NROCK2023

Nordic Rock Meeting

ABSTRACTS

The IV Nordic Symposium on Rock Mechanics and Rock Engineering

Reykjavik Iceland

24 - 26 May 2023

ISRM Specialized Conference

The IV Nordic Symposium
on Rock Mechanics and Rock Engineering

May 24-26, 2023
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PREFACE

The Icelandic Geotechnical Society and The Icelandic Tunnelling Society are pleased to welcome you to the 4th Nordic Symposium on Rock Mechanics and Rock Engineering, the Nordic Rock Meeting (NROCK 2023), in Reykjavik, Iceland 24 - 26 of May 2023. The theme of the symposium covers all aspects of rock mechanics and rock engineering, e.g. utilization of underground space, tunnelling, foundation, mining, infrastructure, stability and geo hazards.

The first Nordic Rock Mechanics Symposium was held 2010 in Kongsberg in Norway, the second in Gothenburg in Sweden 2013 and the third in Helsinki in Finland 2017. The fourth symposium was originally planned in Reykjavík in 2021, but due to the Covid-19 pandemic it was postponed until now. The NROCK 2023 symposium is supported by ISRM (International Society for Rock Mechanics and Rock Engineering) and has a status as an ISRM-sponsored Specialized Conference.

We hope that the symposium exceeds your expectations, with interesting papers, presentations, and field excursions. The aim of the symposium is to strengthen the relationship between practicing experts in the Nordic region and the symposium is an opportunity of learning and sharing experience and knowledge with fellow colleagues about various challenges within the field of rock mechanics and rock engineering.

The participants are engineers, researchers, and scientists from the Nordic countries as well as other countries in the world. We have four keynote presentations, from Canada, Norway, and Iceland, and 22 technical oral presentations from 9 countries. All submitted papers are included in this publication. On the behalf of the Organizing Committee, I would like to use this opportunity to gratefully thank the speakers, authors, reviewers, Session Chairs, the Nordic Advisory Committee, Secretariat and last, but not the least, all the participants, for making these proceedings and symposium come to life.

We hope you have a pleasant stay in Iceland and look forward to seeing you again in the next host country of the Nordic Rock Mechanics Symposium!

Reykjavík, May 2023

Atli Karl Ingimarsson

Chair of the Organizing Committee

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ABSTRACT 01
Session K1.1

Ground Support for Extreme Conditions

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ABSTRACT

Ground support is routinely employed to maintain the structural integrity of excavations in rock. In extreme conditions, such as observed in seismically active mines, and in excavations in squeezing rock, this can be challenging. In seismic conditions, ground support is required to prevent excessive levels of rock mass dilation, sustain confinement around the reinforcement and absorb kinetic energy released through the process of brittle rock mass failure and ejection. This is only possible if the ground support works as an integrated system to maintain the load distribution between all elements. In extreme squeezing ground the role of support is to maintain access for the working life of the excavations. Recent years have seen the development of yielding or energy absorbing reinforcement and surface support elements that can perform better than conventional support in extreme conditions. An improved understanding of the loading mechanisms, and better data on the capacity of ground support, complemented by field observations, have resulted in improved ground support practice for extreme conditions. The long-term performance of ground support can be hindered when exposed to corrosive environments. In extreme corrosive environments ground support is susceptible to degradation that may severely reduce its capacity to meet its performance goals for the intended service life of the excavations. This requires protective processes to prolong the effectiveness of ground support, or to plan for rehabilitation when a reduction in capacity is deemed critical. This paper reviews recent developments in ground support strategies for extreme conditions, including mine seismicity, squeezing environment and corrosive environments. In this context, the role and timing of rehabilitation of ground support can have significant safety and economic implications.

KEYWORDS

Ground support; mine seismicity; squeezing ground; corrosive environments; rehabilitation strategies;

EXTENDED ABSTRACT
Session K1.2

Carbfix - CO_2 mineral storage in basaltic rocks

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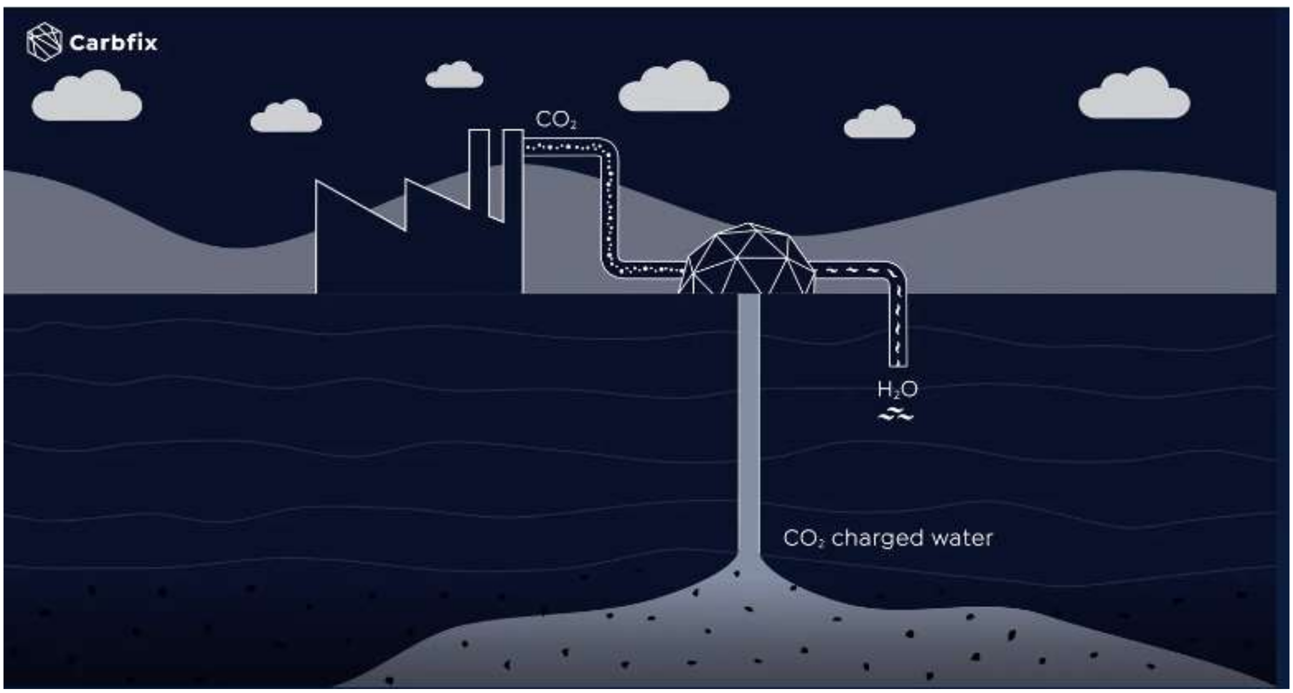
Substantial and sustained reduction of anthropogenic CO_2 emissions to the atmosphere are needed to achieve the goals of the Paris agreement and constrain the current rapid warming to 1,5-2°C. Carbon capture and storage (CCS) solutions play an important role in the transition towards carbon neutrality. CCS includes a range of processes for CO_2 capture, separation, transport, storage, and monitoring, and is considered the key technology for reducing emissions from fossil fuel power plants while these are still part of the energy systems, limiting emissions from many industrial processes such as steel, aluminium and cement production, and to deliver “negative emissions” by removing and permanently storing CO_2 captured directly from air by the second half of the century.

