

# Lessons Learnt from fully equipped in-situ test galleries in soft rock formations for Austrian tunnel projects

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**ABSTRACT:** Fully equipped in-situ test adits are specialized underground constructions near or parallel to main tunnel tubes, essential for complex geotechnical projects. They provide direct subsurface access for understanding ground conditions, reducing uncertainties, optimizing designs, and testing construction methods in real-world settings. These adits significantly improve project outcomes by enabling detailed investigations, refining techniques, and mitigating risks. In-situ test adits allow engineers to map geological structures and assess rock or soil properties, including strength, elasticity, and permeability, under actual conditions. This is particularly valuable in challenging ground conditions like high overburden, soil-like conditions, or transitional materials (hard soil–soft rock, HSSR). Data from adits support tunnel design optimization, validating numerical models for stress distribution and stability. Adits also provide controlled environments for testing construction methods, such as drill-and-blast techniques or tunnel boring machine (TBM) performance, ensuring equipment suitability for specific geology. International case studies confirm the effectiveness of adits in complex underground construction. In Austria, the Brenner Base Tunnel (BBT), an exploration tunnel offered critical Alpine geological insights, enhancing construction safety and efficiency. At the Angath adit of the Angerberg tunnel in Tyrol, Austria, a test gallery provides solutions for managing complex soft rock formations (HSSR), characterized by swelling and anisotropic deformation. Advanced instrumentation, like extensometers and shotcrete strain meters, supported long-term experiments, improving understanding of material behaviour. While constructing adits involves significant initial investment, the long-term benefits outweigh costs. They reduce uncertainties, enhance design precision, and enable effective execution strategies, making them a vital component of modern tunnelling projects..

**KEYWORDS:** In-situ test adits, observational method, tunnel design optimization, soft rock formations.

## 1 INTRODUCTION

Over the past two decades, tunnel construction in Austria has underscored the engineering challenges associated with complex geological formations such as flysch and molasse sequences. Projects including the ÖBB Lainzer Tunnel (Bauer et al., 2011), Asfinag Pfänder Tunnel (John et al., 2009), ÖBB Perschlingtal Tunnels (Benedikt et al., 2016), ÖBB Koralm Base Tunnel (Handke et al., 2010), and Asfinag Bosruck Tunnel (Jiříčný and Marcher, 2011) have revealed the heterogeneous and anisotropic mechanical behavior of these rock masses, including pronounced swelling potential.

Such hard soil–soft rock (HSSR) materials occupy a transitional domain between hard rocks and soils, exhibiting complex mechanical and structural characteristics. Their classification and mechanical response are inherently ambiguous, creating challenges in engineering practice, particularly in tunnelling (e.g. Marcher 2024). Soft rock formations are generally defined as a geomaterial that retains rock-like features but exhibits markedly lower strength and enhanced deformability relative to typical hard rock. Such materials may disintegrate under moderate pressure or undergo rapid strength degradation upon water exposure.

Swelling pressures in such formations are frequently overestimated, often leading to conservative support and lining strategies in tunnel projects. Conversely, underestimation or neglect of anisotropic deformation behavior and swelling tendencies can result in reduced tunneling performance, substantial cost overruns, and shortened maintenance intervals.

This paper underscores the critical importance of long-term in situ testing, supported by detailed investigations, to achieve comprehensive geological characterization, realistic rock mass property evaluation, and site-specific engineering solutions aimed at effectively mitigating the combined effects of swelling and directional deformation in these challenging rock masses.

This paper starts with a review of in-situ testing facilities in soft rock formations, both in Austria and abroad. Drawing on

two case studies of exploratory tunnels in Austria, it examines in detail the fundamental discrepancies between laboratory findings and in-situ observations in soft rock conditions. The paper concludes by emphasizing the role and added value of fully instrumented test galleries.

## 2 INSITU TEST FACILITIES IN SOFT ROCK

### 2.1 Instrumented tunnel construction in Austria

Several Austrian tunnel projects provide valuable insights into instrumentation strategies and deformation behaviors in soft rock formations.

