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The challenges of "hard soil and soft rock": an inside into this material's brittle to ductile behaviour

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Abstract

The paper addresses the geotechnical challenges of transitional rocks, also known as "Hard Soils – Soft Rocks" (HSSR). HSSR materials exhibit mechanical properties that lie between hard rock and (soft) soil. Due to their variability in strength, stiffness, weathering sensitivity, and classification uncertainties, these transitional materials pose significant challenges in engineering applications such as tunnelling, foundation engineering, and deep excavations. The publication explores the spectrum of brittle to ductile behaviour of HSSR materials, highlighting their water sensitivity, anisotropic behaviour, and time-dependent deformations, including clay swelling. Adapted constitutive models and advanced numerical methods capable of representing the complex behaviour of HSSR materials are discussed.

The paper illustrates the limitations of conventional classification systems, which often fail to adequately characterize HSSR materials due to their transitional properties. Parameters such as uniaxial compressive strength (UCS), weathering effects, and anisotropy are identified as critical for classification. Advanced laboratory methods and in-situ tests underscore the importance of integrating laboratory and in-situ data to improve material characterization.

The use of fully equipped in-situ test galleries is demonstrated through a specific project example, providing insights into large-scale observations in an HSSR environment. The integration of results from various scales - in-situ, laboratory, and mineralogical studies at macro, meso, and micro levels - illustrates the scaling problem.

Recommendations include the development of unified classification frameworks that bridge soil and rock mechanics, the consideration of anisotropy, and the refinement of sampling and testing methods. This multidisciplinary approach aims to enhance the predictive accuracy of geotechnical models and to ensure safer, more efficient engineering applications in environments dominated by HSSR materials.

Keywords

Hard soil and soft rock (HSSR), brittle-to-ductile transition, anisotropy, swelling and degradation, geotechnical classification

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1 Introduction

Hard rocks and (soft) soils are clearly described in geotechnical terms. Hard soil and soft rock (HSSR) materials are situated in a transitional zone between soil and rock, embodying properties of both categories. Their classification and mechanical behaviour are often elusive, presenting significant challenges in engineering applications, particularly tunnelling and deep excavation projects. Mischaracterizing HSSR can result in design errors, project delays, and financial overruns. The purpose of this publication is to examine the mechanical behaviours of HSSR, particularly the brittle-to-ductile transition, and its implications for geotechnical design and construction strategies.

Soft rock materials are those that exhibit rock-like characteristics but possess significantly lower strength and higher deformability compared to typical hard rocks. They may crumble under hand pressure or lose strength when exposed to water. Hard soils, on the other hand, display soil-like behaviour with higher strength and lower compressibility than what is observed in typical soil types. The boundaries between these two categories are not clearly defined, leading to ambiguity in classification. Both materials can transition into one another due to weathering or stress conditions, which further complicates their categorization.

This paper begins by detailing the typical characteristics of HSSR materials and subsequently highlights the challenges associated with employing classification systems for these materials. It then examines the difficulties encountered in modelling their behaviour. Based on these findings, strategies to address the primary shortcomings are proposed. The paper concludes with an exploration of future trends and recommendations for HSSR material.

2 Geological and Geomechanical Characteristics of HSSR

2.1 Geological rock formation and environmental impacts

Based on their formation processes, solid rocks are generally classified into three primary categories, namely igneous rocks (also referred to as magmatites), sedimentary rocks, and metamorphic rocks. Within each of these groups, transitional rock types (HSSR materials) are commonly observed, representing intermediate stages of rock transformation. Examples of such transitional rocks include phyllites and shales within the metamorphic group, sandstones, clays, and siltstones among sedimentary rocks, and volcanic ashes and tuffs within the igneous category. Transitional rocks encompass a spectrum of materials ranging from weathered solid rocks - where the bonding between mineral grains progressively deteriorates - to partially consolidated loose rocks, such as mudstones, marlstones, and sandstones. These transitional types reflect varying degrees of lithification and mineral cohesion.

The properties of these rocks are influenced by several factors, including compressive strength, porosity, and the degree of mineral grain bonding. Cohesion, which is a key indicator of compressive strength, is particularly critical in assessing the mechanical behaviour and stability of these rocks under various conditions. Understanding these characteristics is essential for evaluating the performance of rocks in engineering and geological applications.

Prinz and Strauss (2018) define weathering as the process of rock decay and the dissolution of rock structure through physical or chemical mechanisms. Weathering can manifest differently depending on the resistance of the rock to these processes, leading to a classification into “weather-resistant” and “weather-sensitive” rocks. The extent and type of weathering are influenced by factors such as morphological exposure and climatic conditions, which largely govern the intensity of weathering and the development of specific weathering profiles.

The behaviour of clay minerals in response to water, such as intracrystalline swelling caused by water incorporation into interlayer spaces or osmotic swelling due to water absorption in pore spaces are critical for understanding the specific interactions of clay-rich materials with water under varying environmental conditions.

2.2 Main geomechanical characteristics of HSSR

HSSR materials are characterized by intermediate material properties, often defined by unconfined compressive strengths (UCS) ranging from approx. 0.5 to 25 MPa. The classification is complicated by the significant variability in strength and response due to environmental factors. As already mentioned in chapter 2.1 a defining feature of HSSR is its sensitivity to water, which often leads to rapid strength reductions (softening behaviour) and structural disintegration (degradation mechanisms).

HSSR material often exhibits anisotropic behaviour, which is attributed to inherent features such as foliation and bedding. This anisotropy is a direct result of sedimentary or low-grade metamorphic processes, where the alignment of minerals or layering influences mechanical properties. For example, Marcher (2024) highlighted the role of sedimentation and compaction in creating anisotropic features, such as laminations and foliations, which significantly influence the mechanical behaviour of materials like e.g. phyllites, schists or marlstones.

Water sensitivity is a critical feature of HSSR material. Laboratory and field experiments have shown that water ingress not only reduces material strength but also often induces swelling, leading to complex deformation patterns. Tests described by Metzler et al. (2024a) illustrate that cyclic wetting processes exacerbate disintegration in argillaceous soft rocks.

Additionally, time-dependent behaviours such as creep and long-term deformation play a significant role in HSSR.

2.3 Important Parameters for Classification

Soft rocks exhibit geotechnical properties that occupy an intermediate range between those of cohesive soils and hard rocks, without sharply defined boundaries between these classifications [Nickmann et al. 2006]. Despite their importance in geotechnical engineering, research on the influence of sampling and storage conditions on laboratory data for soft rocks (HSSR) remains limited [Ungewitter, 2021 and Metzler et al. 2024a]. The development of standardized workflows for handling HSSR during geotechnical investigations - including sampling, transportation, storage, and laboratory testing under low in-situ stresses – is still a critical area of ongoing research [Ungewitter, 2021]. The integration of field observations with laboratory test results has the potential to uncover consistent trends in the physical and mechanical behaviour of soft rocks, reducing variability in the data and enhancing predictive models [Kanji, 2014].

Uniaxial compressive strength (UCS) is a commonly used parameter for classifying HSSR, although the specific thresholds vary among researchers. Generally, soft rocks are characterized by a UCS of up to 25 MPa [Kanji, 2014 and Kanji 2020 et al.]. A defining feature of HSSR is their pronounced and often irreversible loss of strength upon exposure to water. This water-induced degradation adds to the variability of their mechanical properties [Nickmann, 2009 and Nickmann et al. 2006, 2010]. Laboratory-determined UCS values are influenced by several factors, including sample preparation techniques, sample size, saturation level, and the mineralogical composition of the rock [Agustawijaya 2007, Bostjancic 2023, Metzler et al. 2024a].

A key challenge in understanding HSSR material lies in their high susceptibility to degradation, especially when exposed to environmental factors such as water. Understanding the mechanisms driving this behaviour is essential for designing appropriate sampling and lab testing procedures to preserve in-situ conditions as much as possible.