What we do

Despite the urgent need for rapid deployment of widespread carbon storage sites, experience demonstrates that low public acceptance, high upfront investment costs and uncertain future liabilities have hindered the implementation of conventional carbon storage methods in Europe. The success of CO_2 storage depends on its long-term security. Injection of CO_2 into young basaltic formations provides significant advantages, including great storage potential, and permanent storage by mineralization by combining the injected CO_2 with metals contained in the basalts to form stable carbonate minerals.

Mineral carbonation is a part of the natural carbon cycle, where the carbon moves from one terrestrial reservoir to another. Within the natural cycle, carbon has few years average residence time in the atmosphere, decades in vegetation, decades to tens of thousands of years in soils and in the oceans, and thousands to millions of years in rocks, which is by far largest carbon reservoir on Earth. Mineral carbon storage, however, will only be practical if it is possible to accelerate this process at large enough scales to address the current global challenge. Within this approach the captured carbon is stored via injection into reactive rocks such as mafic or ultra-mafic rocks for rapid mineralisation. Mineral carbonation can be promoted by the dissolution of CO2 into water before or during its injection. No cap rock is required when injecting water charged CO2, as it is denser than CO2-free water. As such it does not have the tendency to migrate back to the surface. By dissolving CO2 into water before or during its injection, solubility trapping is achieved immediately, and the bulk of the carbon is trapped in carbonate minerals within two years of injection at 20-50°C. By provoking the mineralisation of the injected CO2 into carbonate minerals such as calcite (CaCO3), dolomite (CaMg(CO3)2) or magnesite (MgCO3) via its injection into reactive host-rocks, the injected carbon is permanently fixed and there is a negligible risk of it returning to the atmosphere.

Mineral CO2 storage offers a vast storage potential and unlocks large regions in the world where CCS has until now not been considered possible. The largest potential lies offshore within the sub-marine basaltic crust, but suitable formations are also widespread onshore, including volcanic formations, mine tailings and unconventional petroleum reservoirs.



How we do it

Carbfix has since 2014 injected over 90,000 tonnes of CO2 from the Hellisheidi geothermal plant in SW-Iceland into the basaltic reservoir for mineral CO2 storage. Emphasis is currently being placed on making this technology more cost effective and exploring its limits in terms of potential sites and injection methods, including injection of CO2 captured directly from the atmosphere.

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ABSTRACT 02
Session **K2.1**

Engineering Geology in Hydropower Engineering

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ABSTRACT

Norway has more than 100 years of experience in the design and construction of hydropower plants consisting waterway systems that included unlined pressure tunnels and shafts. The waterway systems are in general very long and consist of unlined pressurized headrace tunnels, unlined high-pressure shafts, underground powerhouse caverns, access, and tailrace tunnels. The maximum static head that the unlined pressure tunnel has reached is 1047 meter, which is equivalent to almost 10.5 MPa. This is a world record, and it is obvious that the rock mass in the periphery of unlined pressure tunnels and shafts experience high hydrostatic pressure exerted by the flowing water discharge. Experienced gained from the construction and operation of these unlined pressure tunnels and shafts were the key to develop design criteria and stability assessment principles by giving focus on engineering geology, rock mass quality and geo-tectonic environment. As a result, these criteria and principals have got worldwide acceptance. However, the success of these criteria depends on the engineering geological and geo-tectonic environment prevailing in the are of concern and the operational regime adopted in the hydropower plants. This key-not lecture reviews some of the first attempts of the use of unlined pressure tunnels and shafts concept, highlights major failure cases, discusses the gradual development of design criteria for the unlined pressure tunnels and shafts and highlights recent operational trends that have direct influence on the stability of unlined pressure tunnels and shafts of hydropower plants.

KEYWORDS

Hydropower; Hard rock mass; Water pressure; Design criteria; Operation

ABSTRACT Session K2.2

The unrest on the Reykjanes Peninsula and eruption in Fagradalsfjall 2021 & 2022

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The Reykjanes Peninsula is an oblique transform zone marked with adjacent volcanic systems intersected by strike-slip earthquake faults. For the first time since modern instrumentation was installed (last 30 years) a clear, rapid uplift signal was observed on the peninsula in January 2020, interpreted as a magmatic intrusion. This event was followed by several events of further unrest. Between January to July 2020 three intrusions were detected in the vicinity of Mt. Þorbjörn and from July to August 2020 another near Krýsuvík, all accompanied by increased seismic activity.

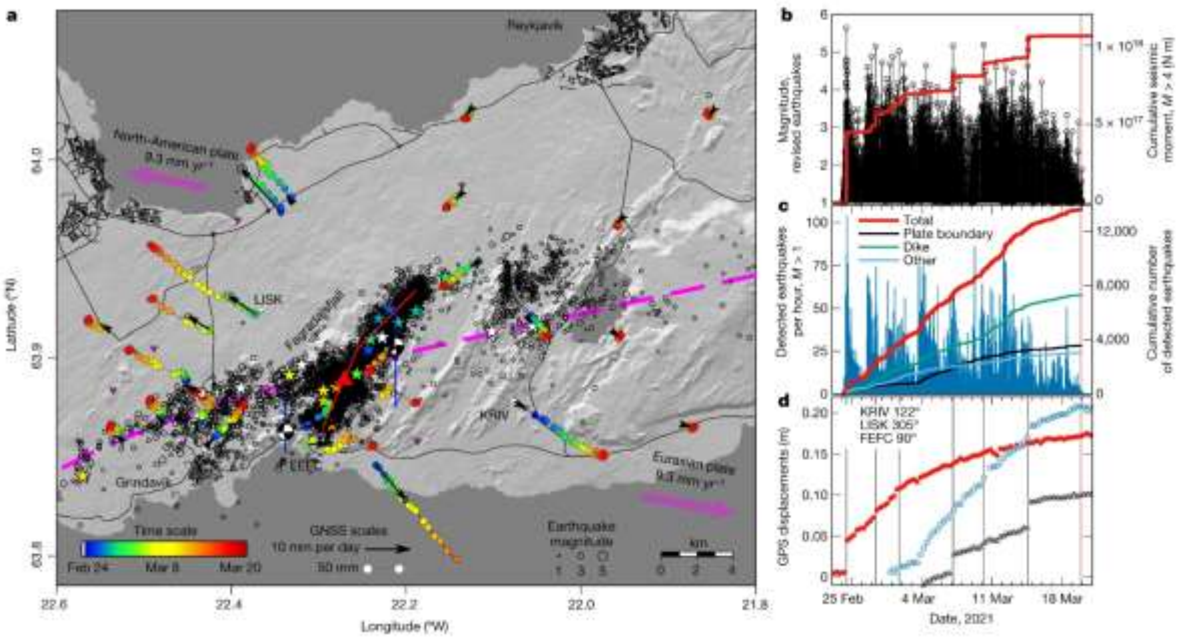

Fig. 1 Map of the Reykjanes Peninsula. Manually reviewed earthquake locations M > 1, covering the period from 24 February to 19 March 2021.

