THM simulations for laboratory heating test and real-scale field test

Simulations THM d’essais de chauffage en laboratoire et en vraie grandeur in situ

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ABSTRACT: In this paper, a program of finite element method (FEM) named SOFT, considering thermo-hydro-mechanical (THM) behavior of soft rock, has been developed to simulate the THM behavior of the soft rock in geological disposal based on a thermo-elasto-viscoplastic model. A thermal heating isotropic test for soil under drained condition in different over-consolidated ratio (OCR), is firstly simulated by the proposed numerical. Meanwhile, a real-scale field test is also simulated by the proposed method. The material parameters of the rock involved in the constitutive model are determined based on element tests for the rock. It is found that the proposed numerical method can well describe the THM behavior of the soft rocks, such as, the temperature change, the change of EPWP and the heat-induced deformation.

RÉSUMÉ : Dans cette étude, nous avons développé un programme aux éléments finis appelé SOFT intégrant le comportement thermo-hydro-mécanique de roches tendres basé sur un modèle thermo-élasto-viscoplastique de façon à simuler le comportement THM de ces roches constituant un site géologique de stockage. Un essai d’échauffement sous chargement isotrope en condition drainée avec différents rapports de surconsolidation a été tout d’abord simulé par le modèle numérique développé. Dans le même temps, un essai en vraie grandeur réalisé in situ a également été simulé. Les paramètres de la roche considérés dans le modèle ont été obtenus à partir d’essais élémentaires réalisés sur ce matériau. Les résultats obtenus montrent que le modèle est capable de bien décrire le comportement THM des roches tendres, incluant le changement en température, le comportement mécanique et les déformations induites par l’élévation de température.

KEYWORDS: THM behavior, thermo-elasto-viscoplastic model, FEM, soft rock, numerical analysis, geological disposal

1 INTRODUCTION

In considering the problem about deep geologic disposal for high level radioactive waste, not only artificial barrier, but also the thermo-hydro- mechanical (THM) behavior of natural barrier, most of which is sedimentary rock or granite, is also a very important factor to be studied. High radioactive substance might permeate with water through barrier systems to biosphere. The temperature emitting from nuclear waste canisters also requests the study of temperature effect on soft sedimentary rock. The water may induce swelling phenomenon which can yield to a damage of the nuclear waste containers due to the generated temperature. All the above phenomena need to be well understood in order to guarantee the safety and the efficiency of the waste sealing construction.

In this paper, a program of finite element method (FEM) named SOFT, considering soil- water-heat coupling problem, has been developed to simulate the above-mentioned THM behavior of geological disposal based on a thermo-elasto - viscoplastic model (Zhang and Zhang, 2009). In order to verify the applicability of the program, a thermal heating isotropic tests for soils under drained condition in different over-consolidated ratio (OCR), are firstly simulated by the proposed program. In the test, the thermal volume change is found to be dependent on OCR, which can also be found in other literature. In this paper, however, the element test is not regarded as an elementary behavior, but a boundary value problem due to the different thermal expansion of water and soil particles. The simulated results show that the THM phenomenon observed in the laboratory test can be explained well by the proposed numerical method.

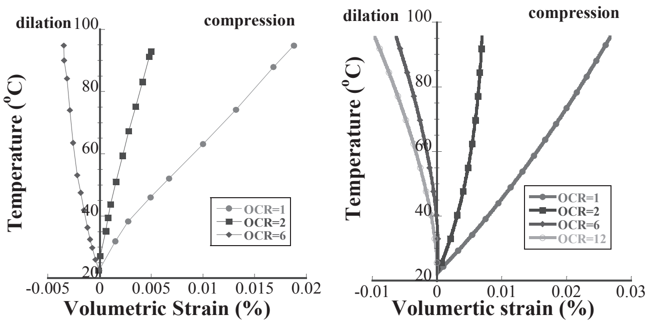
Meanwhile, a real-scale field test reported by Gens et.al (2007) is also simulated by the proposed numerical method. The material parameters of the rock involved in the constitutive model are determined based on element tests for the rock.

