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Rock mechanics: a retrospective on its development and a perspective on the evolution of research and applications

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Review Article

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Abstract

This article presents a speculative exercise aimed at anticipating future developments in rock mechanics, both in its application areas and in research. To frame this discussion within the historical evolution of the field, it seemed relevant to first provide a brief retrospective on the emergence of rock mechanics in the post-war years as a distinct discipline within geotechnical engineering, as well as on its key developments from then to the present. The article identifies application domains where significant advancements are expected, not only within traditional areas, such as civil, mining, and petroleum engineering, but also in areas that have gained importance over time, as well as in emerging application domains. Research in rock mechanics will face new challenges driven by society's demand for safer, more cost-effective, and more sustainable solutions. It must also adapt to, and benefit from, the challenges presented by new applications, the rapid development of communication and digital technologies, and the expanding role of artificial intelligence.

1. Introduction

Rock mechanics emerged as an independent discipline in the 1950s and has since undergone significant development—a trend expected to continue with increasing momentum. This period aligns with the existence of the Brazilian Association for Soil Mechanics and Geotechnical Engineering (ABMS), which is currently celebrating its 75th anniversary. During this time, the core disciplines of geotechnical engineering—soil mechanics, rock mechanics, and engineering geology—have attained their current prominence.

In this context, this article—part of a special issue of Soils and Rocks marking this milestone—begins with a brief retrospective of the most significant advancements in rock mechanics to date, before exploring key areas where substantial progress is anticipated, both in research and practical applications.

2. Retrospective on the development of rock mechanics

2.1 The emergence of rock mechanics as an independent discipline

At the end of the 1950s, rock mechanics had already taken the necessary steps to be recognised as a discipline within geotechnical engineering, gradually gaining independence from both a scientific perspective and in its applications (Brown, 2011). Although the early developments of what would later be known as rock mechanics were systematically recorded from the mid-19th century—particularly in large open-pit and underground mining operations or the construction of railway tunnels—it was only in the early 1950s that various factors converged, leading to its establishment as an independent discipline. The significant post-war investments in infrastructure and resource exploitation undoubtedly played a role in this development.

In 1951, Leopold Müller (Figure 1a) organised the first Geomechanics Colloquium in Salzburg, Austria, which in 2025 marks its 74th consecutive edition and remains one of the world's leading annual conferences dedicated to rock mechanics. In 1956, the first U.S. Rock Mechanics Symposium was held in Golden, Colorado, and has since reached its 59th edition. In 1958, Müller became editor of *Geologie und Bauwesen* (Geology and Construction), a journal founded in 1929, and the leading specialist publication in the field. In 1963, the journal was renamed Rock Mechanics and Engineering Geology (Figure 1b), and today it is known as Rock Mechanics and Rock Engineering. That same year, the International Journal of Rock Mechanics and Mining Sciences was founded. These two journals remain the most influential publications in the field. Talobre (1957) and Müller (1963) were among the first to compile and codify existing knowledge on the subject in book form. In 1958, the International Bureau of Strata Mechanics was established in Leipzig, in the former German Democratic Republic,

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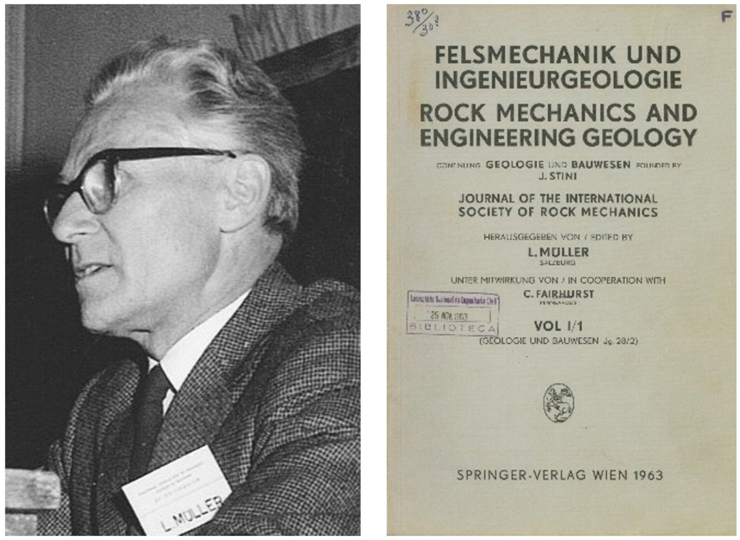


(a) (b)

Figure 1. (a) Leopold Müller (1908-1988) first president of ISRM; (b) cover of the first issue of Rock Mechanics and Engineering Geology (Lamas, 2012).

bringing together Eastern European scientists with a focus on rock mechanics in mining. In 1962, an Austrian-led group of scientists, known as the "Salzburg Group" (*Salzburger Kreis*) and headed by Müller, along with researchers from other countries (Fairhurst, 2012), founded the International Society for Rock Mechanics (ISRM).

Two key events marked the emergence of rock mechanics as an independent discipline prior to the founding of the ISRM (Lamas, 2012). First, Müller maintained a dialogue with Lauritz Bjerrum, then vice president—and later president—of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE). In a letter to Müller, Bjerrum wrote: "I have had correspondence with Professor Terzaghi, Professor Casagrande, and Professor Skempton on the question of whether rock mechanics shall be adopted into our Society and an attempt be made to merge the existing rock mechanics organizations into our International Society. I was personally against a merging, and Professor Terzaghi agreed with me. Professor Casagrande has now taken the decision that no attempt should be made to have Rock Mechanics organizations merged into our Society, but he leaves the question open for a possible cooperation in a joint international society of the two groups of people." Thus, the independence of rock mechanics from the scientific society that had until then represented the entire field of geotechnics was established, with the approval of its leading figures.

The second significant event was an interview given by Müller and Pacher to a Salzburg radio station on the eve of the ISRM's founding assembly. When asked, "What is rock mechanics?" Pacher replied: "It is the scientific discipline that studies the response of jointed rock when subjected to imposed forces, stresses, and deformations." When asked, "Do we know the strength of rocks?" Müller responded: "For rock tested in the laboratory, yes. For rock masses, no. That is what we need to determine. That is why we need an International Society for Rock Mechanics." With this, the central question and the greatest challenge of rock mechanics were defined: "What is the behaviour of rock masses, composed of rock and discontinuity surfaces?"

Manuel Rocha, a scientist and engineer renowned for his research on the mechanical behaviour of rock masses, made significant contributions to the theoretical and experimental foundations of the field (Rocha, 1971a, b; Lemos & Lamas, 2013). Succeeding Müller (Figure 2), Rocha became the second president of ISRM and transformed a small group of mainly European scientists in a large, well-structured society, strengthening its international presence across all continents and promoting the application of rock mechanics in major engineering projects. His work helped solidify the discipline's importance in tunnel construction, dam foundations, and large-scale infrastructure projects. In 1966 he organised the first Congress of the ISRM in Lisbon, a major milestone and a defining moment in the Society's early years. Together, Müller and Rocha played pivotal roles in defining the principles of rock mechanics and ensuring its recognition as an essential engineering discipline worldwide.

2.2 Key developments in rock mechanics

2.2.1 Introduction

The development of rock mechanics after the early 1960s progressed rapidly, driven by society's increasing demand

Figure 2. Leopold Müller (right) hands over the presidency of ISRM to Manuel Rocha (left) during the first Congress in Lisbon in 1966 (Lamas, 2012).

for more complex projects involving greater depths, larger structures, and new technical requirements. However, this progress was also influenced by the need to understand the causes of major failures, such as the collapse of the Malpasset Dam in 1959, the Vajont reservoir slope failure in 1963, and serious accidents in coal mines.

Beyond its traditional applications in civil, mining, and petroleum engineering, rock mechanics expanded into new fields. Notable developments include environmental protection applications, such as underground storage of gases, liquids, and radioactive waste, as well as energy-related advancements, including shale fracturing and geothermal engineering.

Several authors have identified the key advancements and breakthroughs in rock mechanics since its emergence. The following sections list the most significant areas of progress in the field, based on the works of Hoek (2007), Fairhurst (2010), Brown (2011), and Habib & Panet (2012), as well as in the comprehensive state-of-the-art reviews compiled by Hudson (1993) in the early 1990s and Feng (2017) in the 2010's. These are further complemented by the authors' own views.

