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Effect of non-linearity in thermohydromechanical coupling

Effet de non-linéarité sur couplage thermohydromécanique

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ABSTRACT : The interaction of heat sources (canisters and containers of radioactive waste materials) and surrounding repository soils (near field) including the effects of coupling phenomena in soils are investigated. The theoretical aspects of fully coupled thermohydromechanical behaviour of saturated porous media are presented. Linear elastic, nonlinear elastic and elastoplastic constitutive equations are assumed. In nonlinear elastic model, thermal void ratio state surface as a new concept is introduced to include thermal effects and the stress state level influence on volume changes. In elastoplastic behaviour, the thermal effects in cam-clay model are introduced. Comparisons are made among the above models.

RESUME: Les aspects théoriques du comportement thermohydromécanique des milieux poreux saturés sont présentés. Lois de comportements élastique linéaire, élastique non linéaire et élastoplastique sont considérées. Le nouveau concept de la surface d'état de l'indice des vides est introduite dans le cadre du modèle non linéaire. Le modèle d'état critique a été modifié pour prendre en compte les effets thermiques dans la modélisation élastoplastique. Les résultats de ces modèles sont comparés.

1.INTRODUCTION

High - level radioactive waste disposal, frictional heating in fault zones in rocks and soils, cyclic loading of heating - cooling of pavements and road subgrades, and interaction of oil or geothermal energy are some of diverse areas in geotechnical research and activity domain in which the effects of hydrothermal and hydromechanical coupling are very significant.

Based on mixture theory a quasi-static infinitesimal theory of thermoelastic consolidation was developed by Aboustit et al (1985). In this approach the solid is assumed to be elastic linear and saturated by an incompressible fluid. The convection is ignored. The coupling terms between temperature and pressure do not appear in the formulation presented by Aboustit et al(1985). This results in a symmetric general matrix.

A numerical approach of hydrothermoelasticity for fractured rock is given by Noorishad et al.(1984). Booker and Savvidou(1985) provided analytical solutions for a thermoelastic consolidation which takes into account the differential thermal expansion of the pore water and soil skeleton. This approach is based on simple concepts of volume constraint and the effective stress principle. The temperature field is uncoupled from pressure and displacements.

Huang et al(1990) and Aboustit et al(1985) have applied variational principles to field equations to obtain finite element formulation of thermomechanical behaviour of saturated soils. The effect of heat convection is included in analysis presented by Huang et al(1990).

A complete set of governing equations of non-isothermal behaviour of fully saturated porous media with temperature-dependent non-linear elastic behaviour is proposed by Gatmiri (1995) and Gatmiri and Delage (1996). In this analysis a new concept so-called "thermal void ratio state surface" is introduced to include thermal effects, and the stress state level influence on volume changes. The mechanical and hydraulic properties of porous medium are assumed to be temperature-dependent.

The development of critical state concept in geomechanics in order to model the irreversible behaviour, yield phenomena and shear dilatancy of wet clays is a significant advance in describing some important features of the mechanical behaviour of soils. The critical state model leads to an incremental elastic-plastic formulation which is adequate for numerical developments.

Yield surface formulation, plastic flow rule and strain hardening law are the basic elements of an elasto-plastic model of saturated soil in isothermal conditions. In order to consider the effect of thermoplasticity in hydromechanical behaviour of clays, the above mentioned basic elements can be generalized to depend on temperature. Some investigations have been carried out by assuming a temperature-independent yield function such as Lewis et al(1986) and Britto et al(1989). The convection terms are neglected in their formulations. The elastoplastic model used by Britto et al(1989) is an extension of CRISP to thermal effects.

Thermoplasticity of saturated clay materials containing different mineral solids and liquid constituents has been studied by a US-Italian research group, (Duck University and ISMES in Bergamo, Italy). The proposed model by ISMES has a hierarchic structure. Yield function, evolution of hardening parameter and plastic potential are decoupled one from another (Baldi et al(1991)).

