THM Processes in a Fluid-Saturated Poroelastic Geomaterial: Comparison of Analytical Results and Computational Estimates

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ABSTRACT: The theory of poroelasticity, extended to include thermal effects, provides a useful model for the study of the quasi-static response of fluid-saturated geomaterials subjected to heating. The basic model has been used quite extensively for modeling thermo-hydro-mechanical responses of rock encountered in nuclear waste management endeavours and geothermal energy extraction endeavours. The practical application of these theories invariably requires recourse to computational approaches where the governing partial differential equations are solved using Galerkin finite element techniques along with a suitable time-integration technique that assures stability of the solution. In recent years a number of multi-physics codes and general purpose finite element codes have been advocated for the study of such THM responses. The unconditional accuracy of these computational approaches can be assessed only by recourse to comparisons with known analytical solutions. This paper examines the capabilities of two computational codes in predicting the thermo-poroelastic response in a column of heated geomaterial subjected to heat diffusion and pore pressure dissipation through the upper surface, and to surface tractions.

1 INTRODUCTION

This paper deals with the thermoelastic effects in saturated geomaterials. Temperature changes can cause deformations of the pore water and the solid phase, which can lead to changes in pore pressure and effective stress. An increase in the pore pressure, in particular, can cause damage to the solid skeleton. The isothermal theory of three-dimensional consolidation proposed by Biot (1941, 1956) was extended by Rice and Cleary (1976) to include the effects of compressibility of the water and solid phase. Booker and Savvidou (1985, 1989) specifically solved the problem of consolidation of a porous media in the presence of heat sources: point, disk, cylindrical and spherical sources. The investigations of Selvadurai & Nguyen (1995, 1996) and Nguyen and Selvadurai (1995) deal with the thermo-hydro-mechanical behavior of fractured and intact geomaterials proposed for storing heat-emitting nuclear fuel waste. Rutqvist et al. (2001) presented a comparative study of four theories and computational implementations for both fully and partially saturated geomaterials which are subject to thermal loadings. Thermo-hydro-mechanical problems for soils with an elastoplastic skeletal material were considered by Lewis et al. (1986) and Hueckel et al. (1987). Reviews of recent developments in the theory of linear poroelasticity with applications are given by Selvadurai (1996), Wang (2000), Auriault et al. (2002), Coussy (2004) and Abousleiman et al. (2005).

This paper demonstrates the use of the computational multi-physics code COMSOL™ for solving a thermo-hydro-mechanical problem in geomechanics. COMSOL is a finite element code that allows the user to enter, as an input, the governing partial differential equations. For the purpose of validating the COMSOL software, we use an *analytical solution* for a one-dimensional problem of a fluid-saturated geomaterial, initially at a uniform temperature and fluid pressure, which undergoes heat diffusion and pore pressure dissipation due to the reduction of the surface temperature and pressure to zero. In addition, the geomaterial column is subjected to a normal traction at the surface. A further aspect of the research is to provide an inter-code validation of the accuracy of COMSOL through a comparison with results obtained for the one-dimensional problem, using the general purpose finite element code ABAQUS™.

The paper is organized as follows: The governing equations and the three-dimensional theory are presented in Section 1. An analytical solution for the one-dimensional problem is presented in Section 2. In Section 3 we describe the information the COMSOL user should provide to solve a thermo-hydro-mechanical problem via the finite element approach. Finally, in Section 4 we compare the results of the analytical solution from COMSOL and ABAQUS.

2 GOVERNING EQUATIONS

Consider a fully saturated poroelastic medium subjected to external mechanical loading and heating. The poroelastic medium consists of two phases - the porous solid and the liquid occupying the pore space. The porous solid is assumed to be isotropic, linearly elastic, and locally non-deformable (i.e. rigid grain material). It is convenient to use concise notation in which spatial coordinates x, y, z are replaced by $\mathbf{x}(x_1, x_2, x_3)$

