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Proposals for development of a protocol for in-situ stress characterization

A. Hamidi, J.P. Harrison
University of Toronto, Toronto, Canada
asieh.hamidi@utoronto.ca

D. Mas Ivars
Swedish Nuclear Fuel and Waste Management Company (SKB), Solna, Sweden;
Royal Institute of Technology (KTH), Stockholm, Sweden

H. A. Kasani
Nuclear Waste Management Organization, Toronto, Canada

Abstract

Knowledge of the in-situ stress state is necessary to develop safe and reliable designs for underground rock engineering structures, and is crucial for safety-critical projects such as deep geological repositories for nuclear waste. However, obtaining such knowledge is difficult: variability and uncertainty is associated with all in-situ stress measurement techniques, and different experts may generate different assessments due to their differing interpretations of the circumstances.

Protocols for in-situ stress state quantification would help reduce such difficulties and potentially improve confidence in the interpreted stress state. Although some work has been reported on developing protocols in rock engineering, one for the systematic quantification and interpretation of the in-situ stress state is absent. Such a protocol should be universally applicable and accepted, while addressing the needs of practical engineering design, design review, ground investigations, database establishment and analyses, statistical modelling, and quality control. Here we present a methodology for developing such a protocol for the specific engineering objective of the safe and reliable design of nuclear waste repositories.

Keywords

In-situ stress, characterisation, protocol

ISRM

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1 Introduction

Nuclear power contributes significantly to energy production, but safe disposal of nuclear waste remains a critical challenge. Currently, deep underground sites are considered the most favourable solution, with the characteristics of deep geological repository (DGR) systems varying with waste type, host rock, and design. Assessing DGRs for long-lived radioactive waste requires a detailed understanding of near-field components and processes as these are critical to waste isolation and repository performance. Near-field processes influence radionuclide transport, interacting with the far-field and causing thermal, mechanical, and chemical changes in the host rock.

Site characterization for design of DGRs involves diverse geoscientific studies of host rock formations in order to account for different rock types and their properties, and a particularly detailed understanding of the in-situ stress state is required to ensure mechanical stability of associated excavations. Techniques like hydraulic fracturing, acoustic image logging and overcoring are used to determine the in-situ stress state, supported by frequentist, descriptive, and comparative statistical analysis methods together with numerical modelling. Integrated approaches ensure accurate stress characterization while addressing variabilities and uncertainties (e.g., Andersson et al. 2000; Cho et al. 2012; Choi 2007; Christiansson et al. 1996; Lim 2013; Martin et al. 2001; Read & Birch 2008; Sánchez Juncal 2023; Zhang et al. 2017). In-situ stress data inherently vary due to geological factors, measurement methods and data attributes. Variability in geological domains (e.g., formation properties, discontinuities) and diverse measurement methods over many years complicates analysis, highlighting the need for expert-informed decision-making in design. Established protocols can ensure reliability in large-scale, critical projects like DGRs. Incorporating quality control and integrating expert feedback ensures methodological rigour, data integrity, and reproducibility – all of which are key for safety. Structured protocols for in-situ stress characterization would clarify objectives, methodologies, and data management while maintaining consistency across geological conditions.

This paper proposes a methodology for developing a protocol for in-situ stress characterization as a design parameter. By reviewing existing protocols, field practices and analysis methods, we define sub-protocols to screen data and analysis methods, thus ensuring reliability for decision-making. The proposed methodology integrates stress data from multiple sources, together with geological setting, depth and existing knowledge of the in-situ stress state to create site-specific stress models. The paper also outlines stress database development and data consolidation, quality ranking, uncertainty management, and quality assessments. It focuses on two benchmarks – features of protocols, and in-situ stress as a design parameter for DGRs – before moving on to outline protocol mapping and operation.

2 Benchmark I: Protocol

2.1 Protocols, purpose and function

Developing a protocol begins with identifying gaps in current approaches, aiming to bridge knowledge gaps through detailed planning (Cameli et al. 2018). In medicine a protocol is a foundational document that outlines the objective, structure, methodology, and organization of a medical trial. It begins with an explanation of the background and rationale, detailing a carefully constructed plan to address research questions and ensure functionality. Standardized templates or checklists, such as the SPIRIT Statement, define the essential scientific, ethical, and administrative elements of a protocol for clinical trials (Chan et al. 2013). A well-written and approved protocol serves as a binding document to ensure compliance with legal, ethical, and scientific standards, and facilitates the assessment of scientific, ethical, and safety issues, consistent execution of study, and comprehensive evaluation of outcomes.