In this study, the fully coupled Thermo-Hydro-Mechanical (THM) responses of saturated porous media with a linear and non-linear elastic and elastic-plastic behaviour are investigated. The coupling terms among the two phases and heat transfer are considered. Variation of water permeability, water and solid unit weight and pore pressure variations due to thermal effects are included. The non-linear thermoelastic behaviour of soils is modeled by using a new concept so-called « thermal void ratio state surface ». The main frame the thermoelastoplastic model is the critical state model extended to include the thermal effects. The yield function, mechanical and hydraulic properties of soil are assumed to be temperature-dependent.

2.FIELD EQUATIONS

A complete set of field equations of fully coupled thermohydromechanical behaviour of a saturated porous medium is presented by Gatmiri (1995). In the non-linear model temperature-dependent hydraulic and mechanical properties are considered. The modifications due to elastoplastic constitutive law are introduced by Gatmiri (1996), in elastoplastic model a temperature-dependent yield surface with an associated flow rule is considered.

2.1. Solid skeleton behaviour

Equilibrium equation and constitutive law for a non-isothermal isotropic and non-linear case can be written as :

-Equilibrium equation

$$\sigma_{ij,j} + \rho g_i = 0 \quad (1)$$

-Constitutive law under small strain assumption

$$\sigma_{ij}^e = D_{ijkl} (\epsilon_{kl} - \epsilon_{kl}^p - \epsilon_{kl}^t) \quad (2)$$

where ϵ_{kl} is total strain of the skeleton, ϵ_{kl}^t is thermal strain, ϵ_{kl}^p is volumetric strain caused by uniform compression by pore water, with the definition of effective stress as:

$$\sigma_{ij}^e = \sigma_{ij} - \alpha p \delta_{ij} - \beta T \delta_{ij} \quad (3)$$

where α is Biot hydromechanic coupling coefficient, β is thermomechanic coupling coefficient, its general form is $\beta = \frac{1}{m^t D^{-1} m} \alpha_d = K' \alpha_d$, in which α_d is drained thermal expansion coefficient which is usually negative.

2.2. Pore fluid motion equations

The mass balance equation of pore fluid and Darcy law for non-isothermal case become :

$$\dot{\zeta} = -\dot{w}_{i,i} = \alpha \dot{\epsilon}_{ii} + C_a \dot{p} + C_h \dot{T} \quad (4)$$

$$\dot{w}_i = -\Lambda_{ij} (p_{,j} + \rho_w g_j) \quad (5)$$

$$\Lambda_{ij} = \Lambda_{wij} \left(\frac{v_i}{v} \right) \left(\frac{c}{c_i} \right)^3 \Rightarrow \Lambda_{ij} = f(T, c) \quad (6)$$

$$\rho_w = \rho_w(p, T) ; \quad \rho_s = \rho_s(p, T) ; \quad v = v(p, T) \approx v(T) \quad (7)$$

C_a : mixed fluid-solid compressibility; $C_a = \frac{(\alpha-n)}{K_s} + \frac{n}{K_w}$, C_h : coefficient of undrained thermal expansion of mixture; $C_h = (1-n)\alpha_s + n\alpha_w + (\alpha-1)\alpha_d$, where α_s , α_w are coefficients of thermal expansion of solid and water, ζ : volumetric fluid content, and v : water dynamic viscosity.

2.3. Energy Transport Equations and Fourier Law

The energy balance equation can be written as follows (Gatmiri (1995))

- Energy conservation equation

$$\rho_w C_w T_{,i} \dot{w}_{i,i} - h_{i,i} = \beta T_{,i} \dot{\epsilon}_{ii} + C_b \dot{T} - C_T T_{,i} \dot{p} \quad (8)$$

- The Fourier law as an equation governing the heat flow

$$h_i = -k_{ij} T_{,j} \quad (9)$$

where:

h_i : heat flow vector,

k_{ij} : solid-fluid mixture thermal conductivity tensor ;
 $k_{ij} = nk_{ij}^* + (1-n)k_{ij}^s$ in which k_{ij}^* and k_{ij}^s are fluid and solid thermal conductivity tensors,

T_0 : absolute temperature in the stress free state,

$C_b = (\rho C)_M - \{(1-n)C_p \rho_s \alpha_s + nC_w \rho_w \alpha_w\} T_0$ in which

$(\rho C)_M$: Solid-fluid mixture heat capacity = $(1-n)\rho_s C_s + n\rho_w C_w$,

C_s : specific heat capacity of solid,

C_w : specific heat capacity of water,

$C_T = (1-n)C_p \rho_s / K_s + nC_w \rho_w / K_w$.

