Influence on anti-seepage efficiency of curtain by physico-chemical actions of groundwater

Hongyang Zhang*1, 2 and Liwei Han1, 2

1North China University of Water Resources and Electric Power, Zhengzhou, China
2Henan Kun Xin Hydroelectric Construction Limited Company, Zhengzhou, China

ABSTRACT

The anti-seepage effect of curtain under dam foundation may be weakened by the long term physico-chemical actions of groundwater. According to seepage hydraulics and geochemistry theory, and considering seepage, solute transport, geochemistry and curtain erosion, the analysis on the behavior of the curtain under dam foundation was conducted. The analysis results of a case proved that the curtain efficiency was weakening all the time, the primary reason of which is calcium had been always in dissolution during the simulation time. The erosion is much more seriously near the bottom of the curtain than the other parts, and the same from the upstream and downstream. Calcium dissolution is mainly controlled by hydraulic condition and dispersion; it varies in a non-linear way within the domain.

Key words: Anti-seepage behavior of curtain; seepage; solute transport; geochemistry; curtain erosion

INTRODUCTION

Seepage state is controlled by the curtain integrity and its anti-seepage efficiency. Coupled to the variations of seepage pressure and hydrochemistry, the dissolution of calcium ions from cementation zone is taken away by the fluids. The research shows that the curtain efficiency is affected greatly by the flow and chemical fields [1].

In recent years, many researchers were concerned with curtain efficiency. Dam and its curtain working state through the groundwater regime under foundation are analyzed [2-4] by Gu, Fu and Wu. The researches[5-7] by Tong, Song, and Yang indicated that revealing the consequence of water-rock interaction by analyzing the microcosmic state of groundwater around a dam foundation is helpful to evaluate the anti-seepage performance of the curtain (A model coupled of seepage field and stress one was built up by some researchers[8-12]. But it is hardly to find the coupling model for assessing the anti-seepage behavior of curtain under dam foundation, especially in which the chemical reaction was considered.

In this paper, a multi-physics model was set up, coupled of seepage field, a chemical reactive and mass transport field to integrate a description of curtain efficiency variation.

EXPERIMENTAL SECTION

Analysis model

1. Assumptions

Assumption is given as follows. 1) The saturated porous medium is homogeneous and continuum, and the flow of which obeys Darcy’s law. 2) Hydraulic conductivity does not vary with time; 3) The aquifer do not contribute other components to the variation of solute; 4) The amount of ionic moles in groundwater varies only due to the
dissolution/precipitation reactions.

2. Multi-physics Model
A multi-physics model is built by considering seepage [13], chemical reaction [14-15], solute transport [16-18] and curtain erosion [19]. The behavior of seepage is described as,

\[
\frac{\partial}{\partial t} \left( K \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial H}{\partial y} \right) = \mu, \frac{\partial H}{\partial t}
\]

\[H(x, y, t) = f_0(x, y)\]

\[H|_{\Gamma} = f_1(x, y, t); (x, y) \in \Gamma,\]

\[K \frac{\partial H}{\partial n} |_{\Gamma} = f_2(x, y, t); (x, y) \in \Gamma_2\]

Where, \(\mu\) is the specific storability; \(H\) is the hydraulic head; \(K\) is the hydraulic conductivity tensor; \(t\) is the calculate time; \(f_0, f_1, f_2\) are the initial and boundary conditions; \(\Gamma_1, \Gamma_2\) are the boundary conditions of prescribed head and flux; \(n\) is the outward unit normal vector on domain boundary.

The behavior of chemistry is described as,

\[
dC = -(X_{eq} + \mathcal{R}_{e}) - k_{eq} S_{eq} \left[ 1 - \prod_{j=1}^{n_c} (a_i)^{\nu_{ij}} \right] \prod_{j=1}^{n_c} (a_j)^{\nu_{ij}}
\]

\[
\log a_i = \log K_i + \sum_{j=1}^{n_c} v_{ij} \log a_j, a_i = \gamma_i C_i
\]

\[\log \gamma = \begin{cases} 
-Az_i \sqrt{I} & (I < 0.005 \text{mol} / \text{L}) \\
-Az_i \sqrt{I} & (I < 0.1 \text{mol} / \text{L}) \\
-0.5z_i \sqrt{I} & (I < 0.2 \text{mol} / \text{L}), I = \frac{1}{2} \sum_i Z_i C_i \\
-Az_i (\sqrt{I} - 0.3) & (I < 0.5 \text{mol} / \text{L}) \\
-Az_i (\sqrt{I} + h I) & (I < 1 \text{mol} / \text{L})
\end{cases}
\]

\[T_j = \sum_{i=1}^{n_c} v_{ij} C_i \cdot \sum_{i=1}^{n_c} v_{ij} X_{eq} dt, \quad \sum_{i=1}^{n_c} Z_i C_i = 0
\]