In the Pfänder Tunnel, laboratory tests and finite-element analyses were complemented by 10 m-long invert extensometers and 20 m-long slide micrometers installed immediately post-excavation. The marl and clayey marl lithology required careful water management. Extensometer readings in zones of significant crown settlement and invert swelling showed limited correlation with laboratory-predicted deformations. Variations in moisture content affected lining stresses, indicating that laboratory-determined swelling pressures cannot be directly applied in-situ. Back-calculations suggested lining support pressures around 300 kN/m<sup>2</sup> (John 1979; John et al., 2009).

In the Bosruck Tunnel, composed of fractured mudstone, siltstone, dolomite, clayey marl, and rock salt, yielding lining elements accommodating up to 200 mm of displacement were installed in weak zones to prevent overstressing of shotcrete supports. The lining thickness reached 1.3 m in the invert, and instrumentation captured large deformations, illustrating the need for adaptable support systems in heterogeneous geology (Jiříčný and Marcher 2011; Lenz et al., 2010).

The Achrain Tunnel, featuring soft-plastic silty alluvial fan sediments with clayey marl and sandstone interlayers, underwent extensometer monitoring and targeted swelling tests via irrigation. Observations revealed invert heave up to 0.25 m and rock softening (Walter and Kitzler 2011).

In the Strenger Tunnel, excavated in anisotropic quartz phyllite, a comprehensive monitoring program included inclinometers, extensometers, anchor load cells, strain gauges, and earth pressure sensors across 18 cross-sections. Displacements ranged from millimeters in sections with low overburden and favorable schistosity orientation to decimeters in zones where schistosity and tunnel axis were closely aligned. Invert heave and deep rock mass movements have been observed (Huber et al., 2005).

These case studies demonstrate the critical role of in-situ instrumentation, adaptable support systems, and thorough geomechanical assessment in tunneling through complex soft rock formations.

## 2.2 Permanent underground research facilities

Permanent test galleries dedicated to in-situ rock mechanics investigations are scarce. Examples include ZAB – Zentrum am Berg in Leoben, Austria, and the Hagerbach Test Gallery near Sargans, Switzerland.

Especially test galleries aimed at exploring the behavior of hard soil/soft rock (HSSR) formations are rare. The most prominent examples include:

### 2.2.1 Mont Terri Underground (Rock) Research Laboratory

In the heart of the Swiss Jura, just north of St-Ursanne in the Canton of Jura, lies the Mont Terri Underground (Rock) Research Laboratory - a pioneering scientific facility nestled within the Opalinus Clay, a Jurassic argillaceous formation approximately 130 meters thick and deposited around 174 million years ago. The origins of Mont Terri trace back to the construction of the Mont Terri tunnel - part of the A16 Transjurane motorway - excavated between 1988 and 1998. The pilot gallery, initially created as part of the tunnel's emergency infrastructure, presented a unique opportunity: fresh, high-quality exposures of Opalinus Clay and straightforward horizontal access to this deep formation (Kneuker et al., 2021 and Bossard et al. 2017).

By 1996, researchers began transforming this gallery into a dedicated underground laboratory. That year, eight niches were initially excavated and about 15 experiments commenced via boreholes less than 30 meters long. The lab's infrastructure then evolved in stages (expansions were executed around 1998, 2008, and 2018) gradually extending the network of galleries (Thury et al., 1999).

The facility lies at a depth ranging from 250 to 300 meters below ground. Researchers gain access through the motorway's security gallery, entering horizontally into research tunnels within the clay. These research galleries now span a total length of 600 to 700 meters, and the laboratory hosts extensive instrumentation, experiment setups, and networks of boreholes for subsurface investigation. Mont Terri has emerged as an invaluable international research platform, steered by swisstopo (the Swiss Geological Survey) and supported by partner organizations across Belgium, Canada, France, Germany, Japan, Spain, Switzerland, the USA, and more (Bossard et al, 2017, Ziefle et al., 2024).