2 SIMULATION OF ELEMENTARY HEATING TEST

Heat-induced volume strain of geomaterials has been investigated extensively in literature. Drained triaxial (isotropic) consolidation test is usually used to investigate this effect by heating the test specimen, in which a specimen is firstly consolidated to a given stress and then unloaded to reach a specified OCR state. After then it is heated to a prescribed temperature in a very slow rate in order to prevent generation of excessive pore water pressure (EPWP).

A very interesting result shown in the Figure 1 (a) was reported by Baldi et al. (1988), in which the heat-induced volumetric strain measured by the quantity of water discharge was dependent on OCR, that is, the specimen will change from contraction to dilation as OCR increases. Afterwards, some other researchers also reported the same test results, e.g., the works by Cekerevac and Laloui (2004) and Cui et al (2009).

In the present paper, the heating test for soft rock (Baldi et al.,1988) is simulated by the proposed THM-FEM program SOFT to explain the test results. The FEM model used in the THM analysis is shown in Figure 2. Though the test is regarded as a so-called element test of free thermal expansion test, its thermal-mechanical behavior, in the author’s viewpoint, is a boundary value problem. In the simulation, all the boundary conditions are the same as those in the test. For instance, FEM model is only fixed in vertical direction (z) on bottom and other movements are totally free. The initial temperature is 22°C and the specimen is heated gradually up to 90°C with a rate of about 1°C /h. The material parameters and the physical properties of



(a) Experimental result Measured by water discharge (Baldi et al,1988)

(b) Simulated result calculated by water discharge

Figure 1. Relationship between temperature and volumetric strain

the soft rock are listed in Table 1 and Table 2.

In the test, the heat-induced volumetric strain was measured with the amount of drained water indirectly, and its relation with temperature for different OCR is depicted in Figure 1(b). It is found that the thermal volume changes from contraction to dilation as the OCR value increases, which coincides well with the experimental results depicted in Figure 1(a). In Figure 3, however, it is found that volumetric strain of soil is always dilatant with the increase of temperature, no matter what OCR may be! This phenomenon just indicates that during heating, both water and soil particles expend but with different degree because the thermal expansion coefficient of water is much larger than those of soil particle, resulting in an apparent phenomenon of water discharge, which was explained as ‘compression’. In high value of OCR, the expansion of soil particles becomes much larger than those of water, resulting in water absorption, which was explained as ‘expansion’ or dilatant. In conclusion, the observed phenomenon in the laboratory heating test is just a BVP of soil-water-heat interaction, rather than the inherent property of the soil itself.

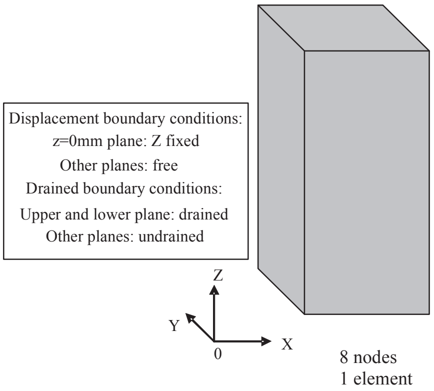


Figure 2. FEM model

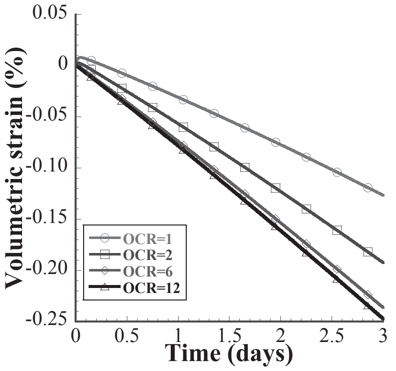


Figure 3. Change of volumetric strain of soil particle due to thermal effect calculated by FEM.