The classification of HSSR materials involves assessing a combination of physical, mechanical, and environmental factors. As already stated, one of the primary parameters used is unconfined compressive strength (UCS). For soft rocks, UCS values typically range from 5 MPa to 25 MPa, while for hard soils, these values fall into the range from 5 MPa down to 0.5 MPa but remain higher than those of typical soils. However, this single parameter is not sufficient to fully capture the transitional behaviour, as UCS values can be highly variable depending on sampling and testing conditions, as well as exceed the theoretical 25 MPa threshold.

Other critical factors include the degree of weathering, which has a profound impact on the material's mechanical properties. Weathering transforms fresh rock into soft rock and, eventually, into residual soil. This progression introduces a spectrum of conditions that require careful observation. The processes of weathering and/or loosening are closely associated with softening and degradation, which both leads to a reduction in strength. This softening is driven by the mechanical-tectonic and/or thermal stress history experienced by the rock. The type and extent of such pre-stresses, particularly tectonic influences, combined with the inherent properties of the rock, define the separation surface structures, including bedding surfaces, schistosity planes, and fissures. However, this article does not address tectonic faults or fault zones and their characteristic deformation structures such as e.g., fault gouges or cataclasites.

The structural features of the material, such as bedding planes or foliation and joints, also play a pivotal role in classification. In soft rocks, these features can dominate their mechanical response, leading to anisotropic behaviour. Similarly, hard soils may exhibit relict structures from their geologic history, influencing their strength and compressibility.

Index properties such as liquid limit, plasticity index, and grain size distribution are traditionally used for soils but have limited applicability to soft rocks. For hard soils, these indices provide insight into their behaviour under different loading conditions. Additionally, parameters like dry density and porosity offer clues about the material's degree of cementation and consolidation, essential for distinguishing between soft rocks and hard soils.

Porosity, as defined by Prinz and Strauß (2018), refers to the proportion of pore volume within a material and serves as a relative measure of density. It is influenced by both the strength of the rock and its depth relative to the current ground surface (overburden). Consequently, in addition to the type and composition of the parent material, the formation process and geological history - including the stress evolution leading to the rock's current state - play a significant role in classifying rocks within the spectrum of transitional rocks and in characterizing their specific material behaviours.

The durability of soft rocks, particularly their tendency to degrade or slake upon exposure to water, is another key consideration. Durability tests, such as the slake durability index, are often conducted to assess the material's resistance to environmental conditions. These tests help in predicting long-term performance and potential changes in material behaviour due to external factors.

In practical applications, the distinction between transitional rocks, loose rocks, and solid rocks can be determined using either water storage tests or compressive strength measurements. According to EN ISO 14689-1:2003, rocks that exhibit changes during water storage tests are classified as 'variably solid rocks' or 'semi-solid rocks.' These rocks typically exhibit characteristics similar to solid rocks under initial conditions but undergo significant degradation when subjected to cycles of drying and re-moistening. This degradation can manifest as an increase in macroscopically visible cracking or progress to the complete disintegration of the rock structure.

In addition to the difficulties of sampling (as mentioned previously) another challenge lies in the in-situ testing of HSSR material. Conventional on-site methods, such as cone penetration testing (CPT), flat dilatometer testing (DMT), and standard penetration testing (SPT), often reach their operational limits because the ground is frequently classified as impenetrable (SPT blow count > 50). Conversely, traditional rotary drilling with diamond drill bits can severely damage samples, often resulting in heavily fragmented or destroyed/damaged drill cores.

Due to these limitations, many types of transitional rocks are difficult or impossible to characterize using conventional classification methods. Most existing systems are designed for discontinuous hard rock and are not well-suited for quasi-continuous materials like typical transitional rocks. In the long term, it will be necessary to either adapt current classification systems or develop entirely new approaches tailored to these intermediate materials (Kanji, 2014).

3 Classification Challenges for HSSR materials

3.1 Classification Systems

Rock Mass Classification Systems (RMCSs) have been integral to the rock engineering industry, enhancing consistency in rock mass evaluation and support design globally for decades. Originally developed primarily in the 1970s to 1090s (see Erharter et al. 2023 and Erharter et al. 2024) a variety of classification systems have later been proposed to handle the unique characteristics of soft rocks and hard soils. For hard soils, traditional soil classification systems like the Unified Soil Classification System (USCS) may suffice but often require augmentation with additional mechanical tests. For soft rocks, systems developed for rocks, such as the Rock Mass Rating (RMR) and Geological Strength

Index (GSI), are sometimes adapted. These systems consider factors such as strength, weathering, and structural conditions.

Hybrid classification systems that integrate elements of both soil and rock mechanics are increasingly used for HSSR materials. For instance, engineering-based classifications focus on the material's behaviour under field conditions, such as its response to excavation or its bearing capacity. Such systems often combine laboratory and field test results to provide a more comprehensive understanding of the material.

3.2 Classification based on UCS

The classification of intact rocks based on their strength has been explored by various authors over the years, with subdivisions ranging across a spectrum from soils to very hard rocks. While there is general consensus on the upper limit of soft rock strength, typically around 25 MPa, the lower boundary for transitional rocks remains less clearly defined.

The lack of clarity arises from differences in both the test methods employed and the associated strength values reported. Terzaghi and Peck (1967) propose a lower boundary between soil and rock defined by an SPT blow count exceeding 50 and a uniaxial compressive strength (UCS) of at least 0.4 MPa. According to their definition, materials exceeding these thresholds should exhibit rock-like rather than soil-like behaviours. In contrast, Dobreiner (1984) specifies a fixed lower limit at the transition point, set at a UCS of 0.5 MPa. Other researchers have incorporated additional parameters to account for variability. Rocha (1975), for example, considers not only strength but also the material's behaviour when submerged in water. More recently, Baud and Gabmin (2011) introduced a criterion based on the limit pressure in borehole expansion tests. Their proposed threshold ranges from 2 to 10 MPa, depending on the ratio between the modulus of elasticity and the limit pressure (Kanji, 2014 and Kanji et al, 2020). These diverse approaches highlight the complexity and ongoing debate surrounding the classification of transitional rocks (see Fig. 1).

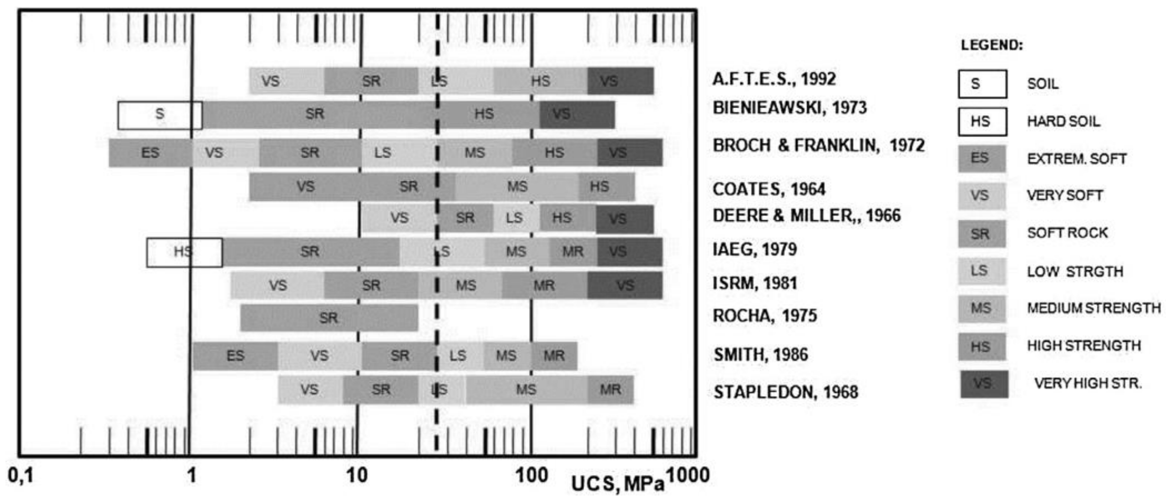


Fig. 1 Classification of rocks according to the strength (UCS) in MPa (Kanji, 2014).