2.2.2 Rock mass investigation

- The establishment of a common language for describing rocks and rock masses, along with its standardisation.
- Advances in drilling technologies and borehole logging, as well as the mapping of borehole surfaces using optical, acoustic, and electrical methods.
- The use of geophysical methods, particularly seismic reflection and refraction, enabling tomography imaging.
- The widespread adoption of discontinuity surface mapping through photogrammetric methods, 3D laser scanning, and digital image processing.
- The development of methods for in situ stress estimation, combined with advanced methodologies for its interpretation.
- The introduction of rock mass classification systems based on various parameters (such as RMR, Q, and GSI), which have provided a codified description of rock masses and are now widely used in design worldwide.
- The 3D representation of terrain—including geology, discontinuities, geotechnical units, and planned engineering works or interventions—integrated with geographic information systems containing geotechnical and other relevant project data, applicable to different branches of engineering.

2.2.3 Properties of rocks and rock masses

- A clear distinction between two scales: the rock sample scale, which can be tested in the laboratory, and the rock mass scale, which is the scale of interest for most engineering applications and must account for the presence of discontinuities.
- The pioneering role of the successive Suggested Methods of the ISRM (International Society for Rock Mechanics and Rock Engineering) and the approval of standards for various common rock mechanics tests used by the industry.
- The development of in situ tests for characterising the mechanical (namely deformability, but also strength) and hydraulic properties of rock masses.
- The use of rigid, servo-controlled testing machines in the laboratory to study progressive rock failure under biaxial and truly triaxial compression states, employing computerised control and data acquisition systems, along with monitoring using specific sensors.
- Advances in numerical modelling of rock and rock mass failure using discontinuous models.
- The development of empirical methodologies for estimating the strength and deformability of rock masses, integrating rock mass classification systems and laboratory test results.
- The development of shear testing methods for discontinuities under constant normal stress or stiffness.
- Advances in understanding the influence of roughness and infill materials in discontinuities on their shear strength and stiffness.
- Improved understanding of fluid flow in discontinuities and discontinuous rock masses.

- The introduction of fracture mechanics principles into rock mechanics and the development of corresponding testing methods.
- Advances in the statistical description of discontinuity networks and the development of methodologies for their representation and simulation.

2.2.4 Analysis methodologies for design and research

- Understanding the interaction between the rock mass and support or reinforcement elements the during excavation.
- The development of numerical models, driven by both the extraordinary growth in computing power and theoretical advancements, enabling their application to increasingly complex analyses—both in research studies of various phenomena and in design calculations.
- The advancement and application of methods using different discretisation techniques for rock masses, allowing continuous and discontinuous, two- and three-dimensional analyses. These include finite element methods, finite difference methods, boundary element methods, mesh-free methods, discrete element methods, and their variants and combinations.
- The "democratisation" of numerical modelling, making it accessible to engineers and technicians who are not specialists in its development. This has been facilitated by the increasing availability of commercial software capable of handling complex problems in terms of geometry, constitutive models, nonlinear analyses, and coupled studies of various phenomena—including mechanical, hydraulic, thermal, and chemical interactions.
- The introduction of reliability-based methods, incorporating probabilistic approaches to account for loads as well as the material and geometrical properties of rock masses.
- The application of probabilistic approaches to defining the geometry of discontinuity networks and the use of Discrete Fracture Networks (DFN) for rock mass modelling.
- The implementation of standardised safety verification methods, based on limit state design and reliability theory principles. This includes the application of the structural Eurocodes in Europe to geotechnical design, which in increasingly used in the design of rock structures for civil engineering projects, as well as the load and resistance factor design (LRFD) in the United States.

2.2.5 Construction

- Advances in mechanised rock mass excavation, both in open-pit and underground settings, driven by increasingly larger, more powerful, and more efficient equipment for civil engineering and mining, while reducing environmental impact.
- Significant progress in full-face tunnel boring machines (TBMs), enabling the excavation of large cross-sections in heterogeneous ground conditions, ranging from soil to hard rock, even under challenging circumstances such as high water pressure or stress states.
- A deeper understanding of the interaction between rock masses and support elements during excavation, leading to the development of integrated construction methodologies for underground works. These include tunnel boring machines, explosives-based techniques such as the New Austrian Tunnelling Method (NATM), and its adaptations for softer ground and at shallow-depth application.
- The development of new materials and reinforcement elements for rock mass support, including fibre-reinforced shotcrete, innovative rock bolting systems using new support concepts and materials, and the prefabrication of support structures.
- Enhanced drilling and rock-cutting techniques driven by a better understanding of mechanical fragmentation processes and explosive-based methods.
- The introduction of new types of explosives for a wide range of applications.
- Major advancements in automation and robotics across all aspects of drilling, mechanised excavation, explosive-based excavation, and the installation of reinforcement and support systems, leading to enhanced performance and efficiency.

2.2.6 Monitoring and observation

- The early development of monitoring equipment using mechanical, optical, electrical, electronic and microseismic techniques.
- The development of equipment and methodologies for measuring coordinates and displacements using high-precision tacheometry and levelling, satellite-based systems such as the US-owned Global Positioning System (GPS) and the international Global Navigation Satellite System (GNSS), digital terrestrial and aerial photogrammetry, laser scanning (LiDAR), and synthetic aperture radar interferometry (InSAR).
- The development of integrated observation systems with remote access and control for data acquisition, storage, processing, interpretation, and the generation of reports and alerts. These systems provide real-time information, enabling timely decision-making, particularly within risk management frameworks.

- The recognition of observation as a fundamental aspect of safety control during construction, particularly by comparing predicted and observed values.
- The integration of observation into a comprehensive process of design, construction, and monitoring, in line with the observational method.
- The use of back-analysis of observational data—both in terms of structural behaviour and failure mechanisms—to determine material property values and improve understanding of failure modes.

3. Perspectives on the evolution of rock mechanics

3.1 Applications

3.1.1 General

Rock mechanics emerged, as mentioned above, in connection with applications in civil and mining engineering. This included railway tunnels and, much later, road tunnels, dam foundations, rock slopes for roadways and open-pit mines, as well as underground mines, particularly coal mines. With the decline in construction works and mining activities in industrialised countries, and the rise of other activities related to underground space, at increasing depths and involving more complex ground conditions, other applications have gained increasing significance. As a result, the current situation is substantially different from that of 75 years ago, and this trend is expected to intensify in the future.

3.1.2 Civil engineering

The challenges within civil engineering will result from the increased complexity of the projects to be undertaken. The growing use of land, both on the surface and underground, means that new constructions will be located in more complex rock masses, either due to their poorer mechanical or hydraulic properties, or due to the stress state and hydrogeological conditions, or even due to a lack of knowledge due to the difficulties in ground investigation. Furthermore, this will lead to construction in areas with higher risks of accidents, such as natural slopes with steep gradients or areas of high seismicity. An additional complexity will lie in the increasing scale of the projects. Mitigating the consequences of incidents and accidents will require the development of increasingly efficient warning systems.

Worth mentioning are underground urban works (such as road, railway, and drainage tunnels, as well as parking caverns), deep transportation tunnels (more than 500 m) (Figure 3), under water tunnels, the prevention of landslides in mountainous and urban areas, as well as caverns for the storage of solids and fluids.

Dams are nowadays built with increasing size (Figure 4), and the foundations of these mega-concrete dams (higher than 250 m) present challenges that differ from those of conventional dams in terms of rock mass relaxation phenomena and high in situ stresses (e.g. Meng et al., 2020). Localised scour downstream of these dams (Figure 5), where turbulent flows interact with fractured rock masses, gains an increasing relevance (Melo, 2025), namely due to the higher design flows resulting from more extreme floods driven by climate changes.

Larger underground power circuits and powerhouses are also becoming increasingly necessary associated with these large hydroelectric projects (Figures 6 and 7), particularly in reversible pump-storage schemes driven by the growing demand for energy storage.

3.1.3 Mining engineering

The mining sector will face challenges similar to those in civil engineering. Future challenges, driven by the global

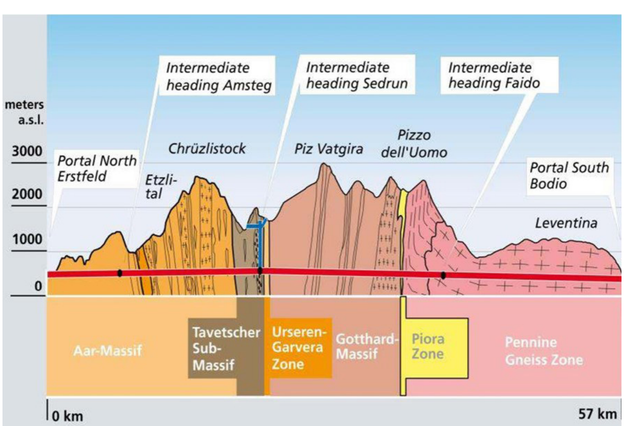


Figure 3. Gotthard Base Tunnel: longitudinal geological profile (ALPTRANSIT, 2021).