In the absence of body forces, the total stresses in the poroelastic medium σ_{ij} must satisfy equilibrium equations,

$$\sigma_{ij,j} = 0 \tag{1}$$

The Duhamel-Neumann form of the constitutive relationship that accounts for thermal effects due to T and pore fluid pressure effects due to p takes the form,

$$\sigma_{ij} = 2G_D\varepsilon_{ij} + (K_D - \frac{2G_D}{3})\varepsilon_V\delta_{ij} - 3K_D\alpha_s T\delta_{ij} - p\delta_{ij} \tag{2}$$

where p is the excess pore pressure, T is the temperature change, ε_{ij} are the strain components, $\varepsilon_V = \varepsilon_{kk}$ is the volumetric strain, α_s is the linear thermal expansion coefficient of the solid phase, K_D, G_D are the bulk and shear modulus of the geomaterial under drained conditions. Note that absence of the thermal expansion coefficient of the fluid α_f in (2) does not imply that it has to be zero. The thermal expansion of the fluid, along with the thermal expansion of the solid phase, affects the value of the pressure.

It is worth noting that when drainage is allowed, the fluid pressure in the geomaterial will dissipate with time. Thus, the mechanical properties K_D, G_D and thermal expansion coefficient of the drained geomaterial will be equivalent to those for a porous geomaterial skeleton with empty pores. However, even when pressure is zero, the liquid is technically present in the porous fully saturated geomaterial. Therefore, the temperature field in (2) must be obtained as a solution of the heat transfer (conduction) equation for a porous medium with liquid filled pores.

The infinitesimal strain components are related to the displacement components u_i by the relationship

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{3}$$

Substituting (2) and (3) into the equilibrium equations (1) leads to,

$$(K_D + \frac{G_D}{3})u_{k,ki} + G_D\nabla\nabla u_i - p_{,i} - K_D 3\alpha_s T_{,i} = 0 \tag{4}$$

Another governing equation can be derived from the void occupancy equation and Darcy's law. The void occupancy equation states that the volume outflow from a geomaterial element must match the decrease in volume of the element plus any increase in volume of the constituents due to an increase in temperature:

$$n\int_0^t v_{l,l}dt + \varepsilon_V + n\frac{p}{K_f} = n(3\alpha_f)T + (1-n)(3\alpha_s)T \tag{5}$$

where $v_{l,l}$ is the divergence of fluid velocity, n is porosity, K_f is the bulk modulus of the fluid.
In turn, Darcy's law can be written as,

$$nv_l = -\frac{k_{lm}}{\gamma} p_{,m} \tag{6}$$

where k_{lm} are components of the permeability tensor, and γ is the unit weight of the fluid. Substitution of (6) into (5) and differentiation of (5) with respect to time results in another governing equation

$$-\frac{k_{lm}}{\gamma} p_{,lm} + \frac{du_{l,l}}{dt} + \frac{n}{K_f}\frac{dp}{dt} = n(3\alpha_f)\frac{dT}{dt} + (1-n)(3\alpha_s)\frac{dT}{dt} \tag{7}$$

The temperature field must satisfy the heat conduction equation,

$$c_{eq}\frac{\partial T}{\partial t} - k_{eq}\nabla\nabla T = 0 \tag{8}$$

where c_{eq} is the effective specific heat of the porous medium and k_{eq} is the effective thermal conductivity of the porous medium. To find these coefficients, it is possible to use, for example, volume averaged estimates. Thus, the specific heat and conductivity can be estimated as,

$$\begin{aligned} c_{eq} &= n\rho_f c_f + (1-n)\rho_s c_s \\ k_{eq} &= nk_f + (1-n)k_s \end{aligned} \tag{9}$$

where ρ_f and ρ_s are the densities of the liquid and solid phase, c_f and c_s are their specific heat capacities, and k_f, k_s are the thermal conductivity of the liquid and solid material.

The governing equations (4), (7) and (8) must be accompanied by initial and boundary conditions. Initial conditions are prescribed for the temperature and the pressure within the domain Ω,

$$\begin{aligned} p(x,t=0) &= p_0(x) \text{ in } \Omega \\ T(x,t=0) &= T_0(x) \text{ in } \Omega \end{aligned} \tag{10}$$

The boundary conditions on the boundary $\Gamma = \partial\Omega$ are,

$$\begin{gathered} T(x,t) = T_\Gamma(x) \text{ on } \Gamma_{T1};\quad -k_{eq}T_{,i}(x,t) = q_i(x) \text{ on } \Gamma_{T2};\ p(x,t) = p_\Gamma(x) \text{ on } \Gamma_{P1} \\ -\frac{k_{lm}}{\gamma} p_{,m} = h_l(x) \text{ on } \Gamma_{P2};\quad u_i(x,t) = u_{i\Gamma}(x) \text{ on } \Gamma_{U1} \\ \sigma_{ij}(x,t)n_j = t_i(x) \text{ on } \Gamma_{U2} \end{gathered} \tag{11}$$

where $\Gamma_{T1} \cup \Gamma_{T2} = \Gamma$, $\Gamma_{P1} \cup \Gamma_{P2} = \Gamma$, $\Gamma_{U1} \cup \Gamma_{U2} = \Gamma$.

