable. Specific decisions and data analysis should be made based mainly on these provisions.

2.3.2 Monitoring data accumulation & data stream process

Aim to create the discussed solution the Arduino platform was chosen, mainly due to the low cost and wide support of the community, i.e. by Internet forums and easily available thematic blogs. Such support is extremely important in case of any problems with the configuration or software of the device. The Arduino is the name of a whole series of platforms that differ in functionality, computing power or size. Thanks to this variety, everyone can find something

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tailored to their needs. In addition to the original Arduino products, there are many cheaper clones on the market, have the same functionality and are fully compatible both from the hardware and software side. Figure 19 shows a device based on the Arduino Uno R3 clone, currently probably the most popular and most universal module in the whole series. The electronic board has a size of 69 x 54 x 15 mm, possess 14 digital and 6 analogue inputs/outputs and allows to connect up to 20 external devices. The device can be powered with direct current with a voltage of 5 to 12V, the power source can be either a battery/accumulator, AC adapter or a computer, that collects data from the device via a USB connector. As mentioned before, a properly configured and programmed Arduino can operate as a stand-alone portable device with a display and battery power, or as a fixed measuring point powered by a larger battery and transmitting data wired or wirelessly to the database.

Figure 19 Top view of the Arduino UNO R3 clone.

The pH is the first parameter that can indicate the quality of water in a given area and whose changes can be troublesome. This is one of the basic factors determined during chemical analyses (Jousma 2006; Macioszczyk, Dobrzyński 2002), so a sensor for measuring pH seems necessary. Such sensor consists of a probe/electrode and an electronic system that converts the signals from the probe into a digital value. There are currently several sensors of this type available on the market for Arduino-type platforms, one of them is shown in Fig. 20.

Some of those devices are marked Laboratory Grade, so their parameters are suitable for professional use. They may recognize pH in the range of 0-14 and can operate in the temperature range from 5 to 60 Celsius degrees. The highest measurement accuracy is achieved at 25°C and it is +/- 0.1, the measurement time may be less than 2 minutes, and the probe's lifespan, are mostly estimated by the manufacturers is over 6 months, depending on the exploitation. The probe and the electronic system can be powered with a voltage in the range of 3.3-5.5 V.

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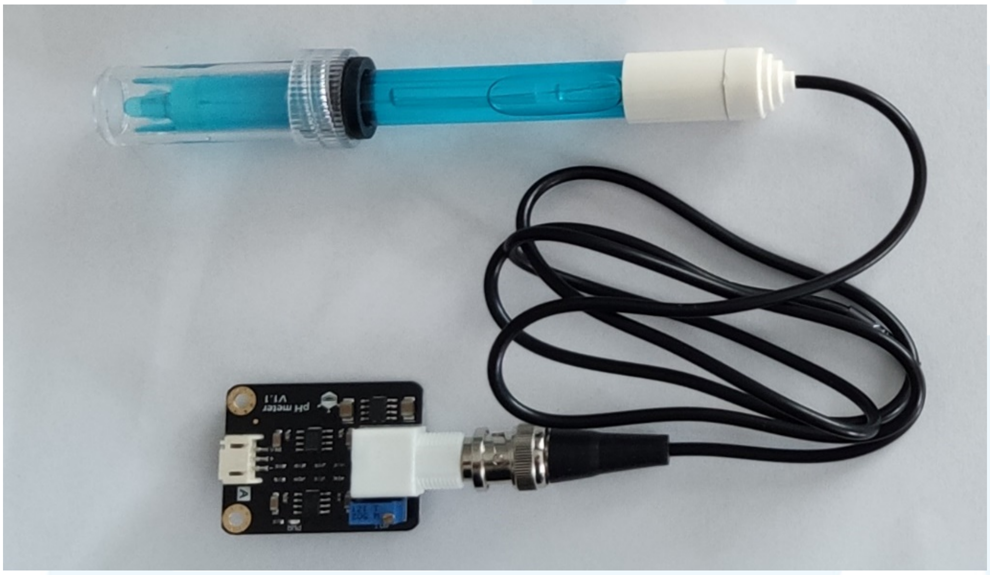

Figure 20 Example of probe for measuring pH with the electronic system.

Another sensor that allows the assessment of water quality is the conductivity meter, enabling the measurement of the electrolytic conductivity, which is an important parameter in this regard (Jousma G. et. Al., 2006). On its basis, it is possible to determine the degree of water mineralization or its contamination, and if this value for a selected point changes significantly over time, it may mean an influx of pollutants. As in the case of the presented pH-meter, there are several solutions from different manufacturers on the market. Figure 21 presents one of those sensors. Similarly, to the pH sensor, there is also a probe and an electronic system that converts signals from analogue to digital, and the accuracy class can also be described as laboratory. The measurement range may be 0-20 mS/cm or 10~100 mS/cm (depending on the version), the operating temperature range is mostly 0-~40ºC and the accuracy is around +/-5%. The electronic system can be powered by 3-5 V. In order to know and specify the conductivity value of a fluid and to correlate it with mineralization/contamination, it is necessary to know the exact temperature of the fluid, because it directly affects the conductivity.

Figure 21 Probe for measuring electrolytic conductivity.

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In order to determine the exact temperature, it is necessary to use a sensor. In this case, it can also be chosen among several solutions available on the market, but it should be remembered about the appropriate operating temperature range and accuracy of the selected solution.

To present wider scope of changes in the water environment (more precisely: in groundwater), it has been decided to use a liquid pressure sensor that allows determining changes in the water table level. For this purpose, we can use one of the solutions available on the market. The device presented in the Figure 22 consists of a pressure sensor enclosed in a steel tube, an electronic system that processes the readings and a 5-meter cable connecting the sensor to the electronic board. Inside this cable, in addition to the power and signal wire, there is also a tube intended to supply atmospheric air to the sensor to compensate for the pressure read on the sensor that monitors the water pressure. This solution is both an advantage and a disadvantage because on one hand, we get a corrected measurement result and there is no need to use an additional atmospheric pressure sensor, and on the other hand, it makes it difficult to use this type of solution in the case of wells where the water table is deeper than 4.5-5 m below the installation level of the device.

This set requires a power supply of at least 12 V, and a maximum of 36V can be used. The operating temperature of the device oscillates between -20 and 70 Celsius degrees, and the measurement accuracy is 0.5%.

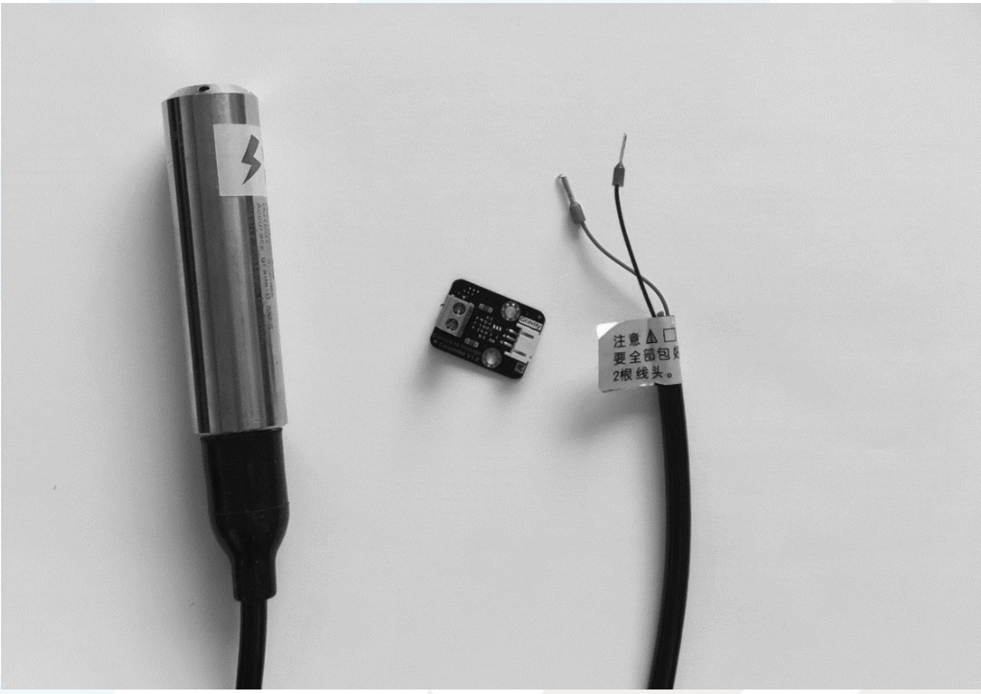

Figure 22 Fluid pressure sensor for reading the position of the water table.

For the same purpose, another sensor can be used (Fig. 23), but it does not have a full housing and its atmospheric pressure compensation. This sensor allows to measure higher pressure ranges, and thus a higher water level above the sensor. Thanks to this, it can be used to monitor the water level in holes deeper than 5 m.

Sensors that can be used to monitor atmospheric air quality include, for example, a dust sensor, which can detect PM 1.0, PM2.5 and PM10 dust. Observing such a range of fractions is sufficient for the air monitoring discussed here. In addition, the sensors to monitor changes in atmospheric pressure and temperature will be used. Sensors that detect gas concentrations do not seem to have a rational use in open space.

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Figure 23 Alternative fluid pressure sensor.

Transfer and data collection from the device

In order to transfer measurements results to the database, it is necessary to use the communication module, in this case, depending on the location of the device in relation to the telecommunications infrastructure, the various types of solutions can be used. The Arduino platform allows connecting Wi-Fi network communication modules, GSM mobile phone modems, or, for example, the Long-Range Radio network. Ultimately, the best solution seems to be the use of LoRaWAN, which is characterized by a significant transmission range, even up to 10-15 km in open terrain. Due to its operating characteristics, LoRaWAN is also more energy efficient compared to Wi-Fi or GSM networks.

The data read from the sensors can be sent to a database, where they are saved, and then they can be processed and visualized (Fig. 24).

Several libraries are available for the Arduino, supporting various database systems, such as:

- PostgreSQL
- MySql
- Firebase
- MSSQL.

At the moment in the Edge device uses an open source PostgreSQL database that allows for quick and easy setup, and with the PostGIS plugin, the usability of an Oracle Spatial database can be get.

As mentioned before, the database is accessed and entered via a ready-made programming library, in this case, the SimplePgSQL.

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Figure 24 Data collection and transfer

2.3.3 Applied analysing and interpretation methodologies for safety status information

In the case of the monitoring system proposed here within the Safe Zone Concept, there is no need to use very extensive data analytics. The visualization in the form of a flat 2D map with point representation of measurement locations and an appropriate colour scale according to the measured parameter seems to be sufficient. Analysis of the trend of changes over time for the observed parameters also seems to be needed in order to predict the occurrence of contamination or to reach its source. The spread of contamination over time with the progress of the area should allow for easier identification of the places of origin or the beginning location of the emission. In addition, the layer which represents the terrain could be helpful, thanks to which it is possible to determine the directions of runoff or migration of waters (Fig. 25).