2.4. General initial and boundary conditions :

The general initial and boundary conditions must be associated with the foregoing equations in order to complete the mixed initial boundary value problem of thermohydromechanics :

$$u(x,0) = 0 \quad \text{on } \Omega \quad (10)$$

$$p(x,0) = p_0 \quad \text{on } \Omega \quad (11)$$

$$T(x,0) = T_0 \quad \text{on } \Omega \quad (12)$$

$$I \begin{cases} \{u(x,t) = \bar{u}(x,t) & \text{on } S_1, x[0,\infty) \\ \{\sigma(x,t) \cdot \underline{n} = \bar{\sigma}(x,t) & \text{on } S_2, x[0,\infty) \end{cases} \quad (13)$$

$$II \begin{cases} \{p(x,t) = \bar{p}(x,t) & \text{on } S'_1, x[0,\infty) \\ \{V_w \cdot \underline{n} = q_w(x,t) & \text{on } S'_2, x[0,\infty) \end{cases} \quad (14)$$

$$III \begin{cases} \{T(x,t) = \bar{T}(x,t) & \text{on } S''_1, x[0,\infty) \\ \{\rho_w C_w V_w^i T_{,i} \underline{n} - h_i \cdot \underline{n} = q_t(x,t) & \text{on } S''_2, x[0,\infty) \end{cases} \quad (15)$$

3. CONSTITUTIVE LAW FOR STRESS-STRAIN-TEMPERATURE

Reconsidering equations (2), the constitutive equation can be written in incremental form :

$$d\sigma_{ij}^e = D_{ijkl} (d\epsilon_{kl} - d\epsilon_{kl}^p - d\epsilon_{kl}^t). \quad (16)$$

strain increment $d\epsilon^t$ due to temperature increment dT can be written as:

$$d\epsilon^t = D_T^{-1} dT \quad (17)$$

where ${}^t D_T^{-1} = \beta_t [1 \ 1 \ 0]$ in which β_t is stress and temperature dependent. Substituting the equation 17 into equation 16, one can obtain :

$$d\sigma^e = D d\epsilon^e - C dT \quad (18)$$

with $C = D D_T^{-1}$ and $d\epsilon^e = d\epsilon - d\epsilon^p$ defined as effective strain.

the stress-strain relationship matrix can be presented by:

$$D = \frac{3B}{9B - E} \begin{bmatrix} 3B + E & 3B - E & 0 \\ 0 & 3B + E & 0 \\ 0 & 0 & E \end{bmatrix}. \quad (19)$$

assuming non-linear stress-strain behaviour, using hyperbolic model, isothermal tangent modulus with a hyperbolic variation can be given :

$$\text{for loading : } E_L = K_L P_{atm} \left(\frac{\sigma_j}{P_{atm}} \right)^n (1 - R_f S_r)^2 \quad (20)$$

$$\text{for unloading: } E_u = K_u P_{atm} \left(\frac{\sigma_j}{P_{atm}} \right)^n \quad (21)$$

with S_r : stress ratio, $S_r = \frac{\sigma_j - \sigma_{j,ub}}{(\sigma_j - \sigma_{j,ub})}$, σ_1, σ_3 : principal stresses,

P_{atm} : atmosphere pressure, K_L, K_u modulus number (dimensionless), n and R_f : constants.

Considering the effect of the heating, the above equations become :

$$\text{Loading: } E = (E_L + E_u) (1 - R_f S_r)^2 \quad (22)$$

$$\text{unloading: } E = E_L + E_u \quad (23)$$

with :

$$E_L = K_L P_{atm} \left[\frac{\sigma_j}{P_{atm}} \right]^n, \quad E_u = m_1 T. \quad (24)$$

In order to calculate the bulk modulus, the volumetric strain can be taken into account via void ratio state surface which depends on temperature.

