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# Some aspects of air-entrainment on decay rates in hydraulic pulse tests

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ABSTRACT

Important factors that can influence interpretation of the pulse tests include the compressibility and viscosity of the fluid that either saturates the pore space of the rock or is used to pressurize the chamber, which generates the pressure pulse. Fluid compressibility can be influenced by entrained air. This paper examines theoretically, the influence of compressibility and viscosity variations in both the interstitial pore water and within the pressurizing chamber, on the performance of the hydraulic pulse test. Convenient analytical results can be derived to account for variations in compressibility and viscosity resulting from entrained air. Theoretical results indicate that the entrained gas content can have an appreciable influence on the pressure decay curves, and particularly high volume fractions of the entrained air can influence the estimation of the permeability from hydraulic pulse tests. The paper concludes with a brief discussion of the influence of dissolved air on the performance of pulse tests.



## 1. Introduction

Hydraulic pulse tests or transient hydraulic tests are used quite extensively to estimate the permeability characteristics of low permeability soils and rocks both in the laboratory and in the field. Detailed references to developments in this area are given by Selvadurai et al. (2005) and Selvadurai (2009). The hydraulic pulse test cannot be regarded as method for directly determining the fluid transport characteristics of a low permeability rock, since its theoretical interpretation requires other material and physical properties of both the porous medium and the permeating fluid. These include the porosity of the connected space in the porous medium, the compressibility of the porous skeleton as well as of the solid material constituting the skeleton, the compressibility of the permeating fluid and its dynamic viscosity. This is in contrast to the steady state hydraulic tests that require only knowledge of the physical dimensions of the flow region, the associated boundary conditions and the flow rates established during steady state flow. The steady state testing for permeability of even low permeability rocks can now be contemplated through the use of advanced experimental and computational techniques (Selvadurai and Selvadurai, 2010; Selvadurai et al., 2011). Many of the parameters that influence the performance of pulse tests can either be measured accurately or be controlled to a degree that their variabilities can be incorporated in any theoretical scheme that is used to interpret the pulse test data. The most important of these parameters is the compressibility of the fluid that is used in the test. There are two basic issues associated with the role of compressibility in not only hydraulic pulse tests but also in steady state tests. First, the requirement of an accessible saturated pore space is essential to the applicability of theoretical modelling based on Darcy flow. Experimental results indicate that the degree of saturation of the pore space can have a significant influence on the estimation of permeability even when performing steady state tests. Fig. 1 shows the results of one-dimensional constant flow steady state tests conducted on samples of Indiana Limestone, measuring 100 mm in diameter and 200 mm in length. The steady state pressures attained during the initiation of steady flow rates through the sample are greatly influenced by the degree of saturation of the cylindrical sample. As the sample approaches full saturation, the pressures required to maintain the specified flow rate stabilize with the result that the accurate estimation of the permeability of the rock is assured. The process of saturating the sample usually involves the application of a constant flow rate through the sample. For rocks with low permeability, an inordinate amount of time will be required to induce saturation without the initiation of excessive pressures, which in turn can cause damage to the porous skeleton through processes such as micro-hydraulic fracturing. Other procedures involve vacuum saturation of the sample, where vacuum is applied over a prolonged period, followed by de-pressurization to remove any excess hydraulic potential. A recent analysis by Selvadurai (2009) indicates that residual hydraulic gradients can also influence the pulse decay observed in a one-dimensional hydraulic pulse test and consequently the interpretation of the permeability of the material. Unless the vacuum saturation followed by depressurization and pulse testing are carried out in an experimental configuration that seals the pressurizing system from exposure to air, the fluid used in conducting the hydraulic pulse test can invariably imbibe air through exposure to the

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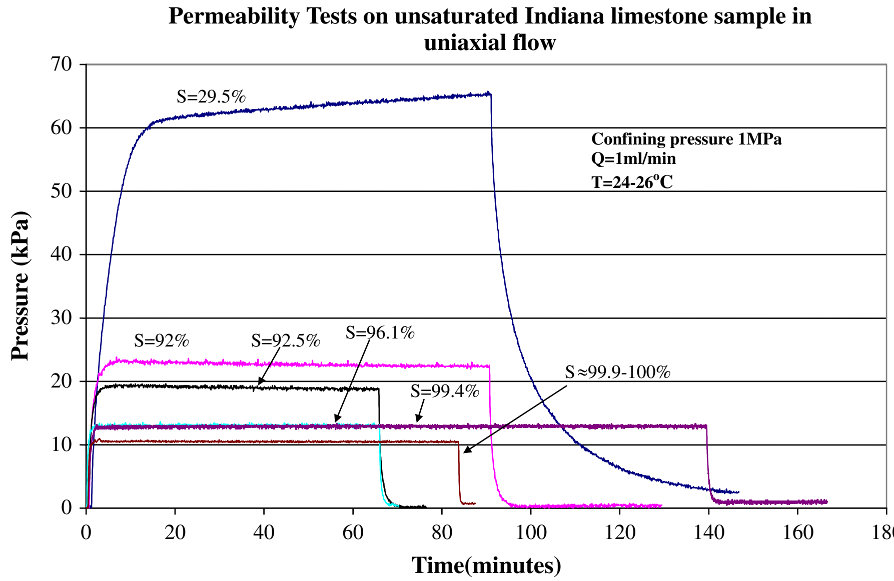