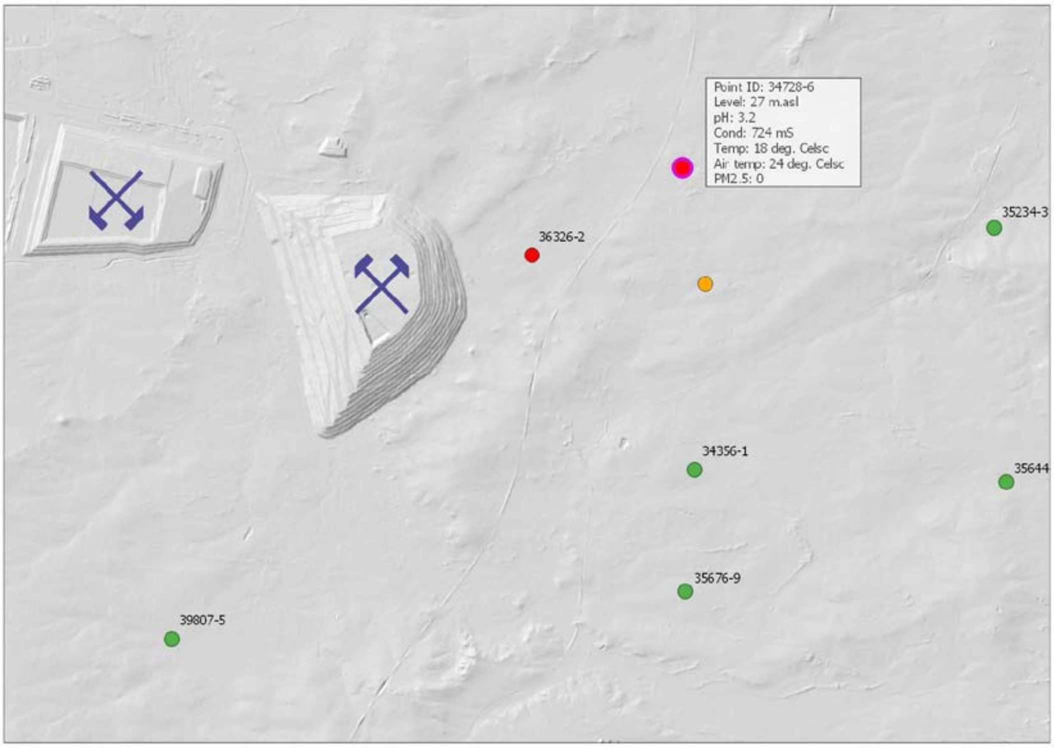

Figure 25 Map visualization example.

In addition, the map should also include potential emitters of pollution, not only related to the mining plant that monitors the environment, but also other entities conducting industrial activity

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in the area. They can also affect the quality of water and air in a given area, which is why they can be important when determining the potential source of emissions. In addition to the map, data visualizations in the form of time charts at measurement points may also prove useful. On their basis it is possible to determine or demonstrate, for example, a continuous upward trend in pH, which may indicate a slow change in the chemical composition of water in a given layer, and thus a long-term inflow acidic waters to the waters of the observed level (Fig. 26).

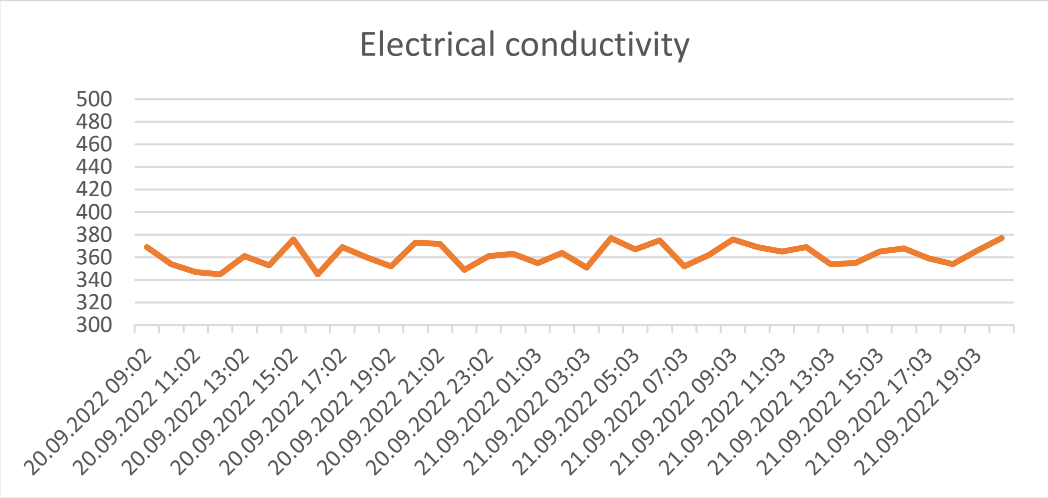

Figure 26 Chart example.

In addition to even such relatively simple data analytics, it also seems reasonable to create an early warning system, sending alerts about registered exceedances to predefined telephone numbers or email addresses.

2.3.4 Integration example: Use case scenario

In mining areas, the groundwater monitoring is carried out at a large number of various measurement points, which can be often the private wells located in home gardens, the depth of which is often not greater than 5 meters. In addition, the measurements are also carried out in much deeper holes, piezometers, often hundreds of meters deep. At the moment it is difficult to conduct measurements in such deep points. In the initial testing phase the measurements were carried out in farm wells. The observations gave readings very close to those obtained during traditional manual monitoring. The installation of the device is quite easy. In the case of devices for measuring in shallow wells, the entire electronic system, including the battery, is contained in one plastic housing. The only thing that needs to be done is to program the depth of immersion of the water pressure sensor in the code. The reason is that in relation to the water sensor depth in correlation with pressure changes in it, the depth of the water table in the well or piezometer is determined.

Increases in parameters such as pH, electrolytic conductivity or water temperature may indicate inflow of waters other than those usually found in a given aquifer. This may indicate water pollution, which should be checked and, if necessary, the procedure for removing and eliminating emissions should be implemented. As it has already been mentioned, the denser the monitoring network, the more precisely it is possible to determine the exact location of the leak. The system of observation of the environment on the surface of the terrain and the Safe Zone Concept proposed within the illuMINEation project does not differ significantly from the previously used form of conducting such works. Only the form of automatic data collection, transmission and initial processing together with visualization is a significant facilitation for

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people dealing with environmental data in a mining plant. This system can also be used in other industries.

The increased frequency of data collection has a positive effect on the possible reaction time to a threat resulting from water or air pollution, which gives hope for faster counteracting and increasing the safety of the natural environment.

The alert system can also be used to inform about, for example, water intakes located in a given area or other entities that are potential emitters of pollution.

2.4 Tailings dam stability [Safe Zone 4]

Tailings storage facilities (TSFs) play a crucial role in the mining industry, serving as repositories for waste materials generated during the extraction and processing of minerals. These facilities, however, inherently pose significant risks due to their nature and the potential consequences of failure. Therefore, it is of paramount importance to carefully analyse the stability of TSFs and ensure the implementation of robust safety measures.

Throughout history, numerous failures of TSFs have occurred, resulting in devastating impacts on local communities, and the environment, and substantial financial losses for mining companies. These incidents have served as stark reminders of the need for diligent monitoring and proactive safety practices within the mining industry.

In this section, our focus will be on the concept of safe zones within TSFs. A safe zone refers to an area within the facility that is designed to mitigate risks and minimize the potential for catastrophic events. By delineating specific safe zones, mining companies can implement targeted measures to enhance the stability and overall safety of TSFs.

It is important to note that a comprehensive description of the solution for TSFs, including advanced data analysis for monitoring and stability control, is provided in Deliverable D4.3 titled "Advanced Data Analysis for TSF Dam Monitoring & Stability Control."

By understanding the inherent risks associated with TSFs and recognizing the significance of safe zones, we can pave the way for effective mitigation strategies and establish a foundation for sustainable and responsible mining practices.

2.4.1 Identification of safety risks and assessment

When it comes to tailings storage facilities (TSFs), assessing the stability of tailings dams is of utmost importance. The most common practice in this regard is to calculate the factor of safety (FOS), which serves as a key indicator of stability. The FOS should exceed a specified value, which depends on the chosen design concept. By evaluating the FOS for each cross section of the tailings dam, we can identify zones with lower FOS values, indicating areas of reduced stability and higher risk. These areas become the primary focus of the safe zone concept.

It is important to note that the FOS calculation depends on various parameters, all of which should be carefully monitored. These parameters include the distribution of pore pressure, mechanical properties of geotechnical layers, the spatial arrangement of these layers, and the geometry of the tailings dam.

Understanding the spatial distribution of pore water pressure within the tailings dam and the foundation ground is crucial. Zones where the pore water pressure increases may indicate potential risks, such as drainage malfunction or elevated pore water pressure in low-permeability layers within the foundation ground. Mitigation measures, such as the installation

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of pumping wells, can be employed to address these risks effectively. Continuous monitoring of pore water pressure using piezometers and other instruments is necessary to promptly identify any changes or anomalies that may compromise the stability of the tailings dam.

In addition to pore water pressure, the spatial distribution of geotechnical layers should be thoroughly assessed. Field tests, including cone penetration tests, and boreholes, can help identify zones where weak layers occupy significant space. These weak layers, such as clay or silt deposits, can pose challenges to stability and require specific engineering interventions. Conversely, areas with limited field testing pose higher risks due to the lack of comprehensive data. To address this, it is essential to conduct additional site investigations and characterizations in those areas to obtain a more accurate understanding of the subsurface conditions and potential risks.

Furthermore, the mechanical properties of geotechnical layers play a crucial role in FOS calculations. These properties, including shear strength, cohesion, and friction angle, are typically determined through laboratory tests on representative soil samples obtained from the tailings dam and foundation ground. Zones with limited laboratory testing should be identified, as they may introduce uncertainties in the FOS assessment and indicate areas that require more detailed characterization. By conducting additional laboratory tests in these zones, engineers can gather essential data to refine the FOS calculations and accurately assess the stability of the tailings dam.

In conjunction with the FOS calculations, it is important to analyse the overall geometry of the tailings dam. Factors such as dam height, slope angle, and the presence of berms or embankments can significantly influence stability. Detailed surveys and topographic measurements should be carried out to ensure accurate characterization of the dam geometry. This information, combined with geotechnical data, facilitates the identification of areas where the FOS is particularly sensitive to changes in slope geometry or other design parameters.

