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

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A B S T R A C T

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.

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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 imbibre air through exposure to the
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 entainment processes.

The objective of this paper is to examine theoretically the influence of air entainment 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 entainment.

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 Hookan 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; Phillips, 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 (o)(exterior region), respectively. In one-dimension, the piezo-conduction equation can be written as

\[ \frac{\partial^2 p}{\partial x^2} = \frac{S_i^{(i)}}{K} \frac{\partial p}{\partial t} : x \in (0, L_0) \]  

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/LT^2). In Eq. (1), \( S_i^{(i)} \) is the specific storage of the porous medium (dimensions: L/T), composed of a solid material that is assumed to be non-deformable and defined by

\[ S_i^{(i)} = \gamma_w \left( n C_w^{(i)} + C_{eff} \right). \]  

In Eq. (2), \( n \) is the porosity and \( C_w^{(i)} \) and \( C_{eff} \) (dimensions: L^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.
appropriate to the pulse test. It is important to note the following:
In order for the diffusive process to achieve a steady state in the flow domain of interest, the one-dimensional domain must necessarily be of finite extent, since the solution for the steady state equivalent of Eq. (1) described by the one-dimensional Laplace’s equation exists only for a finite domain. Alternatively, the analysis of diffusive processes associated with Eq. (1), for short relative time is considerably simplified if the porous domain is assumed to be semi-infinite in extent. The notion of a short time cannot be prescribed a priori since this is dependent on the permeability of the porous medium, which is the parameter sought. The mathematical analysis of the hydraulic pulse test will be examined in relation to a semi-infinite porous domain. The conventional assumption (see e.g. Hsieh et al., 1981; Selvadurai, 2009) is that the fluid pressure satisfies the initial condition

\[ p(x, 0) = 0 \quad ; \quad x \in (0, L_0). \tag{3} \]

The objective of the test is to determine the time-dependent evolution of the pressure in a pressurized chamber in contact with the surface of the fluid-saturated porous medium; \( p(0, t) \) or \( p(t, 0) \), with \( p(0) = p_0 \). The single boundary condition governing the pressurized end (\( x = 0 \)) of the semi-infinite domain is given by

\[ \frac{AK}{\mu^0} \left( \frac{\partial}{\partial x} \right)_x = V_w C_e \left( \frac{\partial p}{\partial t} \right)_{x=0} \tag{4} \]

where \( V_w \) is the volume of fluid that is contained in the region used to supply the fluid flow to the boundary \( x = 0 \) of the sample and \( A \) is the cross-sectional area. We use a Laplace transform technique to solve the initial boundary value problem defined by Eqs. (1), (3) and (4). Applying the Laplace transform to Eq. (1) and making use of the initial condition (Eq. (3)), we obtain the general result

\[ \tilde{p}(x, s) = A(s) \exp(-\alpha x \sqrt{s}) + B(s) \exp(\alpha x \sqrt{s}) \quad ; \quad \alpha^2 = \frac{S^0_v \mu^0}{K Y_w} \tag{5} \]

where \( \tilde{p}(x, s) \) is the Laplace transform of \( p(x, t) \) defined by

\[ \tilde{p}(x, s) = \mathcal{L}[p(x, t)] = \int_0^\infty p(x, t) \exp(-st) \, dt \tag{6} \]

and \( A(s) \) and \( B(s) \) are arbitrary functions of the transform parameter \( s \). Since the porous domain occupies the region \( x \in (0, \infty) \) we require, for regularity conditions, that \( B(s) \equiv 0 \). Employing the boundary condition (Eq. (4)) we can determine the unknown function \( A(s) \) and, by substituting this in Eq. (5), we obtain an explicit expression for \( \tilde{p}(x, s) \). Since we are primarily interested in the time-dependent variation of the cavity pressure at the boundary \( x = 0 \) of the porous domain, we obtain

