Numerical investigation of heat dissipation through granite and clays in multi barrier system of a geological disposal facility

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Abstract:
High level heat emitting long lived vitrified radioactive waste, produced during recycling of the spent nuclear fuel, is under consideration for permanent disposal in deep geological formations having appropriate thermo-mechanical, hydrolgeological and geo-chemical properties. The capability of these rock formations ensuring very long-term confinement and isolation of such waste from the environment is significantly controlled by their efficiency in smoothly dissipating the heat emanating from the waste. A number of rock types such as basalt, granites, clay stones, volcanic tuff, argillites etc are being evaluated worldwide as well as in India. In this study, a granite from Jalore and bentonite clay from Barmer, both from Rajasthan have been evaluated for their heat dissipation capacity. The study revealed that temperature within granite at the centre of the canister reaches 55.21 °C resulting in a thermal stress 25.50 MPa. Bentonite clays experience temperature of 67.42 °C in the central part with maximum thermal stress and displacement of 1.78 MPa and 0.446 mm respectively. The displacement of 0.997 mm has been recorded at the
granite-bentonite clay interface. Thus, no significant possibility of micro crack formation or undesirable displacement is observed within the granite, as well as, in bentonite suggesting their capability to isolate and confine the heat emitting source for extended periods of time.

Keywords: Radioactive waste, Deep Geological Repository, Thermo-Mechanical analysis, Bentonite, Granite

Heat emitting high level radioactive waste\(^1,2,3\) is generated during reprocessing of radioactive spent fuels received from nuclear reactors. Deep Geological Repository (DGR) in suitable geological formations is considered worldwide for permanent disposal of these radioactive wastes. These facilities are expected to provide for isolation and confinement of radioactive waste over tens of thousands of years until their radioactive decay is down to safe natural level\(^4\).

In India, granitic rocks due to their widespread occurrence, high mechanical strength and low porosity are under active consideration for serving as Deep Geological Repository (DGR) at depths of 500-700 m. The DGR facility relies on multi barrier natural and engineered layers (i.e., host rock, swelling clay, canisters and vitrified high level waste) for long term protection against release of radioactive waste into the biosphere even in distant future. A typical DGR is shown in Fig. 1 and a layout of DGRs can accommodate up to 10000 canisters loaded with waste. Radioactive decay of isotopes, present in the waste, cause continuous heat flux from these canisters and hence disposal will result in build-up of heat plume within the rock mass and clay liner. The temperature induces, thermal stresses and displacement within the rock mass due to long-term thermo-mechanical interaction between bentonite clays and the granite rock. This controls the evolution of thermal field within a DGR\(^5,6,7,8\). Most of the DGRs planned in world aim to maintain temperature below 100\(^\circ\)C within any part of DGR at any
point in time. Smooth dissipation of heat across bentonite clay and host rock, say granite, thus is the key requirement for providing safe isolation of radioactive waste. It is worldwide practice to first analyse single canister with multibarrier system\textsuperscript{9,10}, followed by multiple canisters\textsuperscript{11,12} and finally full scale repository\textsuperscript{13}.

In line with above approach, single canister has been analysed in this study in the first phase. The objective of the paper is to estimate and predict the thermo- mechanical stability of a granite designated as the Jalore Granite and bentonite clay of Barmer, both from Rajasthan State, which can be used in constructing a DGR facility. The study estimates the thermomechanical stability of the rock for long term exposure to thermal load through numerical simulation of heat dissipation, resultant thermal stresses, strain, and displacement using key thermal and mechanical properties of these rocks in a meter scale system over a time period of 340 days using three-dimensional finite element (FE) couple code developed in-house. Time dependant variations in vital parameters like temperatures, thermal strain, stress and displacement have all been estimated and critically examined at key locations in the system.