By considering these factors—pore water pressure distribution, spatial arrangement of geotechnical layers, mechanical properties, and dam geometry—we can conduct a comprehensive assessment of safety risks within the TSF. This assessment, along with the FOS calculations, forms the basis for identifying and prioritizing the safe zones within the facility.

Regular monitoring of these parameters is essential to detect any deviations from expected behaviour and to ensure that the safe zones remain stable over time. Continuous monitoring techniques, including automated data acquisition systems, remote sensing technologies, and geotechnical instrumentation, enable real-time assessment of critical factors and provide early warning signs of potential stability issues.

By focusing on these critical aspects of TSF stability assessment, we can better understand the potential risks and take proactive measures to ensure the safety and integrity of the tailings storage facility. This diligent approach to risk identification and assessment forms the foundation for implementing effective risk management strategies and mitigating the potential impacts on local communities, the environment, and the mining company's financial viability.

2.4.2 Monitoring data accumulation & data stream process

The TSF Data Analytics system relies on a comprehensive database to store and process data. The primary source of data for the system is the SEZAM database, which aggregates information from various instrumentation devices deployed within the tailings storage facility. These instruments include piezometers, geodetic benchmarks, field test equipment, and laboratory test results, among others. Additionally, the system can incorporate data from other sources, such as CSV files or data feeds from external monitoring systems.

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Figure 27 TSF Data Analytics front-end of the system.

A key functionality of the TSF Data Analytics system is its ability to visualize the collected data. The system utilizes modern visualization techniques that offer flexibility to adapt to user requirements. Users can easily scale the axes, zoom in or out, and adjust the range of visualization to focus on specific data ranges or time periods. The system also provides the convenience of downloading prepared charts, plots, and maps for further analysis or reporting purposes. Moreover, the visualizations are interactive, allowing users to interact with the data. For instance, by clicking on a specific point, users can access detailed information associated with that point, enabling in-depth analysis and exploration. The following images illustrate an exemplary visualization of the geodetic benchmarks.

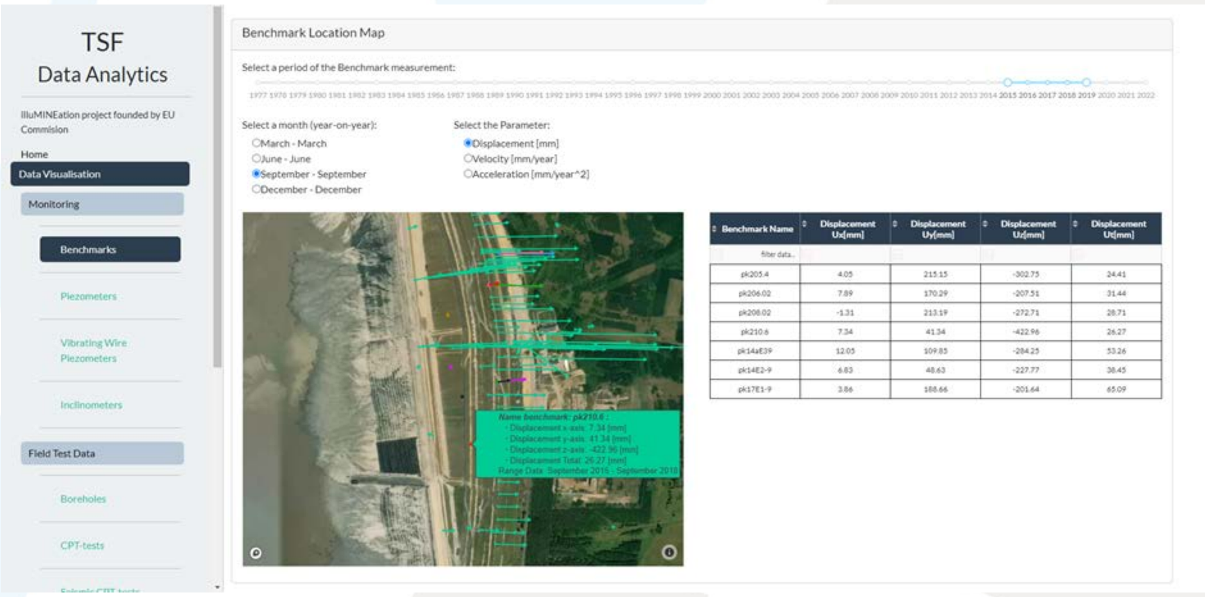

Figure 28 The visualization dashboard of geodetic benchmarks – map indicating their location.

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Figure 29 The visualization dashboard of geodetic benchmarks – benchmark data plots.

Following the visualization stage, the data undergoes analysis using analytical and statistical algorithms, leveraging both machine learning techniques and statistical methods. These algorithms extract valuable insights from the data, enabling trend analysis, anomaly detection, and predictive modelling. The analysed data is then presented through visualizations that provide meaningful representations of the findings. These visualizations may include trend lines, statistical distributions, heatmaps, or any other form suitable for conveying the results of the analysis.

One critical aspect of the TSF Data Analytics system is the utilization of multivariate factor of safety calculations. This calculation involves assessing the stability of the tailings dam under different scenarios by considering multiple factors simultaneously. By incorporating various parameters, such as pore pressure, geotechnical properties, and dam geometry, the system performs comprehensive factor of safety calculations. These calculations provide an understanding of the stability conditions across different areas of the tailings dam and identify zones that may require attention or mitigation measures.

The factor of safety values obtained through the multivariate calculations are then visualized to provide a clear representation of the stability conditions within the TSF. The visualizations may include color-coded maps, contour plots, or graphical representations that highlight areas of concern or potential risks. By integrating the factor of safety calculations with visualization techniques, the TSF Data Analytics system enables engineers and stakeholders to gain a holistic understanding of the stability of the tailings dam and make informed decisions regarding safety measures and risk mitigation strategies.

The system architecture depicted in the diagram below provides a visual representation of how data flows within the TSF Data Analytics system. This architectural framework illustrates the various components and their interconnections, showcasing the seamless flow of data throughout the system's processes. By examining this diagram, stakeholders can gain a comprehensive understanding of how data is collected, processed, and utilized to derive valuable insights for the monitoring and analysis of the tailings storage facility.

Furthermore, the diagram showcases the interconnectedness of the system's modules and highlights the data's journey at each stage. From the initial data acquisition phase, where information from instrumentation devices and external sources is collected, to the visualization

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and analysis stages, where data is transformed into meaningful representations and subjected to analytical algorithms, the flow of data is smooth and continuous.

The architecture diagram serves as a visual aid in comprehending the intricate mechanisms behind the TSF Data Analytics system, illustrating the systematic approach taken to handle data streams effectively. By visually mapping out the data flow, stakeholders can identify potential bottlenecks or areas where optimizations can be implemented to enhance the efficiency and accuracy of data processing.

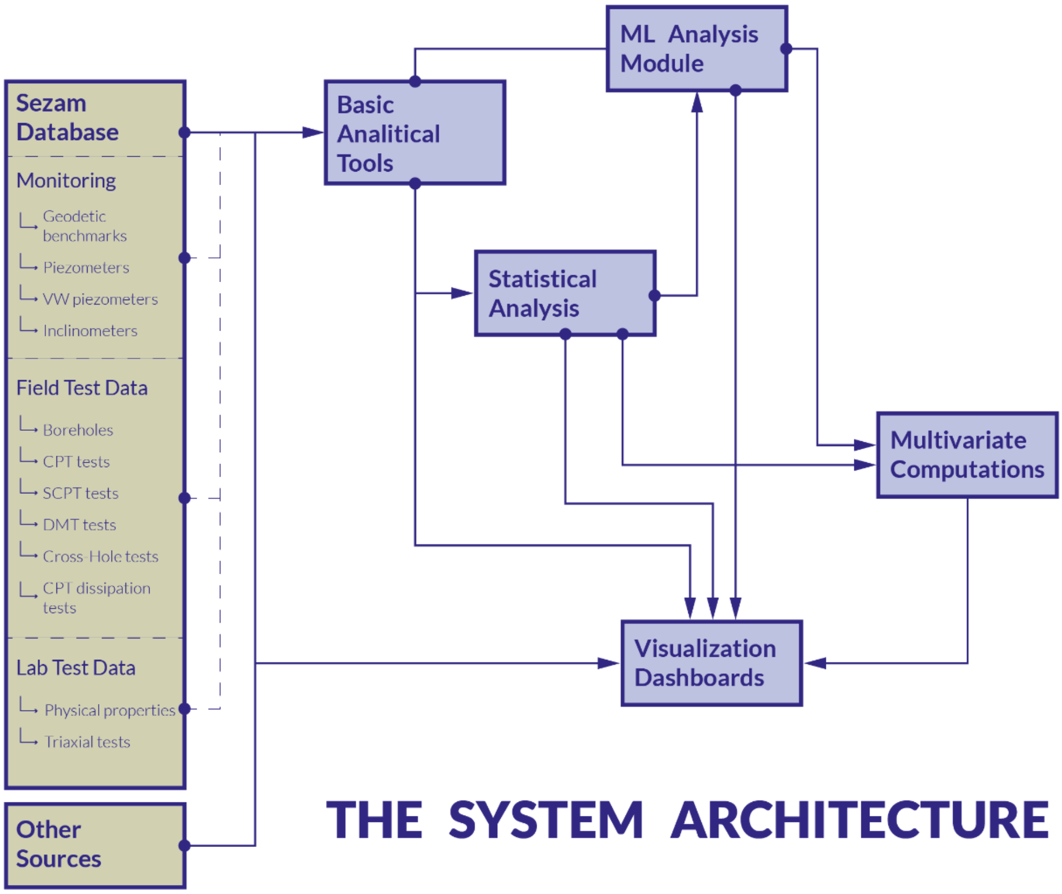

Figure 30 TSF Data Analytics System Architecture.

The continuous accumulation, processing, and analysis of monitoring data in the TSF Data Analytics system allow for ongoing monitoring and assessment of the tailings storage facility's stability. By leveraging modern data analysis techniques, the system empowers mining companies to proactively manage risks, identify potential issues, and implement appropriate measures to ensure the safe operation of the TSF.

2.4.3 Applied analysing and interpretation methodologies for safety status information

In order to ensure the safe operation of a tailings storage facility (TSF), it is crucial to employ robust analysing and interpretation methodologies for assessing the safety status of various parameters. The concept of safe zones plays a significant role in identifying areas within the TSF that require particular attention and monitoring. This section describes methodologies

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applied to assess the safe zones for key parameters, including displacements, inclinometers, pore water pressure, factor of safety, and the number of field and laboratory tests.

The primary objective of analysing and interpreting safety status information is to detect potential risks or deviations from expected behaviour in real-time. By utilizing advanced algorithms and statistical techniques, these methodologies provide valuable insights into the stability and performance of the tailings dam, allowing for timely decision-making and proactive risk mitigation strategies.