3.3 Classification by variability classes

In German-speaking countries, variably solid rocks (“veränderlich feste Gesteine”) are generally classified as solid rocks. However, they are distinguished by their specific characteristics, notably their tendency to lose cohesion upon exposure to atmospheric gases within a time frame ranging from a few days to several years. This loss of strength is irreversible. Consequently, these rocks serve as an intermediate category, bridging the gap between loose rocks and permanently solid rocks (Nickmann et al., 2005).

In common terminology within engineering geology and geotechnics, variably solid rocks are characterized by their distinct properties. These rocks are classified as solid rocks according to DIN EN ISO 14689-1, exhibiting significant internal cohesion that differentiates them from soil. However, they are highly sensitive to changes in water content, which can cause irreversible weakening of their mineral structure. Additionally, the alteration or degradation of these rocks occurs within a relevant timeframe, typically within few years to a decade.

The transitional nature of HSSR material creates challenges in defining clear boundaries between these three rock groups, as their properties are continuously influenced and interconnected through geological processes such as diagenesis, metamorphism, and weathering, as shown in Figure 2.

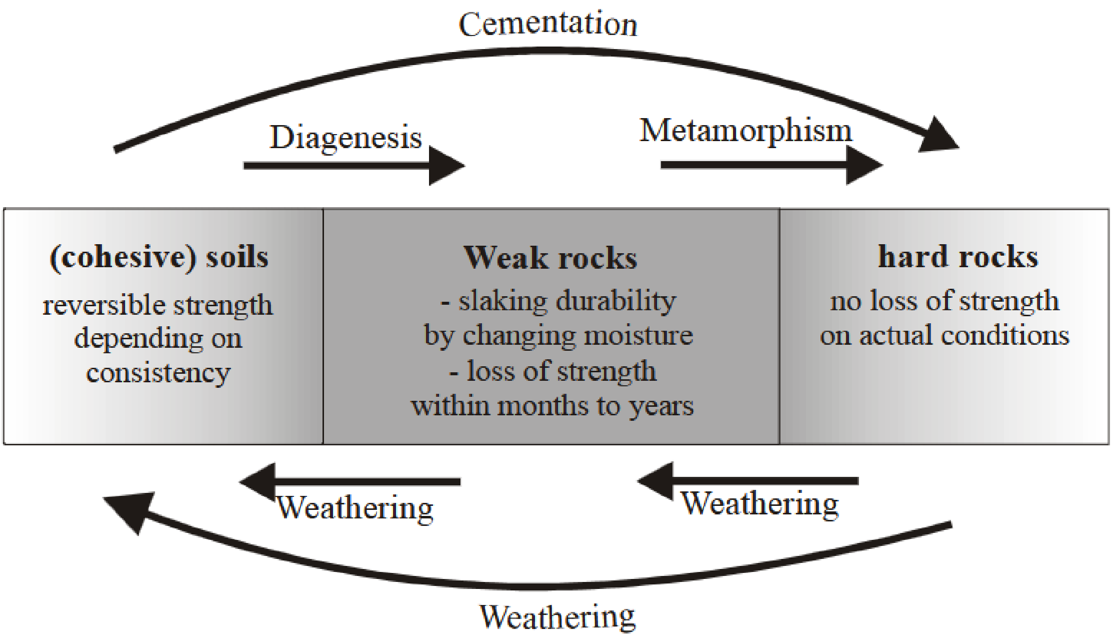


Fig. 2 Position and delimitation of the variable solid rocks (Nickmann, et al., 2006).

Nickmann et al. worked out variability classes. This is based on modified water storage tests, incorporating three cycles of drying and humidification along with a crystallization test, enables the classification of rocks into variability classes. The first water storage test is conducted on samples in their natural moisture state. The immediate reaction of the sample and its condition after 24 hours of water storage are assessed. Following this, the sample is screened and dried in an oven at 50°C, then subjected to two additional cycles of water storage followed by drying.

To distinguish variably solid rocks from solid rocks and to define the variability classes VK 0 and VK 1, a crystallization test is also performed. If the sample withstands the crystallization test without damage, it can be classified as permanently solid (Nickmann et al., 2006).

VK	**I_v**	**class**	**Description**
VK 0	285-300	Hard rock	No change up to the 3rd wetting-drying-cycle, maybe small losses because of loosened aggregates during sample preparation (< 5 %), no reaction in the crystallisation test (loss < 10 %)
VK 1	195-285	Low slake durability	No change up to the 3rd wetting-drying-cycle, maybe small losses because of loosened aggregates during sample preparation (< 5 %), losses in the crystallisation test > 10%
VK 2	145-195	Slow slake durability	No reaction during 1st wetting, up to the 3rd cycle cracking and /or beginning of decay up to 50 % of the original mass
VK 3	92,5-145	Medium slake durability	During 1st wetting cracking or loss of smaller aggregates (max. 10 % of mass), but the sample remains preserved. Up to the 3rd cycle decay into aggregates > 2,5 % of the original mass
VK 4	27,5-92,5	Rapid and high slake durability	During 1st wetting disintegration up to 75 %, up to the 3rd cycle decay into aggregates < 2,5 % of the original mass
VK 5	< 27,5	Immediate and very high slake durability	Spontaneous decay into aggregates < 25 % during 1st wetting, up to the 3rd cycle into flakes < 0,1 %

Fig. 3 Classification of the variability classes of variable solid rocks on the basis of 3-cyclic wetting-drying-test and the crystallization test. (Nickmann, et al., 2006)

During diagenesis and eventually metamorphism, the clay minerals originally deposited in loose sediments are initially transformed into illite and subsequently into non-water-sensitive minerals of the mica group, primarily chlorite and muscovite. [Plinninger et al. 2012]

A clear genetic distinction between cohesive loose sediments and variably solid rocks is not feasible (see also Fig. 2). Historically, uniaxial compressive strength has often been used as a proxy for differentiation, with upper limits for loose sediments typically ranging between 0.5 and 3.6 MPa [Nickmann 2009]. However, some materials unequivocally classified as loose sediments can exhibit strengths of up to approximately 5.0 MPa..

The mineralogical boundary between variably solid (hard) and permanently solid rocks is defined by the transformation of the last illite minerals into stable layer silicates at approximately 350°C, corresponding to a burial depth of around 10 km. While this transformation can be mineralogically verified, a practical construction-relevant conclusion can only be drawn if no illite minerals are detected. In all other cases where illite is present, the assessment of potential variability remains inconclusive. [Plinninger et al. 2012]

3.4 Classification regarding anisotropy

Rocks are classified according to their anisotropic mechanical properties (e.g., compressive strength, point load index, etc.) to help engineers understand their behaviour. Furthermore, the classifications and corresponding indices for intact rocks can be directly used in rock mass rating systems or numerical analyses. For instance, Saroglou et al. (2019) advanced the traditional Rock Mass Rating (RMR) system by incorporating rock anisotropy, explicitly accounting for the degree of anisotropy in their assessment. This modification allows for a more precise characterization of anisotropic rock masses, leading to improved prediction accuracy in rock mass behaviours.

Similarly, Vakili et al. (2014) proposed a novel constitutive model that includes a strength anisotropy index (Rc). This index quantifies the intensity of anisotropy by comparing the maximum and minimum strength values of a rock sample in relation to its planes of weakness. By integrating Rc into their model, Vakili et al. facilitated the accurate simulation of anisotropic behaviours in numerical analyses. This approach addresses the directional variability in mechanical properties, enabling engineers to capture the nuanced failure mechanisms and deformation behaviours that are characteristic of anisotropic rocks.

The incorporation of anisotropic properties into classification systems and numerical models represents a significant step forward in geotechnical engineering. These advancements ensure that designs consider the complex, direction-dependent behaviours of rock materials, ultimately enhancing the safety, reliability, and efficiency of engineering solutions in rock-dominated environments. As research progresses, the continued refinement of these methods will further bridge the gap between laboratory characterization, in-situ behaviours, and computational modelling, providing robust tools for managing the challenges posed by anisotropic rocks.