Jalore granite belongs to the late Proterzoic Malani igneous suite (750 Ma to 730Ma) and occurs extensively in Jalore district of Rajasthan. Jalore granite sample was obtained from a quarry at Bala (latitude 25°49' E and longitude 72°11’ N) in the Jalore district. Major minerals in the granite are quartz, albite, microcline and orthoclase with minor amount of biotite, chlorite and accessory minerals which include hematite, magnetite, titanite and zircon. The major element composition is 71.22\% SiO\textsubscript{2}, 15.50\% Al\textsubscript{2}O\textsubscript{3}, 5.36\% K\textsubscript{2}O, 3.31\% Na\textsubscript{2}O, 1.39\% FeO, 0.71\% CaO and 0.25\% TiO\textsubscript{2}. Bentonite used in this study has been sampled from Akli mine, Barmer district of Rajasthan (latitude 26°03’ E and longitude 71°14’ N). Its physicochemical properties of the bentonite were determined by following ASTM procedures\textsuperscript{14} (ASTM D4318, D7928-17, D720, D698). XRD investigation of bentonite clay shows montmorillonite,
kaolinite, quartz, and accessory minerals which include almandine, anatase, goethite, rutile, ilmenite and zircon. Mechanical and thermal properties of Jalore Granite and Barmer Bentonite used are presented in Table 1. The obtained properties of clay and granite i.e., conductivity, specific heat, etc. are in line of earlier research 14, 15.

Three-dimensional FE model geometry for Jalore Granite, Barmer Bentonite Clay and heat emitting waste canister is developed using in-house finite element coupled code (Fig. 2). The granite and clay are modelled as 10 nodes brick element having displacements (along x, y and z axis) and temperature as degree of freedom at each node. The waste canister is modelled as rigid one and its input temperature time history is transferred onto inner surface of bentonite clay (Fig. 3). The FE model is discretized using more than 50,000 three-dimensional brick elements. The granite rock and bentonite layer are modelled considering them as Mohr-Coulomb material. In the model, mechanical (rigid and fix support) and thermal (temperature time history and convective surface) boundary conditions are applied on canister and clay interfaces. The outer wall of granite block is given atmospheric condition of 25 °C. Steady air surface convective heat dissipation is considered in the analysis.

The time dependant heat flux emission pattern from the waste canister embedded in granite rock was introduced in the model by means of controlling the heat output of the canister. The waste canister surface temperature was initially gradually increased at a rate of 1 °C/10 days from 25 °C to 100 °C. 100 °C temperature was attained on the 140th day, (Fig. 3). Subsequently, it was gradually reduced to attain the initial temperature of 25 °C in another 200 days. A total of 5 sampling points on the mid plane were fixed in the modelled system as shown in Fig. 4 to record the time dependant evolution of temperature, stress, strain and displacement. The maximum stress, temperature, strain and displacement recorded during complete time span of analysis is shown in Table 2. Contour plot of temperature within the system after 140 days shows that there is no adverse or accelerated advancement of heat front over a distance of 0.50
m in 140 days’ time due to adequate thermal conductivity of selected granite and bentonite clay. The midpoint of bentonite layer witnesses maximum temperature of 67.42 °C (Fig. 5). Distribution of the resultant thermal stresses across the system indicate maximum stress build-up of 35.72 MPa at bentonite granite interface, mainly on account of the difference in thermal conductivity of the two materials. The stress contour plot is shown in Fig. 6. The study revealed that temperature within granite reaches 35.42 °C, 45.82 °C, 55.21 °C when waste canister attains temperature of 50 °C, 75 °C and 100 °C respectively. The corresponding thermal stress values within granite for these temperatures are 24.40 MPa, 24.83 MPa and 25.50 MPa, respectively. The magnitude of displacement induced by thermal stresses is higher at the bentonite-granite interface due to the coupling of two materials of different rheologies. However, displacement values across the entire modelled region do not exceed 1 mm (Fig. 7). The displacement within bentonite as well as granite is thus within desirable levels. Similarly, no significant deformations has been noticed within the system; maximum strain value concentration of 0.000389 mm/mm is at the bentonite-granite interface. The thermal stress/ unconfined compressive strength (UCS) ratios for bentonite, granite and their interfaces are of the order of 0.12 and 0.32. Therefore, both the materials are by and large stable with possibility of very minor spalling.