The concept of safe zones is particularly pertinent in identifying areas within the TSF that exhibit higher risks or require more thorough monitoring. By focusing on key parameters, such as displacements, inclinometers, pore water pressure, factor of safety, and the density of field and laboratory tests, the safe zones approach aims to highlight zones that may be more prone to instability or where further investigation is warranted.

Following sections present specific methodologies employed to assess the safe zones for each parameter. These methodologies encompass a combination of data analysis, statistical modelling, and visualization techniques. Through these methodologies, stakeholders gain a comprehensive understanding of the safety status of the TSF and can prioritize resources and interventions accordingly.

Safe Zone Assessment for Displacement Monitoring

In order to effectively assess and identify areas of concern within the tailings storage facility (TSF) regarding displacement monitoring, we have implemented a robust statistical analysis approach. One of the key techniques employed is the creation of hexagonal plots on a map, which enables us to determine the areas with the greatest displacements. This visualization method offers a clear and intuitive representation of the spatial distribution of displacements, allowing users to easily identify regions where displacement values are particularly significant.

By utilizing hexagonal plots, we enhance the interpretation and analysis of displacement data. Each hexagon on the map represents a specific area within the TSF, and within each hexagon, various statistical measures such as mean, maximum, and minimum displacement values can be calculated. These statistical measures provide valuable insights into the magnitude and variability of displacements within each hexagon.

By presenting the statistical values for each hexagon, users can quickly assess the overall trend and severity of displacements across the TSF. The mean displacement value offers an average indication of the displacements within a particular area, while the maximum and minimum values provide insights into the range of displacements observed. These statistical measures allow users to compare and contrast different regions within the TSF, identifying areas of higher displacement that may require further investigation or targeted monitoring efforts.

Moreover, the hexagonal plot approach facilitates a visual understanding of displacement patterns. By observing the distribution of hexagons and the corresponding displacement values on the map, users can identify clusters or hotspots where displacements are particularly pronounced. This visual representation assists in the identification of localized areas that may pose a higher risk of potential stability issues.

The provided image showcases the statistical analysis of velocity displacement on the hexagon map, enabling the identification of the zone with the highest velocity. By examining this visualization, stakeholders can readily pinpoint the area exhibiting the most significant displacement velocities. This approach streamlines the process of identifying regions that warrant closer attention and monitoring due to their pronounced velocity displacements.

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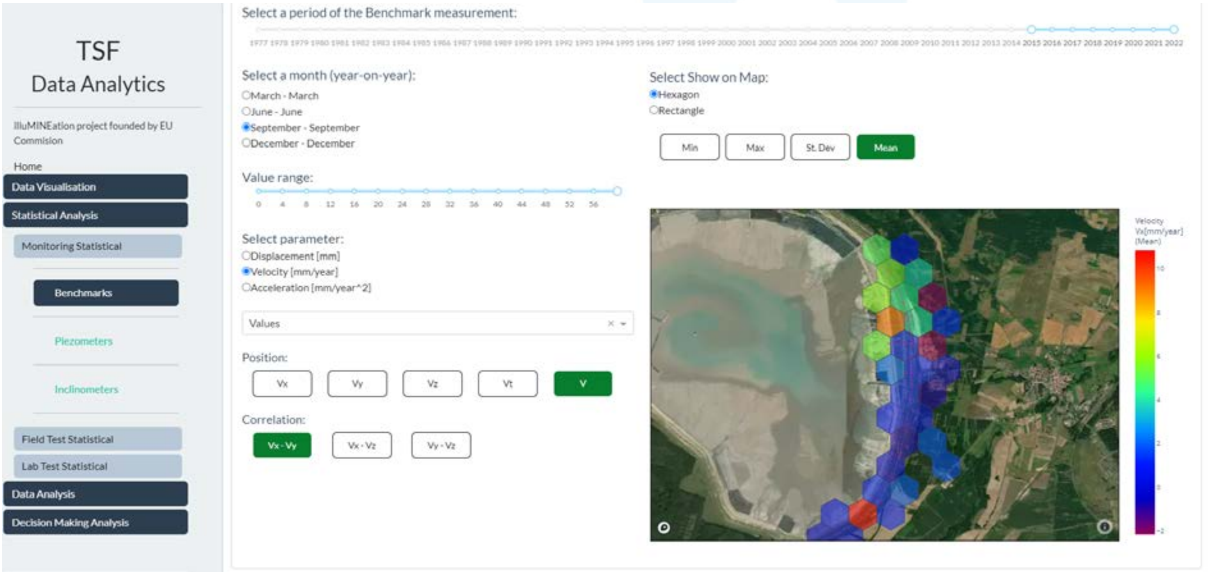

Figure 31 TSF Data Analytics – Displacement statistics.

By applying the safe zone concept to displacement monitoring, we can prioritize resources and interventions based on the severity and spatial distribution of displacements within the TSF. The statistical analysis and visualization techniques employed enable stakeholders to make informed decisions, implementing appropriate monitoring strategies and targeted remedial measures in the areas of greatest concern.

Additionally, upon clicking on a specific hexagon on the map, a more detailed view of the statistics is provided, enhancing the understanding of displacement velocities within that particular area. By interacting with the hexagon visualization, stakeholders can access additional information such as histograms and scatter plots, further enriching the analysis.

The histogram represents the frequency distribution of displacement velocities within the selected hexagon. It provides a visual representation of the velocity range and the corresponding occurrence frequency. By examining the histogram, users can observe the distribution pattern, identify any skewness or outliers, and gain insights into the predominant velocity ranges within the selected hexagon.

Furthermore, a histogram with two random variables can be generated to explore the relationships between displacement velocities and other relevant parameters. This scatter plot offers a comprehensive view of how displacement velocities may correlate with factors such as time, depth, or environmental conditions. By analysing the dispersion and trend of the plotted data points, stakeholders can identify potential patterns, dependencies, or anomalies, contributing to a deeper understanding of the displacement behaviour within the selected hexagon.

These additional visualizations provide valuable context and enable stakeholders to assess the characteristics and potential influencing factors of displacement velocities in a more comprehensive manner. By interacting with the hexagon map and exploring the associated statistics, users can make informed decisions regarding targeted monitoring, risk mitigation strategies, or further investigation in specific areas where displacement velocities exhibit notable patterns or deviations.

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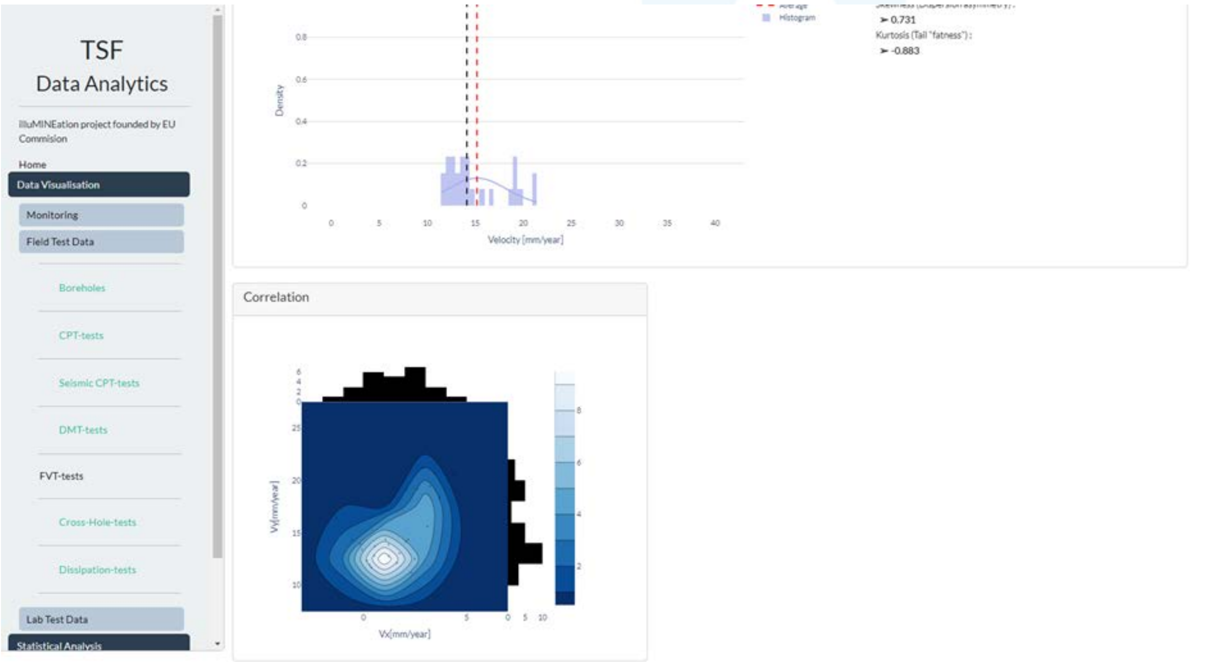

Figure 32 TSF Data Analytics – Displacement histograms.

The interactive nature of the hexagon map visualization and the accompanying statistical representations empower stakeholders to dive deeper into the data, facilitating a thorough analysis of displacement velocities within the tailings storage facility. This comprehensive understanding of displacement behaviour supports proactive decision-making, ensuring the implementation of appropriate measures to mitigate risks and maintain the stability of the TSF.

Safe Zone Assessment for the Shear zones

Detecting shear zones within the tailings storage facility (TSF) is crucial for the accurate factor of safety calculations. The presence of shear zones significantly impacts the stability of the TSF, as these zones typically correspond to weaker geotechnical layers. In order to account for the influence of shear zones, it is essential to identify their locations using inclinometer readings and incorporate them into the calculation models.

To facilitate the visualization and interpretation of shear zones, our system employs a map-based approach. Shear zones are represented on the map as circular indicators, with the diameter of the circle corresponding to the magnitude of the shear zone. Larger diameters indicate larger shear zones, highlighting areas within the TSF that are particularly prone to instability. This visualization technique allows stakeholders to easily identify the spatial distribution and extent of shear zones, enabling focused attention on these critical zones. The provided image showcases the identification of shear zones on the map.