3.5 Classification Challenges

The transitional nature of HSSR presents several challenges for classification. One of the primary issues is the lack of clear boundaries between these materials and their more conventional counterparts. This ambiguity often leads to inconsistencies in classification, particularly when different methods or criteria are used. Additionally, the variability in material properties due to geological heterogeneity adds to the difficulty. For instance, a single homogeneous ground at a project site may exhibit a wide range of conditions, from highly weathered soft rock to intact hard soil.

Another challenge is the impact of sample disturbance on test results. Soft rocks, in particular, are prone to crumbling or losing strength during sampling, making it difficult to obtain representative samples. This issue is compounded by the influence of environmental factors, such as water content and weathering, which can cause rapid changes in material properties. As a result, classification systems must account for these "dynamic" conditions to remain relevant.

Swelling potential further complicates classification, particularly in formations containing significant quantities of clay minerals such as smectite, illite or montmorillonite. These minerals exhibit pronounced swelling behaviours upon water exposure, leading to mechanical property changes that traditional classification systems fail to capture. Sampling and storage conditions also play a critical role. Poor handling practices during field collection can alter material properties, skewing classification outcomes. Metzler et al. (2024b) emphasize the need for rapid sample processing and consistent handling protocols to maintain in-situ conditions.

The intrinsic anisotropy of HSSR, caused by sedimentary bedding and mineralogical layering, affects mechanical behaviour such as deformation and failure mechanisms. This anisotropy necessitates the inclusion of directional parameters in classification frameworks, moving beyond isotropic assumptions.

4 Challenges in Modelling

Modelling the behaviour of HSSR materials is fraught with challenges due to their transitional nature and environmental sensitivity. Traditional isotropic models often fail to represent the directional dependencies and non-linear stress-strain responses inherent to these materials. For instance, anisotropy arising from foliation and bedding requires advanced models that incorporate directional stiffness and strength parameters (e.g., Winkler et al. 2020a and Winkler et al., 2024). Post-peak softening, a defining characteristic of HSSR, necessitates strain-softening laws to capture progressive weakening and localized strain redistribution.

Mechanically, transitional rocks exhibit two distinct phenomena: "pre-peak" hardening, characterized by the mobilization of the friction angle, and "post-peak" softening, marked by a reduction in cohesion and/or friction angle. These behaviours underline the complex mechanical response of transitional rocks under stress, necessitating careful consideration in geotechnical analyses and design. The softening behaviours of transitional materials is influenced not only by the friction angle and cohesion but also by their reduction and interaction under stress. Particularly in transitional zones, a strong correlation exists between the stress level and the progression of the softening branch. As lateral pressure increases, these materials tend to transition towards an ideal-plastic stress-strain response.

Figure 4 illustrates the contrast between rock-like and soil-like materials as a function of stress level. For rock-like marl, a pronounced shift in the failure mechanism is observed, transitioning from brittle behaviours under uniaxial stress to ductile, ideal-plastic behaviours with increasing lateral pressure. In contrast, soil-like materials exhibit a failure mechanism that is far less sensitive to variations in lateral pressure, maintaining a more consistent response under changing stress conditions.

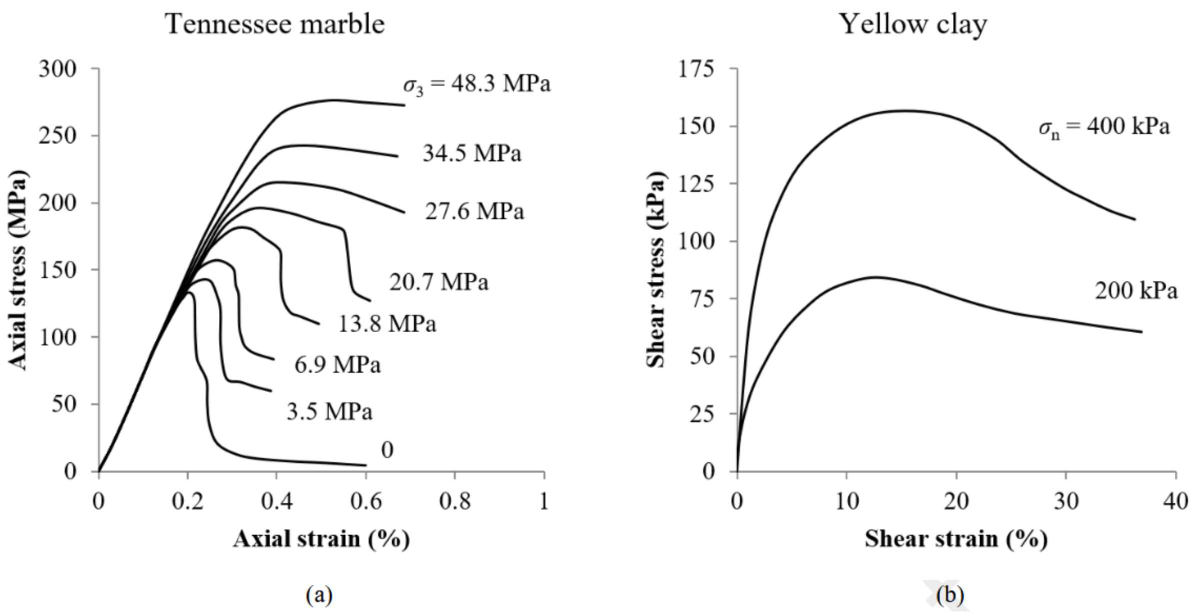


Fig. 4 Triaxial Stress-Strain behaviour as a function of the lateral pressure of marl (left) and clay (right) (Rafiei Renani et al. 2019)

Water introduces additional complexity. The mechanical properties of HSSR drastically change in the presence of water, reducing effective cohesion and stiffness. In this context the swelling potential of many HSSR materials must be mentioned. The swelling behaviour of argillaceous soft rock is governed by intricate interactions among mineralogical composition, moisture content, and prevailing stress conditions (Rauh, 2009; Kirschke, 2010; Cudmani et al., 2021). Laboratory investigations consistently indicate higher swelling potentials compared to in-situ observations. This discrepancy is primarily attributed to factors such as scale effects, boundary conditions, and differing saturation levels (Kirschke, 1996; Rauh, 2009). To bridge this gap, numerical modelling has been increasingly utilized to simulate field-scale behaviours, offering a means to approximate in-situ conditions (e.g., Anagnostou, 1993; Schädlich et al., 2013). However, accurately capturing the time-dependent nature of swelling processes remains a significant challenge in geotechnical analysis.

A study by Metzler et al. (2025) utilizes extensometer data collected from a fully instrumented test gallery (see chapter 5.5) to inform a predictive analysis conducted with PLAXIS 2D, focusing on the application of the PLAXIS Swelling Rock Model developed by Schädlich et al. (2013) and its comparison to swelling phenomena modelled through volumetric strain (John et al 2009). The Swelling Rock Model incorporates a comprehensive range of material-specific parameters, encompassing both elastic and plastic swelling characteristics. Despite its sophistication, the model's complexity, including the need to upscale parameters from rock samples to the rock mass, introduces significant challenges in achieving realistic simulations.

By integrating in-situ field data, laboratory findings, and numerical modelling, it is necessary to refine the understanding of swelling behaviours and enhance predictive capabilities. The study by Wölflingseder et al (2025) emphasizes the critical role of calibration and validation processes in reducing uncertainties associated with upscaling and parameter variability. Through this approach, potential pathways are proposed for advancing long-term predictive modelling, addressing key limitations in the current methodologies, and improving the reliability of geotechnical designs in argillaceous soft rock formations.