The importance of protocols has been emphasized across various practices (Chan et al. 2013; Rennie 2004; Tetzlaff et al. 2012) to address ethical and practical issues, reduce biases, and mitigate harmful consequences by ensuring that essential information is available for informed decision-making. This systematic approach improves cost-effectiveness and avoids personal and social harms (Rennie 2004), and allows transparency in design and methods to prevent incomplete or selective reporting, thereby ensuring ethical practices (Altman et al. 2006). Beyond clinical or similar trials, systematic identification and evaluation of protocols are essential for improving the quality and utility of research reports for diverse stakeholders (Hudson & Feng 2010). A protocol in engineering project design is a systematic framework integrating social, environmental, technical, and economic factors, ensuring reliability and safety throughout the planning process, and serve as a guide for engineers to meet sustainability objectives and navigate project complexities (Molgat 1996). Key steps in protocol development include identifying needs and gaps using reliable evidence, proposing a research-implementation framework, and validating the importance of key knowledge domains (Squires et al. 2015). A well-written protocol is judged on three criteria: whether it answers the set question(s), if it is feasible in the study context, and if it provides sufficient detail for reproducibility (Fathalla 2004). Answering questions related to the compatibility and integrity of protocol components, such as how the specification impacts on implementation, is essential to ensure the protocol meets its functional objectives (Shrivstava et al. 1985).

2.2 Protocol components

Developing protocol components involves a structured process of specification, validation, verification, and implementation, as shown in Table 1.

Table 1 Protocol components (after Sidhu et al. 1991)

Components	Descriptions
Specification	The protocol specification defines the protocol's objectives, inputs, and outputs, ensuring alignment with interfaces and system integrity. Formal specification methods, such as mathematical models or structured frameworks, provide unambiguous and analyzable specifications and use programming languages, whereas informal methods like diagrams or narratives are accessible but prone to errors. Formal methods, especially in multi-layer architectures, enhance reliability by mitigating ambiguities and errors.
Validation	Validation ensures protocols meet their objectives, for stress data case, focusing on stress measurement accuracy, data quality, repeatability, and reliability. Key goals include: - Data compatibility: inputs must be reliable and suits subsequent stages. - Sub-protocol validation: independent validation to ensure it meets its objectives before integration. - Measured data validity: criteria include the testing method, calibration quality, and field performance. - Analysis method adaptability: assessing testing methods and calibration quality. Metrics like measurement error and sensitivity levels evaluate success, while error propagation analysis and testing under complex geological conditions ensure robustness.
Verification	Verification confirms specifications are free of design errors. Formal methods are pivotal, employing: - Synthesis: building a protocol from informal specifications with inherent correctness. - Analysis: assessing protocols for alignment with desired properties. Both approaches foster reliability by systematically addressing potential design flaws.
Implementation	Implementation translates specifications into executable forms, ensuring practical application. Informal implementations define interactions and logic reuse, while formal ones adapt to system requirements for consistency. Detailed specifications minimize design gaps, enabling execution by programming tools.

2.3 Protocols and rock engineering practices for in-situ stress characterization

Protocols enable systematic planning, execution, and validation of engineering design projects. The International Society for Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM) have established guidelines for in-situ stress measurements, applied across engineering applications such as underground excavations, tunnelling, mining, and nuclear waste repository design. Suggested methods (SMs) by the ISRM and ASTM (Hudson et al. 2003; Sjöberg et al. 2003; Haimson & Cornet 2003; Christiansson & Hudson 2003; Stephansson & Zang 2014; ASTM 1997) encompass strategies for direct and indirect in-situ stress estimation in rock masses, and implementing quality control systems for stress estimation which involve reviewing whether estimations meet required quality standards, focusing on validation and assurance rather than implementation (Christiansson & Hudson 2003). ISRM SMs extend to establishing a final rock stress model (FRSM) at a given site by integrating measured data, validating stress components, and considering spatial variations such as depth-dependent stress changes and lateral variations linked to geological structures (Stephansson & Zang 2014). Suggested methods and practices emphasize consistency, simplicity, cost-effectiveness, and reproducibility, and the need for a protocol that minimizes resource requirements while ensuring comparable data collection Turowski et al. (2023).