3 SOLUTION OF ONE - DIMENSIONAL PROBLEM

Consider an idealized problem of a one-dimensional column of fluid-saturated geomaterial occupying the region $0 \le x_2 \le L$ being initially at an elevated temperature T_0. During this heating, fluid drainage across the boundary $x_2 = 0$ is prevented, which results in an initial fluid pressure build-up. Subsequently, the temperature and pressure at the surface of the region are reduced to zero and a compressive load σ_0 is applied at the upper surface of the column. The heat flux, fluid velocity and displacement are zero at the bottom surface of the column. Assuming that there are no lateral displacements

$$u_1(x,t) = u_3(x,t) = 0 \quad ; \quad \varepsilon_V = u_{2,2} \tag{12}$$

The boundary conditions for the temperature, pressure, displacements and stresses are:

$$p(x_2 = 0, t) = 0 \quad ; \quad \left[\frac{\partial p}{\partial x_2}\right](x_2 = L, t) = 0$$

$$T(x_2 = 0,t) = 0 \quad ; \quad \left[\frac{\partial T}{\partial x_2}\right](x_2 = L,t) = 0 \tag{13}$$

$$\sigma_{22}(x_2 = 0,t) = \sigma_0 ; \qquad \sigma_{12}(x_2 = 0,t) = 0$$
$$u_2(x_2 = L,t) = 0$$

The initial conditions for the temperature and pressure are:

$$T(x_2, t = 0) = T_0 \tag{14a}$$
$$p(x_2, t = 0) = p_0 \tag{14b}$$

The temperature field satisfying the partial differential equation (8) governing heat conduction and the boundary/initial conditions (13), (14a) is given by,

$$T(x_2,t) = T_0 \sum_{m=1,3,5...} \frac{4}{m\pi} \sin(\frac{m\pi}{2L} x_2) \exp(-\kappa_m^2 t) \quad ; \quad \kappa_m^2 = \frac{m^2 \pi^2}{4L^2} \frac{k_{eq}}{c_{eq}}$$

(15)

Note that the total normal stress σ_{22} inside the column is equal to the applied stress,

$$\sigma_{22}(x,t) = \sigma_0 \tag{16}$$

From the constitutive equation (2)

$$(K_D + \frac{4}{3} G_D)\varepsilon_{22} - K_D 3\alpha_s T - p = \sigma_{22} = \sigma_0 \tag{17}$$

and, therefore, the normal strain is

$$\varepsilon_{22} = \varepsilon_V = \frac{1}{K_D + \frac{4}{3} G_D}(\sigma_0 + K_D 3\alpha_s T + p) \tag{18}$$

Equation (18) can be used in (7) to obtain a differential equation for the fluid pressure, i.e.

$$-\frac{k_{22}}{\gamma} p_{,22} + [\frac{n}{K_f} + \frac{1}{K_D + \frac{4}{3} G_D}]\frac{dp}{dt} = n3\alpha_f \frac{dT}{dt} + (1-n)3\alpha_s \frac{dT}{dt} - \frac{K_D}{K_D + \frac{4}{3} G_D} 3\alpha_s \frac{dT}{dt} \tag{19}$$

Solution of equation (19) is obtained as the sum of the solution of the homogeneous equation p^H, and a particular solution of the inhomogeneous equation p^*, i.e.,

$$p = p^H + p^* \tag{20}$$

The homogenous equation is obtained from the equation above by setting $T = 0$, and the general solution is given by,

$$p^H(x_2,t) = \sum_{m=1,3,5...} C_m \sin(\frac{m\pi}{2L} x_2) \exp(-\omega_m^2 t) \quad ; \quad \omega_m^2 = \frac{m^2 \pi^2}{4L^2} \frac{k_{22}(K_D + \frac{4}{3} G_D)}{\gamma(1 + \frac{n}{K_f}(K_D + \frac{4}{3} G_D))} \tag{21}$$

where C_m are unknown coefficients. Now we need to find a particular solution of the given equation by considering application of temperature T. The particular solution of (19) is taken in the same form as the temperature field (15),

$$p^*(x_2,t) = \sum_{m=1,3,5...} A_m \sin(\frac{m\pi}{2L} x_2) \exp(-\kappa_m^2 t) \quad ; \quad \kappa_m^2 = \frac{m^2 \pi^2}{4L^2} \frac{k_{eq}}{c_{eq}} \tag{22}$$