\[ \frac{p(t)}{p_0} = \exp \left( \frac{\alpha^2 t}{2} \right) \text{Erfc} \left( \sqrt{\frac{\alpha^2 t}{2}} \right) \tag{7} \]

where

\[ \alpha^2 = \frac{A^2 K}{\mu^0 V_w^2} \left( \frac{C_e}{C_w} \right)^2 \tag{8} \]

and \( \text{Erfc} \) is the complementary error function. The variation in the fluid pressure within the semi-infinite domain can be expressed in the form

\[ \frac{p(x, t)}{p_0} = \frac{2}{\sqrt{\pi}} \int_{\sqrt{2} / \alpha}^{\infty} \exp \left( -t \frac{X^2}{\alpha^2} \right) \text{Erfc} \left( \sqrt{T - \frac{X^2}{4 \alpha^2}} \right) \, dx \tag{9} \]

where

\[ X = \frac{\alpha^2 t}{2} \quad ; \quad T = \frac{\alpha^2 t}{4} \quad ; \quad \tilde{\Phi} = \left( \frac{AK}{\mu^0 V_w C_e} \right) \tag{10} \]

An evaluation of the result (Eq. (9)) indicates that there is a rapid decay of the pulse from the boundary of the porous medium. The expression (Eq. (7)) provides an approximate procedure for assessing the influence of air-entrainment in either the fluid in the pressurized cavity or the fluid in the pore space of the porous medium, on the results from conventional pulse decay tests. The approximate nature of the analysis stems from several aspects, in that the fluids are considered to maintain their respective values of compressibility and viscosity in either the cavity region or the pore space regardless of the pressure decay. If these properties are assumed be influenced either by the pressures applied to create the pulse flow or through the process of fluid movement from the cavity to the pore space, then the problem needs to be re-cast as a moving boundary problem, which requires a more detailed and complicated analysis. Since the intention of the exercise is to ascertain the importance of initial fluid compressibilities and fluid viscosities on the pulse decay process, it is sufficient to restrict attention to the basic model presented here.

We now need to ascertain the influence of air-entrainment on both the compressibility of the fluid regions involved and on the viscosity of the fluid in the pore space. An expression for the effective viscosity \( \mu \) of a fluid containing a dilute suspension of solid spherical particles was developed by Einstein (1906) and takes the form

\[ \mu = \mu_0 \left( 1 + \frac{5}{2} \phi \right) \tag{11} \]

where \( \mu_0 \) is the viscosity of the fluid and \( \phi \) is the concentration of the suspension. This result was extended by Taylor (1954) to include a dilute suspension of drops of a liquid with viscosity \( \mu_d \). The modified expression for the effective viscosity is given by

\[ \mu = \mu_0 \left[ 1 + \frac{5}{2} \phi \left( \frac{\mu_d + (2/5) \mu_0}{\mu_d + \mu_0} \right) \right] . \tag{12} \]

When the drops of liquid are air bubbles, \( \mu_d \) can be neglected in comparison with \( \mu_0 \), and Eq. (12) reduces to

\[ \mu = \mu_0 (1 + \phi) . \tag{13} \]

Several other estimates for the effective viscosity of a fluid containing spherical droplets are available in the literature and these can be found in the articles by Batchelor (1967), Happel and Brenner (1973) and in a comprehensive article by Petford (2009). For purposes of this analysis we shall restrict attention to the estimate (Eq. (13)) given by Taylor (1954). We also note that the volume fraction \( \phi \) corresponds to the air/gas fraction in the fluid.