On the 24th of February 2021, a M5.7 earthquake was recorded NE of Fagradalsfjall and a dyke intrusion was detected beneath Fagradalsfjall a few days later. The intrusion continued until mid-March by which time the estimated length of the dyke was 9 km and the associated volume change 34 million cubic meters. This intrusive event triggered an unprecedented, roughly three-weeks long earthquake sequence, which extended over an area of some 350 km2 and counted over 50.000 earthquakes, of which 600 were above M3. It culminated in an effusive lava forming eruption which commenced on the 19th of March 2021 at 20.35 UTC. Lava was initially erupted from a ~100 m long fissure which opened in Geldingadalur valley in Fagradalsfjall. In the final days before the onset of the eruption, the seismicity as well as all deformation signals had dramatically decreased, at that time unexpected observables shortly before eruption onset.

This was the first eruption on the Reykjanes Peninsula in 800 years, and the first one in Fagradals¬fjall in over 6000 years. The eruption was characterized by lava fountaining and the extrusion of basaltic lava flows, with an initial effusion rate of ~5 m3/s. The effusive eruption was accompanied by the release of magmatic gases. Activity remained stable until the 5th of April when two new fissures opened approximately 500 m north of the initial erupting craters. In total six fissures opened between the 5th and 13th of April. After the 27th of April, lava was erupted from one main vent (the fifth opening in temporal order) which in turn formed a crater that reaches ~120 m over the pre-eruption landscape. Lava was last seen spewing from the vent on September 18th.

Fig. 2 Icelandic Meteorological Office seismologist Kristín Jónsdóttir stands besides erupting craters spewing glowing lava from the Fagradalsfjall's eruption.

In total the eruption which started in the valley of Geldingadalir inside the Fagradalsfjall mountain massive produced a lava field covering about 4.9 km2 and created a total SO2 output of 0.9 Mt. The eruption progressed through different phases characterized by different emission sources, eruptive style, intensities, and associated hazards. However, in terms of intensity the eruption was small and arelatively easily accessible eruption, where the main hazards were in the near field to the thousands of visitors which had to be mindful of volcanic gasses, lava outbreaks and occasional minor lava bombs. By joining forces in monitoring and utilizing the available expertise in different institutions, the Civil Protection, Icelandic Institute of Natural History, Institute of Earth Sciences of the University of Iceland, Iceland Geosurvey, the Environmental Agency, and the Icelandic Meteorological Office, which runs the 24/7 monitoring services, a good overview was established of the evolution of the eruption and its hazards.

Reference: Fig. 1: Overview of seismicity and deformation.
From: Nature 609, 523–528 (2022). https://doi.org/10.1038/s41586-022-05083-4

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ABSTRACT 03
Session 1.1

The potential for geothermal energy exploitation in Norwegian tunnels

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ABSTRACT

Renewable thermal energy is a highly sought-after resource in many parts of the world, as a measure to reduce our reliance on fossil fuels and electric power as energy sources for space heating of buildings. Shallow geothermal energy is one of the preferred environmentally friendly thermal energy resources in Norway, where heat stored underground is utilized in conventional heat pump systems via 200-300 m deep boreholes. However, the underground space in our urban areas are under continuous development and puts increasing demand on both surface and sub-surface city planning. The public need for infrastructure tunnels, road or railway tunnels, is most often prioritized rather than development of geothermal systems. Tunnels can thus be a hurdle for the planning and further development of geothermal utilization in cities. In many European countries' tunnels are now increasingly considered as a source of thermal energy in their self. Large volumes of rock mass and groundwater are made available in tunnels and the tunnel can be "activated" for harnessing the heat energy within, so called *Energy tunnels*. The potential for utilizing geothermal energy from Norwegian tunnels via heat pump systems is now being investigated. The tunnels can be activated in several manners, where both passive closed loop systems or active open loop groundwater systems are the two main potential solutions. The applicability of incorporating these systems are here assessed for the Norwegian tunnel design and an initial view on the potential for utilizing our tunnel infrastructure is given. The potential thermal energy available in existing road and railway tunnels alone range in the several TWh scale if all tunnels are activated. The many thousands of kilometers of tunnels in Norway might thus become a future energy resource and a potential pathway to reach our climate goals and to increase the rate of energy transition to renewable energy sources.

KEYWORDS

Geothermal energy; Tunnels; Heating & Cooling Potential; Urban development

Papers DOI: 10.33112/nrock2023.4

ABSTRACT 04
Session 1.2

SINTEF-TRIPOD in Underground Design – An Important Rock Engineering Tool

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ABSTRACT

Many rock engineering projects today may face rock mechanics challenges such as particularly complicated geometry or excavation plan, and complicated geological conditions. There may be no similar existing experience to lean on. Thus, empirical methods have limitations and uncertainties in such cases. Therefore, SINTEF has developed a reliable rock engineering tool to deal with the challenges. The tool is a combination of Investigation, Numerical modelling, and Monitoring. We use the term "SINTEF-TRIPOD" for the methodology. This paper presents the application of the SINTEF-TRIPOD for few important infrastructure projects in Oslo, which are Follo Line metro project and a water supply project.

KEYWORDS

Metro tunnel; Water supply cavern; Investigation; Numerical model; Monitoring.

Papers DOI: 10.33112/nrock2023.5

ABSTRACT 05
Session 1.3

An investigation of key parameters involved in fault activation mechanisms in CO_2 storage

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ABSTRACT

The objective of this research work is to conduct a comprehensive study of fault activation mechanisms and delve into the mechanisms involved in fault reactivation processes in CO_2 storage. Faults constitute a major component of geological formations and change the rock mass system's mechanical behavior significantly, in particular at large scales. The focus of this research is to conduct an analysis of key caprock geomechanical design parameters and compare the significance of each parameter. In this study, the well-documented studies on caprock integrity analysis and fault activation were reviewed and evaluated. The key geomechanical design parameters associated with CO_2 storage were identified and discussed. Accordingly, a procedure for weighting these parameters was developed based on the Fuzzy Analytic Hierarchy Process (FAHP) and used in the comparison of the selected parameters. Based on the developed weighting scheme, the fault friction angle has the highest significance in caprock behavior followed by rock mass permeability and regional in-situ stress ratio. The obtained results are in harmony with practical observations and published research works. With further verification, the proposed approach can be used in the selection of key geomechanical design data required for CO_2 storage site analysis and design.