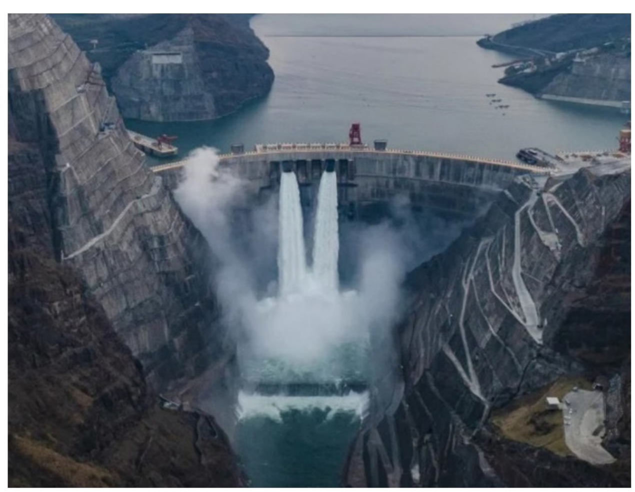


Figure 4. Baihetan mega-dam with two open spillways (Chik, 2023).

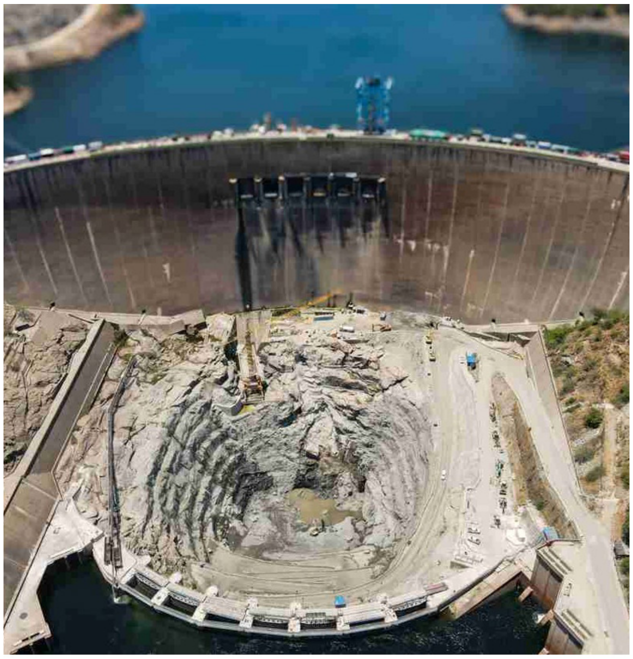


Figure 5. Repair works at the scour hole downstream of Kariba dam (newZWire, 2024).

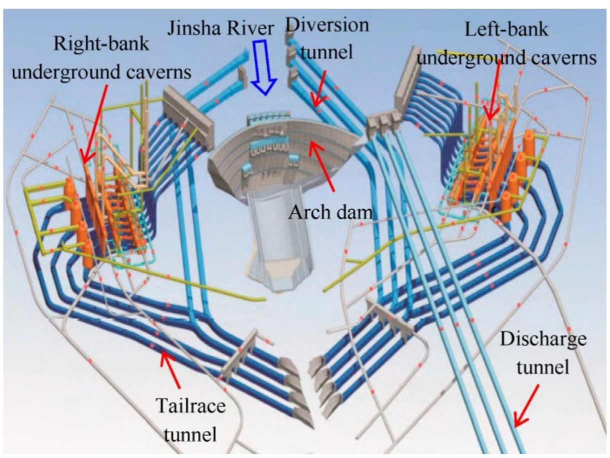


Figure 6. Layout of the Baihetan underground works (Ding et al., 2024).

Figure 7. Frades II underground powerhouse (Lamas, 2023).

Figure 8. Landslide at the 1.2 km deep Kennecott Copper Bingham Canyon open pit mine (Geoengineer, 2013).

demand for minerals, will include the exploration of ores at greater depths, both underground and open pit (Figure 8), with increasing risks. Deep sea mining of metals and other minerals may give its first steps, despite the controversy that surrounds it in terms of seabed conservation and environmental impacts. In coal-producing countries, issues related to advances in exploration methods will require intervention from rock mechanics (Dhar, 2016). Stricter requirements regarding rockburst control, ventilation, temperature regulation, safety, and environmental concerns will become more limiting constrains.

Mine closure does not entirely eliminate the risks of negative effects at the surface in the post-operation period (Didier et al., 2008). Subsidence problems and chimney failures in underground mines (Figure 9), or slope instability in open-pit mines, will continue to demand the input of rock mechanics specialists.

3.1.4 Energy production

The energy sector is facing pressure from two somewhat opposing forces: on one hand, the growing demand for energy driven by population growth and industrial needs, and on the other hand, the tightening environmental restrictions. As a result, the sector is undergoing a transformation process, with the aim of adapting production methods and waste management and storage to new paradigms.

The production of hydrocarbons using unconventional methods in sedimentary rock formations has seen significant developments, with drilling at greater depths, under high temperatures and stress conditions, in rock masses with very low permeability, as is the case with shale gas production. These rock formations require hydraulic fracturing, with intentionally deviated boreholes to reach them, in order to create pathways for fluid circulation to the extraction wells (Figure 10). Rock mechanics will increasingly be required to address these challenges, studying the propagation of fractures and the thermal, hydraulic, mechanical, and chemical (THMC) phenomena in a coupled manner (Pellet, 2018).

Deep enhanced geothermal systems (EGS) are located in crystalline plutonic rock formations, with pre-existing discontinuity networks, which need to be stimulated by hydraulic fracturing to enhance heat exchange between the rock mass and circulating water (Figure 11). They require increasing input from rock mechanics, particularly in the study of rock mass properties, fracture networks, and tectonic stress state, in the use of coupled THMC analyses, as well as in preventing accidents caused by fault reactivation and induced seismicity, which are linked to the dynamic response of the geothermal systems and of propagation of fractures (Pellet, 2017).

Figure 9. Chimney break in a closed gypsum mine (Didier et al., 2008).

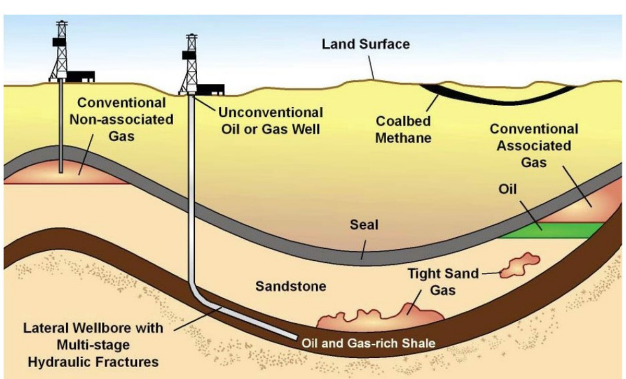


Figure 10. Geometric diagram of conventional and unconventional gas deposits (EIA, 2010).

3.1.5 Environmental constraints

Within the environmental field, rock mechanics will play an increasingly vital role in several areas, including: carbon dioxide sequestration in deep reservoirs to reduce atmospheric emissions, where it is necessary to ensure the gas does not migrate into the atmosphere and to prevent contamination of aquifers; underground storage of radioactive waste, with solutions either already in operation or under development in different geological environments, where it is crucial to assess the damage around the caverns to avoid the migration of radioactive elements; and underground gas storage in salt caverns (Bérest & Côme, 1993; Bérest, 2013). Following the Fukushima nuclear accident in Japan, interest was reignited in a previously considered idea: building nuclear power plants in underground spaces, thereby reducing the risk of airborne radioactive material dispersion in the event of an accident, as well as mitigating the risk associated with seismic activity (Duffaut & Sakurai, 2018).

3.1.6 Built heritage

The preservation of built heritage is an area where rock mechanics has played a significant role. Firstly, the conservation and restoration of monuments and other stone masonry structures

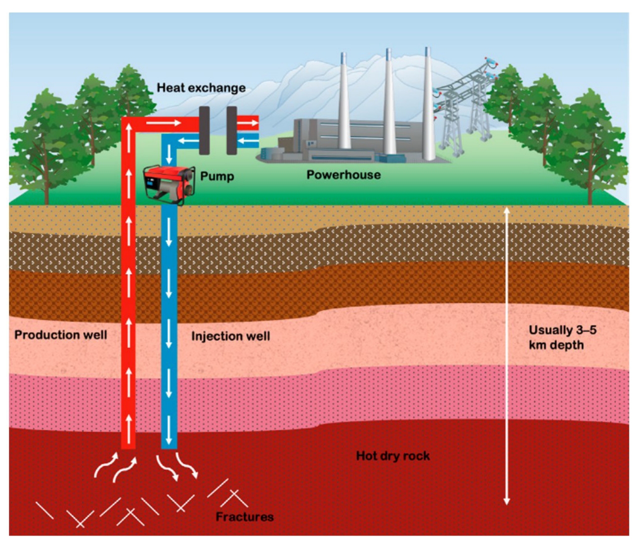


Figure 11. Diagram of an enhanced geothermal system (Cong et al., 2024).

is a field with extensive experience, particularly concerning the degradation processes of rocks over time in response to environmental conditions (Figures 12 and 13), and the most suitable intervention methodologies (Delgado Rodrigues, 2004).

