Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 449–462

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Parametric study of thermo-hydro-mechanical response of claystone with consideration of steel corrosion

Y. Jia [a,*], H.B. Bian [b], G. Duveau [a], J.F. Shao [a]

[a] Laboratory of Mechanics of Lille, University of Lille, Cité Scientifique, Villeneuve-d'Ascq, 59655, France
[b] LEM3 UMR CNRS 7239, Université de Lorraine, Ile du Saulcy, Metz, 57045, France

ARTICLE INFO

Article history:
Received 8 December 2016
Received in revised form
21 March 2017
Accepted 22 March 2017
Available online 23 April 2017

Keywords:
Claystone
Steel corrosion
Thermo-hydro-mechanical (THM) coupling
Disposal tunnel
Corrosion rate
Volumetric expansion of corrosion products

ABSTRACT

In this paper, the thermo-hydro-mechanical (THM) response of claystone is studied via a series of parametric studies, considering the evolution of mechanical properties and deformation behavior of corroded steel. The numerical simulations are performed by using a coupled THM finite element code and two different constitutive models: a visco-elastoplastic model for geological formation and a von Mises type model for steel liner. The mechanical properties and deformation behavior of corroded steel are described in a conceptual model. Finally, a disposal tunnel supported by a steel liner is studied and a series of parametric studies is defined to demonstrate the corrosion effects of steel liner on the THM response of the claystone. The comparison of different numerical calculations exhibits that the volumetric expansion related to corrosion products has an important impact on the stress and displacement fields in the claystone surrounding the disposal tunnel. However, the evolutions of temperature and liquid pressure in the claystone are essentially controlled by its THM properties and independent of the steel corrosion.

1. Introduction

Deep geological repository is currently the only secure way to dispose of high-level radioactive waste (HLW). In order to minimize the release of radionuclide to biosphere and guarantee its stability and durability, disposal tunnel is generally supported by steel liner, providing a relatively light-weight and easy-to-handle characteristic. During the lifetime of repository, steel liner may be corroded by the eventual contact of groundwater coming from the geological formation and then induce the degradation of its useful properties (Push et al., 1985; JNC, 1999; Euratom, 2000), including strength, elastic properties, gas production and volumetric expansion. Therefore, in the underground repository for HLW, the response of geological barrier is affected not only by the decay heat of waste packages, but also by the stress change due to the corrosion of steel liner. In view of these facts, the long-term safety of disposal tunnel requires a good understanding of the thermo-hydro-mechanical (THM) response of geological formation in consideration of corrosion effects of steel liner.

This work is performed in the framework of feasibility study of a deep geological repository for HLW. Based on the design concept of Andra (French National Radioactive Waste Management Agency) during the period from 2004 to 2009 (Andra, 2005), an internal annulus space is reserved between the Callovo-Oxfordian (COx) claystone and steel liner quoted in terms of its diametric distance in order to facilitate the emplacement of waste packages and guarantee the retrievability of waste packages (Fig. 1). During the operation phase of underground repository, under the combined effects of claystone deformation evolution and corrosion of steel liner, the annulus space can be closed and even a structural failure of steel liner may occur (Andra, 2005). As a result, the retrievability of waster packages requires determining the closing time of internal annulus space located between the claystone and steel liner and ensuring the mechanical stability of steel liner for at least 1000 years. In view of these objectives, the emphasis of the present study focuses on the influence of mechanical properties and deformation behavior of corroded steel on the THM response of the COx claystone. Other corrosion phenomena of steel (for instance, water consumption, gas generation/dissipation, and influence of stress/temperature on the corrosion process) are not studied here.

* Corresponding author.
E-mail address: yun.jia@polytech-lille.fr (Y. Jia).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2017.03.007

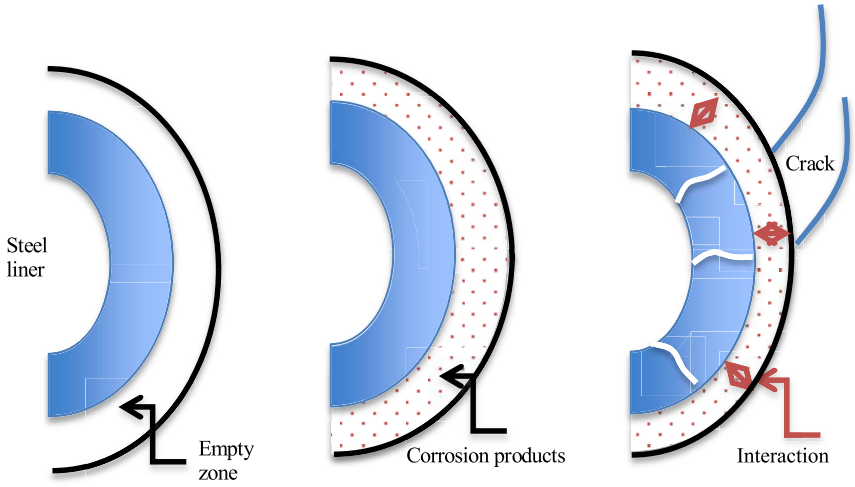

Fig. 1. Influence of corrosion on interaction between host rock and steel liner.