KEYWORDS

CO_2 Storage, Fault activation mechanisms, Numerical modelling, weighting procedures

Papers DOI: 10.33112/nrock2023.6

ABSTRACT 06
Session 1.4

Infrastructure Restriction Volumes for Future Mining at the LKAB Malmberget Mine

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ABSTRACT

Large-scale sublevel cave mining unavoidably results in the rock mass around the orebodies being affected by caving and stress redistribution. Knowledge about the extent of areas that will not allow safe placement of infrastructure is essential for the planning process for deeper mining. This paper presents a case study from the LKAB Malmberget iron ore mine in which "infrastructure restriction volumes" were developed for guidance of where mining infrastructure such as ramps, shafts, etc., should not be located for future mining at depth. The methodology used involved simulating historic and future production in a mine-scale numerical model, containing relevant geology but no infrastructure. The mine-scale model simulates caving and material flow together with mechanical (stress and deformation) calculations in a coupled process. Stresses were extracted from the mine-scale model and applied to local models, built based on case areas with observed and documented damages from the mine. The local models were constructed with detailed geology and explicit infrastructure. Several criteria for predicting damage were tested and compared with mapping data from multiple locations in the mine. The most suitable criterion for prediction of damage that corresponds to infrastructure function being compromised was the Strength-Stress Ratio (SSR), which describes the "margin capacity" of the rock mass. This criterion was then applied to the mine-scale model to create restriction volumes for each year of mining down to a depth of 1900 m, corresponding to the depletion of currently known orebodies in the mine. The restriction volumes consider static (aseismic) loading only. Development of infrastructure inside the restriction volumes should be avoided or minimized, but in cases where developing infrastructure inside the restriction volumes is necessary, this should be done in a way allowing for future rehabilitation. For current infrastructure located inside the restriction volumes rehabilitation or alternative infrastructure plans should be developed.

KEYWORDS

Sublevel caving; numerical modelling, global-local modelling; strength-stress ratio

Papers DOI: 10.33112/nrock2023.7

ABSTRACT 07
Session 1.5

Quantitative numerical assessment of blast-induced wall damage

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ABSTRACT
One of the cost-effective methods used for rock breakage in mining is drilling and blasting. In open pit mining, blast-induced damage can reduce the level of stability of benches and pit slopes, which is a concern for the safety of mine personnel. Rock fracturing and fragmentation by blasting is the result of the coalescence of existing and new fractures (created by the blast) in the rock mass. The stress waves affect the rock mass in a few milliseconds while the effects of gas pressure last in the scale of hundreds of milliseconds and have a greater effect on rock fragmentation. The presence of in-situ fractures can have a significant impact on the extent of blast-induced damage beyond the intended area of the blast. These fractures are generally preferential paths of least resistance for the explosive energy. It is therefore necessary to account for the effect of the in-situ fracture network to reliably characterize fracture development and blast-induced damage. Discrete fracture networks (DFN) are representations of joint systems and can estimate the distribution of in-situ fractures within a rock mass. The combined finite (FEM)/discrete (DEM) element method (or FDEM) is a useful tool to simulate the complex rock blasting process. FEM is used for calculating stress distribution and displacements before fracturing (static phase) and, once the fracture process begins, DEM is used for simulating the fractured medium (large displacement phase). The principal objective of this paper is to develop a DFN-based numerical FDEM model to assess the influence of gas pressure on blast-induced damage using a propagating boundary condition, which simulate the effect of gas pressure on a growing network of fractures. A two-holes open pit bench blast was simulated in 2D environment. In this simulation, gas pressure was applied on a propagating boundary (boundary of developed fractures). The numerical model is simulated based on rock and blast properties obtained from an operating open pit mine. The level of blast-induced damage was quantified based on the area of the blast damage zone and the intensity of blast-induced fractures. The results show that the propagating boundary condition provides a realistic simulation of blast holes interaction and blast-induced fracture development.

KEYWORDS
Blast-induced damage; Wall damage; Discrete Fracture Network; Combined finite/discrete element method; Fracture intensity.

Papers DOI: 10.33112/nrock2023.8

ABSTRACT 08

Session 2.1

Numerical Analysis of the Sensitivity of Joint Parameters to the Cross-cut in Response of Dynamic Loading

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ABSTRACT

Rock masses are far from being continuum and consist essentially of intact rock and discontinuities such as joints. Presences of discontinuities affects the propagation of the stress wave in rock mass. In this paper the impact of joints properties and features on the dynamic response of underground cross-cuts to seismic loading induced during dynamic large-scale field test in Kiirunavaara mine, was numerically investigated. The numerical methods used comprise the finite element code LS-DYNA and the 2D Universal Distinct Element Code (UDEC). The LS-DYNA model simulated the blasting and acquired the crushed zone and the vibration velocities around the crushed boundary. The vibration velocities from LS-DYNA were then used as an input velocity in the UDEC model. The studies of parameters such as joint normal and shear stiffness, joint spacing and joint orientation were conducted. The vibration responses at the wall of the underground cross-cut from UDEC were analyzed and compared to observed field test results. The results show that the normal stiffness has large effects on the peak particle velocity (PPV) while the shear stiffness contributes less influence. However, changes on joint space and orientation affect the PPV at the wall of the cross-cut. The joint stiffness explains the quality of the joint to transmit the stress wave while the joint spacing, joint orientation describe the blocky in burden which explain number of times the stress wave will be reflected before reaching cross-cut wall. The analysis can be useful during designing of the blast, burden as well as cross-cut support.

KEYWORDS

underground cross-cut; joints; numerical modeling; dynamic response

Papers DOI: 10.33112/nrock2023.9

ABSTRACT 09
Session 2.2

Statistical insights arising from point load testing of Danian limestone

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ABSTRACT

The characterisation of the mechanical properties of the rocks can be carried out with conventional strength testing (e.g. unconfined compressive strength tests, tensile strength tests and triaxial tests) or with 'rapid' tests such as the point load test (PLT). Compared to the conventional tests the rapid tests are economical, quick and can also be carried out in situ; on the other hand, the results tend to be more scattered, correlations with the strength parameters depend on the rock type and the experience in using them in the design stage can be limited. This paper presents the results of PLTs carried out on Danian limestone and Maastrichtian chalk specimens, either as irregular lumps or as cylinders/disks, from multiple sites on Zealand in Denmark. The Danian limestone formations are weak sedimentary rocks with highly variable properties in terms of their strength, stiffness and in mass permeability. Their mechanical properties are governed by genesis, induration and the large variability of the fissuring and distribution of fissuring. By statistically analysing the results of the PLTs, it is possible to appreciate the impact that the height to equivalent diameter ratio has on the coefficient of variation for each induration class, which can therefore be used as guidance for specimen selection and/or preparation on site or in the laboratory.