From a structural behaviour perspective, rock mechanics clearly plays a role in the foundation issues of these structures (Jackson & Marra, 2006). It is also important to highlight the widespread use of numerical modelling tools in the analysis of engineering works in rock masses and stone masonry structures. In fact, block or discrete element models, which originally emerged in rock mechanics, have proven highly effective in studying block masonry structures, where discontinuities also play a critical role in terms of stability (Figure 14). Specifically, their application in analysing the behaviour of historical structures under seismic actions is particularly noteworthy (Psycharis et al., 2003). As in other areas, it is anticipated that the use of this type of representation will increase, with progressively greater refinement, supported by more sophisticated constitutive idealisations of materials and discontinuities. In addition to these issues primarily related to mechanical behaviour, the study of ancient structures requires the capacity to analyse and predict the evolution of material deterioration phenomena over time, and therefore, advanced models of interaction between the various physical and chemical phenomena involved.

3.1.7 Extraterrestrial rock mechanics

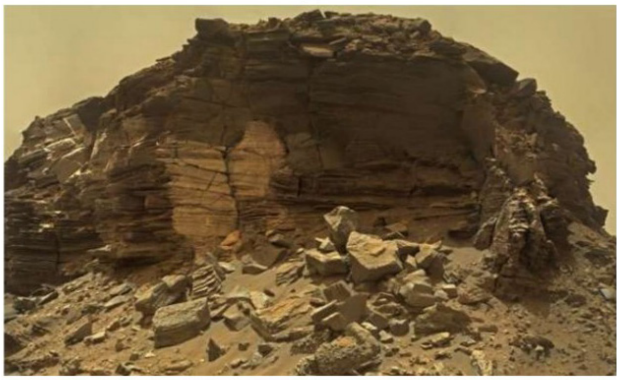
Moving even further beyond the traditional domains of rock mechanics applications, with space exploration and the growing interest in understanding the ground of other planets, as well as the race to establish bases and explore ore on the Moon or Mars, humanity will have to deal with unknown rock masses under conditions different from those on Earth. Extraterrestrial rock mechanics has already seen some development, particularly for drilling operations (Figure 15a) in robots used for missions to Mars. In an analysis of photographs of Mars, Aydan (2017) notes significant similarities in terms of discontinuities, rock weathering, and block sliding and rotational failure mechanisms on slopes (Figure 15b), concluding that the rock mechanics issues on Mars are very similar to those on Earth, provided the different gravitational fields, temperatures, atmospheric

Figure 12. Biocolonisation on limestone of the Jerónimos Monastery in Lisbon (Delgado Rodrigues, 2007).

Figure 13. Disintegration of a granite block (Delgado Rodrigues, 2007).

Figure 14. Roman temple of Évora, in Portugal, and discrete element model (Nayeri, 2012).

(a)



(b)

Figure 15. Extraterrestrial rock mechanics: (a) drilling probe of the Perseverance rover on Mars (ABC News, 2021); (b) slope failure on Mars (Aydan, 2017).

conditions, and the absence of water are properly considered. The growing relevance of this topic is demonstrated by the special issue of the International Journal of Mining Science and Technology recently published (see Tang et al., 2024).

3.2 Rock mass investigation

The different aspects of rock mass investigation will face future challenges of different natures. The increasing use of complex, yet user-friendly, numerical models, combined with empirical methodologies for obtaining values of rock mass properties, has led to the false assumption that it is easy and inexpensive to achieve high reliability levels in design solutions. This is often accompanied by less attention paid to the characterisation of rock masses and a failure to consider the greater uncertainty inevitably associated with a poorer understanding of the ground. This trend towards refining analyses and modelling, while reducing focus on actual geotechnical data, should be avoided. In this regard, the role of experienced engineers is crucial.

Another challenge, somewhat opposite to the previous one, arising from the complexity of some cutting-edge numerical models, concerns the need to have rock mass parameters as input data that are not easily obtained. This is, for instance, the case for discrete block models that require data on the geometry and persistence of discontinuity surfaces. The current ability to model highly complex systems, based on statistical descriptions of discontinuity surfaces using discrete fracture networks (DFNs), combined with particle or block models to simulate rock masses, requires the development of new methodologies for characterising the geometry of the rock masses.

According to Fairhurst (2010), "The critical next step to advance rock mechanics and rock engineering is to obtain reliable field-scale data to verify and improve numerical predictions. Urgent attention should be given to developing cost-effective ways of obtaining such data." The same author further states that "For a rock mechanics focus on the field scale, close interaction with engineering and structural geology is essential for optimal advances."

It is interesting to note the introduction of the concept of a "ground model" in the new generation of Eurocodes, set to come into force in 2028 (CEN, 2024), defined as: "site specific outline of the disposition and character of the ground and groundwater based on the results of ground investigations and other available data". The concept of a model that integrates all available data aligns with the perspective outlined by Fairhurst (2010), who considers rock masses as a whole, where what is relevant is the behaviour at the rock mass scale.

On the other hand, the availability of new technologies, particularly digital imaging obtained from terrestrial or aerial sources, with the increasing use of unmanned aerial vehicles (drones), as well as laser scanning (3D laser scan, LiDAR), combined with artificial intelligence tools for pattern recognition, will lead to a more intense and innovative use of these technologies in the characterisation of rock masses. Besides, the use of unmanned drilling and sampling robots will make the investigation in extreme or hazardous environments possible.

The georeferenced spatial representation of ground investigation data through Building Information Modelling (BIM) methods is already widely used and is, undoubtedly, a methodology that will see notable advances in the near future, with an increasing range of applications.

Knowledge of seismic activity and the risks it poses in the regions where it occurs has advanced significantly, partly due to the greater number and quality of records obtained from seismic networks, as well as InSAR technologies, which enable more precise quantification of surface movements associated with these phenomena (Lanari et al., 2010). Research in this area clearly has strong ties with rock mechanics, and understanding geological phenomena is essential for the engineering of rock masses structures.

3.3 Properties of rocks and rock masses

Based on the knowledge of rock masses obtained from ground investigation, including the results from in situ or laboratory tests, it is possible to quantify the properties of rock masses that are relevant to the analysis and design of projects. Ulusay & Gercek (2017) provide an extensive reflection on the future development needs of testing methods, giving particular emphasis to those listed below:

- rock tests at high temperatures, particularly for issues related to radioactive waste storage;
- dynamic rock tests, particularly shear strength tests of discontinuities subjected to dynamic loading;
- tests for determining the stress state in rock masses, both in the field using a variety of methods, and in the laboratory using acoustic emission techniques;
- sampling techniques and tests for soft rocks;
- tests for rocks known as bimrocks (built-in matrix rocks), composed of rock blocks embedded in a finer-textured matrix;
- true triaxial tests to investigate the influence of the mean principal stress on rock strength, deformability, permeability, and wave propagation;
- tests for determining rock excavability parameters;
- tests to determine damage limits to prevent spalling around excavations;
- tests for assessing rock weatherability and degradation rates.

With regard to underground research laboratories (URLs), it is expected that their number and the range of tests and investigations they can carry out will increase. URLs can play a significant role in the validation of theoretical developments. They are primarily used in experimental investigations related to the coupled study of thermo-hydro-mechanical-chemical processes in rock masses, which is relevant for issues such as radioactive waste storage and geothermal energy production projects (Wang et al., 2017).