**Fig. 1.** Influence of the degree of saturation on the development of steady state pressure–one-dimensional pressure test (Selvadurai, 2009).

atmosphere. In many instances, the sample is removed from a vacuum chamber and transferred to the device that is used to conduct the hydraulic pulse test, making the test procedure susceptible to the influences of air imbibition. Furthermore, the pressurized fluid-filled cavity in contact with the surface of the porous medium can become air-entrained if the porous medium becomes partially saturated in regions close to the fluid contact. Other examples involving transient pore fluid pressure measurement in porous media also indicate that the degree of saturation can have a significant influence on the interpretation of pore fluid pressures. Results presented by Nguyen and Selvadurai (1995) and Selvadurai (2005) illustrate the time-dependent evolution of pore fluid pressures in a cylinder of cementitious material due to boundary heating. Here, de-saturation of the porous medium was present due to thermo-hydro-mechanical coupling and the boundary heating. The computational modelling of this boundary heating problem indicated that the effects of partial saturation should be taken into account to satisfactorily model the time-dependent evolution of pore fluid pressures. A further parameter that can influence the pulse test is the viscosity of the fluid, which can be altered by the air entrainment processes.

The objective of this paper is to examine theoretically the influence of air entrainment in the permeating fluid and the resulting alterations in the compressibility and viscosity of the fluid on the pressure pulse decay in a typical one-dimensional hydraulic pulse test. For the purposes of the exercise we will examine in detail the case where both the pressurizing cavity and the porous medium are air-entrained to the same degree. The theoretical solutions for other situations can be obtained quite conveniently through a suitable adjustment of the respective compressibilities and fluid viscosities to take into account the influence of air entrainment.

## 2. Governing equations

We consider the one-dimensional hydraulic pulse test that has been discussed quite extensively in the literature (see e.g. Brace et al., 1968; Hsieh et al., 1981; Neuzil et al., 1981; Selvadurai and Carnaffan, 1997; Selvadurai et al., 2005). For Darcy flow through the saturated porous medium and Hookean elastic behaviour of the porous skeleton, the problem of pore fluid pressure diffusion in the pore space of the porous medium can be described by the general theory of poroelasticity proposed by Biot (1941). Under certain conditions pertaining to the compressibility of the pore fluid in relation to the compressibility of the porous skeleton, the hydraulic potential in the pore fluid is governed by the *piezo-conduction* or *elastic drive* equation (Barenblatt et al., 1990; Philips, 1991; Selvadurai, 2000, 2002; Ichikawa and Selvadurai, 2012). In order to distinguish the properties of the fluids that are located either within the pore space of the porous medium or within the pressurized reservoir region, we employ the superscripts $^{(i)}$(interior region) and $^{(e)}$(exterior region), respectively. In one-dimension, the piezo-conduction equation can be written as

$$\frac{\partial^2 p}{\partial x^2} = \frac{S_s^{(i)} \mu^{(i)}}{K \gamma_w} \frac{\partial p}{\partial t} \quad ; \quad x \in (0, L_0) \tag{1}$$

where, $p(x,t)$ is the pore fluid pressure (dimensions: M/LT$^2$; M, L and T refer to dimensions of mass, length and time, respectively), $L_0$ is the extent of the domain (dimensions L), $\mu^{(i)}$ is the dynamic viscosity of the fluid in the pore space (dimensions: M/LT;), $K$ is the permeability (dimensions: L$^2$), $\gamma_w$ is the unit weight of water (dimensions: M/L$^2$T$^2$). In Eq. (1), $S_s^{(i)}$ is the specific storage of the porous medium (dimensions: 1/L), composed of a solid material that is assumed to be non-deformable and defined by

$$S_s^{(i)} = \gamma_w \left( n C_w^{(i)} + C_{eff} \right). \tag{2}$$

In Eq. (2), $n$ is the porosity and $C_w^{(i)}$ and $C_{eff}$ (dimensions: LT$^2$/M) are, respectively, the compressibilities of the pore fluid and the porous skeleton. The analysis can be extended to include poroelastic effects and grain compressibility as described by the classical theory of Biot (1941) (see e.g. Selvadurai (1996, 2007)). Also, when considering fully coupled poroelastic effects, the one-dimensional problem needs to be corrected for three-dimensional effects and this aspect is discussed by Selvadurai and Najari (2013). For the purposes of this study, which examines to role of compressibility of the pore fluid, it is sufficient to retain the one-dimensional behaviour described by Eq. (1). The partial differential Eq. (1) can be investigated for several situations of interest to the transient analysis of the one-dimensional pulse test. It should be noted that the result (Eq. (1)) pre-supposes that the porous medium is fully saturated prior to initiating any transient state; for this reason the equation cannot be used to investigate transient responses resulting from the migration of fluid into an *initially dry sample*. The governing partial differential Eq. (1) has to be solved subject to boundary conditions and initial conditions