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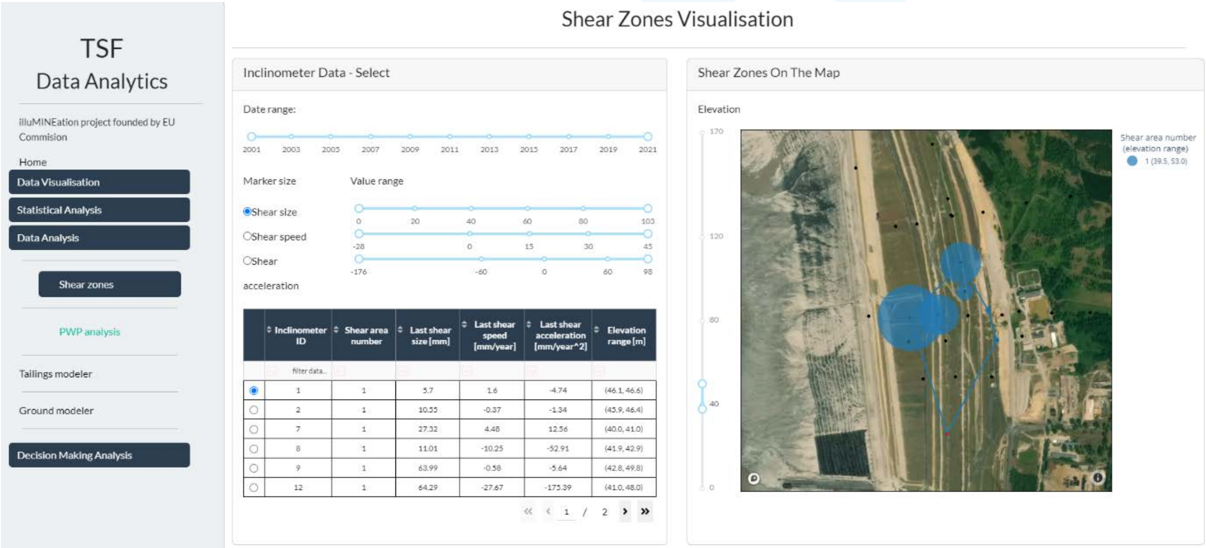

Figure 33 TSF Data Analytics – Shear zone detector.

In addition to the map-based visualization, the shear zones are also presented on depth plots. These plots provide a comprehensive view of the subsurface layers at various depths within the TSF. Shear zones are indicated on the depth plots using circular markers at the specific depths where they occur. This visualization technique assists stakeholders in understanding the vertical distribution of shear zones, providing insights into the depth ranges where these zones are most prevalent.

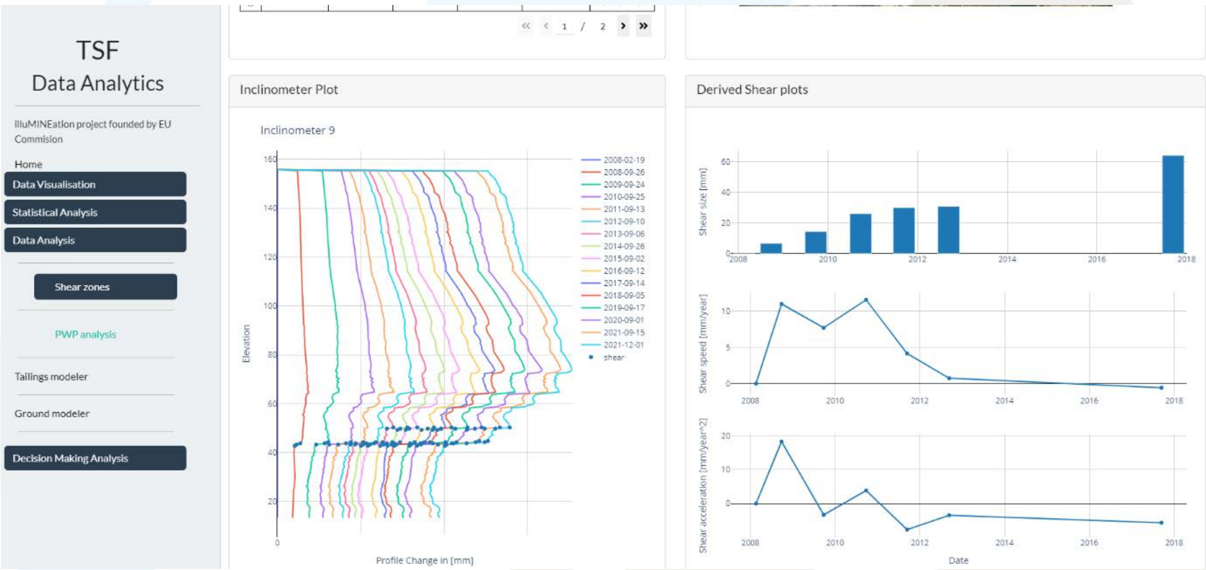

Figure 34 TSF Data Analytics – Shear zone detector.

By incorporating the safe zone concept into the detection and visualization of shear zones, stakeholders can prioritize resources and interventions based on the severity and spatial distribution of these critical areas. The identification and monitoring of shear zones enable accurate factor of safety calculations by incorporating the weaker geotechnical layers affected by these zones.

Through the visual representations and data analysis techniques employed, our system enhances the understanding of shear zones within the TSF. Stakeholders can make informed decisions, implementing appropriate mitigation strategies and targeted monitoring efforts in

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the identified shear zones. This proactive approach ensures the overall stability and safety of the TSF.

Safe Zone for Pore Water Pressure

The pore water pressure monitoring is of utmost importance in assessing the stability and factor of safety within the tailings storage facility (TSF). The pore water pressure, which refers to the pressure exerted by water within the void spaces of the soil matrix, significantly influences the shear strength and stability of geotechnical layers.

Monitoring pore water pressure requires meticulous attention to detail, as any anomalies or abnormal variations can indicate potential risks to the stability of the TSF. Our system emphasizes the careful and continuous monitoring of pore water pressure to ensure the timely detection of any deviations from expected patterns.

To accurately represent the distribution of pore water pressure across the TSF, we employ a kriging algorithm, which generates a continuous function that estimates the pressure values at unsampled locations. This function allows for the visualization of the pore water pressure distribution through a two-dimensional plot, as presented in the image below.

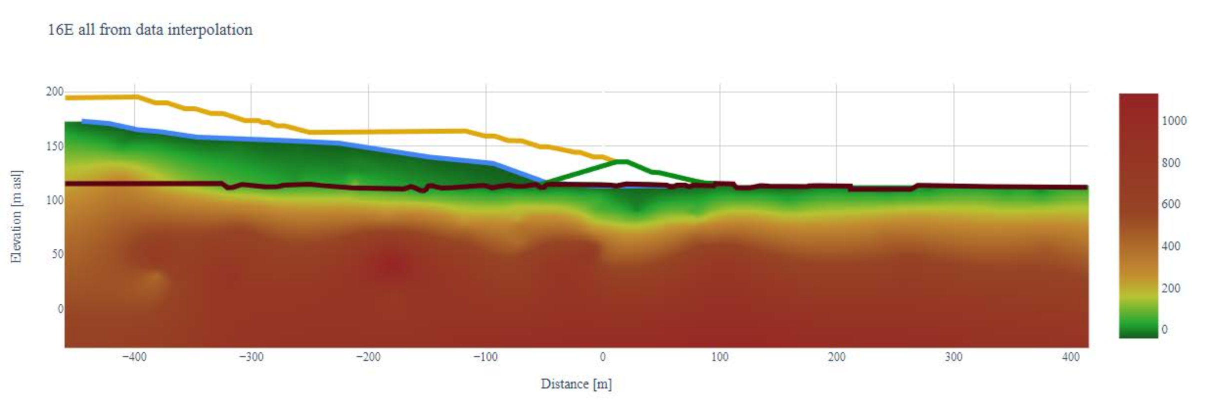

Figure 35 Krigging interpolation of the pore water pressure spatial distribution.

The visualization provides stakeholders with a clear understanding of the spatial variability of pore water pressure within the TSF. By examining the 2D plot, stakeholders can identify areas characterized by higher or lower pore water pressures, enabling targeted investigations and appropriate mitigation measures.

Incorporating the pore water pressure distribution obtained from the kriging algorithm into the factor of safety calculations enhances the accuracy of the analysis. The function derived from the continuous monitoring of pore water pressure ensures that the calculation models reflect the actual conditions and account for the potential influence of water pressures on stability.

By monitoring pore water pressure and integrating it into the analysis, stakeholders can identify critical zones within the TSF that require particular attention and management. Timely detection of pore water pressure anomalies facilitates proactive measures, such as implementing drainage systems or installing pumping wells, to mitigate the risks associated with increased water pressures in low-permeability layers or the malfunctioning of the drainage system.

The careful monitoring and analysis of pore water pressure data support informed decision-making and help ensure the overall stability and safety of the TSF. By incorporating the distribution of pore water pressure into the factor of safety calculations, stakeholders can better evaluate the potential risks and take appropriate actions to maintain the stability of the TSF.

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Identification of Insufficient Number of Tests

The identification of zones within the tailings storage facility (TSF) with insufficient test data is of paramount importance in ensuring accurate and reliable assessments of stability. Insufficient tests can introduce uncertainties and potential risks that need to be addressed to enhance the overall analysis and understanding of the TSF's behaviour.

To effectively identify these zones, our system employs a hexagon plot visualization technique on the map. Each hexagon on the plot represents the number of tests conducted in a particular area of the TSF. The colour gradient within each hexagon reflects the test number, with warmer colours indicating a higher number of tests and cooler colours indicating a lower number of tests.

By examining the hexagon plot, stakeholders can easily identify areas where the test density is insufficient. These zones, characterized by cooler colours, signify regions within the TSF that require further attention in terms of additional testing and data collection. The visualization serves as a visual aid for identifying areas where more comprehensive testing is necessary to improve the understanding of subsurface conditions and enhance the accuracy of stability assessments.

In the image below, the hexagon plot depicting the number of boreholes is presented as an example. The varying colours of the hexagons provide a clear representation of the test number across the TSF. Areas with a higher number of boreholes appear as warmer-coloured hexagons, indicating better test coverage, while cooler-coloured hexagons suggest zones where test density is lacking.