Regarding the properties of rock masses, it is currently common practice to use the Hoek-Brown failure criterion, alongside a set of empirical equations, to estimate the strength and deformability parameters for rock masses. These parameters are typically derived from laboratory triaxial tests and qualitative observations of the rock mass—particularly its discontinuities—using the Geological Strength Index (GSI) (Hoek & Brown, 2019). Often, these equations are used applied without critical evaluation and are regarded as universally valid. The GSI, subjective in nature, exerts an enormous influence on the values of the rock mass strength and deformability properties. This reliance on a single, judgement-based input should be a matter of concern for both field geologists and design engineers. In this context, it is worth recalling the words of Evert Hoek, expressed in a letter to the editor of the News Journal of the International Society of Rock Mechanics in 1994 (Hoek, 1994, p. 24):

> In writing Underground Excavations in Rock almost 15 years ago, Professor E.T. Brown and I developed the Hoek-Brown failure criterion to fill a vacuum which we saw in the process of designing underground excavations. Our approach was entirely empirical, and we worked from very limited data of rather poor quality. Our empirical criterion and our estimates of the input parameters were offered as a temporary solution to an urgent problem.
>
> In retrospect, it is clear that we were naïve in believing that our emergency criterion would soon be replaced by a set of well-researched predictive tools which were well substantiated by field studies and back analyses of real rock engineering case histories. In fact, the reverse has happened, and I am alarmed to see the Hoek-Brown criterion being applied to problems which we did not even dream about when we made those desperate estimates 15 years ago.

This means that it will be important to continue developing studies to seek a robust failure criterion for rock masses, based on solid data and principles—not to immediately replace the Hoek-Brown criterion in rock engineering practice, with which there is extensive experience, but at least for research and specific types of applications. Such a criterion would benefit from considering the intermediate principal stress (Chang & Haimson, 2012), avoiding sharp points on the octahedral stress plane, having a defined yield function (Pan & Hudson, 1988), and being complemented by a definition of post-peak behaviour and the transition to the residual state (Crowder & Bawden, 2004).

Another relevant aspect concerns the intrinsic variability of the values of rock mass properties and the uncertainties associated with them. The values considered in safety verification calculations must account for this uncertainty in order to achieve the desired levels of reliability. In the context of Eurocode 7 (CEN, 2024), this uncertainty is addressed by using representative values of rock mass properties, particularly strength properties such as shear strength. When sufficient data are available to define them probabilistically, these values are referred to as characteristic values. However, data are often scarce, necessitating the use of nominal values instead. This highlights the importance of conducting statistical studies of rock and rock mass properties to support the determination of characteristic values for the most relevant properties in safety verification calculations.

3.4 Analysis methodologies for research and design

3.4.1 Numerical modelling

The methods for analysing rock mechanics problems have evolved from a reliance on physical modelling (Einstein, 2024) towards an increasing reliance on numerical modelling tools, a trend that is expected to continue in the future. In fact, the development of more complex numerical models, potentially capable of more accurately capturing the observed behaviour of rock masses, alongside the increased capacity of computational resources, has allowed for more intensive application of these tools at various stages of the design process. Starfield & Cundall (1988), in a pioneering paper on rock mechanics modelling methodology, emphasised the fundamental role of these models as tools that engineers can

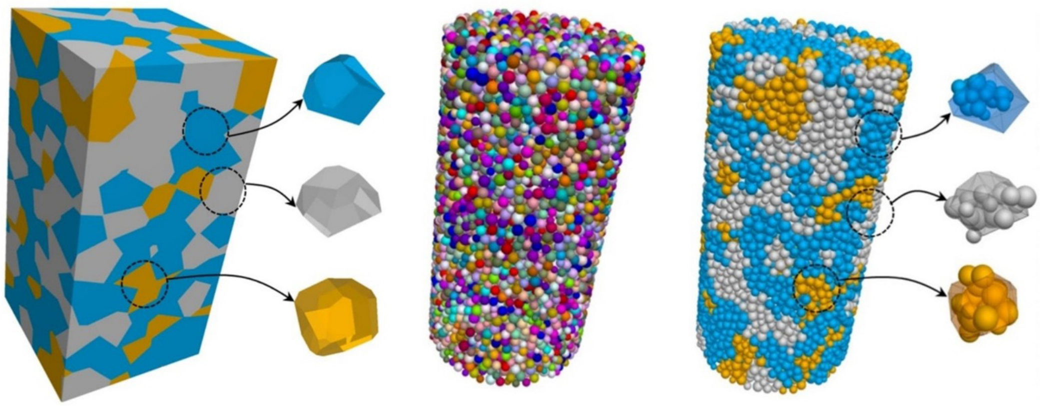


Figure 16. Representation of a rock sample by means of a grain-based bonded-particle model (Bu et al., 2025).

use to understand the dominant factors in a given problem, particularly by testing the various hypotheses consistent with available experimental data. One example that has gained increasing importance is the detailed simulation of laboratory or field testing conditions, allowing for a critical assessment of the experimental results. At the same time, the systematic use of models to analyse observed behaviour, in addition to contributing to the fundamental issue of their validation, enables a detailed analysis of the performance of engineering works. The current development of computational tools points towards the possibility of real-time modelling, with continuous updates of models through advanced calibration techniques (Sjöberg, 2020).

Given that discontinuities are a determining element in the response of rock masses, their representation in numerical models has been, over the past few decades, one of the most important challenges for researchers in this field. The objectives set in the early days of rock mechanics (Rocha, 1964) for the development of analysis methods have largely been achieved with the current finite element and discrete element models, which enable the detailed representation of the discontinuous medium in a variety of situations (Fairhurst, 2019). The simulation of soils and rocks using particle or block systems was already, two decades ago, identified as the future paradigm of modelling in Geotechnics (Cundall, 2001). It is expected that more intensive use of models for engineering works at a finer scale, namely resorting to particle assembly representations (Potyondy & Cundall, 2004), which support the concepts of "Synthetic Rock Mass" (Ivars et al., 2011) and grain-based models (Bu et al., 2025) (Figure 16). These models are obviously more demanding in terms of information, thus requiring more detailed characterization in the field and laboratory.

As the essential parameters governing the mechanical response of rocks and rock masses can only be obtained in statistical terms, it is necessary to incorporate the natural variability of geological media and the uncertainty of our knowledge into the representations (Elmo & Stead, 2020).

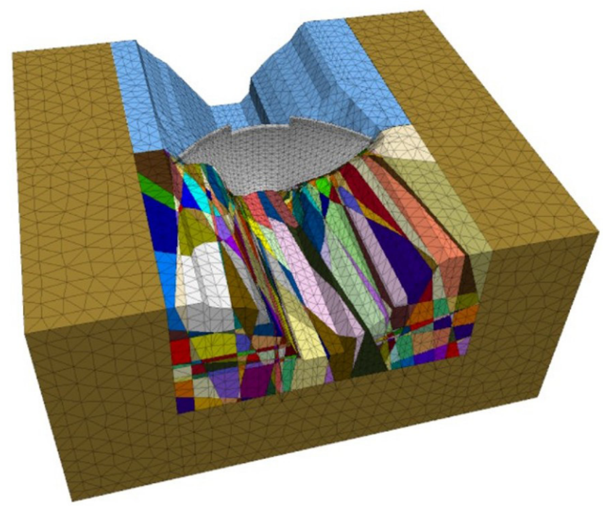


Figure 17. Discrete element model of the Foz Tua dam foundation (Espada et al., 2018).

Consequently, the use of stochastic models, based on realisations of statistical distributions adjusted to the key quantities involved, will inevitably become increasingly important. The computational resources available still limit the number of simulations required by a Monte Carlo analysis in most practical problems. However, the trend towards probabilistic safety concepts is an established fact and will shape the entire modelling practice.

In the context of discontinuous medium models, the issue of fracture propagation through the rock matrix, particularly the extension of pre-existing discontinuities, remains an area where developments are expected in the coming years. This progress will help avoid the overly conservative nature of many discontinuous models. Indeed, in project-scale models, such as those for the safety assessment of dam foundations (Espada et al., 2018) (Figure 17), although it is already possible to represent the rock mass discontinuity network in some detail, the rock blocks are often considered as rigid or elastic. In this line of development, the "Bonded-block models" (Garza-Cruz & Pierce, 2014; Rasmussen & Min, 2023) represent a powerful approach for simulating fracture and fragmentation processes, and thus the continuous-discontinuous transition, which is essential for a more rigorous quantification of the safety of rock mass structures (Figure 18).

A model is always a representation of physical reality, and at every stage of analysis, the question arises about the level of detail required, in line with the specific objectives of each project. Excessive detail can penalise computation times as well as the assessment of results, sometimes without offering significant advantages. For large-scale models, given the impossibility of widespread refinement, the use of multi-scale models should become increasingly important (Liu et al., 2018). This approach is based on the interaction between a coarser mesh that covers the domain under analysis and a simulator of the constitutive behaviour of each element, which can consist of a detailed numerical model of the representative elemental volume (REV) or even utilise artificial intelligence tools, such as neural networks (Masi et al., 2021).