KEYWORDS

Point load test; Danian limestone; weak rock characterization; height to equivalent diameter ratio.

Papers DOI: 10.33112/nrock2023.10

ABSTRACT 10
Session 2.3

Back-calculation of in-situ stress condition based on the performed secondary stress measurements: Connected to the West Link Project, Sweden

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ABSTRACT

A large underground cavern design at a shallow depth requires reliable estimation of in-situ stress conditions. Geological conditions, topography, and tectonic activity influence the magnitude of the in-situ stresses. The objective of this paper is to predict and evaluate the in-situ stress state before the excavation of two pilot tunnels in a railway access cavern. The access cavern, named Mellanplan, is a part of the Korsvägen section at the West Link Project in Gothenburg, Sweden. The first phase of the construction sequence at Mellanplan involved excavation of two pilot tunnels in the top heading, where a rock pillar remained in between the pilots. Before excavating the rock pillar, SINTEF Community performed secondary stress measurements from the roof of the two pilots, utilising the 2D doorstopper method. The results from these stress measurements are assessed and an interpretation of the stress field at Mellanplan is carried out. The concepts from the final rock stress model (FRSM) suggested by Stephansson and Zang (2012) are applied in the back-calculation of the initial stress state. A 3D numerical program, *RS3*, is applied for parameter stress analyses, where various stress inputs are evaluated. The results from stress analyses are validated with the induced stresses obtained from doorstopper measurements. The final rock stress model demonstrates the stress field at Mellanplan as $\sigma_H > \sigma_v > \sigma_h$. The findings in this study reveal that tectonic stress and residual stress have greater contribution towards the major horizontal stress component. Furthermore, σ_v and σ_h. are suggested as gravity induced stresses. Due to the complexity of stresses at shallow depths, there is a possibility of geological structures reducing the already low magnitude of σ_h.

KEYWORDS
Back-calculation; Estimation of in-situ stresses, Rock cavern; 3D modelling, Scandinavian geology

Papers DOI: 10.33112/nrock2023.11

ABSTRACT 11
Session 2.4

Size Dependancy of Post-peak Stress-Strain Properties of Rocks

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ABSTRACT

Post-peak behavior of rock is significant to the stability of surface and underground rock excavations and the performance of drilling and excavation operations. Mechanical properties and damage characteristics of rocks are subjected to the measurement scale. The effect of size on sandstone's post-peak behavior and failure characteristics are investigated during monotonic uniaxial compressive loading. A series of tests were undertaken on sandstone samples with an aspect ratio of 2.5 and diameters of 19mm, 30mm, 42mm, and 63mm. The lateral strain-controlled loading method was adopted to capture the post-peak stress-strain characteristics. The three-dimensional digital image correlation (3D DIC) technique is utilized to investigate field strain patterns and local damage. The brittleness index was found to increase with an increase in diameter, indicating that the rock sample was damaged in a more brittle regime with a larger size. 3D DIC results demonstrated that in the pre-peak regime, the specimen deforms uniformly. In the pos-peak regime, however, the specimen shows localized behavior. This behavior is different for samples having different diameters. The overall post-peak was a combination of class I and class II behavior.

KEYWORDS

Sandstone; Post-peak; Brittleness; Digital Image Correlation, Damage

Papers DOI: 10.33112/nrock2023.12

ABSTRACT 12
Session 2.5

Full-scale pullout tests of rock anchors in limestone testing rock mass uplift failure

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ABSTRACT

Rock anchors is a high-capacity reinforcement measure used to stabilise large-scale infrastructure. In principle, they can fail in four ways: (1) rock mass uplift failure; (2) grout-rock interface failure; (3) tendon-grout interface failure; and (4) steel tendon tensile failure. Full-scale field uplift tests were performed in a limestone quarry. The tests were designed to test failure mode 1, rock mass uplift failure, aiming to estimate the uplift load-bearing capacity of the rock mass. The tests achieved a higher rock mass capacity than what was calculated with the ''weight over overlying rock cone'' method and using presumptive shear strength values along the assumed failure cone. The failure shape showed to be structurally dependent on the rock mass structure, and a uniform cone was not developed. Stress measurements showed an increase in the horizontal stress in the rock mass during the pulling of the anchor, which indicates the formation of a load arch in the rock mass. The results showed that the current design method is over conservative in a medium strong rock mass and there is a need for development in the design method for strong and unweathered rock masses.

KEYWORDS

Rock Anchor; rock mass failure; load bearing arch; failure surface; field test

Papers DOI: 10.33112/nrock2023.13

ABSTRACT 13
Session 2.6

Large-scale laboratory model tests simulating rock mass uplift failure

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ABSTRACT

Rock anchors are high-capacity reinforcement measures used to stabilise large-scale infrastructure. There are four main failure mechanisms for rock anchors, which are: (1) rock mass uplift failure; (2) grout-rock interface failure; (3) tendon-grout interface failure; and (4) steel tendon tensile failure. A large-scale laboratory test rig has been developed to test block models which simulates rock mass uplift failure (failure mode 1). The design methods against failure mode 1 are the most conservative and least satisfactory design methods according to literature. The full-field displacements of the models were monitored with digital image correlation (DIC). The block model tests had higher capacities than what was calculated with the current design methods using the weight of overlying rock cone and presumptive shear strength values along the assumed failure cone. The capacity and failure shape in the block models showed to be structurally dependent on the block model pattern. The horizontal stress in the models increased during the tests, which showed that load arches were induced in the block models during the uplift. The load capacity of the block models increased with model height and horizontal stress level.

KEYWORDS

Block model, anchor pullout, load arching, failure mode, influence of joint pattern.