It is obvious that in each closed stress-temperature, the energy and thermoelastic strain must be recoverable. Volumetric thermoelastic deformation can be found by derivating from the complementary energy potential using the assumptions of logarithmic stress-strain law and a non-linear stress dependent thermal expansion coefficient, the thermal void ratio state surface expression can be given by :

$$e = e_0 + C_{cv} \text{Ln} \frac{p'}{p'_g} + (1 + e_0) \alpha (\Delta T, p') \Delta T \quad (25)$$

where :

$$\alpha (\Delta T, p') = \alpha_0 + \alpha_2 \Delta T + (\alpha_1 + \alpha_3 \Delta T) \text{Ln} \frac{p'}{p'_g} \quad (26)$$

in which $\alpha_0, \alpha_1, \alpha_2, \alpha_3$ are constants, C_{cv} is isothermal compressibility index using the coordinates of $(e$ and $\text{Ln} p')$, p' is effective mean stress, e_0 is initial void ratio and p'_g is the isotropic component of geostatic stress at which elastic strain is null. Stress at the end of saturation can be taken as p'_g in laboratory conditions. The bulk modulus B can be defined by :

$$d\epsilon_v = \frac{1}{1+e_0} \frac{\partial e}{\partial p'} dp' = \frac{1}{B} dp' \quad (27)$$

$$B = (1+e_0) \frac{p'}{C_{cv} + (1+e_0)(\alpha_1 + \alpha_3 \Delta T) \Delta T} \quad (28)$$

The thermal effects represented by D_T can be given by :

$$d\epsilon_1 = \frac{1}{1+e_0} \frac{\partial \epsilon}{\partial T} dT = \beta_T' m dT \quad (29)$$

$$\beta_T = \left[\alpha_0 + 2\alpha_2 \Delta T + (\alpha_1 + 2\alpha_3 \Delta T) \ln \frac{p'}{p_g'} \right] \quad (30)$$

As can be seen in the new above formulation the non-linear stress-dependent thermal expansion coefficient β_T is introduced. The shear strains are assumed to be due to mechanical effects.

4.THERMOELASTOPLASTIC CONSTITUTIVE LAW

The basic elements of thermoplasticity are discussed in detail by Gatmiri (1996) In this paper a summary of equations are given. With the following main effects of temperature, shrinking the elastic domain, dependence of plastic modulus on temperature, and finally development of irreversible strain the variation of yield locus under temperature effects is properly presented through the change in maximum isotropic preconsolidation stress p_c' which will be function of temperature and accumulated of thermoplastic strain:

$$F = F(p', q, e_v^p, \Delta T) = q^2 - M^2 p' (p_c' - p) = 0 \quad (31)$$

$$p_c' = p_c'(\epsilon_v^p, \Delta T) \quad (32)$$

where $\Delta T = T - T_0$, $p' = 1/3 \text{tr}(\sigma) = 1/3 \sigma_{ij} \delta_{ij}$,

$q = \sqrt{3/2} \|\dot{s}\| = \sqrt{3/2} s_{ij} s_{ij} = \sqrt{3J_2(s)}$ in which $s_{ij} = \sigma'_{ij} - p' \delta_{ij}$ and J_2 is second deviatoric stress invariant.

Based on experimental data, it is assumed that the critical state line does not depend on temperature. Thus in $q=Mp'$, M is constant. If $d\epsilon_p$ denotes the increments of plastic strain during the plastic deformation by application of normality rule, one can obtain:

$$d\epsilon_p = \bar{\lambda} \frac{\partial Q}{\partial \sigma} \quad (33)$$

in which Q is a plastic potential and $\bar{\lambda}$ is a proportionality constant, as yet undetermined.

In thermoplastic model proposed here, the plastic strain are evaluated by assuming an associated flow rule ($Q=F$).