### 2.2.2 Bure Underground Research Laboratory (Bure URL)

The Bure URL (Meuse-Haute Marne, France) is a deep underground facility dedicated to the study of nuclear waste disposal in deep clay formations. Located in the Callovo-Oxfordian claystone of northeastern France, the laboratory is accessed through a combination of surface shafts and horizontal access tunnels, allowing researchers and engineers to study the rock in its natural, in-situ conditions. The laboratory lies at a depth of approximately 500 meters below ground, providing a natural environment for investigating the mechanical,

hydraulic, thermal, and chemical behavior of the claystone under conditions relevant to long-term radioactive waste storage (ANDRA). Construction of the laboratory began in the early 2000s, and since then it has been continuously developed and expanded to host a range of large-scale experiments on excavation effects, tunnel sealing, and engineered barrier performance. The underground site includes research galleries, and access tunnels that facilitate controlled investigations of interactions of heat, water, and stress within the host rock. The Bure URL plays a central role in French and international research on disposal, enabling scientists to perform in-situ rock mechanical testing, monitoring of rock mass deformation, and hydro-mechanical studies, all of which are critical for designing safe and long-term disposal solutions. Its combination of depth, access infrastructure, and high-quality clay host rock makes it a leading facility for studying repository-scale rock mechanics and the behavior of clay under thermal and mechanical loads (Armand et al., 2013).

### 2.2.3 Tournemire Underground Laboratory

The Tournemire Underground Laboratory is located in the Aveyron region of southern France, within a narrow-gauge railway tunnel excavated in the 19th century, now repurposed for research. The laboratory is hosted in argillite/claystone formations, providing an ideal setting for investigating the hydro-mechanical and geochemical behavior of clays in a controlled underground environment. Access to the laboratory is provided through the existing tunnel. The overburden is in the range from 200 to 250 meters, allowing researchers to conduct in-situ experiments under natural stress conditions (IRSN, Institut de Radioprotection et de Sûreté Nucléaire). The laboratory has been operational since the early 1990s, managed primarily by IRSN. Its research focuses on the long-term behavior of the clay host rock, Tournemire serves as a key site for rock mechanics, hydrogeology, and geochemical experiments, including the monitoring of stress redistribution, pore water movement, and rock-barrier interactions over time (Bonin 1998).

### 2.2.4 HADES Underground Research Laboratory

The HADES URL is situated in Mol, northeastern Belgium, within the Boom Clay formation, a soft clay layer considered a potential host rock for deep geological disposal of radioactive waste. The laboratory is accessed through shafts, leading to a series of experimental halls and niches located at a depth of approximately 220 meters below ground, providing researchers with in-situ conditions to study the natural behavior of the clay (ONDRAF/NIRAS). Construction of HADES began in 1980, initially as a small-scale research facility, and it has since been expanded to support a wide range of geomechanical, hydrogeological, and geochemical experiments. The laboratory's main focus is on rock mechanics and clay behavior (Li et al., 2023).

### 2.2.5 Horonobe Underground Research Laboratory

The Horonobe Underground Research Laboratory is located in Hokkaido, northern Japan, within a Neogene sedimentary sequence composed mainly of mudstone, siltstone, and sandstone, providing a representative environment for studies related to deep geological disposal of radioactive waste in soft sedimentary rocks. Access to the laboratory is provided through vertical shafts and horizontal research galleries, with the main experimental zones located at a depth of approximately 500 meters below ground, allowing experiments under in-situ stress and hydrogeological conditions. Construction of the Horonobe URL began in 1997, and the facility is operated by the Japan Atomic Energy Agency (JAEA). Its primary research focus is

on the hydro-mechanical, geochemical, and geomechanical behavior of sedimentary claystone. The laboratory supports large-scale in-situ experiments, monitoring of rock deformation, pore water pressures, and the interactions between heat, water, and stress, providing essential data for the safe design of deep geological repositories in sedimentary host rocks (Ozaki et al., 2022).

This body of international research, particularly in the field of nuclear waste disposal, offers valuable insights into swelling behavior and overall rock mass response, allowing certain findings to be considered across diverse geological settings. However, most studies primarily address phenomena associated with the intrinsic geological and mineralogical properties of the rock mass under specific environmental conditions, such as humidity or temperature variations. The interactions and couplings between these phenomena and conventional construction measures - for example, the use of shotcrete linings, systematic rock bolting, or variations in invert geometry (flat versus arched) - are generally not explicitly investigated. Consequently, the direct applicability of results from nuclear waste research to practical challenges in civil tunnelling and infrastructure development remains somewhat limited.

### 2.3 Temporary underground research facilities in Austria

In Austria, there are no permanent underground research facilities in soft rock; however, certain facilities are subjected to intensive monitoring over medium-term periods.

