Mechanics of Materials 93 (2016) 13–31

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Micro–macro approach of salt viscous fatigue under cyclic loading

Ahmad Pouya[a], Cheng Zhu[b], Chloé Arson[b,*]

[a] Laboratory Navier (ENPC/IFSTTAR/CNRS), Paris-Est University, Champs sur Marne, France
[b] School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, USA

ARTICLE INFO

Article history:
Received 5 May 2015
Revised 13 October 2015
Available online 24 October 2015

Keywords:
Salt rock
Viscoplasticity
Fatigue
Micromechanics
Self-consistent method
Numerical simulation

ABSTRACT

The objective of this work is to explain the origin of fatigue observed in salt rock subject to cyclic loading. We used a self-consistent homogenization scheme to upscale the viscoplastic and damage behavior of halite polycrystals from mono-crystal viscous glide and breakage mechanisms. We modeled mono-crystals as spherical inclusions embedded in an infinite homogeneous matrix, and we assumed purely elastic inclusion/matrix interactions. We introduced a failure criterion at the mono-crystal scale in order to predict grain breakage and the subsequent damage effects on salt rock elastic moduli. We wrote an algorithm that allows computing macroscopic and microscopic stresses and strains during creep and cyclic axial loading. Although some simplifying assumptions were made in our micro–macro approach, the model provided micro-mechanical interpretations to important aspects of salt rock viscoplastic and fatigue behavior, which had not been explained so far, such as strain hardening, creep recovery, as well as damage and accelerated creep due to grain breakage. Moreover, incremental viscoplastic strains decreased over the cycles, which is in agreement with the phenomenon of “shakedown” observed in elasto-plastic media. Salt rock can be viewed as a model material. More generally, this research is expected to bring new perspectives to study the microscopic origin of fatigue in viscous polycrystalline materials.

1. Introduction

The mechanical behavior of salt rock was studied extensively during the last decades for its applications to industrial problems like nuclear waste disposals (Munson, 1979; Munson and Dawson, 1979; Langer, 1981; Ghoreychi, 1996; Chan et al., 1997; Hunsche and Hampel, 1999), mining (Chen et al., 2006; Jeremic, 1994; Liang et al., 2007), underground storage of oil and natural gas (Staudtmeister and Rokahr, 1997; Bérest et al., 2001; Wu et al., 2005) and, more recently, Compressed Air Energy Storage (CAES) (Fuenkajorn and Phueakphum, 2010). As an aggregate of halite crystals, natural or synthetic salt has also been frequently considered as a model material to examine a variety of theoretical models of plasticity, viscoplasticity and damage in polycrystalline materials (Stokes, 1966; Carter and Heard, 1970; Carter and Hansen, 1983; Urai et al., 1986; Senseny et al., 1992). Salt cavities used for the underground storage of oil and natural gas undergo weekly to seasonal thermo-mechanical load cycles. CAES facilities are subject to shorter load cycles, of the order of a day. Experimental data shows that the resulting fatigue of salt rock (i.e., the resulting decrease of Young’s modulus and strength) decreases as the load frequency increases. Fatigue is an important dimensioning factor for CAES design. However, due to the numerous variables influencing salt damage under cyclic loading (e.g., stress amplitude, loading frequency), and due to the high number of cycles necessary to assess fatigue effects in the laboratory,

* Corresponding author. Tel.: +404 385 0143.
E-mail address: chloe.arson@ce.gatech.edu, chloe_arson@yahoo.fr (C. Arson).

http://dx.doi.org/10.1016/j.mechmat.2015.10.009

experimental characterization of fatigue in salt rock remains a challenge.

Mechanical properties of rocks subjected to cyclic loads differ greatly from those under static loads. Rock fatigue is largely affected by the boundary and loading conditions, such as the confining stress (jian Ma et al., 2013; Zhu and Arson, 2014), the stress/strain rate (Taylor et al., 1986; Lajtai et al., 1991; Ray et al., 1999), the loading amplitude and the maximum stress (Fuenkajorn and Phueakphum, 2010; Prost, 1988; Tao and Mo, 1990; J.Q. et al., 2010), as well as the type and frequency of the signal (Attewell and Farmer, 1973), and the number of cycles (Singh, 1989). A review of the fatigue behavior of different types of rocks is provided in Bagde and Petroš (2005). The presence of joints (Jafari et al., 2004; Li et al., 2003), the size of grains (Burdine, 1963), humidity conditions (Lajtai et al., 1991; Ishizuka et al., 1990) and fluid migration (Mahnken and Kohlmeier, 2001) play a critical role in the triggering and evolution of fatigue in rocks. Experimental studies of rock fatigue under cyclic loading remain scarce, and mostly focus on salt rock. Therefore, salt rock is an adequate model material to study the microscopic origin of fatigue in crystalline materials. Recently, a model of salt rock fatigue under cyclic loading was proposed in Ladani and Dasgupta (2009).