To find the unknown coefficients A_m, (22) is substituted into (19). This gives

$$A_m = \frac{\left(\frac{K_D}{K_D + 4G_D/3} 3\alpha_s - n3\alpha_f - (1-n)3\alpha_s\right)\frac{4T_0\kappa_m^2}{m\pi}}{\frac{k_{22}}{\gamma}\frac{m^2\pi^2}{4L^2} - \left(\frac{1}{K_D + 4G_D/3} + \frac{n}{K_f}\right)\kappa_m^2} \tag{23}$$

Since the total fluid pressure must satisfy the initial condition,

$$p(x_2, t=0) = p_0 = p_0 \sum_{m=1,3,5} \frac{4}{m\pi}\sin\left(\frac{m\pi}{2L}x_2\right) \tag{24}$$

From (20) and (24) we can establish the following connection between the coefficients,

$$C_m = p_0\frac{4}{m\pi} - A_m \tag{25}$$

The initial fluid pressure can be found from the void occupancy equation (5) at time $t = 0$ and constitutive equation (17),

$$p_0 = \frac{-\sigma_0 + [n3\alpha_f + (1-n)3\alpha_s]T_0(K_D + 4G_D/3) - K_D 3\alpha_s T_0}{1 + (K_D + 4G_D/3)\frac{n}{K_f}} \tag{26}$$

To summarize, the total solution for the fluid pressure is given by,

$$p(x_2, t) = \sum_{m=1,3,5...} C_m \sin\left(\frac{m\pi}{2L}x_2\right)\exp(-\omega_m^2 t) + \sum_{m=1,3,5...} A_m \sin\left(\frac{m\pi}{2L}x_2\right)\exp(-\kappa_m^2 t) \tag{27}$$

where A_m is found from (23), C_m from (25) and the initial pressure p_0 from (26).
This completes the solution for the pressure. Now the strain is derived using constitutive equation (18),

$$\varepsilon_{22} = \varepsilon_V = \frac{1}{K_D + 4G_D/3}(\sigma_0 + K_D 3\alpha_s T + p)$$

The displacement field can be found by integrating the strain,

$$u_2 = \int \frac{1}{K_D + 4G_D/3}(\sigma_0 + K_D 3\alpha_s T + p)\,dx_2 + U \tag{28}$$

where U is the constant of integration. This gives

$$\begin{aligned} u_2 = \frac{1}{K_D + 4G_D/3}\Bigg[&-K_D 3\alpha_s T_0 \sum_{m=1,3,5...}\frac{8L^2}{m^2\pi^2}\cos\left(\frac{m\pi}{2L}x_2\right)\exp(-\kappa_m^2 t) - \\ &- \sum_{m=1,3,5...} C_m \frac{2L}{m\pi}\cos\left(\frac{m\pi}{2L}x_2\right)\exp(-\omega_m^2 t) \\ &- \sum_{m=1,3,5...} A_m \frac{2L}{m\pi}\cos\left(\frac{m\pi}{2L}x_2\right)\exp(-\kappa_m^2 t) + \sigma_0(y - L)\Bigg] \end{aligned} \tag{29}$$

The constant of integration is found by requiring that the displacement be zero at the lower surface, i.e., $u_2(x_2 = L, t) = 0$.

4 RESULTS OBTAINED USING COMSOL™ AND ABAQUS™

The solution for the one-dimensional problem described in the previous section is used to validate performance of the multi-physics code COMSOL. The solution was also verified using the ABAQUS finite element program. We can define a sequence of auxiliary problems. In each auxiliary problem, the temperature is applied gradually within a short period of time, starting from a zero value and reaching a maximum value T_0. The sequence is formed by setting the duration over which the temperature rise takes place to zero. Note that the initial conditions for the original problem, in which the temperature is raised instantaneously to T_0, can be considered as a limit of the sequence of the solutions of these auxiliary problems.