5 Strategies to overcome HSSR shortcomings

5.1 Testing Data

Laboratory tests play a critical role in validating models. Uniaxial and triaxial compression tests, shear tests, and swelling tests are necessary to capture the material's mechanical responses accurately. Testing must also address inherent anisotropy, which significantly affects failure mechanisms and damage progression. Sampling and storage techniques should preserve in-situ conditions, ensuring reliable test results. In Metzler et al. (2024a) several limitations and requirements are summarised.

5.1.1 Data Limitations

The HSSR's behaviours is influenced by its anisotropic nature. This anisotropy complicates the failure mechanisms and requires extensive data to capture directional variations in strength and stiffness. Variability in lab results due to anisotropic behaviours necessitates robust statistical methods and larger sample sizes to establish meaningful trends.

HSSR materials are highly susceptible to degradation upon water exposure. Their strength and stiffness may decrease irreversibly, adding complexity to data interpretation. This sensitivity underscores the need for rapid and careful sample handling, including protection from moisture exchange during storage and transport. Mechanical damage, moisture exchange, and scale effects during these processes can alter the physical and mechanical properties of samples. Effective preservation requires using special equipment and rapid processing to maintain fidelity to in situ conditions. Despite these measures, scale effects limit the direct applicability of laboratory data to full-scale field conditions.

The inherent variability of HSSR materials is reflected in wide-ranging test results, often complicating statistical analysis. For instance, the coefficient of variation (COV) for UCS tests frequently exceeds 100%, indicating significant dispersion in data (Metzler et al. 2024a). This variability necessitates larger, more evenly distributed sample sizes and careful interpretation of outliers. Additionally, variations in testing protocols and equipment among laboratories introduce further uncertainties.

5.1.2 Artificial Samples

Advancements in innovative testing and evaluation methods for anisotropic rocks underscore the demand for precise geomechanical design parameters. However, natural materials' inherent variability and heterogeneity limit the reliability of test data, complicating the assessment of boundary conditions' effects on results and necessitating specialized equipment. Reliable datasets are essential for validating anisotropic constitutive models, particularly in capturing orientation-dependent deformation and strength under varied stress conditions. Unfortunately, such datasets are scarce for soft rocks due to difficulties in testing and obtaining undisturbed samples from the rock mass (e.g., Blümel 2005; Kanji 2014).

Artificial rock samples offer significant potential for optimizing and verifying experimental procedures due to their controllable and consistent behaviour, enabling high repeatability and robust investigations of factors such as shape, size, and boundary effects. Unlike natural rocks, artificial samples reduce variability and support reliable studies under diverse loading and boundary conditions.

Synthetic specimens, such as cement-based anisotropic analogues, present a viable solution by replicating the essential mechanical behaviours of soft rocks in an idealized form (e.g., Winkler et al. 2019). However, the production of cement-based analogues involves challenges beyond the expertise of rock mechanics engineers, and their long production and curing times limit their suitability for extensive laboratory programs requiring continuous sample availability.

To overcome these limitations, additive manufacturing techniques like Binder Jetting Technology (BJT) provide a promising alternative for producing artificial sandstone samples. A laboratory test program, including UCS tests on 3D-printed samples with layered structures to simulate anisotropy, offers a valuable database for validating future constitutive models for anisotropic rocks (e.g., Winkler et al. 2020b).

5.1.3 Recommendations

Adherence to standardized sampling techniques, such as those outlined in EN ISO 22475-1, is essential to minimize disturbances and maintain sample integrity. Sampling should be conducted promptly, with samples stored under conditions that prevent mechanical damage and moisture loss. Larger samples may be required to mitigate scale effects.

Testing protocols must prioritize the accurate reproduction of in-situ conditions. This includes considering water content, anisotropy, and the effects of prolonged storage. Triaxial tests, in particular, require consistent confining pressures to evaluate anisotropy accurately. Multi-stage testing may help reduce sample requirements while maintaining robust data quality.

Field measurements, such as strain and displacement monitoring, should complement laboratory data to bridge the gap between small-scale tests and full-scale geotechnical models. Such in-situ monitoring tools can provide valuable insights into in-situ material behaviours, informing more realistic strength and stiffness parameters.

Continuous refinement of constitutive models based on new data is critical for addressing the challenges posed by HSSR materials. This includes integrating laboratory results with field observations and recalibrating models to reflect the material's anisotropic and moisture-sensitive behaviours.

5.2 Constitutive modelling

5.2.1 FE continuum modelling

When focusing on advancing the numerical modelling of HSSR materials the distinct mechanical behaviours characterized by a stiff response up to a defined yield state, followed by strain hardening and subsequent softening must be considered. The critical influence of confining pressure, where behaviours range from brittle and dilatant under low pressures to ductile and contractive under higher pressures has to be taken into account (e.g. Stauder et al. 2019).

Stauder et al. 2020 compared two constitutive models, the PLAXIS Concrete Model (CM) and the PLAXIS Hardening Soil Model (HS), to assess their suitability for simulating the mechanical response of weak rocks. The CM, originally developed for shotcrete (sprayed concrete) applications, incorporates a detailed representation of strain-hardening and strain-softening regimes and uses a Mohr-Coulomb yield surface to model the failure mechanism. This model features a normalized stress-strain curve divided into four phases, allowing for the accurate depiction of material behaviours under varying conditions. In contrast, the HS model, designed for a broad range of soils, includes shear- and compression-hardening surfaces and relies on a hyperbolic stress-strain relationship for primary triaxial loading.

Stauder et al. 2020 examine three representative materials: Beaucaire marl, a homogeneous overconsolidated soil; soft mudstone; and Red Wildmoor sandstone, a typical weak rock. Laboratory tests, including uniaxial and triaxial compression tests, provided the basis for calibrating the models. The CM demonstrated its capability to predict the stress-strain behaviour of the materials with high accuracy, particularly for capturing stiffness, peak strength, and softening responses. For Beaucaire marl, the CM closely matched laboratory results, while for mudstone, the initial stiffness was slightly overestimated. The sandstone simulations effectively captured the peak and residual strengths but encountered difficulties in representing the initial stiffness.

The findings underscore the CM's potential as a valuable tool for geotechnical applications, particularly in simulating HSSR. However, the study also identifies the dependency of model accuracy on high-quality laboratory data. Parameter calibration using values from the literature was noted to pose risks of misinterpretation and inaccuracies, emphasizing the need for tailored experimental studies.

In conclusion, the study validates the use of the CM for modelling the mechanical behaviours of weak rocks and hard soils, particularly where strain-hardening and softening are prominent. While the HS model provides reasonable strength predictions, its inability to accurately capture stiffness and softening limits its applicability in such contexts. Future work will aim to refine the modelling process through advanced laboratory testing and by investigating volumetric behaviours, ensuring that numerical tools can better support engineering design and analysis in geotechnical projects.

5.2.2 Discrete Element Modelling (DEM)

Emerging computational methodologies, such as "particle-scale modelling of clay minerals" using Discrete Distinct Element Methods (DDEM), present innovative and promising solutions for understanding and predicting the behaviours of complex materials like HSSR, often consisting of various clayey–silty sediments. For example, recent advancements by e.g., Bono et al. (2024) introduced particle-scale models of kaolinite, enabling highly detailed simulations of micro-scale interactions. These models represent a significant step forward, allowing the simulation of platelet interactions with realistic microstructural properties, including overburden stresses and contact dynamic forces.

These particle-scale models provide unparalleled insights into the mechanical and physicochemical interactions that govern the behaviours of clay minerals. They can simulate how individual clay platelets interact under different conditions, such as changes in stress, moisture, or ionic concentration, thereby bridging the gap between fundamental mineral properties and bulk material behaviours. By incorporating realistic geometries and micro-scale characteristics, these models offer a more nuanced understanding of phenomena such as swelling, consolidation, and anisotropic behaviour.