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**Fig. 2.** Influence air solubility on the compressibility of water.
The second parameter that influences the decay of the hydraulic pulse is the compressibility of the permeating fluid in the presence of entrained air. The effective compressibility of a fluid containing a volume fraction of air can be estimated from the elementary Voigt and Reuss bounds applicable to material mixtures (Christensen, 1979). The upper bound (Voigt) is given by (see also Smeulders and van Dongen, 1997)

\[
C_{aw} = (1 - \phi)C_w + \phi C_a
\]  

(14)

where \(C_{aw}\) is the compressibility of water containing an air volume fraction \(\phi\) and \(C_a\) is the compressibility of air. Similarly, the lower bound (Reuss) is given by

\[
\frac{1}{C_{aw}} = \frac{(1 - \phi)}{C_w} + \frac{\phi}{C_a}
\]  

(15)

Both bounds converge to the respective limits as either \(\phi \to 1\) or \(\phi \to 0\). As indicated by Hill (1963), when the shear moduli of two constituents are equal (both zero in the case of air and water), then an exact expression for the overall bulk modulus (and hence compressibility) can be obtained from the rule for isotropic mixtures, and the lower Hashin–Shtrikman bound will coincide with the upper bound, also given by Eq. (14); if the bulk modulus of the spherical fluid inclusion is zero, then the overall bulk modulus of the mixture is also zero regardless of the bulk modulus of the water. Consequently, if the bulk modulus of the air is to be taken into consideration, then the lower bound corresponding to the Reuss estimate (Eq. (15)) will give a more realistic estimate of the exact result.

Therefore, for the purposes of this study we shall first consider the lower bound Reuss estimate for the compressibility of the fluid containing an air fraction \(\phi\), given by Eq. (15) and provide suitable comparisons for the pressure pulse decay patterns derived from the Voigt estimate (Eq. (14)) and Reuss estimate (Eq. (15)).

The result (Eq. (8)) for \(\tilde{\Omega}^2\) can now be written as

\[
\tilde{\Omega}^2 t = T\Psi^R
\]

(16)

where

\[
T = \frac{A^2 Kt}{\mu_0 V_n C_w} ; \quad \Psi^R = \left( \frac{n \left( \frac{C_a}{\phi} (1 - \phi) + \Gamma_s \right) + \Gamma_s}{(1 + \phi) \left( \frac{n \left( \frac{C_a}{\phi} (1 - \phi) + \Gamma_s \right)}{\phi} + 1 \right)} \right)^{1/2}
\]

(17)

\[
\Gamma_s = \frac{C_a}{C_{tw}} ; \quad \Gamma_s = \frac{C_{eff}}{C_w}
\]

(18)

and \(\phi^{(i)}\) and \(\phi^{(e)}\) are, respectively, the volume fractions of the air voids present in the fluid-filled rock mass and the pressurized cavity, respectively. The air volume fractions in the respective regions can be changed to examine the influence of the degree of saturation in the respective regions on the decay pattern of the hydraulic pulse.

For the Voigt estimate,

\[
\Psi^V = \left( \frac{n \left( \frac{C_a}{\phi} (1 - \phi) + \phi^{(i)} + \phi^{(e)} \Gamma_s \right) + \Gamma_s}{(1 + \phi^{(i)} + \phi^{(e)} \Gamma_s \phi)^{1/2}} \right)^{1/2}
\]

(19)

Fig. 3. Decay of pressure in a one-dimensional pulse test: Influence of air void fraction and porosity.

Fig. 4. Decay of pressure in a one-dimensional pulse test: Influence of air void fraction and porosity.
3. Influence of air solubility

As a further discussion related to examining the role of air on the performance of hydraulic pulse tests, we consider the problem where the compressibility of the fluid in particular can be influenced by dissolved air. We note that when solubility is not an issue, the compressibility of the fluid can be bounded by the results (Eqs. (14) and (15)); i.e.

\[
C_w - \phi \Gamma_a \leq C_{aw} 
\]

When solubility becomes important (e.g. pressure, temperature, surface tension, etc., can influence the compressibility), the compressibility estimate needs to be modified: e.g.

\[
\frac{C_{aw}}{C_w} = \frac{\Gamma_a}{\Gamma_a (1-\phi) + \phi} \exp\left[\frac{\Omega^2 t}{\Gamma_a (1-\phi) + \phi}\right]
\]

where \( \Omega^2 = \frac{1}{\psi_R} \).