When the user solves the auxiliary problems with the help of ABAQUS, the step GEOSTATIC is not needed, since the initial temperature and all initial fields are indeed zero. (The step GEOSTATIC is used to find equilibrium state for the geomaterial subject to initial pressure and initial stresses.) One can confirm that the solutions of the auxiliary problems converge, at time $t = 0$, to the current solution, when the temperature is applied instantaneously. Therefore, the step GEOSTATIC must not be used if the user solves the original problem with ABAQUS. In fact, this step will give a wrong solution, in which for example, the displacement is zero at time $t = 0$ for the case of incompressible fluid. Also, note that ABAQUS requires the input of the void ratio e instead of porosity. They are related as,

$$e = \frac{n}{1-n}$$

In the input file the initial pressure can be set equal to zero; the user does not have to evaluate the value of the initial pressure (26).

When solving the problem with COMSOL the user has to modify certain dialog boxes. First of all, in the dialog box of the elasticity problem, in the section "Load" the user has to check the checkbox "Include thermal expansion" and in the field "Temp" put in the name of the variable denoting the temperature T. Then, in the same dialog box, the user has to add the body forces that are caused by the pressure gradient. Thus, according to (4), the parameter "body load" F_x must be assigned the value $-p_{,x}$, the parameter F_y takes the value $-p_{,y}$. Note that the terms containing derivatives of temperature $T_{,i}$ need not be added to the fields of this dialog box since, for the thermo-elastic problem, the temperature gradient is already included as a body force.

Next, the user has to modify the mass conservation equation. COMSOL solves the Darcy's equation in the form of a piezo-conduction equation (Barenblatt et al., 1990; Selvadurai et al., 2005; Selvadurai, 2009)

$$S\frac{\partial p}{\partial t} - \nabla\cdot[\frac{k_s}{\eta}\nabla(p+\rho_f gD)] = Q_s$$

where S is the storage term, Q_s is the liquid source, g is the gravitational acceleration, ρ_f is the fluid density, k_s is the saturated permeability coefficient, η is the viscosity of the fluid.

To match this form of mass conservation law with the given equation (7), in the dialog box of the Darcy's equation, in the section Coefficients, the user has to add source terms according to (7). For the right-hand side of the Darcy's equation Q_s, the user has to input

$$-vyt + n*3*\alpha_f*(Tt + T0/t0*(t<t0)) + (1-n)*3*\alpha_s*(Tt + T0/t0*(t<t0))$$

Here the vertical displacement in COMSOL is denoted by v, the coordinate $y = x_2$, vyt is the derivative of v with respect to y and time t, $T0$ is the initial (applied) temperature, $t0$ is an arbitrarily chosen but small value of time. The expression $(t<t0)$ is 1 if the condition inside the brackets is satisfied, and it is 0 otherwise.

The term containing $T0/t0$ should not be omitted since it represents an approximate derivative of the Heaviside function $T_0\mathrm{H}(t)$ with respect to time.

To eliminate the effect of self weight, the user can set gravitational acceleration equal to zero, i.e., $g = 0$.

The storage parameter S must be set to n/K_f. Thus, in the case of an incompressible fluid $S = 0$. Also, the user has to make sure that $k_s/\eta = k_{22}/\gamma$ as in (7). As in ABAQUS, there is no need for the user to know the initial pressure (26), it can be set to zero.

In the dialog box "Conduction" in the section Init, the user has to specify the initial temperature T_0. Also, in the section "Thermal Properties", the user can specify effective heat capacity and effective thermal conductivity for the porous media.

5 NUMERICAL RESULTS

Consider the THM problem for a 1D column of height $L = 10$ m. The column occupies the domain $0 \le x_2 \le L$. The column is initially at the elevated temperature equal to $T_0 = 100C$ and is acted upon by the non-zero pore pressure that builds up initially due to the absence of fluid drainage across the boundaries. The pressure and the temperature at the upper surface $x_2 = 0$ are reduced to zero and the constant compressive stress $\sigma_0 = -10$ MPa is applied at the upper surface. The following properties are used:

Table 1. Properties of soil

Property	Value
Porosity n	0.25
Young's modulus	$E = 60*10^9$ Pa
Poisson's ratio	ν = 0.3
Unit weight of water	9800 N/m^3
Fluid permeability	k = 2.94e-12 m/s
Effective thermal conductivity	k_{eq} = 4 (W/mºC)
Effective specific heat	c_{eq} = 2465000 (J/kg/ºC)
Linear thermal expansion of solid phase	$\alpha_s = 8.3 *10^{-6}$ (1/ ºC)
Linear thermal expansion of liquid	neglected
Fluid bulk modulus	$K_f = \infty$ or 2.2*10^9 Pa (two values are used to examine effect of fluid compressibility)

In the figures presented here the analytical solution is shown with a solid line and the COMSOL solution is shown in dotted lines. Figure 1 shows the temperature distribution through the depth of the geomaterial column at 1, 100, and 365 days after initiation of heat diffusion. At time $t = 0$ the temperature change was equal to $T_0 = 100^0 C$. For $t > 0$ on the upper surface $x_2 = 0$ the temperature change is reduced to zero. The computational results obtained using the ABAQUS code are very close to the analytical and COMSOL results, and, thus, are not shown here.

Figure 2 shows the distribution of pore fluid pressure with depth within the column subjected to the axial stress σ_0, aforementioned temperature change, and zero pressure at the upper surface. In Figure 2, the results obtained using ABAQUS are shown as circles. As expected, with time, the pressure dissipates inside the geomaterial. The maximum pressure is attained here at time $t = 0$, for the case of an incompressible fluid. Note that the initial fluid pressure in the absence of the temperature change is equal to 10 MPa (which is consistent with undrained response of a saturated geomaterial) but with the temperature increase included, the pressure reaches the value 36.3 MPa. This value can be obtained from the result (26). The positive value of the initial pressure caused by temperature change alone ($36.3 - 10$ =26.3 MPa) can be explained in the following way: Thermal expansion of the solid phase and zero thermal expansion of the fluid would lead to pore fluid tension, and thus negative pressures, if the pores were free to deform in the lateral direction. However, due to constraint on lateral displacements, $u_1 = u_3 = 0$, the resulting fluid pressure is positive, i.e., the fluid is still in compression.

Figure 3 shows the absolute value of the surface displacement. The displacement is a maximum at time $t = 0$ and at that time it is caused entirely by heating. Then the displacement is reduced due to the heat dissipation and the permanently applied compressive stress. Note that the heating (positive temperature change) causes the upward displacement, while the applied compressive stress leads to the downward displacement.

Figure 4 shows the pressure distribution versus time at depth 10 m, where the pressure takes the maximum value. The pressure is shown for two values of compressibility: zero (incompressible fluid) and 4.54e-10 1/Pa. Note that the pressure gets smaller for larger values of compressibility, which is the expected result. Similarly, Figure 5 shows the surface displacement versus time for the porous medium saturated with an incompressible fluid and a fluid with compressibility 4.54e-10 1/Pa.

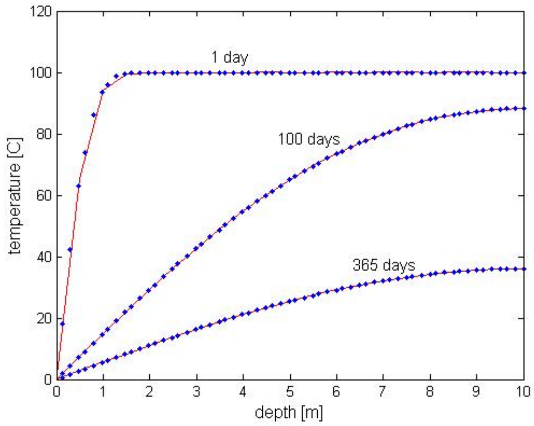

Figure 1. Temperature distribution within a one-dimensional element subjected to initial temperature change 100^o C and subsequent heat dissipation due to reduction of temperature at the upper surface to zero.