To accurately parameterize and validate these computational models, specialized laboratory techniques such as X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) play a critical role. XRD is essential for identifying and quantifying the mineralogical composition within clay samples. It provides the foundational data on the types and proportions of clay minerals present, which directly influence their mechanical and chemical properties. SEM complements this by offering high-resolution imaging of the microstructure, allowing researchers to observe platelet morphology, orientation, and particle interactions. When paired with Energy-Dispersive X-ray Spectroscopy (EDS), SEM also facilitates precise compositional analyses at localized scales.

5.3 Anisotropy – Testing Procedure

The anisotropic nature of intact rocks results in important implications for mechanical behaviours, and practical approaches for sampling and testing. Intact rock anisotropy arises from geological processes that create microstructural features such as schistosity, foliation, and bedding planes. These features impart direction-dependent mechanical properties to rocks, posing significant challenges for geotechnical design and engineering.

In Iskin (2020) the mechanical behaviour of anisotropic rocks is assessed through laboratory tests, including uniaxial and triaxial compression, point load, and Brazilian tests. Each test type reveals unique aspects of anisotropic response. The uniaxial compression test, widely used in rock engineering, demonstrates how compressive strength varies with the orientation angle (β) relative to planes of weakness. Typically, maximum strength occurs at β=0 or 90°, while minimum strength is observed around β=30°. Variations in strength often follow characteristic patterns, such as shoulder-shaped, U-shaped, or wavy curves, depending on the rock type and the nature of its planes of weakness. Stiffness anisotropy is another crucial phenomenon observable in uniaxial tests. The tangential stiffness (Et) varies with β, often displaying U-shaped or decreasing trends. U-shaped curves are common in rocks with defined planes of weakness, where shearing along these planes reduces stiffness. In contrast, decreasing curves occur in weaker, more porous rocks with thinly laminated planes.

The paper also addresses the challenges and best practices in sampling and testing anisotropic rocks. Proper sampling is critical, especially for soft or foliated rocks, where disturbance can significantly alter test results. Recommendations include overcoring techniques, selecting appropriate drilling diameters, and considering geological complexities when orienting core drills. Testing protocols emphasize the importance of maintaining consistent confinement pressures, accurately documenting pre-existing disturbances, and prioritizing key orientation angles (β=0°,30°,90°) for mechanical characterization.

Specific suggestions for each test type include ensuring representative stress-strain data in uniaxial and triaxial tests, carefully interpreting point load indices, and accounting for dip directions (Ψ) of weak planes. For Brazilian tests, obtaining valid tensile strength indices requires close attention to failure modes, as combined tensile-shear fractures often occur in anisotropic samples.

5.4 In-situ testing

Applicability, limitations, and parameter determination for geotechnical investigations using cone penetration tests (CPT) and flat dilatometer tests (DMT) in transitional materials classified as hard soils and soft rocks (HSSR) is summarized in Stauder et al. 2021. The study focuses on determining whether conventional CPT and DMT equipment can reliably penetrate and measure parameters in HSSR, with tests conducted at five distinct locations in southeastern Austria. The test site spans multiple geological layers, including stiff clays, silty sands, and cemented sandstone with UCS values ranging up to 4.5 MPa.

Cone penetration tests (CPT) involve driving an instrumented cone into the ground at a controlled rate, recording parameters such as cone resistance (qc), sleeve friction (fs), and pore water pressure (u2) for CPTu tests. Flat dilatometer tests (DMT), on the other hand, measure soil stiffness, strength, and in-situ stress using a blade with a flexible steel membrane that records expansion pressures. The experimental campaign included 24 CPT soundings and 3 DMT soundings. Multiple configurations were employed to test the limits of standard equipment, including variations in cone diameter, apex angle, and the use of friction-reducing devices such as lubricants and cam-mounted rods. Results demonstrated that larger cone areas reduced rod friction, enabling deeper penetration, but required greater thrust force. Interestingly, 15 cm^2 cones proved more effective than smaller or larger alternatives due to their optimal balance of penetration force and rod stability. Apex angle reduction from 60° to 40° also enhanced penetration depth, as sharper angles generated lower shear deformation during cone advancement. However, this configuration posed challenges related to wear, limiting its practical applicability.

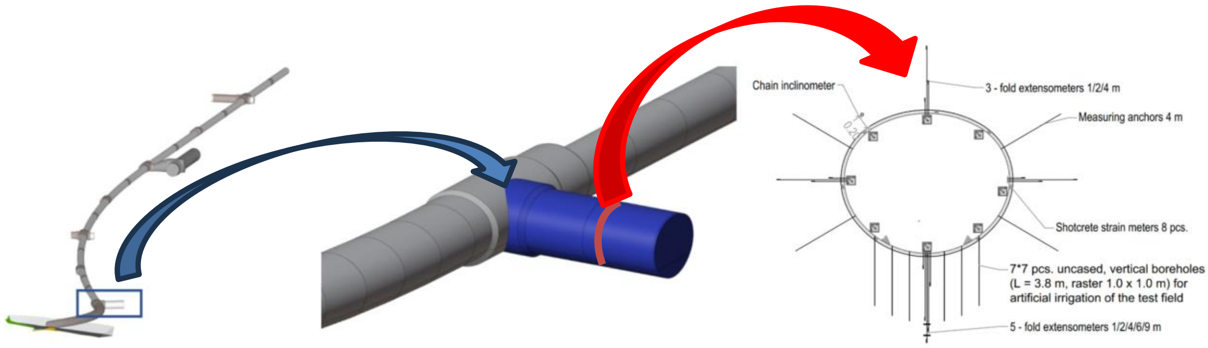
In terms of friction-reducing measures, various approaches were tested, including Pagani hulls, cams, and water lubrication. Friction reduction significantly enhanced penetration depth and reduced thrust force, with the best performance observed when using continuous widening techniques rather than localized cam-based modifications. These findings underscore the importance of minimizing rod-ground friction for reliable CPT performance in HSSR conditions.

Notably, the study identified practical limitations for CPT in HSSR. While the equipment successfully penetrated clay and siltstone layers with UCS values up to 3 MPa, harder sandstone layers (UCS ~4.5 MPa) remained inaccessible, suggesting an upper limit for CPT applicability in such materials. Additionally, correlations derived from CPT and DMT data need further calibration to account for the unique properties of HSSR, as current models often overestimate stiffness and friction angle in cemented or overconsolidated layers.

Overall, the findings demonstrate the potential of CPT and DMT for characterizing HSSR, especially when combined with enhancements like friction reducers and optimized cone geometries. The centimetre-scale resolution of CPT data is particularly advantageous for identifying thin soil layers and transitions between soil and rock, making it a valuable tool for geotechnical site investigations. However, the study emphasizes the importance of integrating CPT and DMT data with complementary methods, such as core drilling, to provide a comprehensive understanding of complex subsurface conditions.

5.5 Fully equipped test galleries

The use of a fully equipped test gallery, such as the one recently implemented in the construction site of the Angath adit tunnel of OEBB (Austrian Federal Railway Association) within the Unterangerberg Formation (which is molasse, an argillaceous soft rock) in Tyrol/Austria, offers substantial advantages for understanding and managing the challenges associated with argillaceous soft rocks (Metzler et al. 2024b). It consists of alternating layers of dark grey-to-black mud-, and marlstone, with interbedded layers of light grey sandstone, which are categorized as HSSR lithologies. These rocks exhibit complex mechanical behaviours, including anisotropy, swelling, and stress-dependent deformation, which are often difficult to predict or accurately model through laboratory tests alone.



(a) (b) (c)

Fig. 5: BIM model of the Angath adit tunnel with the test gallery marked in blue (a). Section of the BIM model with the perpendicularly aligned test gallery (blue) (b). Exemplary monitoring cross-section of block 2 of the test gallery (red) (c). Based on Metzler. et al. 2024b.