#### 2.3.1 BBT 3rd tube – exploratory tunnel

Whereas the majority of long, deep-seated base tunnels, including those in Austria (Semmering and Koralm Base Tunnels), are realized in a twin-tube configuration, the Brenner Base Tunnel - at 64 km the world's longest railway tunnel - includes, in addition to its two main tubes for bidirectional traffic, a continuous exploratory tunnel (Fig. 1; Eckbauer et al., 2014; Bergmeister, 2015). Situated between and slightly below the main tubes, this tunnel is driven first and serves during construction for (a) geotechnical exploration, (b) groundwater drainage, and (c) intervention measures such as pre-injection sealing or ground improvement ahead of the main excavations. Beyond mitigating construction risks, it also provides operational advantages, functioning (d) as a core element of the safety and emergency system and (e) as an essential facility for inspection and maintenance (see details in Marcher 2024). By accommodating much of the technical infrastructure, the

exploratory tunnel allows maintenance activities to be carried out independently of rail operations, avoiding closures of the main tubes. Water drainage is likewise managed through the exploratory tunnel, which allows all associated cleaning and inspection works to be performed independently of railway operations in the main tubes. A factor that has thus far received little attention in the professional discourse is (f) the geothermal potential of the surrounding rock mass and, consequently, of the drainage water that flows by gravity towards the tunnel portals, which should not be disregarded in future considerations (Geisler et al. 2022 and Geisler et al. 2023).

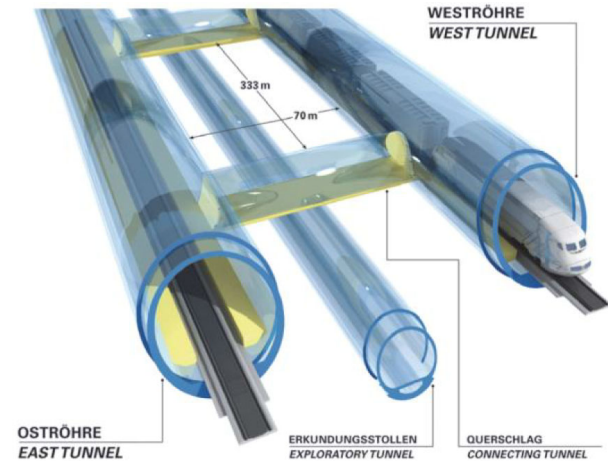


Figure 1. Tunnel layout of the Brenner Base Tunnel with two main tubes and the exploratory tunnel, see Eckbauer et al. (2014).

#### 2.3.2 Angath test adit – Angerberg Tunnel

The Angath adit, located in the Lower Inn Valley (Tyrol, Austria), forms part of the “Schaftenau–Radfeld” section of the Berlin–Palermo trans-European railway corridor and serves as the northern access to the Brenner Base Tunnel. Geologically, the tunnel is situated within the Unterangerberg Formation, a molasse sequence characterized by argillaceous soft rock. Constructed by ÖBB between 2023 and 2025, it fulfills multiple functions: during construction, it acts as an exploratory and logistics tunnel for the future Angerberg Tunnel, and in operation, it will serve as its emergency tunnel, connected by six cross-passages. One of those cross-passages is designed as an in-situ test gallery and is equipped with advanced geotechnical monitoring systems to support research and optimization of tunneling methods (see Fig. 2).

