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On the mechanical and hydraulic response of sedimentary rocks in the presence of discontinuities

E. Haghighat, S. Pietruszczak [*]

Department of Civil Engineering, McMaster University, Hamilton, Ont., Canada

HIGHLIGHTS

- A framework for modeling time-dependent deformation in sedimentary rocks is presented.
- It includes description of localized deformation associated with propagation of macrocracks.
- Numerical analysis of damage around a deep underground excavation is performed.
- A modified Fourier/Darcy's law is introduced which incorporates an embedded discontinuity.
- Anisotropic flow around impervious cracks is analyzed.

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This paper is dedicated to prof. Tomek Hueckel on the occasion of his 70th birthday

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ABSTRACT

In this study, the mechanical and hydraulic properties of sedimentary rocks are examined. The first part is focused on the analysis of the onset and propagation of damage. The formulation of the problem involves the specification of an anisotropic failure criterion as well as description of inelastic deformation, which includes the time-dependent effects. The discrete propagation of macrocracks is simulated using an enhanced constitutive law with embedded discontinuity. The framework is applied to the assessment of long-term damage around a deep-excavation in an anisotropic shale formation. In the second part, the steady state flow in the presence of embedded discontinuities/cracks is addressed by applying a modified form of Darcy's law. The approach is illustrated by examining the flow pattern in a sedimentary rock sample that contains randomly distributed sealed fractures.

1. Introduction

The assessment of mechanical and hydraulic properties of sedimentary rocks is of a significant interest for a broad range of geo-engineering applications. Among those, perhaps the most critical one is the use of these formations for the geological disposal of nuclear waste. The feasibility of sedimentary rocks, in particular shale/clay, for the disposal concepts has been evaluated in a number of countries (e.g., France, Belgium, Switzerland, etc.) and it has been assessed as a favorable medium for the purpose of the long-term storage. This is primarily due to their adequate isolation properties, which include low permeability, geological stability and self-healing capacity. However, technical uncertainties about the safety of using geological repositories for the final isolation of high and/or intermediate level nuclear waste still remain unresolved. In particular, the issues related to the assessment of the effects of repository construction and burial of thermally hot wastes on the host rock are still poorly understood. This presents a major concern, as the geologic behavior of the repository area must be predicted over time spans of hundreds of thousands of years. This assessment should include not

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[*] Corresponding author. Tel.: +1 905 925 9140x24007.
E-mail address: pietrusz@mcmaster.ca (S. Pietruszczak).

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only the mechanical response, but also the mechanisms of groundwater flow into and radionuclide transport out of the repository.

The mechanical properties of shales are strongly influenced by their microstructure. At both the micro and mesoscales, the material displays an inherent anisotropy. In the former case, the texture consists of mineral particles (mostly flakes of clay minerals) which have a preferred orientation due to the sedimentation process. At a mesoscale, there are distinguishable bedding planes marking the limits of strata that can be clearly seen by a visual inspection. The anisotropy has a profound effect on both the strength and deformation properties, which has been documented by a large number of experimental studies. The strength in the compression regime is usually assessed based on the results of triaxial tests that are conducted at different orientation of the bedding planes (cf. Refs. [1–6]). The results generally indicate that the maximum strength is associated with specimens in which the direction of major principal stress is either parallel or perpendicular to the bedding planes, while the minimum strength has been observed for orientations between 30 and 60°. The failure mode evolves with the confining pressure. At high pressures, the response is ductile and significant irreversible deformations develop. At low confinement, the unstable strain softening behavior, associated with brittle failure, takes place. The tensile properties are typically assessed from the results of Brazilian indirect tensile tests. In general, the strength for tension perpendicular to the bedding planes is significantly lower than that for tension along the bedding planes.[7,8] There is also a strong experimental evidence that the behavior of shale is time-dependent and the effect of creep is significant (e.g. Refs. [9,10]). The quantitative aspects are, once more, influenced by the orientation of the bedding planes and at higher deviatoric stress intensities a prolonged period of creep might cause a spontaneous failure of the material.