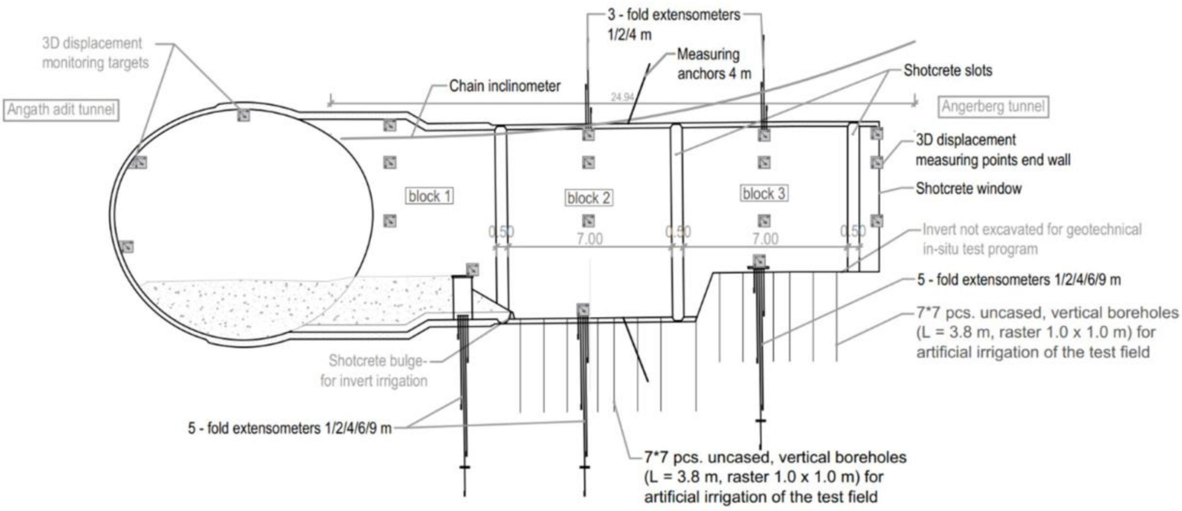


Fig. 6: Longitudinal section of the in-situ tests located in the test gallery. View in the direction of the Angath adit tunnel excavation. Metzler. et al. 2024b.

A test gallery provides a controlled in-situ environment for conducting comprehensive geotechnical measurements and monitoring programs. These setups enable real-time assessment of rock mass behaviours under near-field conditions, including the effects of excavation, support systems, and environmental changes. The test gallery at Angath is outfitted with extensive instrumentation, including extensometers, shotcrete strain meters, chain inclinometers, and geodetic targets. Additionally, long-term experiments such as irrigation testing allow for the evaluation of swelling behaviour and time-dependent deformation, providing insights unattainable through laboratory methods (see Figures 5 and 6).

One key advantage is the ability to capture the scale effects and heterogeneities inherent in argillaceous formations. Laboratory tests are typically conducted on small, homogenous samples, often leading to an overestimation of swelling pressures and deformation rates when extrapolated to field conditions. The test gallery enables the study of large-scale interactions and the role of discontinuities, bedding, and varying mineral compositions in influencing mechanical responses.

Furthermore, the test gallery contributes to safer and more cost-effective tunnelling practices. By observing the interactions between rock mass and support systems, it is possible to optimize support designs, such as shotcrete thickness or the use of invert closures, to mitigate swelling and deformation.

6 Future Trends and Recommendations

Research on HSSR should focus on refining sampling and laboratory testing protocols to better capture the in-situ characteristics of these materials. The development of standardized workflows for geotechnical investigations of HSSR materials could improve the reliability and reproducibility of test results. Additionally, enhanced understanding of the mechanisms driving water-induced degradation in HSSR could inform the design of mitigation strategies and predictive models, thereby contributing to safer and more efficient engineering practices.

Future research must focus on standardizing classification methods for HSSR materials and improving predictive models that account for softening and degradation, as well as anisotropy and other environmental interactions such as swelling mechanisms. Therefore, there is need to focus on expanding the experimental database to include a wider variety of hard soils and soft rocks, refining the constitutive model's parameterization for improved stress-strain predictions.

Advancements in testing and monitoring technologies, promise to enhance HSSR characterization and classification. Developing unified frameworks that combine soil and rock mechanics principles is another promising approach. These frameworks would consider the full spectrum of material behaviour, from soil-like to rock-like, providing a more holistic basis for classification. Moreover, practical criteria tailored to specific engineering applications, such as slope stability, foundation design or tunnel design could enhance the utility of these systems. Collaboration among geologists, engineers, and material scientists is essential for bridging gaps in understanding HSSR's complex behaviour.

To address these challenges, geotechnical engineers are increasingly turning to advanced techniques for characterization and classification. Digital imaging and geophysical methods offer non-destructive ways to assess material structure and heterogeneity, providing valuable data for classification. Additionally, there is a growing emphasis on integrating environmental factors, such as weathering potential and water sensitivity, into classification schemes.

Integrating laboratory data with field observations is critical for refining classification approaches for HSSR materials. Advanced testing methods offer potential pathways for more accurate characterization. While CPT and DMT methods can be effectively adapted for HSSR conditions, their limitations highlight the need for further refinement of empirical correlations and equipment design. Future research should focus on developing tailored models for HSSR, validating existing equations with extensive field data, and exploring advanced techniques for measuring mechanical properties in challenging geotechnical environments. These advancements will enhance the reliability of in-situ testing methods and support better decision-making in geotechnical design and construction.

A fully equipped test gallery represents an invaluable tool for addressing the complexities of argillaceous soft rocks. It bridges the gap between laboratory testing and field-scale behaviour, enhances the reliability of geotechnical models, and informs the design and construction of safe, efficient, and sustainable tunnelling projects. The insights gained from such facilities significantly reduce uncertainties and contribute to advancements in the field of geotechnical engineering.

RMCCs were developed before the advent of modern data acquisition technologies, such as detailed scan/image capturing of newly exposed rock surfaces, or Measure While Drilling (MWD) data, and geophysical methods applied directly at the excavation face. During that period, high-resolution datasets with extensive rock mass coverage, advanced statistical learning techniques, and significant computational power were unavailable. With the current advancements in data accessibility and automation in tunnelling, these traditional classification systems show limitations that could lead to suboptimal decisions. Modern data-driven approaches offer the potential to address these shortcomings more effectively (see Dickmann et al. 2021, Sapronova et al. 2021, Sapronova et al. 2024, Hansen et al. 2024).

The integration of particle-scale modelling with data from XRD and SEM represents an innovative approach in geotechnical and materials research. It not only enhances the predictive accuracy of numerical simulations but also opens new avenues for tailoring material properties through design or treatment. For instance, these approaches can be used to optimize the performance of clay barriers in waste containment systems, predict the behaviour of expansive soils, or improve the design of engineering structures in clay-rich terrains. Such advancements underline the importance of combining sophisticated computational models with robust experimental techniques to address the complex challenges associated with clay mineral behaviour in engineering and environmental contexts.

7 Conclusions

Understanding the brittle-to-ductile transition and the effect of anisotropy is crucial for effective design and construction in HSSR material environment. Tailored characterization, robust modelling, and adaptive strategies are key to mitigating risks and ensuring successful project outcomes.

While the classification of soft rock and hard soil materials remains a complex task, ongoing advancements in testing methods are helping to overcome these challenges. By embracing a multidisciplinary approach and focusing on the material's in-situ behaviour, engineers can achieve more accurate and reliable classifications, ultimately leading to safer and more efficient geotechnical designs.