Hudson and Feng (2010) introduced technical systematic auditing to evaluate the accuracy and validity of rock stress measurements and modelling through structured questioning. Auditing ensures analysis and design are logical, comprehensive, and scientifically sound, aligning with project goals, site-specific conditions, and standards. Information on these SMs and protocols is given in Table 2.

While auditing evaluates whether necessary factors, parameters, and mechanisms are appropriately considered, a protocol prescribes standardized procedures to ensure consistency and repeatability in project execution. Despite these differences, protocols for assessing in-situ stress characteristics provide a systematic framework that complements the flexibility and oversight offered by auditing.

Table 2 Summary of rock mechanics practices and protocols for in-situ stress assessments in the nuclear waste industry

Year	Author(s)	Purpose	Description and highlights
1968	McClain	Hydraulic fracturing (HF) for Radioactive Waste Disposal	Stress-strain behaviour due to injected waste, predicting vertical fracture formation as primary failure mechanism & its dependency on principal stress field orientation.
1977	ASTM D4729-19	Standard Test Method for Flat Jack	Defines the method for determining in-situ stress and modulus of deformation using the flat jack technique.
1977	ASTM D4645-08	Standard Test Method for HF	Establishes the method for determining in-situ stress in rock using HF techniques.
1996	Chandler et al.	HF, overcoring, convergence measurements, & URL	Magnitude and variability of in-situ stress, the importance of integrating excavation, multiple measurement methods, and boundary information for stress tensor determination.
2000	ASTM D4623-16	Standard Test Method for Overcoring	Details the procedure for determining in-situ stress using a three-component borehole deformation gauge.
2003	Christiansson & Hudson	ISRM SMs for Rock Stress Estimation—Part 4	Quality control in rock stress estimation to ensure accurate & reliable results.
2003	Haimson & Cornet	ISRM SMs for Rock Stress Estimation—Part 3	Describes HF and hydraulic testing of pre-existing fractures (HTPF) for stress estimation.
2003	Hudson et al.	ISRM SMs for Rock Stress Estimation—Part 1	Strategic approach for estimating stress state in rock masses, within rock mechanics & engineering design.
2003	Sjöberg et al.	ISRM SMs for Rock Stress Estimation—Part 2	Overcoring methods for estimating in-situ stress.
2004	Fairhurst	Underground Research Laboratory (URL), Pinawa	Technical suitability of granite as a host rock & challenges of stress redistribution, thermal effects, excavation damaged zone (EDZ), emphasizes scale effects (size and time).
2010	Hudson & Feng	Technical Auditing Procedure	Questioning to evaluate completeness, accuracy, & scientific validity of rock stress measurements, analyses, & designs.
2014	Stephansson & Zang	ISRM SMs for Rock Stress Estimation—Part 5	Guidelines for establishing a final rock stress model (FRSM) of a given site, updated previous suggested methods.
2015	Zhao et al.	In-Situ Stress Measurements in Xinjiang, China	Evaluates in-situ stress using HF & uniaxial compression tests, while acknowledging HF method limitations, suggested geophysical methods to address fracture influence on stress.
2017	Zhang et al.	In-Situ Stress and Fracture Characterization, China	Uses HF & acoustic logging to estimate stress orientations & natural fractures

3 Benchmark II: In-situ stress as a design parameter for nuclear waste repositories

3.1 Quantifying variability and uncertainty in stress data and challenges

Establishing preliminary design parameters to assess underground conditions involves investigations and site descriptions, including site-specific data with regional context, and considering geoscientific properties, environmental factors, and human land use (Follin & Stigsson 2014). In-situ stress is a critical factor in designing DGRs, as it significantly impacts coupled models of rock structure, water flow, construction and overall stability, and radionuclide migration calculations. Effective site assessment procedures for potential repository locations often rely on precise in-situ stress measurements (Cooling & Hudson 1986). In-situ stress characterization is a fundamental step in designing DGRs, but stress data from various sites and methods often show significant spatial variability (Javaid et al. 2021).

Stress heterogeneity refers to the variability of stress components within a zone of interest, often influenced by perturbations such as geological defects. However, this variability should not be confused with functional variations, such as linear changes in vertical stress with depth, which typically indicate homogeneous conditions. A statistically robust definition, states that stress heterogeneity arises when clustering analysis identifies multiple distinct stress domains within a region (Javaid & Harrison 2021).