Considering the dependence of yield surface on temperature we have

$$d\epsilon_p = \bar{\lambda} \frac{\partial F}{\partial \sigma} + \bar{\lambda} m \frac{\partial F}{\partial T} \quad (34)$$

Stress-strain relation for a non-isothermal behaviour can be presented in the following form:

$$d\sigma = [D_e - D_{ec}^p - D_{et}^p] d\epsilon - [D_e D_T^{-1} + C_{Te}^p - C_{Tt}^p - C_{ce}^p - C_{ct}^p] dT \quad (35)$$

$$d\sigma = D^{ep} \cdot d\epsilon - C^{ep} \cdot dT \quad (36)$$

with :

D_e : elastic stress-deformation matrix

$$D_{ec}^p = \frac{1}{H} \left[\left(\frac{\partial F}{\partial \sigma} \right) \cdot D_e \cdot \left(\frac{\partial F}{\partial \sigma} \right)^T \right] \quad (37)$$

$$D_{et}^p = \frac{1}{H} \left[\left(\frac{\partial F}{\partial \sigma} \right)^T \cdot D_e \cdot \left(D_{cv} \cdot m \cdot \frac{\partial F}{\partial T} \right) \right] \quad (38)$$

$$C_{ce}^p = D_e \cdot (m^T \cdot \beta)^T \cdot D_e \cdot D_e^{-1} \quad (39)$$

$$C_{ct}^p = \frac{1}{H} \left(\frac{\partial F}{\partial T} \right) \cdot D_e \cdot \left(\frac{\partial F}{\partial \sigma} \right)^T \quad (40)$$

$$C_{Te}^p = \frac{1}{H} \left(\frac{\partial F}{\partial T} \right) \cdot D_e \cdot \left(m \cdot \frac{\partial F}{\partial T} \right) \quad (41)$$

$$C_{ce}^p = \frac{1}{H} \left(\frac{\partial F}{\partial \sigma} \right)^T \cdot C_e \cdot \left(D_e \cdot \frac{\partial F}{\partial \sigma} \right) \quad (42)$$

$$C_{ct}^p = \frac{1}{H} \left(\frac{\partial F}{\partial \sigma} \right)^T \cdot C_e \cdot \left(D_e \cdot m \cdot \frac{\partial F}{\partial T} \right) \quad (43)$$

$$H = \left(\frac{\partial F}{\partial \sigma} \right)^T \cdot D_e \cdot \frac{\partial F}{\partial \sigma} + \left(\frac{\partial F}{\partial \sigma} \right)^T \cdot D_e \cdot m \cdot \frac{\partial F}{\partial T} - \frac{\partial F}{\partial p_c'} \cdot \frac{\partial p_c'}{\partial \epsilon_v^p} \cdot m \cdot \frac{\partial F}{\partial \sigma} \quad (44)$$

Details of mathematical operations are given by Gatmiri (1996).

The elastoplastic matrix D^{ep} and the thermomechanical coupling matrix C^{ep} take the place of elasticity matrices in incremental analysis. It is important to note that the general form of yield surface chosen here allows either isotropic or kinematics hardening to be considered. In this study the isotropic hardening is assumed.

As it is mentioned, the dependence of the yield surface on temperature is modeled through the choice of a temperature-dependent apparent preconsolidation isotropic stress expression given as:

$$p_c' = p_c'(\epsilon_v^p, \Delta T) \quad (45)$$

It is known that temperature changes do not affect λ and κ significantly, but due to thermal volumetric strain, a parallel shift should be considered in the normal compression line. Based on this observation following expression for p_c' can be proposed:

$$p_c' = p_{0c} \exp\left(\frac{(1+e_0)\epsilon_v^{TP}}{\lambda - \kappa}\right) \quad (46)$$

The research group at ISMES, based on their own observation, have proposed an expression as follows :

$$p_c' = 2(\bar{a} \exp\left(\frac{e_1 + (1+e_0)\epsilon_v^{TP}}{\lambda - K_T}\right) + a_1 \Delta t + a_2 |\Delta T| \Delta T) \quad (47)$$

$$K_T = \frac{K_i}{1+e_0} + (\alpha_1 + \alpha_3 \Delta T) \Delta T \quad (48)$$

where \bar{a} is a dimensional coefficient, e_0 and e_1 are the initial void ratio and that referred to the state of unit stress, respectively ; a_1 and a_2 are coefficient of thermal sensibility of the yield surface. K_T is a temperature-dependent bulk modulus.