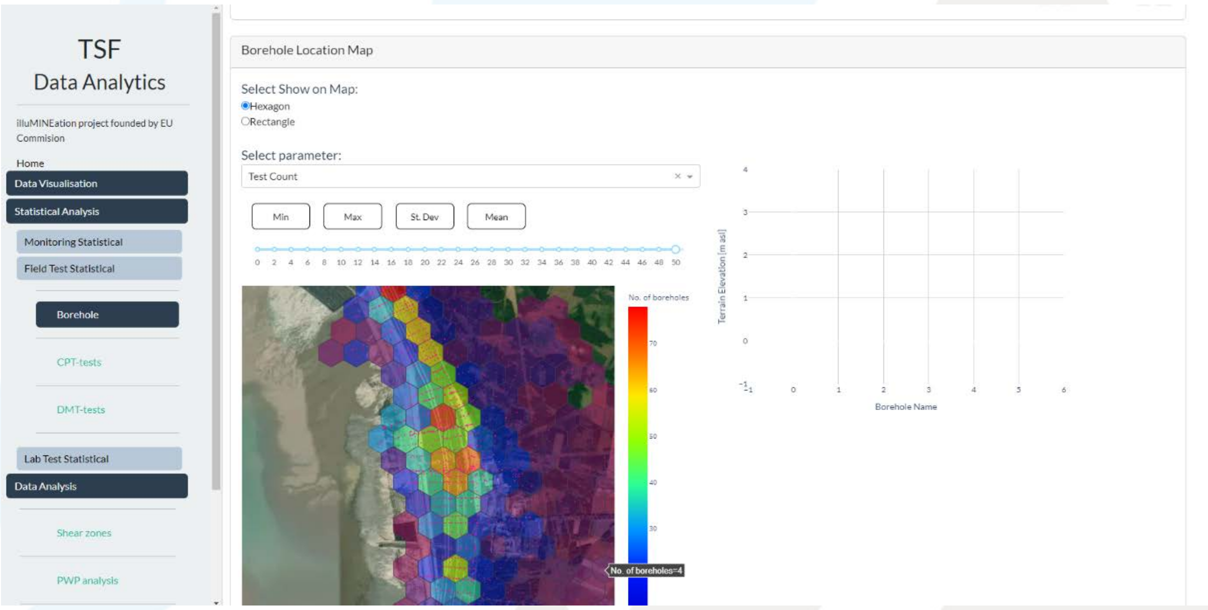

Figure 36 Number of boreholes on the map.

Identifying zones with insufficient test density enables stakeholders to prioritize future testing efforts, ensuring a more comprehensive understanding of the TSF's geotechnical characteristics. By focusing on these areas, additional boreholes and other testing methods can be strategically deployed to collect critical data and reduce uncertainties in the analysis.

Through the utilization of the hexagon plot visualization technique, our system empowers stakeholders to identify and address zones within the TSF where the test density is insufficient. This proactive approach aids in enhancing the accuracy of stability assessments, mitigating potential risks, and promoting overall safety within the mining operation.

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Safe Zones for Factor of Safety

The factor of safety calculation plays a pivotal role in determining the stability of tailings dams within the mining industry. This analysis is of paramount importance as it provides critical insights into whether the structure is capable of withstanding the imposed loads and potential failure mechanisms. By assessing the factor of safety, engineers and stakeholders can make informed decisions regarding the design, maintenance, and monitoring of tailings dams.

To gain a comprehensive understanding of the stability calculation, our system employs a sensitivity analysis approach. This analysis allows us to identify the factors that have the most significant influence on the stability calculation. By determining the sensitivity of various factors, such as pore water pressure, geotechnical layer properties, and geometry, we can prioritize our attention and resources towards those aspects that have the greatest impact on the factor of safety.

The results of the sensitivity analysis are visualized using a polar plot, as depicted below. This plot provides an intuitive representation of the relative influence of different factors on the stability calculation. By examining the polar plot, stakeholders can identify the key factors that significantly affect the factor of safety. This understanding helps in focusing efforts on monitoring and managing these influential factors to ensure the stability of the tailings dam.

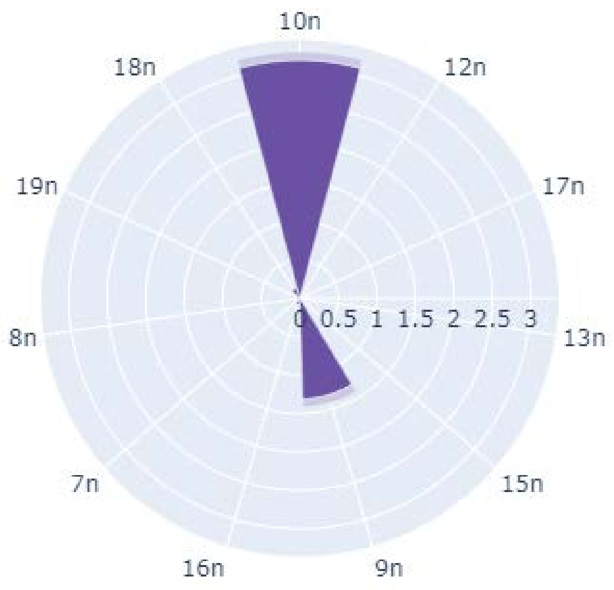

Figure 37 Sensitivity analysis results.

Building upon the sensitivity analysis, our system conducts factor of safety calculations using various scenarios. These scenarios encompass a range of possible conditions and loading scenarios that the tailings dam may encounter. By evaluating the factor of safety under different scenarios, stakeholders can identify the worst-case situations and understand the critical conditions that should be addressed for the overall stability of the structure.

To facilitate easy interpretation and comparison of the results, the factor of safety calculations for different scenarios are plotted on a parallel plot, as shown below. The parallel plot visually presents the factor of safety values for each scenario, enabling stakeholders to quickly identify which scenarios yield the lowest factor of safety. By observing the parallel plot, engineers can pinpoint the most critical scenarios and focus their attention on the necessary risk mitigation strategies.

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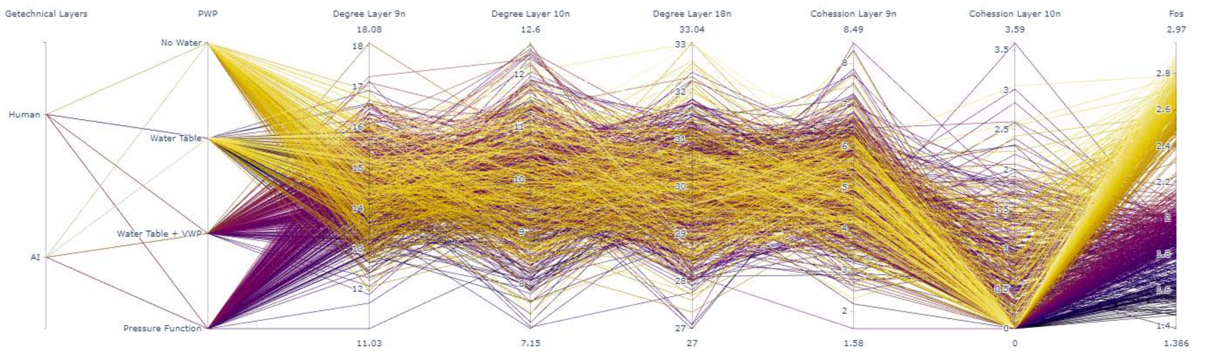

Figure 38 Parallel plot which visualize the multivariant calculations.

The factor of safety calculations is performed for every cross-section of the tailings dam, allowing for a comprehensive assessment of stability throughout the structure. By examining the factor of safety values for each cross-section, stakeholders can identify specific areas that require immediate attention and potential remedial actions. The visualization of the factor of safety calculations in a single cross-section, as depicted in the image below, provides valuable insights into the variations in stability across the tailings dam.

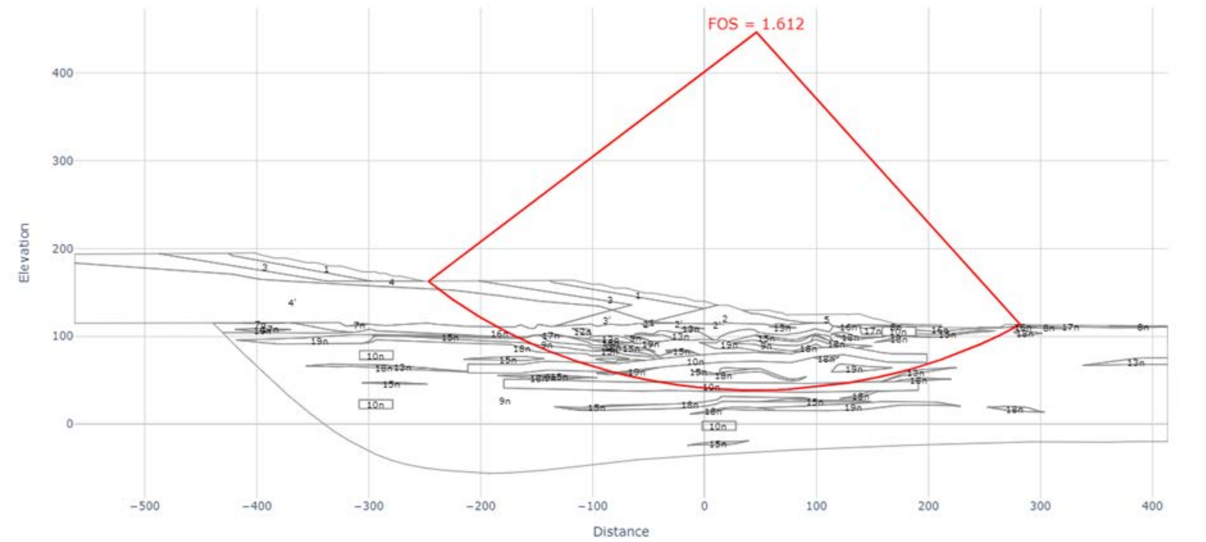

Figure 39 Critical slip surface visualization.

Through the utilization of sensitivity analysis, scenario-based calculations, and cross-sectional assessments, our system empowers stakeholders to identify safe zones within the tailings dam. These safe zones correspond to cross-sections and conditions where the factor of safety meets or exceeds the required threshold, ensuring the stability and integrity of the structure.

2.4.4 Integration example: Use case scenario

The Zelazny Most tailings storage facility (TSF) is located in Lubin, Poland South- West part of the country), and serves as a significant component of KGHM's mining operations. Situated in close proximity to the company's mining sites, the facility plays a crucial role in the storage and management of mining waste generated during the extraction and processing of valuable minerals.

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Covering a vast area of approximately 15.3 m^3, the Zelazny Most TSF provides KGHM with the necessary capacity to store more than 700 million of cubic meters of tailings. Its strategic location ensures convenient access for the efficient transport of mining waste from the production areas to the storage facility. This proximity minimizes transportation costs and streamlines the waste management process.

The Zelazny Most tailings storage facility (TSF) was constructed using the upstream method, which is a widely employed technique for building tailings dams. The upstream construction method involves the gradual raising of the dam by placing new layers of tailings material on top of previously deposited material.

As construction progressed, the upstream method involved depositing tailings material directly onto the previously placed layers. The tailings, a mixture of finely ground rock particles and water, were transported from the mining and processing operations to the TSF using pipelines. The tailings were released onto the upstream face of the dam, allowing the dam to gradually grow in height and size.

Figure 40 The Zelazny Most TSF.

To enhance the stability of the dam, engineering measures were implemented. These included the construction of internal drainage systems, such as toe drains and filter zones, to control water flow and prevent excessive pore pressure build-up. Additionally, erosion control measures, such as the installation of erosion protection layers or vegetation, were employed to safeguard the dam's integrity.