Although spatial variability with depth and lateral heterogeneity are crucial factors in DGR design (Follin & Stigsson 2014; Andersson et al. 2007), no standardized or universally agreed approach exists for objectively quantifying stress variability or establishing well-defined heuristics for partitioning in-situ stress data into distinct domains. This lack of standardization leads to inconsistencies and subjectivity in stress domain characterization, as partitioning methods are sensitive to depth, sample size, and measurement methods, leading to variability and uncertainty due to geological complexities (Javaid et al. 2023a). In early design phases, precise information on stress components (e.g., orientations, magnitudes) and rock mass properties may be unavailable, making it essential to estimate failure risks while addressing uncertainties. In-situ stress data analyses must therefore manage complexities across methods, and variability in data quality and quantity (Musolino et al. 2022).

3.2 Frequentist and Bayesian statistical approaches for in-situ stress characterization

In-situ stress measurements are time- and cost-intensive, requiring significant expertise to ensure reliability. Data management optimizes costs and reduces uncertainty in estimates (Musolino et al. 2022). A standardized protocol can mitigate uncertainties by providing consistent workflows for reliable decision-making during repository design. Numerous methods have been developed to determine the in-situ stress state for DGR design. Examples include incorporation of numerical and geomechanics models (Corkum et al. 2018; Martin 2007), frequentist statistics, and Bayesian analysis of Cartesian stress components to assess variability and uncertainty at different depths (Javaid et al. 2023b). Table 3 gives a summary.

Table 3 Summary of applied methods for in-situ stress characterization

Year	Author(s)	Technique	Key contribution
2020	Feng et al.	Bayesian framework for stress data analysis.	Bayesian principles to stress characterization, its transparency in uncertainty quantification.
2021	Feng et al.	Hierarchical Bayesian approach for stress estimation. - Incorporates additional prior information.	Probabilistic approach improves uncertainty quantification and allows formal inclusion of supplementary stress information.
2023b	Javaid et al.	Bayesian linear segmented regression of Cartesian stress components.	Bayesian methods are shown to be superior to frequentist methods, due to the ability to account for variability & uncertainty in stress orientations with limited data.
2024	Feng et al.	Bayesian hierarchical model for partial pooling of adjacent overcoring (OC) tests.	Combining adjacent OC tests, incorporating prior knowledge to reduce uncertainties in stress data.
2024	Javaid et al.	Bayesian linear segmented regression for characterization of stress domain boundaries, applied to, Forsmark, Sweden.	Bayesian regression to quantify variability and uncertainty in stress domain boundaries.
2024	Kumar & Tiwari	Bayesian multi-model inference, compared to Monte Carlo & frequentist approaches.	Bayesian methods allow integration of uncertainties in model types and parameters.
2024	Li et al.	Improved overcoring technique with enhanced accuracy, and GM-BPNN for predicting stress	Improved stress measurement accuracy via GM-BPNN model showed high predictive accuracy.
2024	Sharma et al.	Bayesian approach for geotechnical site characterization with limited/missing data.	Bayesian methods' flexibility in handling data limitations, enhancing geotechnical data analysis.
2024	Zheng et al.	Bayesian inference approach combining analytical solutions and finite difference models. - Uses MAP estimation and MCMC sampling to analyse posterior distributions.	Ability of Bayesian methods to incorporate prior knowledge, uncertainty analysis, use of diagnostic tools for exploratory analysis, and their advantages over frequentist methods in tackling uncertainty.

4 Protocol mapping and operation

Continuing from section 2.2 above, a protocol for in-situ stress characterization should be structured around the four primary components of specification, validation, verification, and implementation (shown as I, II, III, & IV below). Each component should encompass sub-protocols to address specific aspects of data collection, analysis, and application. The protocol is described below and a schematic is shown in Fig. 1.