Table 1. Material parameters of rock

Young's modulus E (MPa)	300.0
Poisson's ratio ν	0.35
Stress ratio at critical R_{CS}(=$\sigma_1/\ \sigma_3$)	10.9
Plastic stiffness E_p	0.02
Potential shape parameter β	1.5
Time dependent parameter α	0.42
Time dependent parameter C_n	0.025
Overconsolidation parameter **a**	2000
Reference void ratio e_0(σ_{m0}=98kPa)	0.85

Table 2. Physical properties of rock

Preconsolidation pressure (MPa)	0.6
Thermal expansion coefficient α_T (1/K)	8.0×10^{-6}
α_{Water} (1/K)	2.1×10^{-4}
Permeability k (m/s)	5×10^{-13}
Thermal conductivity K_t (kJ m^{-1} $K^{-1}$$Min^{-1}$)	0.18
Specific heat C (kJ Mg^{-1} K^{-1})	840
Heat transfer coefficient of air boundary α_c((kJ m^{-2} K^{-1} Min^{-1})	230
Specific heat of water C_{water} (kJ Mg^{-1} K^{-1})	4184

3 SIMULATION OF FIELD TEST

A field test of heating process (HE-D), carried out in a soft rock called as Opalinus clay by Mont Terri underground laboratory (Gens et al., 2007), is also simulated with the SOFT. For simplicity, only the case with symmetric condition is considered in this paper. Compared to the simulation by Gens et al. (2007), only 1/8 area is considered. Figure 4 shows 3D mesh that consisted of 4275 cubic isoparametric elements.

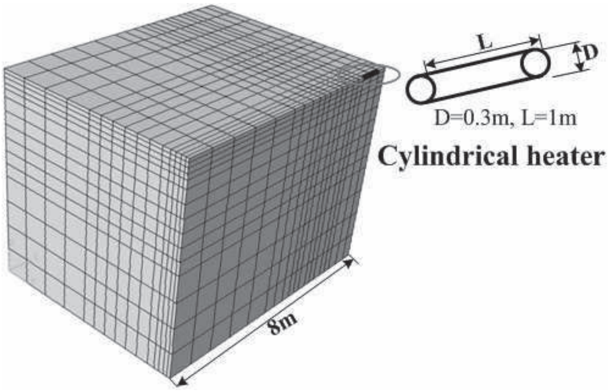


Figure 4. 3D FEM mesh

In order to investigate the mechanical behavior of the rock near HE-D experiment site, triaxial compression test under confining pressure of 8MPa was conducted by Jia et al (2007), whose results are first simulated by the proposed model and the results are shown in Figure 5. By this simulation, the parameters of the rock are determined and listed in Table 3 and Table 4. It can be seen that the proposed model can well describe the behavior of test rock.

Table 3. Material parameters of rock

Young's modulus ***E*** (MPa)	9800.0
Poisson's ratio ν	0.295
Stress ratio at critical $R_{CS}(=\sigma_1/\sigma_3)$	3.0
Plastic stiffness E_p	0.002
Potential shape parameter β	1.5
Time dependent parameter α	1.5
Time dependent parameter C_n	0.005
Overconsolidation parameter **a**	8000
Reference void ratio $e_0(\sigma_{m0}$=98kPa)	0.159

Table 4. Physical properties of rock

Preconsolidation pressure (MPa)	900
Thermal expansion coefficient α_T (1/K)	8.0×10^{-6}
α_{Water} (1/K)	2.1×10^{-4}
Permeability ***k*** (m/s)	5×10^{-12}
Thermal conductivity K_t (kJ m^{-1} $K^{-1}Min^{-1}$)	0.18
Specific heat ***C*** (kJ Mg^{-1} K^{-1})	840
Heat transfer coefficient of air boundary α_c((kJ m^{-2} K^{-1} Min^{-1})	230
Specific heat of water C_{water} (kJ Mg^{-1} K^{-1})	4184