4. Numerical results

The modelling presented here gives an exact closed form result for the time-dependent decay of boundary pressure in a one-dimensional hydraulic pulse test where both the viscosity and the compressibility of the fluid can be influenced by the presence of entrained air. The parameter that governs this influence, \( \psi_R \), is defined by Eq. (17). We note that in the limit as \( \phi \to 0 \), Eq. (17) gives \( \psi_R = 1 \) and the result (Eq. (7)) gives the classical expression for the time-dependent decay of the pressure pulse. There are several non-dimensional parameters that govern the pressure decay at the boundary of a one-dimensional pulse test: These include \( T, n, \Gamma_a, \Gamma_s, \phi_i, \phi_e \), and \( \psi_R \); the last parameter represents the contribution from the compressibility of water.
containing a specified volume fraction of entrained air. Admittedly, the consideration of all of the above parameters for numerical evaluation of the influence of $\phi^{(i)}$ and $\phi^{(c)}$ on the pressure decay curve will involve a prohibitive amount of calculation, which, in view of the closed form nature of the result, is unwarranted. Here, we focus attention on a typical set of calculations where $T$ (Eq. (17)) is regarded as a variable for which calculations are developed for the range $T \in (0,5)$. Since $T$ depends on the permeability that is sought, it is instructive to place this range in terms of a typical experimental scenario. For this purpose, we can interpret the numerical results in relation to a one-dimensional pulse test conducted on a cylindrical sample of diameter 100 mm and length 150 mm, with a fluid volume of 10 ml in the pressure measuring system, along with the following mechanical and physical parameters:

\[ A \approx 7.5 \times 10^{-3} \text{ m}^2 \quad V_w \approx 10^{-5} \text{ m}^3 \quad n = 0.01 \quad T = 5 \]

\[ C_w \approx 4.5 \times 10^{-7} \text{ m}^2 / \text{kN} \quad \mu \approx 10^{-6} \text{kNs/m}^2. \]
For this experimental situation, 
\[ K_t = 1.72 \times 10^{-17} \text{ m}^2/\text{s}. \]

For a rock with permeability \( K \approx 10^{-20}\text{ m}^2/\text{s} \), this would correspond to a test of approximately 1/2 hour duration; for permeability \( K \approx 10^{-22}\text{ m}^2/\text{s} \), the corresponding test duration is approximately 2 days. To develop the numerical results, we assume typical properties for the compressibilities of air and water at 20 °C (Batchelor, 1967)

\[ C_{w} \approx 4.5 \times 10^{-7} \text{ m}^2/\text{kN} \quad \text{and} \quad C_{a} \approx 7 \times 10^{-3} \text{ m}^2/\text{kN}. \]

The compressibility of the rock skeleton can vary depending on the type of rock being tested; for example for Barre Granite and Indiana Limestone (Selvadurai et al., 2005; Selvadurai and Glowacki, 2008)

\[ (C_{\text{eff}})_{\text{Barre Granite}} \approx 3.75 \times 10^{-3} \text{ m}^2/\text{kN} \quad \text{and} \quad (C_{\text{eff}})_{\text{Indiana Limestone}} \approx 4.4 \times 10^{-7} \text{ m}^2/\text{kN}. \]

The parameter \( \Gamma_a \) is set to a fixed value corresponding the compressibilities defined previously and to account for a range of compressibilities of the rock, we assign a range of values for \( \Gamma_i \); i.e.

\[ \Gamma_a \approx (1.55)10^4 \quad \Gamma_i \approx 0.02 \times 2.0. \]

