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Innovative Concept for Analysing a Rock Salt Cavern under Cyclic Thermo-Mechanical Loading

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Abstract

The current paper aims to present an iterative scheme to explore the response of rock salt around energy storage caverns under thermo-mechanical cyclic loadings. Based on this, predictions from numerical simulations and measurements from laboratory investigations interact and get closer to realistic conditions. An exemplary iteration-cycle is conducted for one specific point in the vicinity of a cavern that is considered as critical in terms of the integrity-underlying rock salt behaviour, e.g. stress-strain relations and dilatancy development. The introduced scheme can be also used in those applications in which rare observations regarding the real behaviour of the system exist.

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Keywords: Rock salt cavern; Thermo-mechanical cyclic loading; Triaxial test; Finite Element Method; Constitutive Modelling

1. Introduction

The utilization of wind energy plants or solar panels is strongly dependent on wind and sunshine intensity. Accordingly, one consequence of the transition from fossil to renewable energy resources is the fact that the energy produced by these resources has a fluctuating nature. Although, those energy resources are somehow inexhaustible, there could be a time lag between the supply and the demand for electricity when these resources are employed. This may lead to an undersupply of electricity in the power grid during the peak of electricity consumption. To overcome this problem and to provide a sustainable power supply, storing energy in the form of compressed air or hydrogen in deep salt caverns has been studied in numerous research projects during recent years (e.g. [1–3]). Due to special geological conditions in Northwestern Germany that is geographically close to the offshore wind farms in the North Sea, one promising possibility is to store the energy in deep salt caverns by compressed air or hydrogen. Using solution-mined salt caverns for storing natural gas or crude oil over long time periods has been executed for decades [4,5]. In contrast, in the current application weekly to daily cycles of filling and withdrawing of gas from the caverns is the main concern. For this reason, the resulting cyclic characteristic of thermo-mechanical loading in the vicinity of the caverns

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has to be carefully taken into account. In this paper, the authors introduce an innovative concept to analyse the rock salt caverns under cyclic thermo-mechanical loading. Experimental investigation, constitutive modelling as well as numerical simulations are closely linked with this objective to explore the most realistic system response of a rock salt cavern under a characteristic loading condition for the aforementioned application. The scheme of this workflow is described in Sec. 2. In this paper, the experimental setup is introduced in Sec. 3. Then, the fundamental assumptions of constitutive modelling and numerical simulation are introduced in Sec. 4 and 5, respectively. This is followed by an exemplary application pointing out the interaction between experiments, numerical analysis and constitutive modelling in Sec. 6. It is worth to be mentioned that the introduced concept in this paper can be also applied for those applications in which measurements of the system response is not straightforward.

2. Methodology and workflow

A rock salt cavern is an underground cavity mined at depth of several hundred meters and used to store energy carriers. Technically, the solution-mining technique is utilized to leach out the salt and form these types of caverns. Since the solution-mined caverns are very deep structures, conducting the field measurements which might help us to understand the real response of the host rock are practically very difficult. In this paper, an iterative procedure aiming to find the most realistic stress-strain relation in the field is introduced. Fig. 1 represents the main steps of the iterative concept. As seen, the three investigation levels i.e. experimental, constitutive modelling and numerical analysis interact with each other in a systematic manner in order to improve the assumptions, evaluations and predictions. The first step of the investigation is based on former experience in similar projects and a literature database. At this step, the existing information regarding the rock salt behaviour including the executed experimental tests on rock salt and the existing models are collected from literature. These information might be not directly congruous to the cyclic thermo-mechanical condition in the caverns which are in the focus of the current research project. For example, during the past four decades, numerous studies have been performed in an attempt to predict the mechanical behaviour of salt under constant loading. Even though those tests cannot reflect the whole range of rock salt behaviour for the certain application, they are appropriate as an overall starting point for selecting a basic constitutive model. Obviously, the selected basic model does not reproduce all the relevant responses of the rock salt. Therefore, once the basic constitutive model is selected, its capabilities are improved by adding different features to it. In general, the accuracy level of one satisfying model depends on rheological behaviour and on the underlying processes at micro-scale on one hand and on the other hand, it also depends on the loading scenario that is going to be applied. Knowledge about these fundamental conditions allows us to formulate which material properties are of higher importance and to decide which ones might be negligible. In the context of this research, those properties of high interest are identified as elastic deformation, viscoplastic deformation, creep deformation and damage evolution.

Once a suitable constitutive law was chosen, in the subsequent step a numerical simulation can be carried out. The numerical computations represent realistic scenarios including all relevant loading phases even those prior to the caverns actual usage. That are the excavation (leaching), followed by a constant brine-pressure and a debrining phase. After also keeping pressure of debrining phases constant for some time, a first fill and succeeding cycles of charging and discharging pressure are applied. Stresses and strains at the points along the cavern's vicinity can be plotted and compared to experimental data used for calibrating the constitutive law. Depending on similarity of stress-strain-behaviour predicted by numerical results and observed by means of experimental data one can decide, if the assumptions are sufficient or an improvement or update is needed. In case results are not sufficient, critical locations at the wall of the cavern can be determined and the corresponding stresses and temperatures can be the starting point for the new experimental investigation. In this way, the new applied stress paths will be closer to the realistic ones. To close the current iteration, relevant measurements from experiments are the basis for a new calibration of the constitutive model and all following steps.

3. Experimental setup

A new triaxial device was developed at the Chair of Foundation Engineering, Soil and Rock Mechanics (Ruhr-Universität Bochum) to run element tests corresponding to the expected loading conditions in a salt cavern with