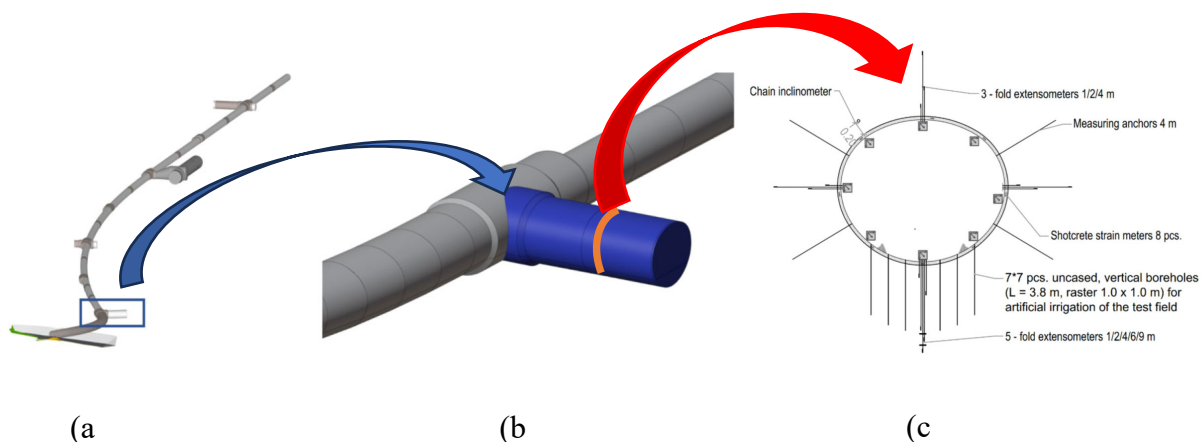


Figure 2. BIM model of the Angath adit tunnel with the test gallery marked in blue (a). Section of the BIM model with the perpendicularly aligned test gallery (blue) (b). Exemplary monitoring cross-section of block 2 of the test gallery (red) (c). Based on Metzler. et al. 2024.

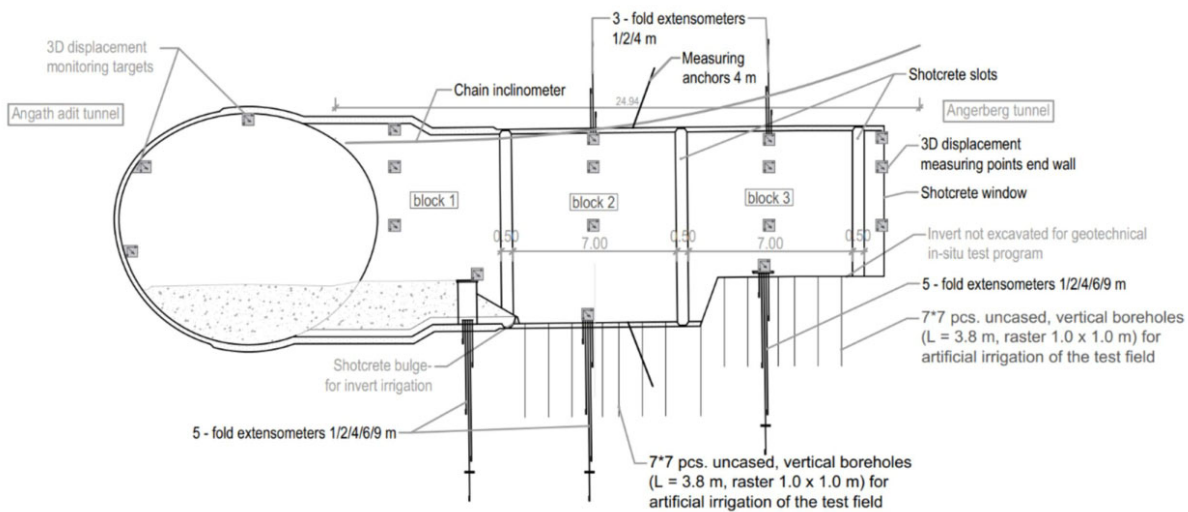


Figure 3. Longitudinal section of the in-situ tests located in the test gallery. View in the direction of the Angath adit tunnel excavation. Metzler. et al. 2024.

### 3 RESULTS AND DISCUSSION

From the large number of examples and applications resulting from research and development activities in such research facilities, only selected results can be presented in this paper. This selection is not intended to be exhaustive, but rather to illustrate, by way of example, the insights and practical experience that can be gained through these investigations and testing programs.

#### 3.1 BBT exploratory tunnel (3<sup>rd</sup> tube)

In conventionally excavated sections of the exploratory tunnel, geological face mapping has been carried out regularly, with detailed documentation in fault zones and at reduced frequency in homogeneous sections. Key parameters such as rock (mass) type, strength, weathering, discontinuity patterns, and groundwater are recorded. Rock samples are systematically taken: a “small test series” every 250 m within the same lithology, and a “large test series” every 1,000 m or upon encountering a new lithology. Laboratory analyses included strength testing, abrasion tests, and thin-section petrography (Bergmeister et al. 2017).