The next assumption pertains to the volume fractions of air in the pressurized fluid and in the pore fluid space of the tested rock. For the purposes of the calculations, we shall assume that \( \phi^{(1)} = \phi^{(2)} = \phi \), which provides a basis for examining the influence of the air fraction on the typical decay rates. We vary the porosity \( n \) and \( \Gamma_i \) to determine the influence of the volume fraction of the gaseous phase \( \phi \) on the decay rates. Figs. 3 to 5 illustrate the influence of the entrained gaseous phase content, the porosity and the relative compressibility of the porous skeleton to that of water, on the decay pattern of the one-dimensional pressure pulse test. These results indicate that the influence of any entrained air on the decay rate is marginal for air fractions even up to 10%. As the entrained air void content decreases, the bulk compressibility of the fluid phase will be dominated by the compressibility of air and this is expected to influence the pulse decay rate. Fluids with a high pore volume of gas/air can be encountered in sediment environments (Wheeler, 1988; Pietruszczak and Pande, 1996) and heated deep earth environments (Norris, 1993). Fig. 5 illustrates the influence of high air content on the pulse decay rate for volume fraction \( \phi \in (0.04). \)

We next consider the role of dissolved air content and air solubility on the results of hydraulic pulse tests. The parameters used in the computations are as follows:

\[ C_{w} \approx 4.5 \times 10^{-7} \text{ m}^2/\text{kN} \quad \text{and} \quad C_{a} \approx 7 \times 10^{-3} \text{ m}^2/\text{kN} \]

\[ (C_{\text{eff}})_{\text{Barre Granite}} \approx 3.75 \times 10^{-3} \text{ m}^2/\text{kN} \quad \text{and} \quad (C_{\text{eff}})_{\text{Indiana Limestone}} \approx 4.4 \times 10^{-7} \text{ m}^2/\text{kN} \]

\[ \Gamma_a \approx 1.5 \times 10^4 \quad \Gamma_i \approx 0.02 \quad \text{and} \quad H' = 0.0178. \]

The effective compressibility of the air–water mixture taking into account the air fraction and solubility, is determined from Eq. (21). As evident from Fig. 2, the influence of dissolution on the compressibility of the pore fluid is accentuated at low air content \( \phi \). The numerical evaluations are performed for pulse decay tests conducted with \( \phi = 0.005 \) and \( \phi = 0.010 \) and either with \( H' = 0.0178 \) or \( H' = 0 \). The latter estimate indicates the situation where dissolution is absent. Fig. 6 illustrates the decay responses obtained with either \( \psi^m \) (i.e. \( H' = 0 \)) or \( \psi^p \) (i.e. \( H' = 0.0178 \)). It is evident that there are appreciable differences between the two estimates as \( \phi \) becomes small. Fig. 6 also illustrates the hydraulic pulse decay as a function of the air fraction. As the entrained air void content decreases, the pulse decay is enhanced. This observation could provide a possible explanation of the decay pattern in hydraulic pulse tests conducted on the same sample in successive tests. As the number of tests increases the pore space could be progressively saturated with the result that the pulse decay is enhanced (Selvadurai et al., 2005, 2011; Selvadurai and Jenner, in press) (Figures 7 and 8).

5. Concluding remarks

While all precautions can be taken to ensure that the fluids used in permeability testing of low permeability materials is free of an air fraction, it is difficult to completely satisfy this requirement. The influence of the air fraction becomes more acute during testing that involves transient flow pulse tests, which depend on the compressibility of the pore fluid. The paper presents a technique for examining the influence of a volume fraction of entrained air on the pressure pulse decay that can be observed in a one-dimensional pulse test. The additional compressibility of the pore fluid that can result from an entrained air fraction can influence the decay data. The effective compressibility is accommodated through a multiphase Reuss/Voigt estimate for the compressibility of the pore fluid and a Taylor estimate for the viscosity. The influence of the additional compressibility of the entrained air can be considered marginal for air fractions of less than 10%. For higher values of the air fraction, the phases can exist as separate phases in the same connected pore space and the interpretation of the permeability can be influenced by the effective compressibility of the fluid phase. The preliminary calculations presented in the paper also point to the influence of dissolved air content on the performance of hydraulic pulse tests.

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References