In this study two options are made and incorporated in finite element program. The first one consists on proposition of an expression for the apparent preconsolidation isotropic stress as:

$$P_c' = P_{c0} \exp\left(\frac{(1+e_0)\epsilon_v^p}{\lambda - \kappa}\right) + a_1 \Delta T + a_2 |\Delta T| \Delta T \quad (49)$$

in which the effect of temperature on λ and κ are neglected and two thermal sensibility coefficients are considered. In second option the equation (47) is adopted. In the both options a_1 , a_2 and α_3 are negative constants.

5.FINITE ELEMENT FORMULATION

The Bubnov-Galerkin integral forms of field equations has been developed such as basis of spatial and temporal discretized matrix form. Application of weighted residual method and the Galerkin choice of weighted functions to the equations represented in the terms of nodal point values of the field variables for the total spatial discrete form of domain Ω and application of the single-step integration has resulted in the following global matrix form.

$$\begin{Bmatrix} [R] & [L] & [C] \\ [B_T] & \theta \Delta t [K_T] + [C_{TT}] & [C_{TW}] \\ [C] & [C_{wT}] & \theta \Delta t [K_w] + [C_{wP}] \end{Bmatrix} \begin{Bmatrix} \Delta U \\ \Delta T \\ \Delta P_w \end{Bmatrix} =$$

$$\Delta t \begin{Bmatrix} 0 \\ F_{in} - [K_T] T_c \\ F_{w,1} - [K_w] p_{w,1} \end{Bmatrix} + \begin{Bmatrix} \Delta F_\sigma \\ \theta \Delta t \Delta F_q \\ \theta \Delta t \Delta F_w \end{Bmatrix}$$

where:

$$[R] = \int_{\Omega} B^T D_{ep} B d\Omega \quad [L] = \int_{\Omega} B^T C_{ep} N d\Omega$$

$$[C] = \int_{\Omega} B^T \alpha m N d\Omega \quad \{F_\sigma\} = \int_{\Gamma} \bar{N}^T \bar{\sigma} d\Gamma$$

$$[C] = - \int_{\Omega} N^T \cdot \alpha \cdot m^T \cdot B \cdot d\Omega \quad [C_{wP}] = - \int_{\Omega} N_w^T \cdot C_a \cdot N_w \cdot d\Omega$$

$$[C_{wT}] = - \int_{\Omega} N_w^T \cdot C_h \cdot N_w d\Omega \quad [K_w] = \int_{\Omega} (\nabla N_w)^T \cdot \Lambda_w \cdot \nabla N_w d\Omega$$

$$\begin{aligned}
 [K_1] &= \int_{\Omega} (\nabla N_1)^T \cdot k \cdot \nabla N_1 \cdot d\Omega & [B_1] &= - \int_{\Omega} N_1^T \cdot \beta T_{\infty} \cdot m^T [B] d\Omega \\
 [C_{1w}] &= - \int_{\Omega} N_1^T \cdot C_b \cdot N_1 d\Omega & [C_{1T}] &= - \int_{\Omega} N_1^T \cdot C_T T_{\infty} \cdot N_1 \cdot d\Omega \\
 \{F_w\} &= \int_{\Omega} (\nabla N_w)^T \Lambda_w \gamma_w \nabla z d\Omega + \int_{\Gamma} \bar{N}_w^T \cdot q_w \cdot d\Gamma \\
 \{F_q\} &= \int_{\Omega} \bar{N}^T \cdot q_1 \cdot d\Gamma
 \end{aligned}$$

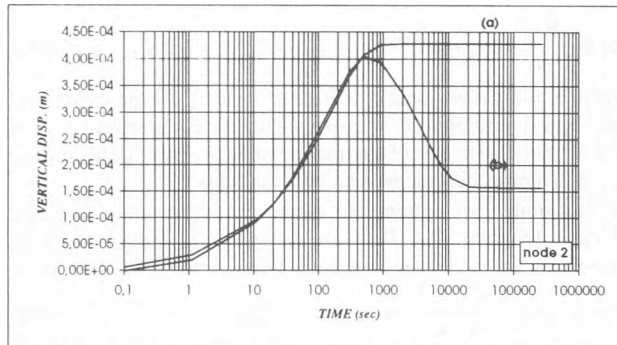
Based on formulation presented here, a finite element package is developed by the first author.