A trend that will certainly become more prominent is the use of coupled models that account for the interaction of various physical phenomena. Analysis of hydromechanical interaction resulting from fluid flow in rock masses, particularly through discontinuities, is already common today, namely in dam foundation studies. In petroleum engineering, the importance of hydraulic fracturing phenomena is also notable. In environmental problems, the transportation of contaminants is a major concern. The inclusion of thermal variables and their interaction with mechanical, hydraulic, and even chemical processes (THMC) is crucial in environmental problems, such as waste storage (Radakovic-Guzina et al., 2023), or in geothermal engineering projects (Jing et al., 2000). Long-term behaviour prediction is an essential requirement for these projects, including thermal and creep effects on the integrity of the openings (Rutqvist & Tsang, 2024) (Figure 19). The rigorous characterisation of the parameters governing the interaction between various physical quantities is the most significant challenge for the success of these coupled models.

The consideration of the time variable is always a factor of complexity in modelling tasks. In this field, processes of slow evolution come first—those related to long-term behaviour, such as creep, weathering, or material degradation. At the other end of the time scale are dynamic phenomena, as in blasting or seismic loading, which typically involve high computational costs.

In recent years, the most influential developments in numerical modelling methodologies have perhaps resulted more from advances in software than from the underlying theoretical formulations. Foremost among these are the model

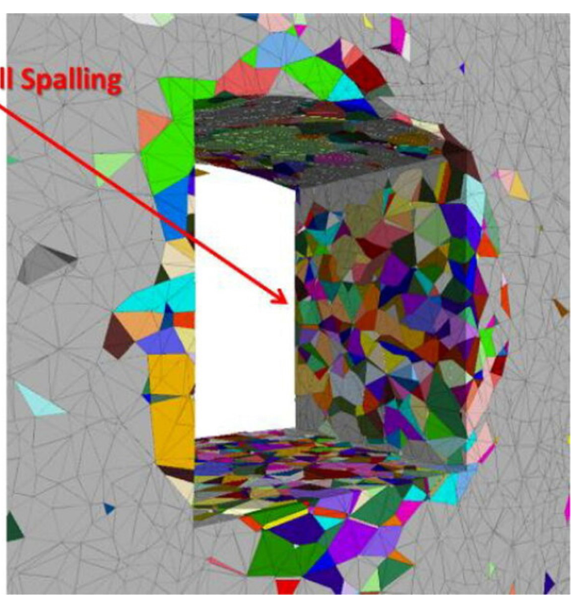


Figure 18. Bonded-block model for studying the deformational behaviour of block caving (Fairhurst, 2019).

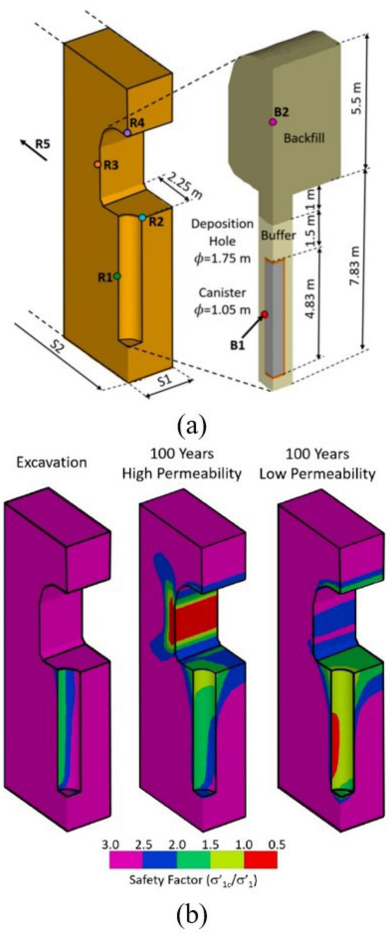


Figure 19. (a) Geometry of a deposition hole; (b) Safety factor against damage at excavation and at 100 years for high and low permeability (Rutqvist & Tsang, 2024).

generation methods, which enable the creation of larger and more complex systems with less effort from the engineer. The integration of CAD technologies with analysis codes is expected to become increasingly widespread, facilitating the realistic simulation of rock mass features, and its progressive updating as additional information becomes available. Internal scripting languages increase software versatility, allowing engineers to programme and automate tasks, as well as incorporating new constitutive models for materials or discontinuities.

Computational speed is crucial for enabling more refined and complex models. In this context, task parallelisation has emerged as the primary strategy. Many software packages already make efficient use of multiple processors on standard machines. However, massive parallelisation across distributed memory networks is fundamental to achieving a significant increase in processing speed. It is also worth noting the widespread accessibility of computational resources via global networks (cloud computing), offering engineers increasingly powerful tools.

3.4.2 Safety verification for design

Another relevant aspect in the analysis of rock mechanics problems is the safety verification in the context of the design of geotechnical structures. The most commonly adopted approach has been the use of global safety factors, with specific values assigned to different types of structures and safety checks. Their values are established empirically and deterministically, reflecting accumulated experience. While they have limitations in accounting for uncertainties of various natures and origins, they offer important advantages: they are calibrated through widespread practical use and are straightforward to apply.

More recently, design codes for geotechnical structures have been introduced that take into account the random nature of uncertainties associated with the properties involved in safety verification. Examples include the safety verification methodologies based on limit state design and semi-probabilistic methods, as recommended in Eurocode 7 (CEN, 2024) in Europe, which apply partial factors to representative values of loads and their effects, resistances, and material properties. Similarly, in the USA, the Load and Resistance Factor Design (LRFD) approach (AASHTO, 2020) uses coefficients that are applied to nominal values of loads and resistances. Semi-probabilistic methods are approximations of the results obtained from fully probabilistic methods, using representative values and partial factors to account for uncertainty and achieve the desired reliability. A major advantage of this approach is that, once the values of the relevant properties and the partial factors are defined, safety verification can be carried out in a manner similar to deterministic approaches, allowing for relatively easily straightforward application in most design instances (Lamas et al., 2023).

However, semi-probabilistic methods also present limitations, including: the assumption of independence between the various properties treated as random variables; the fact that some properties may have both stabilising and destabilising effects; the absence of defined partial factors for certain properties, particularly material properties; and the inapplicability of methodologies based on partial factors and representative values to address uncertainties associated with geometric properties. The latter two are particularly significant in rock engineering: (i) the partial factors provided in Eurocode 7 for material properties only cover the parameters of the Mohr-Coulomb criterion, requiring the use of approximate linearisation techniques when applying non-linear failure criteria commonly used in rock masses, such as Hoek-Brown and Barton-Bandis; and (ii) the probabilistic treatment of the geometric properties of discontinuity surfaces, particularly their orientation, is not possible within the semi-probabilistic method adopted in Eurocode 7, even though the geometry has as much influence on safety verification as the strength properties themselves.

These challenges can be addressed through structural reliability theory and the use of probabilistic methods, which is permitted in the second generation of Eurocodes whenever the uncertainties in the representation of loads, their effects, material properties and resistances are such that reliability-based methods offer a significantly improved representation over the use of partial factors (CEN, 2023). Rock masses are considered to fall within this category, as their behaviour is strongly influenced by the presence of discontinuities.

Probabilistic methods, which have already been applied in rock engineering in limited and relatively simple cases, are expected to undergo significant development in the coming years (Low, 2019; Harrison, 2019). Both exact probabilistic methods—such as the Monte Carlo method and its variants—and approximate probabilistic methods, such as FORM (First Order Reliability Methods) and others, are likely to see continued theoretical advancement and broader application to increasingly complex geotechnical structures (Schweckendiek et al., 2024). This evolution will undoubtedly be supported by the anticipated rapid growth in computational capabilities required to implement such methods.

3.5 Construction

There are undoubtedly numerous aspects related to engineering works in rock masses that are expected to undergo significant developments in the near future, particularly those concerning the utilisation of underground space. The growing demand for excavations with larger cross-sections, greater lengths, and at greater depths—delivered at costs competitive with surface alternatives and within increasingly shorter timeframes—will require the integration of improved ground characterisation with more realistic analyses of excavation behaviour, alongside the adoption of construction methods that incorporate innovative concepts and emerging technologies.

The substantial advances in technologies associated with tunnel construction—both in terms of excavation efficiency and in the reinforcement and support of the rock mass—deserve particular attention. Galler (2017) presents an interesting analysis of the key aspects of excavation methods using explosives and tunnel boring machines (TBMs), along with expected developments in this field. A particularly important area is the potential to produce high-quality raw materials from excavated spoil, which holds considerable environmental and economic value.

