Abstract

This thesis investigates geomechanical aspects of underground gas storage in depleted hydrocarbon reservoirs, with a particular focus on the cyclic behaviour of clayey caprock materials. Repeated fluid injection and withdrawal alter the stress state within the reservoir material, also affecting the surrounding formation and potentially compromising the integrity of the caprock. Therefore, understanding and properly modelling the mechanical response of caprocks under the effects of these complex loading conditions is essential for the long-term evaluation of storage efficiency.

The first objective of this research was to develop an appropriate constitutive model to capture the cyclic response of clayey caprock. An extensive literature review of experimental studies on the mechanical behaviour of caprocks constituted by structured, stiff, clayey materials, was conducted, so to identify the relevant aspects of the required constitutive model. In addition, experimental data from a study conducted on Santerno clay, a structured Italian clay extracted from a depleted hydrocarbon reservoir in the Po Valley in Italy were critically reviewed. Destructuration and strain rate dependency were identified as the key governing mechanisms ruling the mechanical response, particularly under cyclic loadings.

Based on these observations, this study extended the existing elasto-plastic framework originally proposed by Gens & Nova (1993) for modelling the response of structured soils and soft rocks, by incorporating a viscoplastic approach. Such a viscoplastic addition was essential in order to reproduce the strong strain-rate dependency of the mechanical response of the material under monotonic and cyclic loading. Cyclic tests have indeed shown that inelastic strain accumulation upon cyclic loading results in the progressive degradation of the material structure, eventually leading to fragile failure. This strain accumulation was found to be highly dependent on the maximum deviator stress applied, the loading period, and the amplitude. Such dependencies were attributed to the simultaneous action of cyclic degradation and viscous mechanism upon mechanical loading, resulting in interaction between the two. The proposed constitutive model, named EVP-GN, reproduced the fatigue life trends of Santerno clay under various cyclic loading conditions fairly well.

The thesis also explored geomechanical subsurface storage simulations at the reservoir scale. These simulations employed a synthetic reservoir model, named PUNQ (Production forecasting with Uncertainty Quantification), and a realistic reservoir model, named Field_Reg, to study stress dynamics in the surrounding region of the reservoir and resulting subsidence. Simulating storage loading with the PUNQ model emphasised the importance of considering inelastic deformations, since these promote stress arching and lead to different vertical and horizontal stress trends compared to simplified linear elastic solutions.

Field_Reg simulations, which included a production phase followed by storage loading, showed that the chosen constitutive model for the reservoir and caprock material accurately predicted the observed ground surface displacements during the production phase. Subsequently, different storage loading conditions were simulated, with a specific focus on the influence of amplitude and maximum pore fluid pressure in the reservoir storage conditions. The stress paths observed in the monitoring elements of the surrounding rock differed from those of conventional triaxial cyclic loading. These simulated stress dynamics provide valuable insights for geotechnical laboratory testing, helping to improve the selection of appropriate loading histories for studying load paths occurring in situ on a laboratory scale.

Finally, the effect of cyclic loadings as observed at the reservoir scale were modelled using the previously introduced EVP-GN framework. This evaluation used a decoupled approach. The strain loading histories obtained from selected caprock elements in the Field_Reg simulations were regularised and applied to single-element numerical simulations under triaxial conditions. The results were analysed to gain a better understanding of the mechanical implications of underground gas storage operations.

In conclusion, the ultimate objective of this research was to promote a more in-depth discussion of the assessment of caprock material response in the context of underground energy storage operations. To this end, it proposed a novel phenomenological approach to capture the complex interactions between destructuration and time-dependent mechanisms in clayey caprock materials and demonstrated its applicability to subsurface storage simulations.