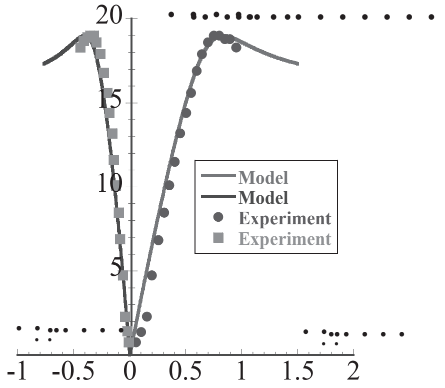


Figure 5. Simulation of triaxial test under confining pressure of 8 MPa for Opalinus clay

Figure 6 shows the change of temperature at the center of heater. The temperature reached about 40° at first heating phase, and then increased very sharply at the second heating phase up to the highest temperature of about 100°. When the power of heater is switched off, the temperature decreased sharply. It also can be seen that the calculated result can well describe the experimental data. Figure 6 also shows the change of temperatures at different position. On the whole, the THM-FEM analysis can well describe the HE-D experiment.

Figure 7 shows the change of temperature at different positions. It is known from the figure that the nearer the distance from heater is, the higher temperature will be. There is no prominent increase of temperature at the distance 5m far away from the heater due to the small heat conductivity of the rock.

