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PHD OFFER

MECHANICAL STABILITY OF SALT CAVERNS UNDER SEISMIC SOLLICITATION : APPLICATION TO UNDERGROUND HYDROGEN STORAGE (UHS)

Type of contract : Doctoral contract.

Start date : October 2025

Location : Verneuil-en-Halatte (60), 40 mn north of Paris.

Access : A free private bus ensures the connection between the Creil station and the Ineris site.

Telework : 100 days/year

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CONTEXT

The French National Institute for Industrial Environment and Risks (Ineris) is an industrial and commercial public establishment under the aegis of the Ministry of the Environment. The Institute's mission is to contribute to the prevention of risks caused by economic activities to health, environment, and the safety of people and goods.

OBJECTIVES OF THE THESIS

This PhD thesis is part of the European project FrHyGe (*Full Qualification in France of Large-Scale Hydrogen Underground Storage and Replication from Germany to All European Countries*), partially funded by the Clean Hydrogen Partnership under grant agreement No. 101137892. Storing hydrogen in underground salt caverns presents specific challenges, particularly in regions exposed to natural and induced seismicity. Ensuring the safety and stability of these storage systems under seismic loading requires a deep understanding of their geomechanical and geophysical responses, extending beyond the specific site of Manosque, in order to inform applications at the European scale.

Manosque, located in southeastern France, serves as a key case study due to its seismic history, including the earthquakes of 1509 and 1708, which caused significant structural damage. These events highlight the need to analyze the dynamic interactions between seismic waves, salt caverns, and well infrastructure. Existing methodologies, particularly those based on semi-analytical solutions (Kurosé, 2023), investigate wave diffraction, dynamic response spectra, and mechanical impacts in elastic and anisotropic host rocks. This research aims to establish a robust scientific framework for assessing the mechanical integrity of salt caverns and wells under extreme seismic loading conditions by adapting and extending these approaches to viscoplastic media such as salt.

This doctoral research aims to advance the scientific understanding of the mechanisms governing the response of underground hydrogen storage systems to seismic loading. This advancement will be grounded in analyses and developments situated at the intersection of geophysics and geomechanics.

The main objectives of the research are as follows:

- Qualitative and quantitative analysis of historical seismic data from the Manosque region and, where appropriate, from other relevant sites. These analyses will serve to define representative seismic scenarios that will be used as inputs for numerical simulations.
- Advanced numerical modeling: Develop three-dimensional numerical models to simulate seismic wave propagation, diffraction, and interaction with salt caverns (including empty and pressurized cavities). These models will incorporate sophisticated constitutive laws, such as viscoplastic and damageable models, to more accurately capture the mechanical behavior of salt under dynamic conditions.
- Damage and fracture analysis under quasi-static conditions, driven by loading conditions identified through dynamic analyses. This will include both continuous models based on post-processed stress fields and discrete models that explicitly represent fracture initiation and propagation.
- Dynamic response analysis: Investigate the structural behavior of the system by analyzing the temporal evolution and spatial distribution of stress fields, stress concentration zones, strain fields, and the mechanisms of damage and failure in salt caverns and wells subjected to seismic loading. This analysis will leverage previously characterized response spectra to quantify dynamic effects and identify critical loading conditions. Different cavern fill levels will be considered to evaluate their influence and to identify the most critical configurations.
- Identification of key physical and geometrical parameters that govern the system's response under seismic loading.
- Extension of the modeling framework to other European sites with varying geological and seismic contexts. This includes assessing the applicability of the developed methodologies to different storage systems and operational scenarios.
- Development of a probabilistic risk assessment framework to quantify the likelihood and consequences of structural failure under seismic loading. This will lead to recommendations for design optimization, operational safety, and monitoring protocols.

METHODOLOGICAL APPROACH

The research work is structured into several key phases:

Phase 1: Seismic Hazard Analysis

This initial phase aims to characterize the seismic environment of the Manosque region and other selected sites. Historical seismic records will be analyzed in parallel with scenario-based modeling to define key parameters such as wave amplitude, frequency content, and attenuation properties. This phase will also incorporate site-specific geological data to account for subsurface condition variability.

Phase 2: Wave Propagation Modeling (in homogeneous and heterogeneous media, with empty or pressurized caverns)

Building on existing studies, this phase will develop numerical models to simulate the propagation and diffraction of seismic waves around salt caverns. The models will include both elastic and viscoplastic material behaviors to accurately represent the effects of seismic waves on cavern walls and internal structures. The influence of wave type (P, SH, SV) and angle of incidence will be systematically investigated to identify the most critical loading configurations.