There is a fundamental difference, in terms of the energy input pattern, between excavation methods using explosives and those employing mechanical means (Hudson, 2012), which deserve careful consideration. In blasting, large amounts of energy are introduced within a matter of seconds, with intervals of many hours—or even days—between successive blasts. In contrast, mechanical excavation applies much smaller amounts of energy, but in a continuous manner. This marked contrast between the two excavation methods is likely to drive the development of construction techniques capable of delivering higher energy input in a continuous mode, as illustrated in Figure 20.

An increase in energy input during mechanical excavation will naturally result in a higher rate of penetration—either through applying greater thrust to the ground using more powerful motors, or by reducing the resistance of the rock mass to penetration. In this context, a noteworthy area of development is the use of microwaves to rapidly heat certain mineral constituents of the rock, as well as the water present, thereby inducing microcracks and fractures within the rock. When integrated into mechanical excavation equipment, such as tunnel boring machines (TBMs), this technology would enable rock fracturing and fragmentation to be achieved not only through the cutting action of the TBM's head but also via the thermal effects generated by microwave energy. Ongoing research in this field (Zhao et al., 2018) is expected to enhance the efficiency of mechanical excavation methods by increasing the continuous input of energy, ultimately leading to more cost-effective and time-efficient solutions.

3.6 Monitoring and observation

Long-term monitoring, used during the service life of structures and other engineering works, is essential when failure could pose a risk to public safety or carries significant economic consequences, as in the case with dams or bridges. In geotechnical engineering—where knowledge of material properties is often very limited—monitoring becomes particularly important during excavation phases, as it provides information on the behaviour of geotechnical structures that are constantly evolving. In mining engineering, monitoring is a continuous activity throughout the operational life of a mine. In civil engineering, excavation typically takes place over a limited period and is often followed by a phase in which service loads are applied. It is during these phases that monitoring becomes most significant, enabling the observation of the behaviour of the engineering works and providing real-time information to support the necessary decision-making to ensure safety.

Future developments in the monitoring of rock engineering works are expected to evolve along two main lines. Firstly, through the adoption of emerging technologies and equipment, and secondly, through the real-time integration of monitoring data with numerical analysis of rock mass behaviour.

On the technological front, the role of non-traditional geodetic methods in monitoring is set to grow significantly. Displacement monitoring at specific points using GNSS (Shimizu & Nakashima, 2017) has already achieved a millimetre-level precision, and the anticipated reduction in the cost of high-precision equipment will encourage wider adoption. Terrestrial and aerial digital photogrammetry now benefits from the widespread use of unmanned aerial

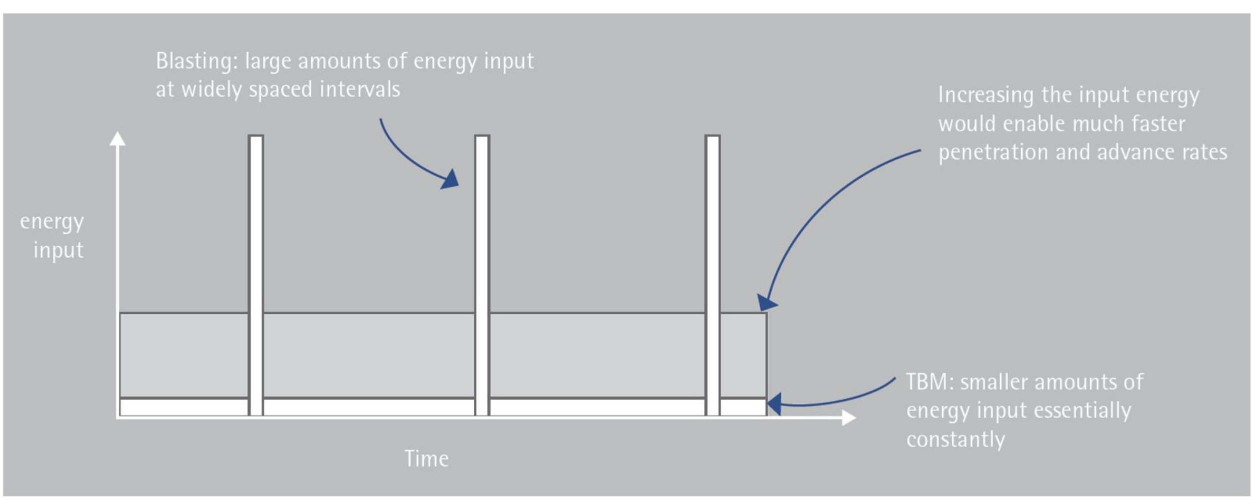


Figure 20. Energy associated with the excavation of rock masses by explosives and tunnel boring machines (Hudson, 2012)

vehicles (UAVs) for image capture, enabling the extraction of coordinates of the photographed surfaces and the generation of three-dimensional models of the observed objects. Laser scanning (LiDAR), like photogrammetry, is already widely used in slope monitoring (Figure 21), particularly in large open-pit mines and large natural slopes (Jaboyedoff et al., 2018; Kim et al., 2018). More recently, InSAR technology (Roque, 2020) has been applied to detect ground movements, including the monitoring of slopes (Figure 22). Advances in numerical processing associated with these techniques, as well as in computational power, are set to make them indispensable tools for monitoring surface displacements.

Microseismic techniques have been increasingly used to monitor micro-cracking in rocks subjected to high stress conditions. These techniques are more commonly applied in deep mines (Durrheim, 2017) and in sectors related to the oil and gas industry. More recently, they have also been used during the excavation of deep tunnels for road infrastructure or power conduits of hydroelectric schemes, with the aim of controlling and mitigating the effects of rockbursts during excavation (Feng et al., 2017). As activity at greater depths continues to expand, this technology has become the subject of ongoing research and is expected to see broader adoption.

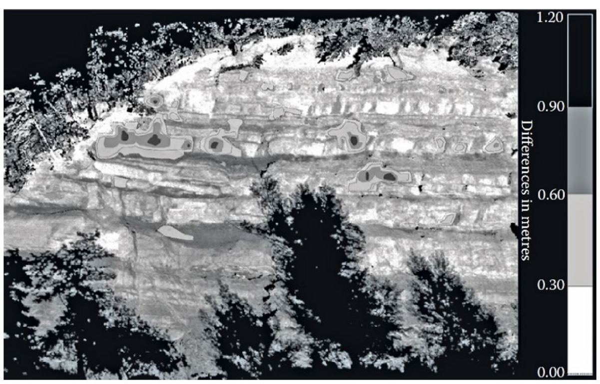


Figure 21. Comparative model showing block movements over time on a rock slope (Jaboyedoff et al., 2018).

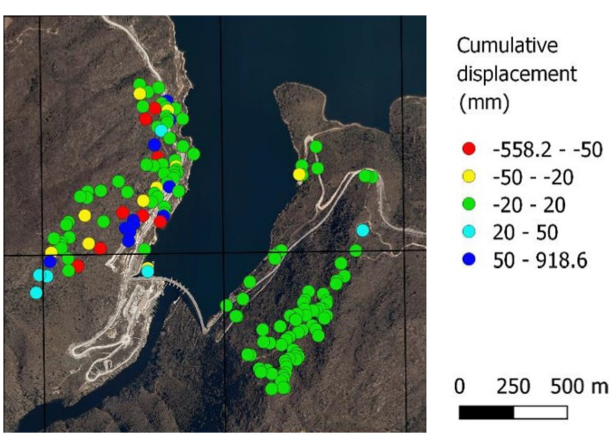


Figure 22. Accumulated displacement over a two-year period in the direction of slope inclination upstream of a dam (Roque, 2020).

The use of smart sensors is already common rock engineering (Yang et al., 2007). Smart sensors can be defined as devices that takes input from the physical environment and use built-in computational resources to perform predefined functions upon detection of specific input. and processing the data before transmitting it (Posey, 2021). These sensors operate within the framework of the Internet of Things (IoT), which involves connecting various types of objects to the internet, enabling their synchronisation and remote control—a bridge between the physical and digital worlds. It is clear that the application of smart sensors, based on IoT principles, combined with dedicated visualisation software, represents a particularly promising direction for geotechnical monitoring (Carri et al., 2021).

One area where advanced research is already underway is in the monitoring of rock bolts using smart sensors. Millions of rock-bolts are installed worldwide each year to reinforce slopes and excavations in rock, and their proper performance is essential for the stability of rock masses. However, their performance is usually assessed using pull-out tests, which are destructive and conducted after installation. The large-scale use of smart sensors—particularly piezoelectric and fibre optic types—aims to provide continuous information on installed forces, corrosion, and the condition of the grout (Song et al., 2017). This is just one example among many ongoing developments that are expected to see broad application in geotechnical works.