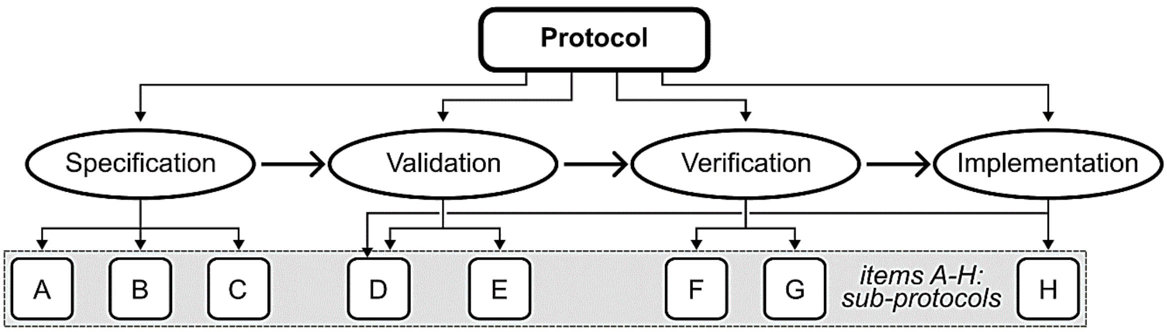

Fig. 1 Protocol development flowchart

I. Specification: Specification of the rules, requirements, and processes for developing a protocol, ensuring it aligns with the objectives of in-situ stress characterization and project design. Includes:

A. Sub-protocols for stress data collection from multiple sources, including direct measurements, geomechanical analyses, and geophysical surveys. A consolidated stress database with ranked data quality is established to standardize data integration.
B. Sub-protocols to specify characterization methods and the type and amount of data required at different stages of repository design. These ensure relevance and reliability, providing a foundation for site-specific adaptations.
C. Sub-protocols to identify stress domains and characterize uncertainty in their boundaries. Data, including geological, geomechanical, geophysical and geochemical sources, are integrated for a comprehensive assessment.

II. Validation: Ensure that the protocol components are relevant, reliable, and aligned with geological and design parameters, including:

D. Sub-protocols for conducting in-situ stress characterization at different stages of the project. These guidelines integrate probabilistic methods and site-specific data to address variability and uncertainty.
E. Testing and validation of the protocol to evaluate its adaptability to the site's geological complexities. Validation ensures the protocol performs consistently under real-world conditions and meets the design requirements.

III. Verification: Verification assesses protocols performance through scenario-specific tests, computational models, and alignment with engineering standards. Includes:

F. Sub-protocols to guide elicitation of priors for Bayesian characterization of in-situ stress. Verification ensures that the priors accurately reflect site-specific knowledge.
G. Compilation and verification of all sub-protocols into a coherent, comprehensive protocol for in-situ stress characterization. Scenario testing evaluates protocols performance and consistency across varying conditions.

IV. Implementation: Implementation translates the protocol's specifications into functional tools and practices, ensuring it meets design and operational needs:

D. As per item II(D) above.
H. Finalized protocols are implemented and tested, ensuring their compatibility with site operations and project design workflows. Continuous feedback loops address gaps and refine the implementation process.

The protocol is an iterative process that integrates data collection, probabilistic analysis, and validation methods to create a reliable framework for in-situ stress characterization. In our later work it will be tailored to the specific geological and operational conditions at Forsmark.

The framework ensures each protocol component – specification, validation, verification, implementation – works synergistically, enabling effective characterization of in-situ stress as a critical design parameter.

5 Conclusions and future work

In-situ stress characterization plays a pivotal role in the design and safety assessment of deep geological repositories for nuclear waste. This paper highlights the complexities associated with in-situ stress data, emphasizing the need for robust frameworks to manage variability and uncertainty. Spatial heterogeneity, depth-wise variability, and inconsistencies in measurement methods are key challenges that affect the reliability of stress data for repository design. These complexities necessitate a multidisciplinary approach, incorporating geological, geophysical, and geomechanical data to ensure comprehensive site evaluations.

A standardized methodology for development of a stress characterization protocol is proposed, encompassing four primary components: specification, validation, verification, and implementation. This framework systematically addresses data collection, integration, and analysis, ensuring consistency across site-specific and regional geology. Validation and verification processes, underpinned by probabilistic and computational methods, bolster the reliability of the protocol in diverse geological settings. The iterative nature of this framework ensures adaptability to site-specific complexities. Ultimately, the proposed protocol underscores the importance of standardized, transparent workflows for in-situ stress characterization. By combining advanced statistical techniques and a robust framework, the protocol will contribute to enhancing the reliability of DGR designs, ensuring safety and performance over extended operational timelines. Ongoing work will focus on developing the protocol, incorporating tools and exploring their application to broader geotechnical challenges. This approach will establish a foundation for advancing DGR design and addressing the long-term challenges associated with nuclear waste disposal.

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