The Zelazny Most tailings storage facility (TSF) employs various monitoring instruments to ensure the ongoing safety and stability of the structure. In addition, the staff conducts regular visual inspections, checks for any abnormalities, and performs manual monitoring to ensure everything is functioning properly. These instruments provide critical data on different parameters and help detect potential risks. The following instruments are used:

1. Open Standpipe Piezometers: Open standpipe piezometers are installed at strategic locations within the TSF to measure the water pressure in the dam and surrounding areas. These piezometers consist of a perforated pipe with a monitoring point open to the surrounding groundwater.

2. Vibrating Wire Piezometers: Vibrating wire piezometers are another type of instrument used for measuring water pressure within the TSF. These piezometers employ a vibrating wire

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element that is sensitive to changes in pressure. As water pressure fluctuates, it causes variations in the vibrating wire's frequency, which can be measured and translated into pressure readings. Vibrating wire piezometers are known for their accuracy and reliability in monitoring pore water pressure in the dam.

3. Inclinometers: Inclinometers are installed at specific locations along the slopes and within the TSF to monitor any horizontal. These instruments consist of a casing with a series of sensors that measure angular displacement. By regularly measuring the inclinometer readings, any changes in slope stability or deformations can be detected, allowing for appropriate actions to be taken to mitigate potential risks.

4. Geodetic Benchmarks: which include manual measurement points, automatic GPS measurement points, and tachymeter. Geodetic benchmarks are permanent markers placed at precise locations around the TSF. These benchmarks serve as reference points for geodetic surveys and monitoring. Surveying techniques, such as GPS or total station measurements, are used to periodically determine the vertical and horizontal movements of these benchmarks. Geodetic surveys provide valuable information on ground settlement and deformation, aiding in the assessment of overall dam stability. The objective of geodetic measurements is the periodic control and assessment of displacements of earth embankment dams and areas adjacent to the dams, with regard to maintaining safe operating conditions of the reservoir. The measurements also cover installations and associated structures. AGH has been conducting geodetic measurements since 1981. Currently, geodetic measurements are carried out four times a year. These measurements are performed using automatic monitoring points. The purpose of automatic geodetic monitoring is to perform real-time measurements of earth embankment dams and to detect and notify about any exceedances to initiate necessary control or emergency procedures. These points also serve as a reference system for measurements of control points.

The data collected from these monitoring instruments is regularly monitored and analysed by qualified personnel. Real-time measurements and continuous data analysis help identify any deviations or abnormal trends, allowing for timely interventions and appropriate corrective measures to maintain the safety and integrity of the Zelazny Most TSF.

The testing phase of the TSF Analytics system plays a crucial role in assessing the safety of the Tailings Storage Facility (TSF). A comprehensive testing scheme was implemented to ensure the reliability and functionality of the system. The testing process followed a well-defined procedure, which involved both internal and external verification.

The testing phase commenced with the deployment of a new version of the system. The internal verification phase was conducted by GEOTEKO and Cuprum, independent parties responsible for verifying different aspects of the system. This approach ensured that the verification process was performed by individuals who were not directly involved in programming the system. Any identified bugs or issues were promptly addressed and corrected by the development team.

Once the necessary corrections were made, the system underwent external testing by the KGHM team. Their role was to provide valuable feedback on various aspects of the system, including its functionalities, user-friendliness, bugs, and visualization styles. The feedback received from the external testers was compiled and documented in an Excel file, which was then shared with the developer team.

KGHM team, with its extensive knowledge and experience in maintaining and managing Tailings Storage Facilities (TSFs), has conducted thorough testing of the TSF system. They possess exceptional expertise in this field, making them well-equipped to assess and ensure the system's functionality and reliability. Furthermore, KGHM has a proven track record in building and testing databases, and their meticulous approach ensures the accuracy and efficiency of the "SEZAM" database. As the client for the entire system, KGHM plays a crucial

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role in driving the project's success by providing valuable insights and requirements for the TSF safety system.

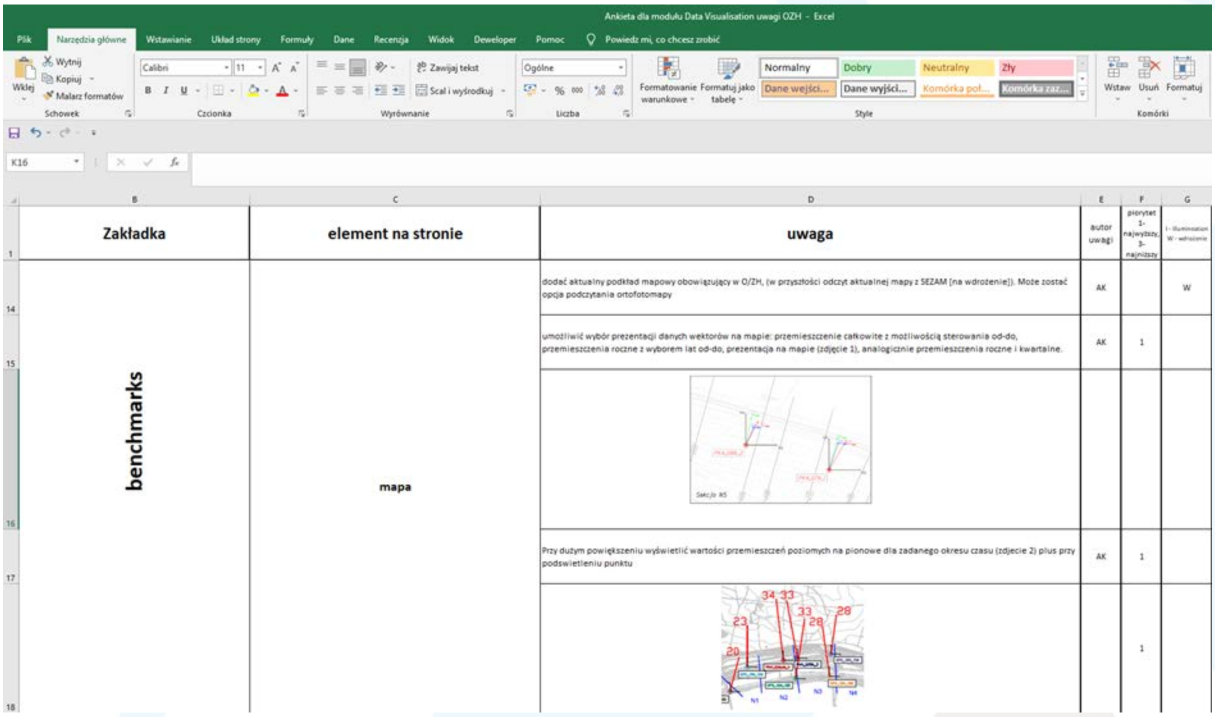

Figure 41 The Excel file with comments from KGHM team.

The feedback and comments from the external testers were thoroughly reviewed and discussed. The development team prioritized the identified issues and implemented the necessary corrections and improvements. This iterative process ensured that the system evolved and improved based on the valuable input received from the external testers. Subsequently, a new version of the system, incorporating the implemented changes, was released.

The testing and verification phase of the system followed a cyclical process, as depicted in the accompanying diagram. This iterative approach allowed for continuous improvement and refinement of the system's performance and reliability. Each cycle of testing and verification aimed to address any potential issues, enhance the system's functionality, and ensure its overall effectiveness in assessing the safety of the TSF.

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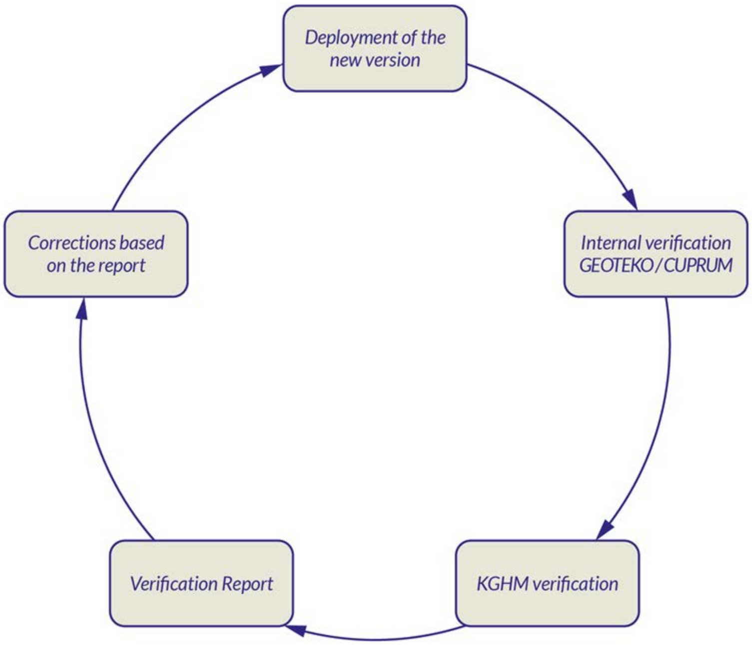

Figure 42 The testing phase scheme.

The engineering system testing phase is of utmost importance as it enables the identification of any potential weaknesses, vulnerabilities, or shortcomings in the system. It ensures that the system meets the required standards, performs its intended functions accurately, and provides reliable results. Thorough testing and verification processes help in minimizing risks, enhancing the system's robustness, and instilling confidence in its performance.

During testing and verification, great care must be taken to ensure the accuracy, completeness, and reliability of the results. Rigorous testing methodologies, including various test cases and scenarios, should be employed to assess the system comprehensively. Verification by external parties brings valuable insights and perspectives, contributing to the overall improvement of the system's performance and user experience.

In summary, the testing phase of the system plays a crucial role in assessing the safety of the TSF. The testing scheme, including internal and external verification, ensures that the system functions reliably and meets the necessary standards. Through iterative cycles of testing and continuous improvement, the system evolves to deliver accurate and dependable results. The engineering system testing phase is vital in guaranteeing the robustness and effectiveness of the system, minimizing risks, and ultimately enhancing the safety of the TSF.

Additionally, the testing phases were divided into two parts to ensure a comprehensive evaluation of the system. The first testing phase, described in the Deliverable 2.2: Outcome of the Initial Testing has already been completed. This initial testing phase aimed to assess the system's performance, functionality, and reliability based on predefined criteria and test scenarios.

The results of the initial testing phase provided valuable insights into the system's strengths and weaknesses. Identified issues, bugs, and areas for improvement were addressed and corrected to enhance the system's overall performance and user experience. The findings and outcomes of the initial testing phase served as a foundation for further refinement and optimization of the system.

The second part of the testing phase, referred to as the final tests, is scheduled to commence shortly. The final tests will be documented in Deliverable 2.3: Outcome of the Final Testing. These tests will focus on evaluating the system's performance, stability, and functionality in real-world scenarios and under varying conditions.

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During the final testing phase, a wide range of test cases and scenarios will be executed to thoroughly assess the system's capabilities. The aim is to validate the system's ability to accurately assess the safety of the TSF, considering different inputs, configurations, and operational scenarios. The results of the final testing will provide a comprehensive understanding of the system's performance and its readiness for practical deployment.