3.7 Artificial intelligence

Many rock engineering problems—whether at the surface or underground—are characterised by limited information about the ground conditions or the interactions between the ground and the structures to be built. In some cases, there is also limited understanding of the phenomena that govern the behaviour of rock masses and associated structures. Using Holling's conceptual classification of modelling problems, as illustrated in Figure 23 (Starfield & Cundall, 1988), problems falling within region 1 are defined

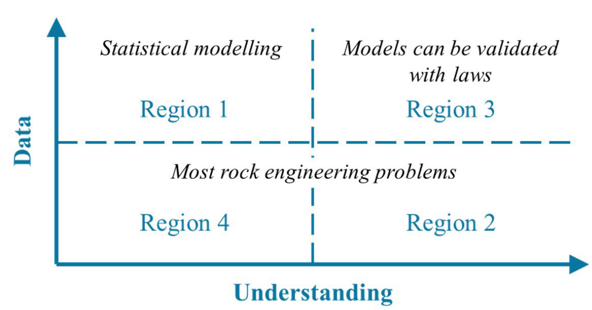


Figure 23. Holling's (Holling, 1978) conceptual classification of modelling problems (adapted from Starfield & Cundall, 1988).

by having good data but limited understanding, making statistical models appropriate. Problems in region 3 benefit from both good data and good understanding, which enables the development of reliable models that can be validated. In contrast, modelling problems in regions 2 and 4 are characterised by data scarcity—either because it does not exist or it is not accessible. Most rock engineering problems fall into these latter regions, yet methodologies typical of region 3 are often applied, which may not be appropriate (Feng & Yang, 2017). Given the limitations of analytical or numerical models under such conditions, artificial intelligence (AI) methods have become increasingly attractive, as they do not present a total dependence on prior knowledge of the governing phenomena or the formulation of hypotheses (Lawal & Kwon, 2021).

Methods that broadly fall within the scope of artificial intelligence (AI) have been playing an increasingly significant role across various fields of rock mechanics. One of the principal strengths of these techniques lies in their ability to identify behavioural patterns and generate automated predictions through the analysis of databases, without requiring direct intervention from the engineer. Besides, they possess a generalization ability to perform well on new data, beyond the specific training set. This approach has shown strong performance across a wide range of applications related to engineering works in rock masses (Feng & Yang, 2017).

In the context of rock mass characterisation, several authors have applied AI methods to rock mass classification systems (Saadati et al., 2024) and to estimate mechanical properties of the rock mass based on databases containing various parameters obtained from ground investigation activities (Elmo & Stead, 2020). A comprehensive review of such applications within the field of mining engineering is provided by Lawal & Kwon (2021).

Within numerical modelling, the development of constitutive models based on neural networks has been proposed by various researchers as an alternative to traditional mechanics-based formulations. This approach is expected to see broader application in the future, particularly in cases involving materials with complex behaviour or poorly defined loading conditions, where conventional constitutive laws fail to produce satisfactory simulations (Feng & Yang, 2017; Masi et al., 2021).

A more demanding application area involves the use of AI techniques to directly predict the behaviour of engineering works without using classical mechanical modelling (Morgenroth et al., 2019). This path is especially relevant in problems where conventional models are difficult to use—either due to the complexity of the underlying physical phenomena or the challenges associated with calibrating models with representative material parameters. Resende et al. (2008) used neural networks to predict vibrations caused by blasting, achieving accuracy comparable to traditional statistical analyses. Sousa et al. (2018) discuss the application of several AI techniques in the design and construction of deep underground works in rock masses, covering areas from the evaluation of mechanical properties to the prediction of dynamic instability phenomena, such as rockbursts. The prediction of rockbursts is, in fact, a field with considerable ongoing research activity, with AI and machine learning techniques being actively explored to address the limitations of conventional mechanical models. The aforementioned works by Morgenroth et al. (2019) and Lawal & Kwon (2021) present a range of recent developments in this area.

Finally, the review article by Feng et al. (2024) is worth mentioning, as it introduces a somewhat visionary idea: an artificial intelligence system for rock mechanics and engineering, built around the metaverse concept—"a virtual world where humans, as avatars, interact with each other in a 3D space that mimics reality" (CD, 2025). This AI system includes intelligent recognition of 3D geological structures, 3D geostress and rock mechanical behaviour; intelligent evaluation, monitoring and early warning of rock engineering disasters; as well as intelligent design and construction of rock engineering structures. The authors view AI as a key driver of a new technological revolution and industrial transformation, with significant potential for addressing challenges in rock mechanics and engineering.

4. Final remarks

Rock mechanics and rock engineering, like geotechnical engineering in general and other branches of engineering, have been undergoing an evolutionary process that in many ways parallels the transition from Industry 3.0 to Industry 4.0. The fundamental foundations of rock mechanics as a discipline were established in the 1950s, and from then until the early 21st century, substantial progress was made in its application across a wide range of engineering projects as well as in applied research.

Increasingly sophisticated testing methods and calculation models were developed, concepts were introduced that improved understanding of rock masses, their behaviour, and safety-related issues. Robot-assisted construction techniques, which are more efficient and environmentally friendly, were introduced, alongside new technologies for monitoring the performance of engineering works. In recent years, in parallel with the rise of Industry 4.0, there has been a rapid technological shift driven by the introduction of remote inspection, monitoring, and control methods, using augmented reality; the widespread use of geo-referencing systems, displacement measurements, and satellite imagery; the application of artificial intelligence (AI) to solve problems with clear advantages over traditional approaches; the emergence of the concept of digital twins in rock engineering and virtual rock masses; and the use of the internet (IoT) to facilitate communication between physical systems and human users.

Engineers will need to rise to the challenges posed by this transition. However, doing so requires a solid background education in rock engineering. It is widely recognised that one of the main causes of deficiencies—or even failures—in rock engineering is the inadequate education and training of professionals. As a discipline that lies at the intersection of several others, university curricula in civil or mining engineering often either omit rock engineering entirely or fail to provide sufficient coverage of essential geological knowledge. Likewise, geology degrees rarely provide students with the necessary engineering background. In Europe, for example, the decline in projects where rock engineering is essential—such as large dam foundations, major underground works, or surface and underground mining operations—may explain a diminished interest in the discipline. As a result, rock engineering issues are frequently addressed by professionals without specialist knowledge in the field. It is vital that this situation be reviewed in the near future.

International exchange, as in other technological fields, is essential for the sharing of knowledge and experience, and to engage professionals in activities that go beyond national boundaries. Within the European context, greater participation in European initiatives is highly relevant—whether in technical regulation and standardisation through bodies like the European Committee for Standardization (CEN) or the International Organization for Standardization (ISO), or in partnerships for research, development, and innovation. Active engagement in working groups or technical committees of international societies—such as the International Society for Rock Mechanics and Rock Engineering (ISRM), the International Commission on Large Dams (ICOLD), or the International Tunnelling and Underground Space Association (ITA)—is also highly valuable.

It is also worth reflecting on the future role of key platforms for professional interaction, namely working meetings and conferences. Changes in working practices, accelerated during the COVID-19 pandemic, have led to many events being held, at least partially, online. While the savings in time and cost are immense, essential personal contact tends to diminish, and the overall balance of advantages and disadvantages remains uncertain. Online events introduced greater efficiency, by dramatically increasing professional interaction among in all tasks; however, they cannot fully replicate the synergies built through in-personal contact, which remains indispensable.

Technical and scientific societies—both national and international—are already adapting to the reality that information is now freely and easily accessible to anyone via the internet, aided by selective search tools. The spontaneous formation of groups for exchange of information and knowledge may, to some extent, substitute some of the traditional roles of these societies. However, such organisations may in fact become even more valuable, serving as hosts to technical committees responsible for curating the growing volume of available information and producing guidelines, manuals, recommendations, and other publications of value to their members. They can also play a pivotal role by organising traditional in-person events, such as conferences and technical exhibitions, in partnership with industry, alongside a wide array of knowledge dissemination and discussion initiatives held online. Additionally, they should strengthen efforts to recognise the merit of individual and collective members and enhance their visibility and influence within technical and scientific communities, as well as among policymakers. By transforming their scope of activities and modes of operation, technical and scientific societies can successfully meet the challenges ahead and continue to engage the professional and academic communities—particularly younger members—making membership clearly advantageous and encouraging active participation in their initiatives.

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Declaration of interests

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors’ contributions

Luís Lamas: conceptualization, methodology, investigation, validation, data curation, writing - original draft preparation. José Vieira de Lemos: conceptualization, methodology, investigation, validation, data curation, writing - original draft preparation.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of generative artificial intelligence. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

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