The thermo-mechanical numerical modelling using inhouse FE coupled code is carried out for estimation of thermal mechanical interaction stability, design and layout of typical Indian DGR nearfield system using Jalore Granite and Barmer Bentonite Clay. The results reveal that layers of the selected site-specific granite and bentonite will remain stable under continuous thermal load with the possibility of minor micro-fracturing at the bentonite-granite interface. The study further shows that Granite from Jalore and the Barmer Bentonite clay have adequate strength and thermal conductivity for smooth heat dissipation through them without undergoing any appreciable degradation. It is however emphasized that the results of these studies address only
one of the desirable aspects of host rock i.e., heat dissipation and therefore we do not make any recommendation for the final suitability of these rocks towards hosting heat emitting wastes. Further research and development on Jalore Granite evaluating hydraulic-geochemical-radiological and mechanical properties must be carried out for assessment of the granite area for housing deep geological repository. Similar studies must be taken up on the other granitic massifs in India as well. Detailed exploration for bentonite clay and their characterization is also called for.

Reference:


5. Andrew Fraser Harris, Christopher Ian McDermott, Alexander Bond, Kate Thatcher, Simon Norris, A non-linear elastic approach to modelling the hydro-mechanical behaviour of the SEALEX experiments on compacted MX-80 bentonite, Environmental Earth Science, 2016, 75, 1445


Threshold of Jalore Granite, Rock Mechanics and Rock Engineering, 2018, 51, 2949-2956
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A- at 0.05m (Canister-clay interface)
B- at 0.15m (Clay mid location)
C- at 0.25m in (Clay-granite interface)
D- at 0.40m in (Granite mid location)
E- at 0.55m in (Granite outer surface)

I- Waste Canister
II- Bentonite clay layer
III- Granite rock
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<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Properties</th>
<th>Granite Rock</th>
<th>Compacted Bentonite Clay</th>
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<tbody>
<tr>
<td>1.</td>
<td>Shear Modulus (GPa)</td>
<td>20.10</td>
<td>0.243</td>
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<td>2.</td>
<td>Bulk Modulus (GPa)</td>
<td>33.05</td>
<td>0.321</td>
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<tr>
<td>3.</td>
<td>Density (Kg/m3)</td>
<td>2700</td>
<td>1800</td>
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<td>4.</td>
<td>Tensile Strength (GPa)</td>
<td>0.0125</td>
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<tr>
<td>5.</td>
<td>Cohesion (GPa)</td>
<td>0.060</td>
<td>0.0015</td>
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<tr>
<td>6.</td>
<td>Friction Angle</td>
<td>58</td>
<td>48</td>
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<td>7.</td>
<td>GSI</td>
<td>70</td>
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<tr>
<td>8.</td>
<td>Porosity</td>
<td>0.05</td>
<td>0.3</td>
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<tr>
<td>9.</td>
<td>Thermal Conductivity (W/m.K)</td>
<td>2.30</td>
<td>1.65</td>
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<td>10.</td>
<td>Specific Heat (J/Kg.K)</td>
<td>1510</td>
<td>875</td>
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<td>11.</td>
<td>Thermal Expansion Coefficient (1/K)</td>
<td>2e-6</td>
<td>3.5e-5</td>
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<td>12.</td>
<td>UCS (MPa)</td>
<td>110</td>
<td>15</td>
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Table 2: Variation of maximum temperature, thermal strain, stress and displacement

<table>
<thead>
<tr>
<th>Sr.no.</th>
<th>Parameters</th>
<th>A (Canister clay interface)</th>
<th>B (Clay mid location)</th>
<th>C (Clay-granite interface)</th>
<th>D (Granite mid location)</th>
<th>E (Granite surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Temperature ($^\circ$C)</td>
<td>97.81</td>
<td>67.42</td>
<td>59.09</td>
<td>55.21</td>
<td>50.69</td>
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<td>2.</td>
<td>Thermal Strain (mm/mm)</td>
<td>0.00030</td>
<td>0.00032</td>
<td>0.000389</td>
<td>0.000274</td>
<td>0.000137</td>
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<td>3.</td>
<td>Thermal Stress (MPa)</td>
<td>1.78</td>
<td>1.78</td>
<td>35.72</td>
<td>25.50</td>
<td>11.56</td>
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<td>4.</td>
<td>Displacement (mm)</td>
<td>0.000</td>
<td>0.446</td>
<td>0.997</td>
<td>0.334</td>
<td>0.000</td>
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