In the present paper, we analyze the origin of salt fatigue from the mechanisms of deformation of halite crystals forming the polycrystalline aggregate. Homogenization schemes were proposed to upscale microscopic gliding mechanisms in granular (Balendran and Nemat-Nasser, 1993) and polycrystalline (Mirkhani and Joshi, 2014) media. In salt polycrystals, plastic and viscous deformation result from several fundamental mechanisms, e.g., dislocation glide, dislocation climb, polygonalization, inter-granular slip, dissolution-precipitation. Under stress and temperature typical of storage conditions, dislocation glide is the predominant mechanism that contributes to macroscopic salt rock deformation (Munson, 1979; Senseny et al., 1992; Arson et al., 2012). Dislocation glide can only occur on specific crystallographic planes, and in a limited number of directions. The non-elastic deformation of mono crystals (also called "grains" in the following) can result in geometric incompatibilities between adjacent grains. Restricted movements within monocrystals originate internal stresses within the polycrystal. Following the micromechanical approach adopted by Pouya to study salt rock plastic behavior (Pouya, 1991a, 2000), our goal is to model the viscous behavior of polycrystalline salt by upscaling viscous gliding mechanisms formulated at the crystal scale. Our study focuses on the combination of time-dependent gliding and breakage mechanisms that occur at the grain scale under cyclic loading. We presented a preliminary computational method in Pouya et al. (2014); Zhu et al. (2015). In this paper, we propose a homogenization scheme based on Hill's incremental interaction model (Hill, 1965), in which we account for the heterogeneity of the elastic stiffness tensor that results from different damage mechanisms occurring at the grain scale. In order to focus on the effects of grain breakage on macroscopic viscoplastic strains, we disregard the viscous accommodation of the matrix in the inclusion-matrix interaction model. Note that in the absence of damage, this simplifying assumption yields the Kröner–Weng interaction model (Kröner, 1961; Weng, 1982). Viscous accommodation (Rougier et al., 1994; Mercier and Molinari, 2009) falls beyond the scope of this paper. For future work, a review of incremental, secant, tangent, affine and variational formulations may be found in Masson and Zaoui, (1999); Masson et al. (2000); Bornert et al. (2001); Nebozhyn et al. (2001).

In Section 2, we explain the microscopic origin of fatigue in salt rock. We present the homogenization scheme in Section 3. In Section 4, we explain a method to calculate the internal stress and damage in the polycrystal during cyclic loading. We calibrated our micro-macro model of salt viscous fatigue against creep tests reported in the literature: results are reported in Section 5. We simulated creep tests (Section 6) and cyclic loading tests (Section 7), and conducted several parametric studies in order to examine the micro-mechanical origin of fatigue.

2. Microscopic origin of fatigue in salt rock

2.1. Macroscopic fatigue behavior

Table A.3 in Appendix A gives an overview of the main experimental results obtained for salt rock under cyclic loading. Observations made in a variety of salt rocks are very similar. The Young's modulus and the compressive strength decrease as the number of loading cycles increase (Fuenkajorn and Phueakphum, 2010; Dubey and Gairola, 2000; Ma et al., 2013). Fatigue initiates faster for lower loading frequency (Fuenkajorn and Phueakphum, 2010; Ma et al., 2013; Liang et al., 2011; Liu et al., 2014). The degradation of elastic moduli increases with the maximum stress and with the amplitude of the loading (Guo et al., 2012). Compared to amplitude and frequency, the confining stress does not influence fatigue significantly (Ma et al., 2013). The influence of the orientation of the bedding planes was investigated in Dubey and Gairola (2000). Memory effects in salt subject to triaxial stress states were analyzed in Filimonov et al. (2001). It has to be noted that the range of frequencies investigated in laboratory studies are significantly higher than those in actual CAES conditions. Low frequency experiments are more difficult to conduct in the laboratory, because they require more time: a sufficiently long loading period and a large number of loading cycles. Laboratory tests, performed at the macroscopic scale, were not able to reveal the microscopic origin of fatigue. The micro-macro modeling approach presented in this paper addresses this shortcoming: numerical simulations were conducted to relate the development of salt fatigue under cyclic loading to the evolution of micro-stresses in halite grains. Note that a few experimental studies relate texture development to the macroscopic strain rates of halite polycrystals subjected to creep loading (Wenk, 1999; Lebensohn et al., 2003), but, to the authors' best knowledge, no such work was published on the development of textures during cyclic loading. In the absence of experimental data on the role of the lattice, we focus our micro-macro analysis of salt fatigue on viscoplastic deformation and damage that occur at the crystal scale.

2.2. Halite crystalline structure and gliding mechanisms

Halite is a Face-Centered Cubic crystal (FCC). If all constituents of the crystal were atoms, intra-granular