Approx. 17 km of the exploratory tunnel within the quartz phyllite and schist formations was excavated using an open gripper TBM, thereby allowing a substantial extension and optimization of the exploration concept. Due to the machine configuration, approximately 30 m of the excavated rock mass (located between the cutterhead shield and the point of invert segment installation) remains predominantly exposed. This configuration enables comprehensive geological documentation of the entire tunnel perimeter under near in-situ conditions.

A key aspect is the correlation of TBM operational parameters with the encountered rock mass conditions, which offers significant potential for improving predictions in the main tubes. Traditionally, such correlations between geological mapping and TBM data have relied on subjective interpretation. Machine learning (ML), as a subset of artificial intelligence (AI), offers an efficient means to extract patterns from large

datasets and can be applied for automatic classification of TBM data. In this context, an artificial neural network (ANN) was trained on data from a 15 km section of the exploratory tunnel. The objective was to transfer the gained knowledge to the main tunnels, which will be driven with shielded TBMs that have only limited capability for direct geological observation (Reinhold et al., 2017; Bergmeister et al., 2017).

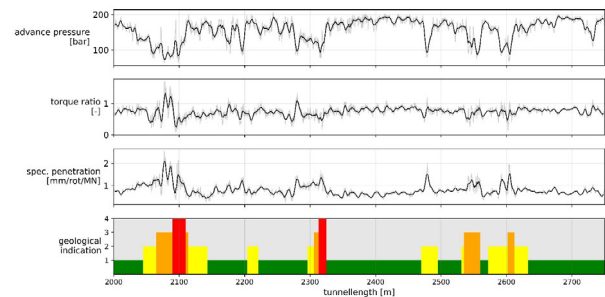


Figure 4. Example section of the TBM parameters between TM 3500 and 4000; several features show a distinctive response to the encountered fault zone (Marcher et al., 2020).

The TBM dataset, recorded at one-second intervals, included operational parameters such as torque, thrust, and specific penetration (lines 1 to 3 in Fig. 4). These were used as input variables to the ANN, while the output was defined by a geological indication (GI) system with four classes: (1) stable rock [green], (2) structurally induced overbreaks [yellow], (3) squeezing ground [orange], and (4) geotechnically critical fault zones [red] (Reinhold et al., 2017). Fig. 4 shows an example section of TBM operating parameters between TM 3500 and TM 4000, illustrating distinctive responses to the encountered fault zone (red in line 4 of Fig. 4). Results (Fig. 5) demonstrate a high level of agreement between ANN-based classifications (lines 3 and 4 in Fig. 5) and those made by experienced geologists (line 2 in Fig. 5).

Since geological documentation is often influenced by subjective judgment and individual expertise, the application of ANN-based classification provides a consistent and reproducible framework. When trained on prior observations,

such systems can support decision-making and contribute to more reliable geotechnical documentation in tunneling practice (Marcher et al., 2020; Erharter et al., 2020).

There is a growing emphasis on real-time data analysis, particularly on the continuous characterization and classification of TBM system behavior. TBM operating data provides a seamless record of tunneling conditions, making it a valuable basis for identifying system performance. A recently introduced contractual standard in Austria (ÖNORM B 2203-2) has formalized this concept of “data-driven tunneling classification” in engineering practice. The classification framework relies on the torque ratio as a key indicator, distinguishing between “regular” and “exceptional” excavation advances. In Erharter et al. (2025), the torque ratio is applied to data-driven advance classification, demonstrating how it can be used to pre-classify TBM datasets effectively.

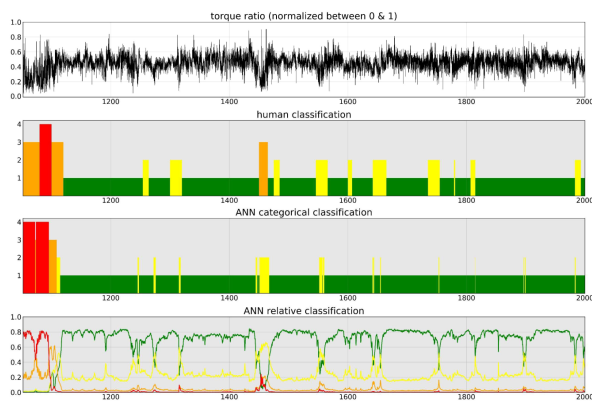


Figure 5. LSTM-network classification of TM 1000 – 2000 (Marcher et al., 2020).