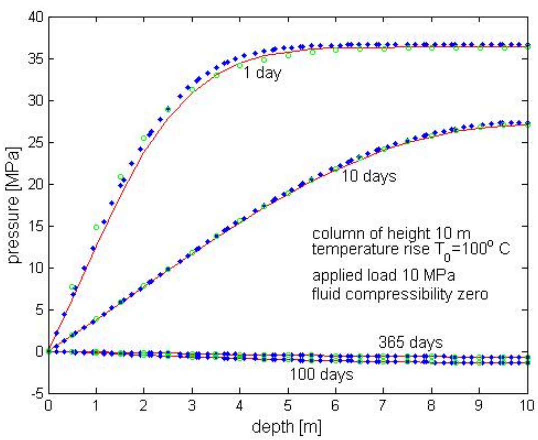

Figure 2. Pore fluid pressure distribution within a one-dimensional element subjected to the temperature change in Figure 1, and a compressive load 10 MPa at the upper surface. Pore fluid pressure at the upper surface is zero, and the fluid velocity is zero at the bottom surface.

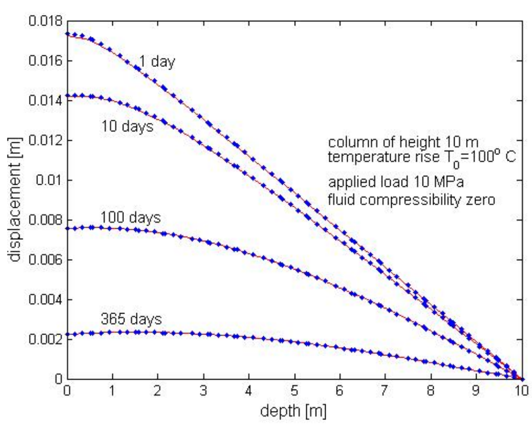

Figure 3. Displacement distribution within the one-dimensional element subjected to the temperature change shown in Figure 1, and compressive load 10 MPa at the upper surface. Displacement is zero at the base.

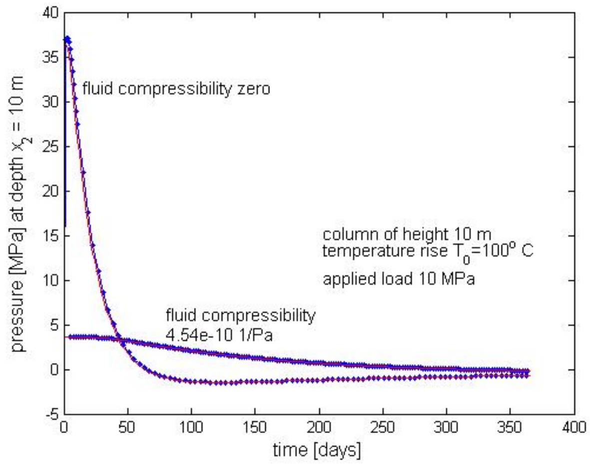

Figure 4. Pore fluid pressure distribution at a 10 m depth in a one-dimensional element subjected to the temperature change of Figure 1, and compressive load 10 MPa at the upper surface.

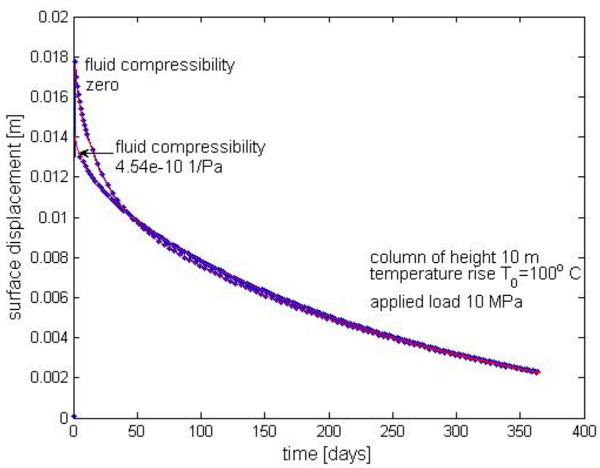

Figure 5. Surface displacement of a one-dimensional element subjected to the temperature change shown in Figure 1, and compressive load 10 MPa at the upper surface.

6 CONCLUSIONS

In the present paper we have examined the effect of heating on the deformation of a fluid-saturated porous medium. The solution for the one-dimensional problem of a geomaterial column initially at a uniform temperature and pore fluid pressure subjected to subsequent heat dissipation, is obtained analytically in the form of a power series expansion. In addition, the authors demonstrate the applicability of two commercial finite element codes COMSOL and ABAQUS to solve thermo-hydro-mechanical problems. The computational results for a one-dimensional problem are validated through comparison with an analytical solution and satisfactory agreement is observed.

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