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Session 3.1

Analysis of water ingress, grouting effort and pore pressure reduction caused by hard rock tunnels

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ABSTRACT

Norwegian ground conditions with hard bedrock underlying soft, marine clay deposits are challenging with respect to the risk of settlements caused by water ingress to tunnels. Settlements in clay-filled depressions and damage to nearby buildings are one of the main risks associated with future upgrading of infrastructure. This paper presents a database and findings from 44 tunnels in the Oslo-region, excavated between 1975 and 2020. One of the main findings is that few of the tunnels in the database meet the strict leakage limits necessary to avoid settlements for future tunnel projects. Previously, water ingress of typically 3-7 l/min/100 m has been allowed to limit pore pressure reduction to 10-30 kPa (1-3 m water head), limiting settlements and building damage. In areas where the pore pressures already have been affected by water ingress to an existing tunnel, any additional leakage and pore pressure decrease due to a new tunnel will cause additional settlements. Previous reduction in pore pressure results in an even stricter water ingress limits for new tunnels. Hence, water control through improved pre-excavation grouting (PEG) techniques and better monitoring of pore pressure development during excavation is needed. To ensure necessary data-collection for future research it is important to increase the quality of collected data.

KEYWORDS

Urban tunnelling; Water ingress; Pore pressure; Settlements; Pre-excavation grouting.

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ABSTRACT 15
Session 3.2

PU grouting in cold environment at fully operating Fljótsdalur Powerplant

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ABSTRACT

Post grouting in rock was performed with polyurethane close to the pressure shaft valve chamber in the Fljótsdalur powerstation in autumn 2021 while the powerstation was in full operation. Sudden increase in leakage had been observed in the valve chamber during unit trips and associated water-hammering of the rockmass in the powerhouse area, in addition the total leakage in the tunnel system around the valve chamber, had gradually increased since commissioning of the powerplant in 2007 from 10 l/sec to 20 l/sec, going up to 50 l/sec during unit trips when the production is stopped. To prevent potential future problems caused by frequent transient state in the waterway, it was decided to perform grouting in the area. Detailed geological investigations of the rock mass between the valve chamber and the headrace tunnel gave premises for design of new grouting curtain and the choice of grouting material. Difficult conditions with cold water, highly permeable fracture zone and unpredictable changes in pathways resulted in challenging work where collaboration between contractor, client and consultants was essential. Roughly 17.000 liters of polyurethane was injected into the rock mass to seal the bedrock and the constant leakage was reduced down to 4 l/sec. Several unit trips have occurred since the work was completed and to-date, no increase in leakage has been observed.

KEYWORDS

Polyurethane; grouting, cold environment; hydropower plant

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Session 3.3

Spiling in unstable tunnel sections – a benchmark and case study review

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ABSTRACT

In unstable ground, the tunnel can be pre-supported by driving spiles and forepoles into the crown and walls ahead of the excavation face with a small inclination angle upward. In Sweden, the nomenclature for this type of pre-support is "spiling". Spiling, which is a temporary support, is frequently used in Swedish tunnels. However, there is a lack of guidelines and international standardization for the design of spiling. This paper explores the design of spiling in unstable ground with focus on tunnels excavated in the Nordic countries with generally hard rock masses. Based on a benchmark, case and literature study review, example of guidelines and starting points in the design of spiling have been compiled. Cases, with different types of designed and installed spiling, are presented in the paper, followed by a discussion of when, and for what rock conditions, to use rebar spiles, pipe spiles, or self-drilling spiles to achieve a safe excavation progress. Analytical design methodologies used in Swedish cases are presented, including beam models for spiling sections between supporting arches or the face. Cases where numerical modelling have been used in the design of spiling are also described. The findings presented in this paper shows a lack of guidelines on how to design spiling. Future research work linked to model uncertainty, local arching effect and quality assessment is suggested, which will be beneficial for tunnel engineers in designing spiling in the future.

KEYWORDS

Spile, forepole, design, analytical, numerical

Extended ABSTRACT 22
Session 4.5

TIGHT – A research project on modern rock mass grouting techniques

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One important element of tunnelling in urban areas or elsewhere where a strict requirement applies for water control is the technique of rock mass grouting. Norway is one of the countries globally that has been the driver for this development whilst on the other hand the technology is mainly empirical based.

Different approaches exist in the tunnelling industry to reduce groundwater ingress to tunnels to achieve specified leakage limits. The project TIGHT was established to improve Pre-Excavation Grouting techniques though a research-based approach and to take forward detailed understanding of improving high-pressure grouting in tunnels through a combination of work by academics, a PhD, and site-based studies on construction projects. TIGHT aimed at building upon empirical field experience to scientifically optimise the approach to pre-excavation grouting (PEG).

Rock mass grouting is a common method for reducing water inflow in tunnelling projects in hard rock, using cementitious grouts being carried out during excavation. The cost related to grouting constitute 20-30% of the tunnelling costs in projects where the groundwater level must be maintained at a certain level due to urban areas and/or in order to prevent damage to the environment. However, there is a significant unforeseeable aspect of grouting for all parties involved which needs to reduced. Increased knowledge is therefore crucial for optimising the existing grouting methods by reducing the amount of grouting materials used and the time spent on grouting operations. The future in tunnelling would likely implement pre-excavation grouting or rock mass grouting as a standard procedure integrated into the tunnelling cycle.

The official report from TIGHT was issued in Norwegian in 2020, presented to the country’s national tunnelling industry over recent months, and its findings have been shared with the national and international tunnelling societies in various ways.

Some of the key outcomes of TIGHT are that even with the risk of jacking the use of high pressure grouting will continue but with an apparent reduction and increased caution to obtain effective spread of the injection. In this context the need of addressing properly cost, time and environmental concerns has an impact on the decision on grout pressure to be applied. While some may view high flow rates of grout to be a good thing due to jacking, it may not therefore always be so effective.

The outcome of the research suggest that the Norwegian approach to grouting would preferably be shifted to have more focused, site-specific designs and procedures. By that, high pressure is a need, but the pressure needs to be balanced with circumstances like in-situ stress, rock overburden and other elements that cause resistance on the grout penetration.

The TIGHT project aimed at combining studies of both theory, laboratory testing and practical tunnelling work to analyse, and better understand, the interplay of multiple variables in the task of high-pressure grouting of rock mass. Researchers looked at variables in particular such as materials, geology, rock mechanics and experience in the field. A vital threshold zone in the studies was the tipping point where hydraulic jacking by the high pressure suddenly opens up cracks wider in a local rock mass, leading to much greater grout consumption.

From numerical simulation it was found that the angle of borehole incidence to crack orientation has little influence on the spread of grout, whilst viscosity has more bearing. The penetration point needs to be open enough to permit and not throttle flow. Water in cracks has some positive effect on grout dispersion.

Enlarged cracks allow the viscous properties of cement to become more dominant to flow behaviour with ensuing consequences for pressure control, especially in small cracks. Grout, then, is also partly diverted from the intended zones, but there can be instances where jacking opens up filled cracks in aid of grouting.

Further, there is no doubt that finding the optimal cement mix is challenging and products with seemingly the same properties behave differently. Therefore, a much more intensive testing would be needed both before commencing the grout works as well as during the works to control that the wanted behaviour of the grout mix is actually achieved and also maintained during the execution of the works.