The hydraulic properties of shales are also affected by the microstructure. The shale matrix contains both the micropores (pores less than 2 nm diameter) and mesopores (pores with 2–50 nm diameter). The smaller pores in the matrix are mainly associated with clay minerals and organic matter. Clay minerals account for about 50–60 wt% of most shales. As a result of this type of microstructure, the hydraulic conductivity of shale is very low and remains within the range of 10^{-13}–10^{-9} m/s. The conductivity in the direction parallel to the bedding planes is typically around 10^{-14}–10^{-12} m/s, while that in the direction normal to it is within the range of 10^{-15}–10^{-13} m/s. The porosity of shale is 1%–10%.

Over the last few decades, an extensive research effort has been devoted to modeling of the mechanical behavior of anisotropic rocks. A comprehensive review on this topic, examining different approaches, is provided for example in Refs. [11,12]. Some further details on the attempts to assess the conditions at failure and on the existing approaches for dealing with description of damage propagation are provided in Ref. [13]. This paper is an extension of research recently reported in Ref. [13]. Its primary objective is to outline a methodology for assessing the long-term damage in the host rock due to a deep geological excavation. In addition, the issue of the description of hydraulic properties of sedimentary rocks in the presence of discontinuities is also addressed. The paper is organized in the following sequence. In the next section, the general formulation of the constitutive relations governing the homogeneous as well as the localized deformation mode is outlined. This includes the specification of an anisotropic failure criterion as well as a description of both the instantaneous and time-dependent inelastic deformation. The discrete propagation of damage is simulated using an enhanced constitutive law with embedded discontinuity. The framework is then applied to the numerical analysis of a borehole excavation problem and the assessment of the evolution of the excavation damage zone (EDZ). In Section 3, the steady state flow in the presence of embedded discontinuities/cracks is addressed by invoking a modified form of Darcy's law. The approach is illustrated by examining the flow pattern in a constant head permeability test conducted on a sedimentary rock sample that contains randomly distributed sealed fractures. The paper ends by providing some final remarks.

2. Analysis of damage induced by a deep excavation in an anisotropic shale formation

In this section, the problem of assessment of damage around a deep geological excavation in a sedimentary rock formation is addressed. The analysis employs constitutive relations that describe both the homogeneous deformation mode, associated with anisotropic response, as well as the localized deformation involving the onset and propagation of macrocracks. Below, the details of the formulation are provided first followed by a discussion on the numerical results.

2.1. Formulation of the problem

The conditions at failure, which are identified here with the onset of formation of macrocracks, are defined by invoking the Mohr–Coulomb criterion with a constraint imposed on the strength in the tensile regime. Thus,

$$\begin{aligned} &F = \max\left(F_1, F_2\right) = 0; \\ &F_1 = \sqrt{3}\bar{\sigma} - \eta_f g(\theta)\ (\sigma_m + C)\,; \\ &F_2 = \max_{n_i}\left(\sigma_{ij} n_i n_j - f_t(n_i)\right) \end{aligned} \tag{1}$$

where, $\bar{\sigma} = (J_2)^{1/2}$; $\sigma_m = -\frac{1}{3} I_1$; $\theta = \frac{1}{3}\ \sin^{-1}\left(\frac{-3\sqrt{3}}{2}\frac{J_3}{\bar{\sigma}^3}\right)$ and

$$\begin{aligned} &g(\theta) = \frac{3 - \sin\phi}{2\sqrt{3}\cos\theta - 2\sin\theta\ \sin\phi}; \\ &\eta_f = \frac{6\sin\phi}{3 - \sin\phi}; \qquad C = c\ \cot\phi. \end{aligned} \tag{2}$$

In the expressions above, I_1 is the first stress invariant, while J_2, J_3 are the basic invariants of the stress deviator. Moreover, θ is Lode's angle, ϕ and c are the angle of friction and cohesion, respectively. For the tension cut-off criterion, i.e. the last equation in (1), n_i defines the unit normal to the plane, while f_t is the corresponding tensile strength.