Phase 3: Dynamic Response and Failure Mechanism Analysis

Using methods based on response spectra (previously identified and characterized), this phase will assess the mechanical response of salt caverns and wells under dynamic loading to establish damage and failure analysis frameworks. Stress concentration factors and strain amplitudes will be calculated to evaluate the stability of critical structural elements. Coupled hydro-mechanical models, potentially including fracture networks, will be introduced to account for fluid–structure interactions, particularly under hydrogen-saturated conditions.

Phase 4: Application to European Sites and Risk Assessment

This phase will apply the developed methodologies to two sites, including Manosque, adapting the models to different geological contexts to propose a general risk analysis framework. A probabilistic risk assessment approach will be employed, integrating seismic hazard data with numerical simulation outcomes to estimate failure probabilities. This phase will culminate in the formulation of safety and design recommendations.

RESEARCH TIMELINE

- Year 1: Literature review, seismic hazard characterization and definition, familiarization with modeling tools, and development of initial numerical models.
- Year 2: Simulations using refined and enriched models; dynamic response analysis and sensitivity studies.
- Year 3: Generalization of results, refinement of the risk assessment methodology, dissemination through publications, and thesis writing.

EXPECTED CONTRIBUTIONS

This research will deliver several key contributions to the fields of geomechanics and geophysics:

- A comprehensive seismic hazard characterization for the Manosque region and other European sites.
- Advanced numerical models for simulating the dynamic behavior of salt caverns and wells under seismic loading.
- A generalized framework for assessing and mitigating seismic risks in underground hydrogen storage systems i.e., quantification of stability risks and critical thresholds for hydrogen storage caverns under seismic loading.

- Evidence-based design and operational recommendations to enhance the safety and scalability of hydrogen storage infrastructure.

RELEVANCE TO FRHYGE PROJECT

As part of the FrHyGe project (Clean Hydrogen Partnership n°101137892), this thesis tackles the challenge of ensuring the safety and stability of hydrogen storage in seismically active regions. Its findings will support the scalable deployment of underground hydrogen storage in Europe, contributing to the energy transition.

PROFILE

Solid background in geomechanics, geophysics, and rock physics.

Strong skills in numerical modelling and programming (Fortran, Python, VB.NET or JavaScript), with an interest in developing analytical solutions.

Motivation, ability to work as part of a team.

REFERENCES

- Kurose, A. (2000) Effets des séismes sur les ouvrages souterrains. PhD Ecole Polytechnique, Palaiseau, France, 248 p.
- Kurose, A. & Bérest, P (2000). A Concept for Earthquake-Resistant Design of Underground Structures: Stress Response Spectrum. 4th North American Rock Mechanics Symposium, 2000, Seattle, United States. pp.1043-1049, https://hal.science/hal-00116132v1
- Lu, L., Shi, Y., Wang, M., Ye, M., Zuo, C., & Shun X. (2025) Seismic performance of salt cavern gas storage subjected to moderate earthquake loads in compressed CO2 energy storage scenarios. Energy Reports, vol13, June, Pages 2366-2383, https://doi.org/10.1016/j.egyr.2025.01.043
- Djizanne H., Zapf D., Habbani H., Körner F. & Brouard B. (2025) Advanced constitutive models for dimensioning salt caverns in Underground Hydrogen Storage. 11th Conference on the Mechanical Behavior of Salt (SaltMech XI), July 8-10, 2025, in Santa Fe, New Mexico, USA
- Pouya A. & Bemani Yazdi P., A damage-plasticity model for cohesive fractures (2015) Int. J. Rock Mechanics & Mining Sciences 73(2015)194-202.
- Zhu Cheng, Pouya A. & Arson C., (2015) Micro-Macro Analysis and Phenomenological Modelling of Salt, Viscous Damage and Application to Salt Caverns. Rock Mech Rock Eng (2015) 48:2567-2580.

GENERAL INFORMATION

Location : Verneuil-en-Halatte

Frequent travel will be required as part of the thesis work, both within France (Ineris Nancy and other FrHyGe project partners) and abroad (targeted conferences).

Supervisor : Amade POUYA (Université Gustave Eiffel, UGE, Ecole des Ponts)

Co-supervisors : Hippolyte DJIZANNE (Ineris) and Benoît BROUARD (Brouard Consulting)

Application :

2105€ gross salary per month
31 paid leave days and 18 « RTT » days off per year
Flexible hours
Company restaurant