References

Agustawijaya DS (2007) The Uniaxial Compressive Strength of Soft Rock. Civil Engineering Dimension 9(1) 9-14

Anagnostou G (1993) A model for swelling rock in tunnelling. Rock Mech Rock Eng 26:307–331. https://doi.org/10.1007/BF01027115

Baud JP, Gambin M. (2011) Classification of soils and rocks based on pressuremeter tests under high pressure. In: Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering. Athens: Mill Press; 2011. pp. 325e30

Bono J., McDowell G. (2024) Modelling the mechanical behaviour of clay using particle-scale simulations. Granular Matter (2024) 26:29 https://doi.org/10.1007/s10035-024-01401-x

Bostjancic T (2023) Correlating lab data in argillaceous soft rocks: towards a comprehensive database. Graz University of Technology, Graz

Cudmani R, Heyer D, Birle E, Möller P (2021) Untersuchung der Quellempfindlichkeit veränderlich fester Gesteine bei der Verwendung als Erdbaustoff. Bundesanstalt für Straßenwesen. TU München

Dickmann, T., Hecht-Mendez, J., Krüger, D., Sapronova, A., Unterlaß, P.J., Marcher, T. (2021) Towards the integration of smart techniques for tunnel seismic applications. Geomechanik und Tunnelbau 14, 609–615 (2021) https://doi.org/10.1002/geot.202100046

Dobereiner L. (1984) Engineering geology of weak sandstones [PhD Thesis]. London: University of London

Erharter G.H., Neil B., Hansen T.F., Sumit S., Marcher T. (2024) International Distribution and Development of Rock Mass Classification: A Review. Rock Mechanics and Rock Engineering. 10.1007/s00603-024-04215-8

Erharter, G., Hansen, T.F., Qi, S., Bar, N., Marcher, T. (2023) A 2023 perspective on rock mass classification systems. In: Proceedings of the 15th ISRM Congress

Hansen T.F., Aarset A. (2024) Unsupervised machine learning for data-driven classification of rock mass using drilling data. 10.48550/arXiv.2405.02631

Iskin F. (2020) An Overview on Intact Rock Anisotropy and Suggestions for Sampling and Testing. In: 1. Hard Soil Soft Rock Minisymposium. T. Marcher (ed.). NAWI Graz. ISBN 978-3-900484-88-0.

John M, Marcher T, Pilser G, Alber O (2009) Considerations of swelling for the second tube Pfändertunnel. In: Proceeding ITA-AITES World Tunnel Congress - Safe Tunnelling for the City and for the Environment

Kanji MA (2014) Critical issues in soft rocks. J Rock Mech Geotechn Eng 6(3):186–195. https://doi.org/10.1016/j.jrmge.2014.04.002

Kanji MA, He M, Ribeiro e Sousa L (2020) Soft rock mechanics and engineering. In: Kanji MA, He M, Ribeiro e Sousa L (eds) Soft rock mechanics and engineering. Springer International Publishing

Kirschke D (1996) Neue Versuchstechniken und Erkenntnisse zum Anhydritschwellen. In: Taschenbuch für den Tunnelbau 1996, 20th edn. Glückauf, Essen, pp 203–225

Kirschke D (2010) Lösungsansätze für den Tunnelbau in quell- und schwellfähigem Gebirge. Geomech und Tunnelbau 3:547–556

Marcher T (2024) The rock mechanical relevance of anisotropy in tunnel design. Geomech Tunnel 17(1):29–33. https://doi.org/10.1002/geot.202300052

Metzler I, Bostjancic T, Marcher T (2024a) The challenge of classification of argillaceous soft rock (HSSR). In: Proceedings of the 1st international rock mass classification conference

Metzler I., Frühwirt T., Hölzl H., Marcher T. (2024b) Argillaceous Soft Rock in-situ Test Program in Tunneling. Rock Mechanics and Rock Engineering. https://doi.org/10.1007/s00603-024-04302-w

Metzler I., Wölflingseder M., Fernandes Couto J., Marcher T. (2025) Modeling the swelling extent of argillaceous soft rock using the PLAXIS swelling rock model. To be published in proceedings Eurock 2025. Trondheim, Norway.

Nickmann M (2009) Abgrenzung und Klassifizierung veränderlich fester Gesteine unter ingenieurgeologischen Aspekten. Technische Universität München

Nickmann M, Sailer S, Ljubesic J, Thuro K (2010) Engineering geological investigations into the border between hard and weak rocks. In: Geologically active: proceeding of the 11th IAEG congress

Nickmann M, Spaun G, Thuro K (2006) Engineering geological classification of weak rocks. IAEG. https://www.researchgate.net/publication/237508777

Plinninger, R. J., Spaun, G., Nickmann, M. (2012) Geotechnische Aspekte der Beprobung und Untersuchung veränderlich fester Gesteine. In: C. Vogt (Hg.): Bauen in Boden und Fels. 8. Kolloquium. Ostfildern: TAE

Prinz H, Strauß R (2018) Ingenieurgeologie. Springer, Berlin, Heidelberg

Rafiei Renani, H., Martin, C. (2019) Factor of safety of strain-softening slopes. Journal of Rock Mechanics and Geotechnical

Rauh F (2009) Untersuchungen zum Quellverhalten von Anhydrit und Tongesteinen im Tunnelbau. TU München

Rocha M. (1975) Some problems related to the rock mechanics of low strength natural materials. In: Proceedings of the 5th Pan-American Conference on Soil Mechanics and Foundation Engineering, Buenos Aires; pp. 489e514

Sapronova, A., Hammoud, A., Klein, F., Marcher, T. (2024) Correlational analysis of MWD data for rock mass characterization and risk assessment. In: Proceedings of the Fourth EAGE Digitalization Conference & Exhibition, vol. 2024, pp. 1–4. European Association of Geoscientists & Engineers, Mar 2024. https://doi.org/10.3997/2214-4609.202439009

Sapronova, A., Unterlass, P.J., Hecht-Mendez, J., Dickmann, T., Marcher, T. (2021) Sparse data transformation for unsupervised clustering for the exploration ahead of tunnel face 2021(1), 1–5 (2021) https://doi.org/10.3997/2214-4609.202120199

Saroglou, H., Tsiambaos, G. (2007) Classification of anisotropic rocks. Issue March, pp. 191-196

Schädlich B, Marcher T, Schweiger HF (2013) Application of a constitutive model for swelling rock to tunnelling. Geotech Eng J SEAGS AGSSEA 44:47–54

Stauder S., Marcher T. (2019) The brittle to ductile behavior of “hard soil and soft rock” – experimental review and challenges for constitutive modelling. ISRM International Symposium. Brazil

Stauder S., Marcher T., Harmuth M., (2021) Equipment limits and parameter determination of cone penetration and flat dilatometer tests in hard soils and soft rocks. Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney

Stauder S., Wallner C., Marcher T. (2020) Numerical modelling of “hard soil and soft rock” – a contribution towards the understanding of the mechanical behaviour of weak rock. ITA-AITES World Tunnel Congress, WTC2020 Kuala Lumpur Convention Centre, Malaysia

Terzaghi K., Peck, R.B. (1967) Soil mechanics in engineering practice, 2nd Ed., Wiley, New York

Ungewitter C (2021) Entwicklung eines Arbeitsablaufs zur Ermittlung charakteristischer Festigkeits- und Steifigkeitsparameter veränderlich-fester Gesteine unter Berücksichtigung des Porenwasserdrucks, Bundesanstalt für Wasserbau

Vakili, A., Albrecht, J., Sandy, M. (2014) Rock strength anisotropy and its importance in underground geotechnical design. Third Australasian Ground Control in Mining Conference, Issue May, pp. 167-179

Winkler M.B., Marcher T. (2019) Artificial Test Samples to simulate "soft rock anisotropy". Extended abstract. Booklet: Recent Advances In Tunneling Research. Workshop Tongji-ACTUE-Cork-SFB837, Leoben (Austria)

Winkler M.B., Marcher T. (2020a) Different aspects of modelling elasticity and strength of anisotropic rocks. ISRM International Symposium Eurock 2020 – Hard Rock Engineering Trondheim, Norway

Winkler M.B., Marcher T. (2020b) Investigation of synthetic materials for the simulation of soft anisotropic rocks. Extended abstract IACMAG Torino, Italy

Winkler MB, Frühwirt T, Marcher T (2024) Elastic behavior of transversely isotropic cylindrical rock samples under uniaxial compression considering ideal and frictional boundary conditions. Appl Sci (Switzerland) 14(1):17. https://doi.org/10.3390/app14010017