6.COMPARISON OF ABOVE MODELS

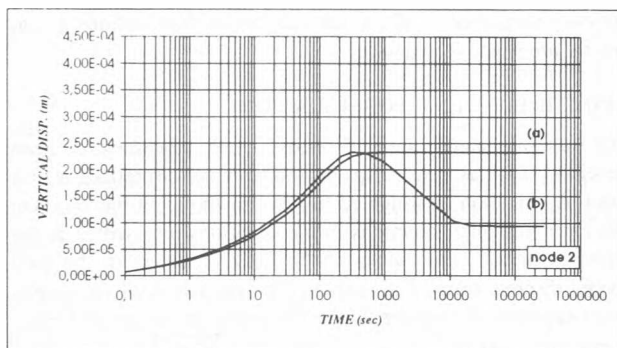
The sand column considered by Aboustit et al(1985) is used for our numerical calculation. The common parameters used in this analysis are :

- hydraulic permeability : $K = 4 \times 10^{-6}$ m/s
- Biot hydromechanic coupling coefficient $\alpha = 1$
- thermal conductivity, $k = 0.2$ cal/m/s/C°
- heat capacity of matrix, $m = 40$ cal/m³/C°
- solid thermal expansion coefficient : $\alpha_s = 0.3 \times 10^{-6}$ 1/C°

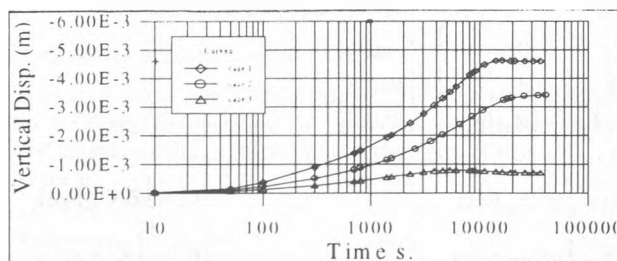
For linear elastic model the mechanical properties are :
 Young's modulus : $E = 6000$ Pa,- Poisson's ratio : $\nu = 0.4$
 and the following parameters for hyperbolic model are used :
 $K_1 = K_u = 60$; $n=0.5$; $R_f = 0.75$; $K_b = 100$; $m = 0.2$



a : Linear elastic



b : Non-linear elastic



Elastoplastic

Fig.1 : Comparison of Surface Settlements in different Models

The comparison of surface displacement in linear and non-linear cases are presented in figure 1-a,b.

For Thermoelastoplastic consolidation, the material properties are assumed as followings :

$\kappa = 0.05$, $\lambda = 0.14$, $M = 1.05$, $\Gamma = 2.44$, $e_0 = 1.0$, $a_1 = -9e-9$, $a_2 = -4.7e-11$, and two other constants, initial preconsolidation stress and overconsolidation ratio, are different in each case.

In figure 1-c, the settlement variations in time for different values of preconsolidation stress and overconsolidation ratio are presented. these values in three cases are as following:

- | | | | |
|-----|--------------------|-----|----------|
| I | $p'_c = 100$ kPa | and | OCR = 10 |
| II | $p'_c = 30$ kPa | and | OCR = 1 |
| III | $p'_c = \sigma'_v$ | and | OCR = 1 |

7.CONCLUSION

The values of parameters in non-linear case lead to elastic and bulk moduli profiles with a significant variation in depth. The hardening effect is combined with softening effect of temperature during the evolution of pore pressure and temperature. With the set of mechanical and thermal parameters chosen in this example the hardening effect is predominant. In elastoplastic model as it can be seen in the third case material behaviour is similar to elastic one but it is not exactly the same because of variation of elastic constants in depth. The reversal of the settlement has not been observed in two other cases. This means that the settlement due to applied stress on the surface during the plastification is greater than thermal expansion of mixture.

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