Thermo-hydraulic-mechanical analysis of deep geological disposal of high level nuclear waste

S. ZHANG, Central South University, China
Y. L. XIONG and Feng ZHANG, Nagoya Institute of Technology
FAX: 052-735-7923, E-mail: cho.ho@nitech.ac.jp

In deep geological disposal for high-level radioactive waste (HLW), one of the most important factors is to study the thermo-hydraulic-mechanical (THM) behavior of natural barrier that consists of host rock, most made from sedimentary rock or granite. In this paper, based on a new simple thermo-elasto-viscoplastic model of soft rock proposed by, a finite element method (FEM) has been developed to simulate the THM behavior of geological disposal. 2D and 3D analyses are conducted to estimate long-term stability of the host rock. For simplicity, mechanical behavior of artificial barrier, usually composed of buffer material of bentonite, metal container and glass-mixed nuclear waste, is assumed to be elastic in the simulation. It is known from the analyses that thermal conductivity plays a very important role in the heat-induced stress-strain field. In some circumstances, long-term instable state of the host rock might occur if the heat generated from the nuclear waste is not properly treated.

1. Introduction

Deep geologic disposal is a nuclear waste repository excavated below 300m within a stable geologic environment. It entails a combination of waste form, waste package, engineered seals and geology that is designed to provide a high level of long-term isolation and containment without future maintenance. In other words, the repository and the surrounding rock form a multiple barrier, divided into three layers from inside to outside, which are technological barrier, engineered barrier and natural barrier. For permanent disposal, the natural barrier, mainly a rock bed, is the outermost and the most important. Because of homogeneity, completeness and convenience in construction, some soft sedimentary rocks are suitable to definitively dispose of HLW. Many interacted factors should be considered reliance on these rocks medium, such as thermal, hydrogeological, mechanical, chemical and radioactive. Among which, thermal-mechanical coupling is a key factor, because the temperature and its change influence the mechanical behaviors of soft sedimentary rock greatly. If once the rock, as the natural barrier structure, was damaged under the high temperature, macro cracks will occur, and directly result in a catastrophe that the most important barrier will become invalid. Therefore, it is necessary to investigate the thermal-mechanical coupling properties of the host rocks, which can be summarized as two factors: a proper constitutive model and a corresponding numerical method for boundary value problems.

In this paper, based on a thermo-elasto-viscoplastic model of soft sedimentary rock proposed by Zhang & Zhang (2009), the THM behavior of soft sedimentary rock as the natural barrier of the deep geological disposal, is simulated by finite element method (FEM). 2D and 3D analyses are conducted to estimate long-term stability of the host rock.

2. COMPARISON BETWEEN 2D AND 3D ANALYSIS

2D FEM mesh is showed in Fig1, in which the area is a square of 400m×400m, the right and left side are fixed in x direction, while the bottom side is restricted in y direction. The initial stress is calculated by gravitational analysis. For thermal condition, the initial temperature of whole considered area is 20°C. The ground surface is always kept 20°C all time and the heat insulation is assumed for other three sides. The analysis area is divided into 420 four-node quadrilateral isoparametric elements. The nuclear waste repository is a circle with 10m radius and its center lies at the place 90m above the bottom.

In FEM analysis, time spans of 3 years and 30 years are simulated after filling of nuclear waste respectively. The heat emission of both two cases is showed in Fig.2. In the THM analysis with FEM, the influence of the convection of water flow is neglected because the maximum velocity of pore water is usually less than $10^{-9}$(cm/s) within the soft rock. The soft rock is considered to be saturated and the initial water head is 400m. The nuclear waste is simulated by elastic material in FEM simulation and the parameters of the materials used are listed in Table 1.

Fig.3 shows 3D FEM mesh that consists of 10080 eight-node hexahedrons whose vertical section is the same as the 2D mesh. The initial and boundary conditions of the stress, the temperature and water head are also the same as 2D analysis. The thickness of the repository is the same as the diameter, that is, 10m. Due to the limitation of calculated time, only 3 years is calculated in 3D simulation.
Table 1 Parameters of materials and conditions

<table>
<thead>
<tr>
<th></th>
<th>(E) (MPa)</th>
<th>(\nu)</th>
<th>(\gamma_s)</th>
<th>(\sigma_{33}) (kPa)</th>
<th>(k_o)</th>
<th>(C)</th>
<th>(k_i)</th>
<th>(\alpha_i)</th>
<th>(\beta)</th>
<th>(\sigma_{min}) (MPa)</th>
<th>(\mu)</th>
<th>(\eta)</th>
<th>(\alpha)</th>
<th>(\sigma)</th>
<th>(\rho) (MPa)</th>
<th>(\gamma)</th>
<th>(\kappa)</th>
<th>(\theta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural host rock</td>
<td>900</td>
<td>0.2</td>
<td>2.5</td>
<td>1.0e-08</td>
<td>0.999</td>
<td>840</td>
<td>2.0</td>
<td>-8.0e-06</td>
<td>0.2</td>
<td>0.04</td>
<td>0.2</td>
<td>0.7</td>
<td>1.5</td>
<td>1.0e-08</td>
<td>500</td>
<td>98</td>
<td>0.5</td>
<td>0.025</td>
</tr>
<tr>
<td>(thermo-elasto-viscoplastic model)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear waste</td>
<td>900</td>
<td>0.2</td>
<td>2.5</td>
<td>1.0e-08</td>
<td>0.999</td>
<td>840</td>
<td>2.0</td>
<td>-8.0e-06</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>20</td>
<td>0.999</td>
<td>0.5</td>
<td>98</td>
<td>0.5</td>
<td>0.025</td>
<td>0.72</td>
</tr>
<tr>
<td>(elastic model)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water</td>
<td>4184</td>
<td>-2.1e-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig.3 3D FEM mesh

Fig.4 Distribution of \(\sqrt{2I_2}\) at specified times (2D)

Fig.5 Distribution of temperature at specified times (2D)

Fig.6 Distribution of water head at specified times (2D)

Fig.7 Distribution of \(\sqrt{2I_2}\) at the end of 3 years (3D)

Fig.8 Distribution of water head at the end of 3 years (3D)

Fig.9 Distribution of temperature at the end of 3 years (3D)

3.CONCLUSIONS

In this paper, 2D and 3D THM analyses on deep geological disposal of HLW with FEM have been carried out. From 2D simulation with the spans of 3 years and 30 years, it is revealed that the heat generated from HLW transfers very slowly in the natural barrier and high temperature is only restricted in the region near the waste repository. The thermal conductivity plays an important role in the thermo-mechanical behavior of the natural barrier.

It is revealed by the comparisons of 2D and 3D analyses that the magnitude of change in THM quantities, such as stress and strain field, the temperature and water head, are much smaller in 3D analysis than those in 2D analysis.

REFERENCES