As the steel used in HLW repository is quite different from the typical archaeological materials which have been largely studied, based on the previous studies on the steel corrosion (Johnson and Francis, 1980; Cragnolino et al., 2000; Foct and Gras, 2003; Chitty et al., 2005; Martin et al., 2006; Lee et al., 2008; Vardon et al., 2014; Bildstein and Claret, 2015; Jia et al., 2016), one can observe that the archaeological analysis combined with the THM numerical model is capable of providing more detailed information on the influence of steel corrosion for a very long period of time. Vardon et al. (2014) used this method to study the effect of gas migration on the THM behavior of a bentonite buffer. Bildstein and Claret (2015) exhibited that the corrosion of steel barriers plays an important role in the long-term stability of underground repository. Jia et al. (2016) also used this method to simulate a disposal tunnel. The obtained numerical results have illustrated that the steel corrosion has a major impact on the THM response of claystone in the near field of tunnel. However, the effects of different corrosion phenomena have not been fully understood, for instance, the Young's modulus of corroded steel, the amplitude of volumetric expansion of corrosion products, and the corrosion velocity. As the major harmful effect of the corrosion of steel liner is the reduction of its thickness, leading to loss of mechanical strength and even structural failure (Fig. 1), the present study aims at studying the influence of mechanical properties and deformation behavior of corroded steel on the THM response of claystone.

The paper is organized as follows. Firstly, a visco-elastoplastic model specifically developed for the COx claystone is briefly introduced as well as the elastoplastic model of von Mises type for the description of mechanical behavior of steel. After that, a conceptual method is proposed for the description of mechanical properties and deformation behavior of corroded steel. A disposal tunnel supported by steel liner is simulated and analyzed. A series of parametric studies is then performed to investigate the influence of steel corrosion on the THM response of claystone. The analysis of numerical results allows us to capture the impacts of different corrosion phenomena on the THM response of claystone.

2. Review of constitutive models for COx claystone and steel liner

Under the hypotheses of small deformations and small perturbations, the total incremental strain tensor $d\varepsilon_{ij}$ could be decomposed into an elastic part $d\varepsilon_{ij}^{e}$ and a plastic one $d\varepsilon_{ij}^{p}$:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} \quad (1)$$

In practice, the claystone in the near field of disposal repository is desaturated during the exploration phase. However, as the disposal tunnel is supported by a steel line to create an impervious condition at the inner wall of the tunnel, the claystone will be resaturated progressively. As the present study is devoted to studying the THM response of claystone after the installation of steel liner, the studied claystone is assumed to be saturated by water (noted by index lq). The thermo-poroelastic constitutive equations for saturated porous media are used for the claystone (Biot, 1955, 1973; Coussy, 2004).

For the steel liner, it is waterproof in intact state. The corrosion may induce a permeability increase in steel and the research on this evolution is still in progress. However, this increase should be limited under confined condition in the disposal tunnel (Andra, 2005). For simplicity, it is assumed that the steel liner is always waterproof at different corrosion states and then no evolution of liquid pressure is observed in the steel liner.

2.1. Visco-elastoplastic model for Callovo-Oxfordian claystone

In the literature, numerous research programs (Chiarelli, 2000; Andra, 2005) have been performed to study the THM response of the COx claystone. Based on the experimental investigation, a small anisotropic behavior and a damage mechanism are observed in the studied claystone. For the sake of simplicity and putting the emphasis on the influence of steel corrosion on the THM coupling processes, the anisotropy and damage of the claystone are neglected in the present work. In this paper, tensile stresses are positive and compressive stresses are negative.

Moreover, two important plastic deformations are observed in the COx claystone on different time scales (i.e. the instantaneous plastic deformation on the short-term scale and the creep deformation on the long-term scale). In view of these facts, the visco-elastoplastic model proposed by Zhou et al. (2008) is adopted in the present work. The advantage of this model is that the instantaneous plastic deformation and the viscoplastic deformation are described by a unique set of mathematical functions. Moreover, the evolutions of both instantaneous plastic yield surface and viscoplastic loading surface are related to the same internal variable (i.e. the equivalent plastic shear strain γ^{p}). Therefore, by using a small