The research project TIGHT (True Improvement in Grouting High pressure Technology for tunnelling) has improved the understanding and procedures for pre-excavation grouting in such a way that it produces more cost- and time-effective grouting methods that benefit all the participants in this research project, including the public owners who finance the building of road- and railway tunnels through the national budget. Other owners and operators of tunnels and underground openings will benefit from the results of TIGHT as well.

Based on the results from TIGHT, the project-specific solutions should seek local, site-specific approaches to grouting based on a comprehensive design approach covering all elements of the grouting system and controls and held to consistently. By continuously employing the same cement mix design for grout, the same mixing method and equipment, and a faster more rigorous management of jacking risk the workflow processes would have better opportunity to minimise variations in grouting performance. Including the understanding that high or moderate pressure is required to be able to insert cement into cracks and joints in the rock mass, but still have control on the flow. Jacking may not be the key of the problem, rather control of the grouting procedures that follow immediately upon such instances being triggered and this is where research is currently ongoing, ie. how to detect an incident and how to react on the alarms that go off. Widespread and uniform methods from a general solution would not be the expected outcome, whilst project-specific solutions will continue to be required.

TIGHT may have led to development of technology and also benefit projects on time and cost aspects of grouting, however the field of pre-excavation grouting of the rock mass is a huge theme to investigate. There are still lots of issues that could have been developed and dealt with in other research projects; like the understanding on how contract conditions could better reflect grouting quality and quantity; how can the industry better establish relevant laboratory testing on grout penetration on cracks and joints in the rock mass to mention a few, and last but not least, how can we take benefit and learn from the endless amounts of data that is collected at the drilling jumbo and the grouting rig for each grouted hole in the rock mass.

TIGHT is a project that has been financed by the Norwegian Research Council as a competence building project (KPN-BIA) involving a number of participants from the tunnelling industry in Norway; Statens Vegvesen, Jernbaneverket, BASF, Mapei, Geovita, LNS, ITS, Normet, Bever Control, AMV and Veidekke together with NGI, NTNU and SINTEF.

Picture shows preparations for pre-excavation grouting at Implenia/Acciona tunnel face in Moss. Picture by AMV

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Session 3.5

Savilahti Underground Sport and Event Center

Case study

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ABSTRACT

An underground sport and event center is being constructed in the area called Savilahti, located in the city of Kuopio. The facility is designed for 2500 people but it also serves as a civil defence shelter for 7000 people. This type of concept is very common in Finland. The span of the largest cavern hall is 50 m which is the largest underground span in Finland. The length of the cavern hall is 88 m, height 17 m and total volume 88 000 m^3. Interesting feature is, and also a challenge that Savilahti cavern utilizes the old existing underground caverns that were built already in late 1930's and served for military purposes. Savilahti cavern is situated relatively close to the rock surface with minimum rock roof around 15 m. The cavern is situated in tonalitic gneiss and granite with good properties and quality, but the area has also joints and several fracture zones that needed rock investigations and special attention in the design process. Rock mechanics simulations were performed with 3DEC-code to ensure the cavern stability and fulfill the requirements for the civil defense shelter.

At the time of writing this abstract the construction works are underway. The cavern was excavated during 2021-2022. The photogrammetry was intensively used e.g. for rock mapping, modelling, grouting and rock support design The rock monitoring with several extensometers were also performed during excavation. The results showed that the measured displacements were close (a bit less) to the anticipated ones. Savilahti underground sport and event center will be completed and ready for use in spring 2024.

Figure 1. Savilahti Underground Sport and Event Center (Photo: LUOLA, www.savilahti.com).

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Session 3.6

Extreme Challenges in Vadlaheidi Road Tunnel Case History

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ABSTRACT

Vadlaheidi road tunnel is in the Northern part of Iceland. The tunnel's cross-section is according to Norwegian design guidelines and is called T9.5, with a cross-sectional area of approximately 66 m^2. The total length of the tunnel in rock is 7.2 km and it connects Eyjafjordur in the west to Fnjoskadalur in the East.

Figure 1. Location of Vadlaheidi road tunnel

Tunnel excavation started in July 2013 and the tunnel was opened for public traffic late December 2018, about two years later than originally scheduled.

There were two main reasons for this delay. Firstly, high water temperature and inflow of hot water that caused extremely poor working conditions and frequent grouting operations during the tunnel excavation from the west side. Secondly, an extreme collapse in the tunnel on the East side, causing a large inflow of relatively cold water resulting in filling and closing the tunnel for months.

Tunnel excavation from the West side started on July 3rd, 2013. On February 15th, 2014, a large inflow of 46°C hot water, approximately 350 l/s, occurred. The total length of the tunnel was at that time 1870 m. The excavation was continued with very frequent grouting operations, increasing water temperature and rapidly decreasing working conditions. It was therefore decided to post grout the area. The grouting work was executed in June and July of 2014. Although a relatively successful post-grouting operation the working conditions were extreme due to water and rock temperature up to around 63°C. Late

August the contractor decided to stop the excavation and move to the East side. The tunnel length at the west side was at that time 2695 m.

Figure 2. Inflow of 46°C hot water, total of 350 l/s.

Tunnel excavation from the East side started on September 5th, 2014. After relatively successful tunnel excavation work, an extreme collapse occurred on April 17th, 2015, from a 10 m wide fault zone. The tunnel length was at that time 1475 m.

Figure 3. Collapse in the tunnel

Shortly after the collapse, an inflow of 7°C cold water of up to 518 l/s followed. The tunnel was filled with water and tunnel excavation consequently stopped.

Pumping of water from the tunnel started in October 2015 and preparation work for continuing tunnel excavation started in January 2016. After successful grouting and consolidation grouting work, as well as very heavy reinforcement of the roof part, using a pipe umbrella, to excavate through the fault zone, tunnel excavation commenced on the East side on October 19th, 2016 and break-through was obtained on April 28th, 2017.

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Session 4.1

Digitalization in rock mechanics: A parametric design for numerical models in Norway

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ABSTRACT

Determination of stress magnitude and orientation plays a vital role in rock mechanics and the underground works industry. Local stress fields are disturbed during excavation and new induced stresses influence the surrounding rock mass. Information about their magnitude and orientation is crucial because in some cases the rock strength is exceeded, resulting in instabilities which can have undesired consequences. In turn, the stress state of the rock mass may vary with diverse locations because of factors such as regional tectonics, geology, and/or topography. A rule of thumb points out that on early stages the engineer should search for stress information on a radius of 50 km. Due to scarce and restricted information this is not always possible. For example, Norwegian hydropower depends on knowledge of local rock stresses in order to find the best location and design of solutions in the underground, and to minimize the need for steel lining in pressurized tunnels.