Also, the potential of “data-driven anomaly detection” as a valuable decision support tool in tunneling has to be emphasized. By providing “real-time monitoring” of TBM operational data, this method can assist engineers in identifying geological anomalies early, improving risk assessment, and optimizing excavation strategies. The integration of machine learning models into TBM control systems can enhance process automation and safety, minimizing unexpected delays and mitigating tunnel instability risks.

### 3.2 Angath adit

The Angath test gallery is equipped with comprehensive geotechnical instrumentation, including extensometers, shotcrete strain gauges, chain inclinometers, and geodetic targets. Long-term experiments, such as controlled irrigation tests, are conducted to assess swelling behaviour and time-dependent deformation, yielding insights that cannot be achieved through laboratory testing (Fig. 2, 3). A major advantage of such in-situ investigations lies in their ability to capture scale effects and the natural heterogeneity of soft rock formations. Laboratory tests on small, homogeneous samples often overestimate swelling pressures and deformation rates, whereas the test gallery allows the analysis of large-scale interactions, discontinuities, bedding structures, and mineralogical variability. Beyond advancing scientific understanding, the facility provides direct benefits for tunnelling practice: observations of rock mass–support interaction enable the optimization of support measures, such as shotcrete thickness and invert closures, thereby enhancing both safety and cost-efficiency.

In-situ monitoring in the Angath test gallery shows overall stable excavation behavior, with a generally stable face and

only minor stratification-related breakouts. Irrigation experiments in the invert simulate long-term water exposure and reveal progressive cracking and disintegration of clay-rich layers, reproducing conditions that could also arise in the main tunnels under elevated groundwater levels. Geological heterogeneity plays a decisive role: the interbedded formations of the Unterangerberg Formation exhibit anisotropic swelling, with clay-rich beds showing stronger deformation than adjacent sandstone layers. Scale effects further explain why laboratory tests, based on small homogeneous samples, tend to overestimate swelling pressures compared to in-situ observations, where discontinuities and variable water access strongly influence the response (Metzler et al. 2024). In practice, in-situ swelling pressures remain lower than the constant-volume swelling pressures derived from laboratory tests, highlighting the conservative nature of laboratory-based estimates.

Stress redistribution around the excavation and the restraining effect of immediate support measures (e.g., shotcrete, bolts, invert closures) significantly mitigate swelling deformations. Monitoring data confirm that displacements are generally small, with the crown and sidewalls responding mainly to excavation, while invert displacements evolve under irrigation. Block-specific responses illustrate the influence of support design: in block 3 with an open invert, uplift progresses continuously, while block 2 with a closed invert shows stabilization (see Fig. 3 for block arrangements). Hydraulic communication between blocks further illustrates the complex interaction of water pathways and swelling activation. The activated rock mass depth is currently limited to about 0.5–1 m, though irrigation boreholes reach 4 m, indicating ongoing processes. Extrapolation suggests swelling durations of several years, with final uplift values far below free-swelling laboratory estimates.

These results underline the critical differences between laboratory and in-situ observations, caused by scale, boundary conditions, stress redistribution, partial saturation, geological heterogeneity, and construction practices. In-situ testing therefore provides a more reliable basis for predicting swelling in complex interbedded formations, enabling optimized support design and reducing uncertainty in tunnel construction under hard soil–soft rock (HSSR) conditions.

## 4 CONCLUSIONS

In-situ test adits provide direct access to the subsurface, enabling precise geological mapping and geotechnical investigations under real conditions. They are particularly valuable in complex ground (e.g., squeezing rock, soil-like or transitional hard soil–soft rock formations), where conventional investigations are insufficient. Data from such adits support the optimization of tunnel design, validation of numerical models, and refinement of support systems.

A fully equipped test gallery represents an invaluable tool for addressing the complexities of soft rock formations. 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.

Moreover, they allow testing of construction methods and TBM performance in controlled settings. Despite higher upfront costs, test adits reduce geological uncertainties and enhance safety, efficiency, and reliability, as demonstrated in projects such as the Brenner Base Tunnel and the Angath adit in Tyrol.

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