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Analysis of small temperature oscillation in a deformable solid matrix containing a spherical cavity filled with a compressible liquid – Analytical solutions for damage initiation induced by pore pressure variation

Heraldo S. Da Costa Mattos*, Luciana P. Teixeira, Maria Laura Martins-Costa

Laboratory of Theoretical and Applied Mechanics, Graduate Program in Mechanical Engineering, Department of Mechanical Engineering, Universidade Federal Fluminense, Rua Passo da Pátria 156, 24210-240 Niterói, RJ, Brazil

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ABSTRACT

This paper analyzes the possibility of damage initiation induced by a very small temperature variation near a liquid-filled spherical cavity inside a deformable solid matrix. Experiments confirm that small temperature variations in a (compressible) liquid-filled cavity can induce high pressure peaks, depending on the initial temperature and pressures. The main motivation of the study is to verify the possibility of damage initiation induced by a very small temperature variation in a saturated liquid-filled porous medium with ultra-low permeability. Depending on the interaction between micro-cracks and pores, this damage may significantly affect the permeability conditions. The study of a single water-filled pore in an infinite matrix is quite a convenient preliminary step, since the stress field in the solid matrix is independent of its constitutive behavior (a statically determinate problem) what allows simplifying the complex coupled non-linear analysis. An abstract thermodynamic framework is used to present constitutive theories for generalized compressible Newtonian fluids and for elastic and elasto-plastic solid matrix behaviors. Both theories encompass a wide variety of constitutive models for solids and fluids found in the literature and can be applied in many engineering problems involving liquid-filled porous media. Using an adequate equation of state for the thermodynamic pressure proposed for liquid water at high pressures, it is possible to predict analytically if a very small liquid temperature variation (maximum of 5 K) can induce the matrix failure. Two examples of matrix behaviors are analyzed: brittle-elastic and elasto-plastic. Adequate failure criteria are used in each case to predict analytically the critical pressure required for the damage initiation. Once this pressure is determined, the temperature variation necessary to the damage initiation can also be obtained using the state law proposed for the thermodynamic pressure.

1. Introduction

Along the past few years, many studies have been performed about the influence of temperature gradients in the fracture and permeability of liquid-filled porous media. Most of them are concerned with the modeling of the fracture propagation

* Corresponding author.
E-mail address: heraldo@mec.uff.br (H.S. Da Costa Mattos).

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due to temperature gradients in the porous matrix or with the fluid flow. As examples the works of Bunger, Gordeliy, and Detournay (2013), Kgatle and Mason (2014), Khanna, Bortolan Neto, and Kotousov (2014), Mishuris, Wrobel, and Linkov (2012), and Shojaei et al. (2014) could be quoted. In many engineering applications, such as geological deposits and geothermal systems, the analysis of the influence of small temperature variations of the fluid (water) in the porous matrix integrity can be essential for a safer and more reliable project.

In low permeability porous media, like those used for geological deposits and geothermal exploration regions, some studies indicate that the temperature variation of the environment surrounding the structure may affect the process safety, dynamics and efficiency (Min, Lee, & Stephansson, 2013, for instance). The generation of thermal stresses in the matrix is important for fracture shear slip. Many studies have shown that shear dilation of fracture can be a source of significant liquid flow in fractured rock (Min et al., 2013). Rutqvist and Tsang (2008) showed that multiple locations around near-field can undergo shear slips along discontinuities due to thermal stresses. These situations are generally called “thermally induced fracture problems” in liquid-filled porous media.

However, so far, only a few studies have analyzed the influence of a small temperature variation (in time) of the liquid in the fracture and permeability of ultra-low permeability liquid-filled porous media (roughly speaking, with permeability of the order of nanodarcys). In da Costa Mattos, Reis, Puente Angulo, and Martins-Costa (2015) it is shown, both experimentally and theoretically, that a small temperature variation may induce huge pressure peaks in water-filled pores. In a low permeability water-filled porous medium, a small variation in the liquid temperature may induce pressure peaks that affect the stress distribution on the solid matrix, eventually inducing crack initiation and propagation. Depending on the interaction between cracks and pores, permeability can be strongly affected. Although these two situations are directly dependent on the temperature, the term “thermally induced fracture” was not used in the present work for the situation which is addressed in this paper (pressure peaks induced by small liquid temperature variations) to avoid confusion with another case, in which temperature gradients are involved.

Permeability plays an important role in different engineering applications such as geothermal systems and deep geological repositories. The increase in permeability can be positive in Geothermal Systems and aquifers (see Hofmann et al., 2014, for instance). Rocks such as granite and schist are generally poor aquifers because they have a very low porosity, but, if these rocks are highly fractured, they can make good aquifers. On the other side, an increase in permeability must be avoided in applications such as deep geological repositories for the long-term storage of nuclear waste (Rutqvist, Freifeld, Min, Elsworth, & Tsang, 2008; Wang, 2014).

Deep geological repositories (typically below 300 m) must be within a stable geologic structure. Important discussions have been conducted about the conditions and interferences that can compromise the security of those areas. These places are generally used for storing waste from nuclear processes, which must be contained and isolated until they reach safe radioactive levels for humans and the environment. The heat-generating nuclear waste can be a source for the alteration of the permeability and the basic requirement of a repository is that the radionuclides are secured against any possibility of transport back to the environment. Geological disposal of radioactive wastes is based on the principle that the deep rock environment is stable and unaffected by environmental change for a very large period of time. Potentially adequate rock formations could be clay-rich rocks, salt formations, but also hard igneous and metamorphic rocks (such as granite and gneiss). All these rocks are supposed to have stability, low permeability and good containment properties. Even selecting areas of high rigidity and low permeability rocks, which are less susceptible to changes in their stress state, chemical groundwater state and groundwater pressure, the technical aspects involving the possible occurrence of structural failures and the need to maintain low temperatures in these locations are beginning to be questioned, because of the long isolation period and the very high danger involved in case of leakage. The brittle behavior of igneous and metamorphic rocks makes them particularly sensitive to water pressure peaks inside the pores, mainly in the case of very low permeability.

Exploitation of geothermal systems, on the other hand, does not aim at the maintenance of the porous structure, but at the induction of artificial failures. In the past, it depended on naturally occurring heat, water, and rock permeability, sufficient to allow energy extraction. Now hydraulic stimulation, the so-called enhanced geothermal systems technologies, is employed. Essentially, the permeability is enhanced by pumping high-pressure cold water through an injection well into the rock, when natural cracks and pores do not allow economic flow rates, fracturing the rock. The operation of these environments depends on high permeability and porosity for the transport of water under high pressure conditions. However, if these conditions do not occur naturally, the porous system must be stimulated to generate or modify a reservoir to make it sufficiently productive.

Thus, a general study about the fracture and consequent permeability change induced by small temperature variations in water-filled, low permeability porous rocks is essential to an adequate characterization of such systems (Berryman, 2016; Kanaun, 2017). However, a fully coupled thermo/hydro/mechanical modeling of such a complex problem in saturated/unsaturated media requires time and a careful experimental program of validation that should be made step by step.

The present paper analyzes the possibility of fracture initiation due to a small temperature variation in a water-filled pore inside a solid matrix. The focus is the possibility of damage initiation in saturated liquid-filled porous media with ultra-low permeability induced by a very small temperature variation, since experiments confirm that small water temperature variations (less than 3 K) in a closed system can induce high pressure peaks (above 60 bar), depending on the initial temperature and pressures.

The study is restricted to a single water-filled pore (a spherical cavity under internal pressure) in an infinite matrix undergoing small transformations. This particular problem is quite convenient for the purposes of the paper, since the stress