As part of the NoRSTRESS project, the authors have created a shallow 3D model of Norway where it is possible to extract a given area by centre and square side size on a 20 m resolution. This allows for fast and accurate creation of volumes and meshes for further numerical modelling on different scales. There is no evidence of such an effort in the literature for any other country. The results are expected to help evaluating stress magnitude and orientation on early project stages as well as to contribute to develop a 3D stress map of Norway. To have a better overview and understanding of the ground conditions to come will be useful, not only for the hydropower industry, but also for the emerging mining business.

KEYWORDS

parametric design; rock mechanics; numerical modelling; rock stress

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Session 4.2

Strategic management of water-filled tunnels

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ABSTRACT

In Scandinavia and worldwide, rock tunnels are largely used to transport water in many industries and municipal activities, e.g. hydro and nuclear power, water transport for drinking and wastewater, raw water supply to industrial facilities, etc. These tunnels are usually constantly filled with water but need monitoring and maintenance inspections at regular intervals.

According to the Swedish Energiforsk report (2021:730) "Inner waterways in a hydropower plant commonly have very limited access for inspections and some have never been inspected since the commissioning. Many plant owners lack systematic management of the inner waterways”. We do believe that this problem exists not only in Sweden and not only in hydropower plants.

Degradation of tunnel structure has many similarities in dry and water-filled tunnels; in the water-filled state, however, the hydrostatic pressure and its variation as well as physical erosion by flowing water are also added as possible negative factors.

Tunnel inspections must affect operations as little as possible. This can be achieved by performing inspection and maintenance with a ROV (Remotely operated vehicle) equipped with sonar, cameras and measuring instruments without emptying the tunnel of water and under safe working conditions. The combination of the correct size of the ROV and the length of the cable allows the inspection of tunnels of up to 20 km from a single-entry point.

We present the technical capacity of ROVs equipped with 3D sonar and examples of geological interpretation of inspection results from water-filled tunnels and maintenance solutions. We argue that a ROV equipped with 3D multibeam sonar is currently the most advanced instrument for performing inspections of water-filled tunnels in a safe work environment manner and should be considered as one of the tools for strategic management of inner waterways.

KEYWORDS

HYDROPOWER; ROV; SONAR; INSPECTION; TUNNEL

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ABSTRACT 19
Session 4.3

Deep learning application in characterization and prediction of overbreak geometry in tunnels using point cloud data

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ABSTRACT

An overbreak during the construction of underground mining tunnels is a common geotechnical and operational problem, which is caused by a combination of geological, geotechnical, structural and operational factors, in which partial or reduced information is available, thus conditioning tunnel stability and consequently the safety of personnel during construction. Additionally, studying an overbreak during early stages allows to validate assumptions applied during engineering stages. Throughout history, different methods have been proposed for the overbreak estimation, these ranging from an empirical, analytical (including numerical modelling), observational or even through the application of machine learning.

This work proposes a different approach to most of the studies carried out, which usually consider an average or expected value of overbreak. On this occasion, Deep Learning architectures are used to characterize and predict the complete geometry of the tunnel based off of a training carried out using point clouds of the sectors already excavated.

The results obtained show that it is possible to use autoencoder-type architectures to carry out the characterization and prediction of the tunnel's geometries from point clouds of previously excavated sectors, which has a relevant value for back analysis and potentially predictive analysis, which would in turn impact tunnel stability and/or safety in the different operation cycles during the construction of underground mining galleries and/or tunnels and civil works' projects and operations.

KEYWORDS

Tunnels; Overbreak; Point Cloud Data; Deep Learning; Autoencoders

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ABSTRACT 20
Session 4.4

Rapid photogrammetric method for rock mass characterization in underground excavations

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ABSTRACT

Underground excavation mapping and rock mass characterization are critical for ensuring the safety, proper design, and maintenance of underground infrastructure. Traditional mapping methods typically involve manual inspections and measurements that require contact with the tunnel surface, which can be time-consuming, expensive, and pose safety risks to personnel. In recent years, photogrammetry has emerged as an alternative method for generating high-resolution digital 3D models of tunnels, enabling rapid and remote rock mass measurements. In this paper, we present a method for tunnel and stope scanning using photogrammetry and remote rock mass mapping from 3D models. Two case studies are presented to demonstrate the effectiveness of the proposed method. In the first case, a multi-camera rig consisting of action cameras is used for video-based photogrammetric reconstruction of underground tunnel excavation. The rock mass data is then extracted from the model and visualized. In the second case, a drone workflow is used to map out rock mass features in stopes. Images taken with the drone are processed to create a 3D point cloud of the stope, which is then used to extract discontinuities from the rock mass surfaces. The orientation and spacing of these discontinuities are measured and visualized on top of the photorealistic 3D mesh of the stope for inspection. The proposed method significantly reduces the data capture process. The advancements in camera and software technologies have made it possible to acquire rapid and accurate 3D models of underground excavations that can be used as a source of rock mass data. Our results demonstrate that photogrammetry is a robust approach for underground rock mass inspection and remote mapping.

KEYWORDS

Rock mass characterization; fracture mapping; photogrammetry; underground; tunnel

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ABSTRACT 21
Session 4.5

Geoscientific investigation for the site selection of high level radiowaste disposal in South Korea

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ABSTRACT

According to the 2nd master plan for high-level radioactive waste(HLW) announced by the South Korean government in 2021, the operation of the HLW disposal repository from site selection is planned to be carried out within 37 years. In particular, the site selection was decided within 13 years after the start of the project through a step-by-step process like other countries. Unlike Northern Europe such as Sweden and Finland, where crystalline rocks are the main composition, South Korea has various rock types similar to Switzerland. The Korea Institute of Geoscience and Mineral Resources published 8 types of geoenvironmental information maps, including rock types, lineament, faults, and geothermals etc., which can be used in the national screening stage. Geoscientific researches are being conducted for each rock type in consideration of the distribution area of rock types in the South Korea obtained from the geoenvironmental information map. Considering the depth of HLW disposal repository, drillings are performed at a depth of 750 m according to the rock types, and evaluation parameters for each research field used in basic and detailed investigations are obtained. Investigations using deep boreholes, which began in 2020, were conducted in granite, sedimentary rocks including mudstone and sandstone, and gneiss. Another investigation is planned for volcanic rocks next year. The evaluation parameters obtained during the geoscientific investigation include geological parameters such as lithology, joint and fault, hydraulic parameters such as hydraulic conductivity and storage coefficient, geochemical parameters such as hydrochemistry, sorption and nuclides, and geothermal parameters such as thermal conductivity and geothermal gradient. There are also mechanical parameters such as strength, and in-situ stress. These data are expected to be used as basic data for site selection for HLW disposal in Korea in the future.

KEYWORDS

high-level radiowaste(HLW); geoenvironmental information; site selection; evaluation parameter; rock type