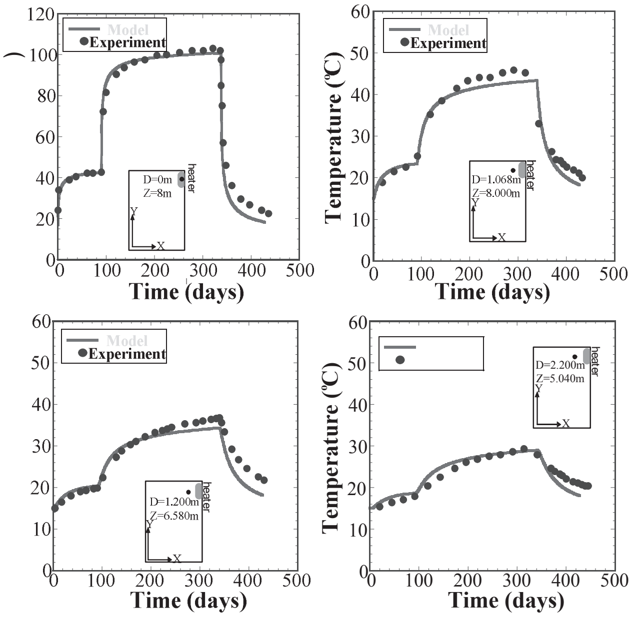


Figure 6. Change of temperature at different position

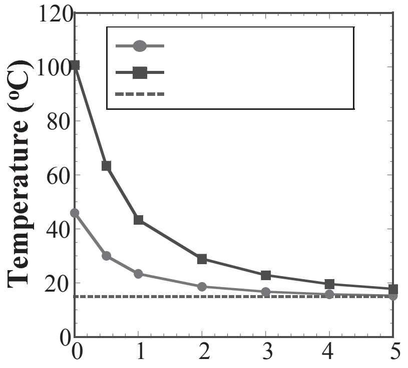


Figure 7. Computed temperature distributions at various times on cross section

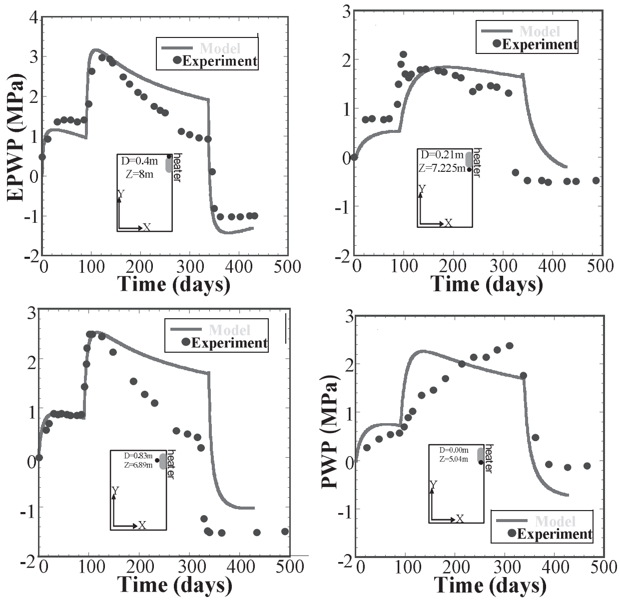


Figure 8. Variation of EPWP at different position

The evolution of EPWP with time is depicted in Figure 8 at the different sites. It is found that the EPWP increases sharply when temperature rises up suddenly, and then it will decrease with time even though the temperature is increasing. The highest value of EPWP is up to 3MPa. The increase of EPWP is due to the fact that thermal expansion coefficient of water is much higher than that of rock. Owing to the low permeability of rock, drainage is slow and the pore water expansion is impeded, resulting in the EPWP increase at the beginning. At later time, as mentioned above, migration of water from the heat source is gradually accelerated due to the increase of permeability, allowing pore pressure to dissipate.

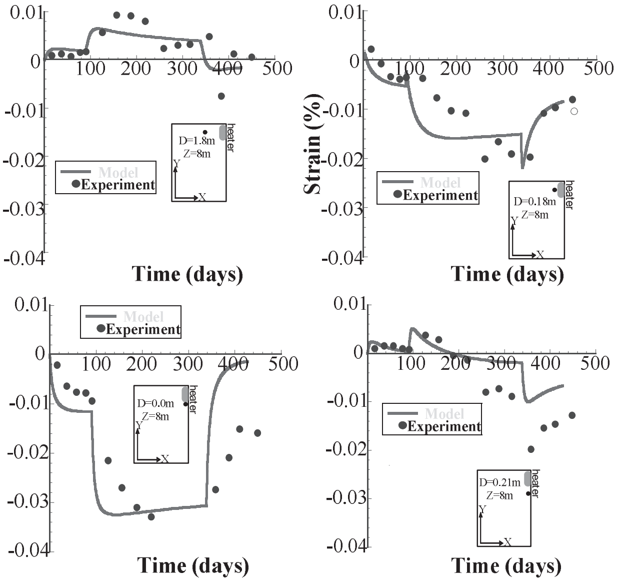


Figure 9. Variation of deformation at different position

At the same time, heat-induced deformation is also investigated. Figure 9 shows the calculated and test results at different positions. It is found that the calculation can describe the change of the deformation qualitatively if compared with the test data. The deformation of the rock near the heater is expansive; while the deformation of the rock far away from the heater is contractive. It is very easy to understand that the rock may behave expansive due to the significant increase of temperature; nevertheless, the change of temperature at the places far away from the heater is rather. Therefore, the dilation of the rock far away from the heater is very small compared with the rock in the vicinity of the heater. As the results, swelling force caused by the expansion of the rock near the heater will cause contraction of the rock far away from the heater.

4 CONCLUSIONS

In the paper, the following two conclusions can be made:

a) An isotropic element heating test is simulated by the proposed THM analysis based on an elasto-viscoplastic model. The calculation can well explain the phenomenon observed in the test that the heat-induced volumetric strain measured by water discharge changes from contraction to dilation with the increase of OCR in isotropic heating process. In the calculation with THM analysis, soil skeleton is always dilative with the increase of temperature regardless of what kind of OCR may be. The discharge of the water is just caused by different thermal expansion properties of the soil and the water! In a word, this phenomenon is merely a boundary value problem with soil-water interaction, not an inherent property of the rock itself!

b) A field test of heating process (Gens, 2007) is also simulated with the same THM analysis based on the same elasto-viscoplastic model. It is found that the proposed numerical method can well describe the THM behavior, such as, the temperature change, the change of EPWP and the heat-induced deformation.

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