The division of the testing phases into the initial and final tests ensures a systematic approach to testing and allows for iterative improvements based on the feedback and insights gained. The outcomes of the final testing will serve as a comprehensive evaluation of the system's capabilities, reliability, and suitability for assessing the safety of the TSF.

By following this structured testing approach and documenting the outcomes in deliverable reports, the testing process remains transparent and traceable. It provides stakeholders with clear visibility into the progress and results of the testing phase, enabling informed decision-making and further refinement of the system if needed.

Overall, the division of the testing phases into the initial and final tests, as documented in deliverables 2.2 and 2.3, ensures a thorough evaluation of the system's performance and functionality. The testing process demonstrates the commitment to delivering a robust and reliable solution for assessing the safety of the TSF, with the final test outcomes providing the necessary validation and confidence in the system's capabilities.

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3 Conclusions

3.1 [Safe zone 1] Conclusion & Future outlook

The actual application of the Safe Zone concept is also subject to a permanent learning process. The implementation will show to what extent the concept can be integrated into daily operations and which optimizations are necessary for this. Furthermore, the basic concept within the illuMINEation project allows the linking of different data streams, which may in the future reveal system interrelationships that are currently unknown and based on which new improved models can be developed. The observational design of the safe zone concepts will contribute to the continuous development and adaptation of implemented algorithms. The safe zone concept will evolve in the general direction of automation of simple chores and data processing. So far, this automation trend will not cover decision-making procedures because it is primarily a sociological acceptance and reasonability issue. The key technology for future automatization of the safe zone concept lies in artificial intelligence and machine learning. In the future, artificial systems will take over the learning and interpretation processes, offering vital information to individuals at various levels as they make decisions. In the case of the safe zone concept, the transition from human to artificial intelligence will be gradual rather than abrupt. Both ways might be used, and moving responsibility to automation over time could be a viable option only if an effective application can be achieved. Integration of artificial systems is essential at an early stage for model training and gathering experience about a correct application and implementation can look like. The future will demonstrate the application of such technologies, but many unresolved problems about the environmental conditions underground must be resolved first.

In general, the purpose of the monitoring system within the safe zone concept is to provide data for analysing methods and information preparation supporting the engineer in assessing atmospheric and geotechnical related risks. In dependence on the different atmospheric and geotechnical health and safety considerations, different requirements will be set on the monitoring system. The use of scientific and technical analysing procedures for obtaining required information will address the required data and hence regulate the system design.

The safe zone concept idea is supported by a mine-wide long-term monitoring system. Collected data from newly developed intelligent rock bolts are connected with existing monitoring system, broadening the scope of available information. Although the system brings many new options, its limitations must also be recognized for a successful mine-wide installation. On the one hand, the concept of using affordable measurement bolts is the premise for a mine-wide application, but on the other hand, compromises the sensor accuracy and coupling to the rock bolt. This means, more specifically, atmospheric measurements should only be taken on the excavation surface, and not over the whole cross-section. Moreover, printed strain gauges are limited to bolt length and deformation characteristics. Furthermore, only sensors that are able to be connected to the rock bolt and readout unit can be employed.

Although the system is still quite customizable, the underlying notion of using intelligent rock bolts is established, as is the framework of available data given for analysis. This notion differs from the idea of developing a monitoring system for specific needs in that it takes a broader approach to present data delivery. As a result, the above-mentioned hierarchy must be followed in a different direction, resulting in: Which information may be extracted based on the monitoring system's framework, and does this information match pronounced requirements in terms of risk assessment support?

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Intelligent rock bolts are rock bolts which can be installed with standard procedures and are equipped with different types of sensors. Every single rock bolt is equipped with single or multiple strain gauges on the tendon. In the framework of the illuMINEation project, two different rock bolt heads are developed. Those rock bolt heads, serve on the one hand as a read-out unit of the strain gauges and on the other hand as a sensor carrier for all installable sensors. The reason for developing two different sensor heads is the required power supply. One sensor head will be equipped with low power consumption units as it is deformation read out, temperature and air pressure sensor. Those heads are standardized and sensor content is fixed. In addition, a second sensor head is designed for flexible decision of different sensor with high power consumption. This sensor head will mainly carry electrochemical gas sensor tailored to the need of the mines.

3.2 [Safe zone 2] Conclusion & Future outlook

During this task, an infrared stereo camera system with in-built detection capabilities was evaluated for the tasks of human and selected equipment tracking in mining environments. Compared to other sensor technologies commonly deployed for detecting personnel in the vicinity of heavy mobile machinery, the investigated system features a number of interesting properties. While many camera-based sensors suffer from rapidly degrading performance in low-light scenarios, the system was shown to be highly robust towards different light conditions, ranging from strong sun exposure in open-pit mines to underground operation under extremely low illumination levels. The method does not require the mining personnel to wear any sort of powered devices, such as radio-frequency transponders. The only prerequisite for human detection and tracking in the surrounding of a vehicle is that mining personnel are equipped with high-visibility clothing with reflective markers. As this is a pre-existing requirement at any responsible mining site, there are no modifications necessary on the personnel side to implement and successfully deploy the system. The system was further demonstrated to cope well with various environmental challenges, including exposure to high amounts of dust and water mist in the line of sight between the camera and detection target. The initial detection range of 10 meters was successfully increased to 20 meters during the project by adopting modifications on a sensory level (image sensors, lenses) as well as accelerations of the detection algorithms.

The underlying working principle of the evaluated sensor system results in a few application limitations. As common for all camera-based system, detection is only possible when a line of sight between the camera and the detection target exists. The system is not suitable for the detection of personnel or equipment through tunnel walls, behind obstacles, or around corners, and needs to be combined with other sensing technologies if detection is required even in these situations. Detection data is also acquired in a local context only, that is, in the reference system of the host vehicle. To map these local detections into a global mine map context, the vehicle itself needs to be localized inside the mining environment by some other means (UWB, WIFI, etc.). Finally, the working principle of the sensor system allows for detecting personnel wearing high-visibility clothing and equipment fitted with infrared LED patterns but does not extend to detection targets that do not fulfil these criteria. Combinations with other sensor technologies are therefore a likely scenario for deploying safe mining applications with shared workspaces for mobile equipment and personnel.

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3.3 [Safe zone 3] Conclusion & Future outlook

The general concept of environmental monitoring presented here, based on relatively low-cost sensors and publicly available programming/development platforms, should be very helpful in monitoring the state of the environment.

The use of open source software for data collection and analysis also allows for cost reduction, which means that such a system can be used by companies who often limit their monitoring to the minimum necessary, as well as by government organizations and various associations deeply interested in the state of the environment. The research team of the illuMINEation project will continue to work on the development of this solution as it seems to be future-proof and worth attention. At the moment, there is still the phase of the prototype verification and it is necessary to refine such elements as the housing or power supply and data transfer to the surface from deep holes, but these do not seem to be problems impossible to solve.

3.4 [Safe zone 4] Conclusion & Future outlook

The identification and assessment of safe zones play a crucial role in ensuring the stability of tailings storage facilities. Throughout this chapter, we have explored various aspects related to safe zones, including the Factor of Safety, displacements, inclinometer readings, pore water pressure, and the number of tests conducted.

The factor of Safety stands out as the most important parameter in assessing the overall stability of tailings dams. By calculating the Factor of Safety, we can determine whether the structure can withstand the imposed loads and potential failure mechanisms. It serves as a primary indicator of the safety margin and guides decision-making processes for design, maintenance, and monitoring strategies.

However, the concept of safe zones extends beyond the Factor of Safety alone. Displacement monitoring provides valuable insights into the areas of the tailings dam experiencing the greatest movement. By visualizing and analysing displacement data, we can identify zones that require particular attention and potential remedial actions.

Inclinometer readings allow for the detection of shear zones within the tailings dam. These zones are critical in assessing the stability calculation, as they indicate weaker geotechnical layers that should be considered in the model. Visualizing shear zones on maps and depth plots helps pinpoint areas with significant shear activity and aids in prioritizing mitigation efforts.

Pore water pressure monitoring is of paramount importance in understanding the state of water within the tailings dam. Anomalies in pore water pressure can indicate potential risks, such as drainage malfunctions or increasing pressure in low-permeability layers. Creating continuous functions for pore water pressure distribution through techniques like kriging enables comprehensive visualization and incorporation of this critical parameter in stability calculations.

The spatial density of tests also plays a pivotal role in assessing safe zones. Identifying areas with insufficient test data is essential as it helps determine the regions that require further investigation. Through visualization techniques such as hexagon plots on maps, we can easily identify zones with a limited number of tests, ensuring more comprehensive and accurate assessments of stability.

In conclusion, the safe zone concept 4, encompassing factors such as the Factor of Safety, displacements, inclinometer readings, pore water pressure, and test data density, is vital for the stability assessment of tailings storage facilities. By diligently monitoring and analysing these parameters, mining companies can proactively identify areas of concern, mitigate potential risks, and ensure the safety of local communities, the environment, and their financial investments.

While our work has focused on safe zones for key parameters such as the Factor of Safety,

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displacements, inclinometer readings, pore water pressure, and test data density, it is important to note that the concept of safe zones can be extended to other instrumentation readings as well. For example, monitoring the performance of pumping wells can provide valuable insights into groundwater control and potential risks associated with pore water pressure management.

In addition, while we have utilized a 2D model for calculating the Factor of Safety, further development can explore the implementation of a 3D model. Incorporating the third dimension would allow for a more accurate representation of the complex geometry and layering within the tailings storage facility. This advancement would provide a more comprehensive assessment of stability, considering spatial variations and potential interactions between different layers.

Furthermore, the continuous advancement of data analytics and machine learning techniques presents opportunities for enhancing the analysis and interpretation of monitoring data. By leveraging these advanced methodologies, it becomes possible to extract more detailed insights, detect subtle patterns, and identify potential warning signs of instability. This, in turn, can support more proactive decision-making and early intervention to mitigate risks.

Moreover, the integration of real-time monitoring systems and automated data processing can significantly enhance the efficiency and effectiveness of stability assessments. By implementing real-time data streams and advanced algorithms, mining companies can continuously monitor the status of their tailings storage facilities, quickly identify deviations from expected behaviour, and promptly initiate appropriate measures to ensure safety.

In conclusion, the development and refinement of safe zones for tailings storage facilities are ongoing endeavours. Expanding the scope to encompass other instrumentation readings, incorporating 3D modelling, utilizing advanced data analytics, integrating real-time monitoring, and embracing comprehensive risk assessment methodologies are promising directions for further development. These advancements will contribute to more robust and proactive approaches in ensuring the stability, safety, and sustainability of tailings storage facilities in the mining industry.

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