Where, \(C\) is the total concentration, while \(C_i\) is the special one from the mineral dissolution concerned; \(X_{eq}\) is the change of concentration related to thermodynamics; \(N_c\) is the amount of species; \(a_i\) is the activity of component \(i\); \(K_i\) is the stoichiometric coefficient of species \(i\); \(v_{ij}\) is the stoichiometric coefficient of species \(j\) in reaction \(i\); \(a_j\) is activity of species \(j\) in groundwater; \(T_j\) is moles of species \(j\); \(\mathcal{R}_{kin}\) is a temporal variation related to kinetics; \(k_p\) is the rate of reaction \(p\); \(S_p\) is the specific surface area of mineral \(p\); \(K_p\) is the equilibrium constant of reaction \(p\); \(Eq\) and \(Kin\) refer to thermodynamics and kinetics, respectively.
The behavior of solution transport is described as,

\[
\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left[ D_x \frac{\partial C}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D_y \frac{\partial C}{\partial y} \right] - \frac{\partial (u_x C)}{\partial x} - \frac{\partial (u_y C)}{\partial y} + W
\]

\[C(x, y, 0) = f_s(x, y, t), \quad C[B_i = f_i(x, y, t); (x, y) \in B_i]
\]

\[D_x \frac{\partial C}{\partial x} n_1 + D_y \frac{\partial C}{\partial y} n_2 - \frac{\partial (u_x C)}{\partial x} - \frac{\partial (u_y C)}{\partial y} [B_2 = f_t(x, y, t); (x, y) \in B_2]
\]

Where, \(u_x\) and \(u_y\) is the fluid velocity along x and y axis, respectively; \(D_x\) is the longitudinal hydrodynamic dispersion coefficient; \(D_y\) is the transverse hydrodynamic dispersion coefficient; \(W\) denotes the source/sink term caused by all chemical reactions; \(B_i\) \(B_2\) are the boundary conditions; \((n_1, n_2)\) is the outward unit normal vector on domain boundary.

The behavior of curtain erosion is described as,

\[
\frac{\partial \theta \cdot C}{\partial t} + \frac{\partial C_{\text{solid}}}{\partial t} = \text{div} \left[ D(C) \cdot \text{grad}(C) \right]
\]

Where, \(\theta\) is the curtain porosity; \(C_{\text{solid}}\) is the ionic concentration concerned; \(D(C)\) is the ionic dispersion.

So, the analysis model simulating curtain efficiency is consists of above four modules. In this paper, as numerical simulation, the separately coupling which is often used in solving separately coupled models with solving equations in certain order, was adopted, which reduces calculation time and improve efficiency.

An example

1. General description

The dam site, 60 m wide in foundation and divided into 17 sections, is located on a series of limestone and dolomite. The level was 135 m in upstream, while 15 m in downstream. And the curtain constructed at upstream is 100 m deep and 5 m wide to reduce leakage.

2. Parameters

The simulation parameters are shown in table 1, table 2 and table 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(K^+ + Na^+)</th>
<th>(Ca^{2+})</th>
<th>(Mg^{2+})</th>
<th>(HCO_3^-)</th>
<th>(CO_3^{2-})</th>
<th>(SO_4^{2-})</th>
<th>(Cl^-)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir-water</td>
<td>7.73</td>
<td>16.19</td>
<td>1.89</td>
<td>53.42</td>
<td>/</td>
<td>14.25</td>
<td>4.20</td>
<td>8.44</td>
</tr>
<tr>
<td>4#</td>
<td>15.24</td>
<td>36.00</td>
<td>3.81</td>
<td>/</td>
<td>32.87</td>
<td>15.70</td>
<td>4.23</td>
<td>11.31</td>
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<tr>
<td>5#</td>
<td>41.59</td>
<td>25.93</td>
<td>3.90</td>
<td>/</td>
<td>44.22</td>
<td>14.72</td>
<td>4.21</td>
<td>11.44</td>
</tr>
<tr>
<td>6#</td>
<td>20.31</td>
<td>16.95</td>
<td>4.18</td>
<td>64.10</td>
<td>10.46</td>
<td>14.23</td>
<td>7.39</td>
<td>9.37</td>
</tr>
<tr>
<td>7#</td>
<td>17.77</td>
<td>98.13</td>
<td>2.99</td>
<td>/</td>
<td>31.52</td>
<td>14.97</td>
<td>4.48</td>
<td>12.03</td>
</tr>
<tr>
<td>8#</td>
<td>23.49</td>
<td>82.18</td>
<td>3.10</td>
<td>/</td>
<td>36.90</td>
<td>15.47</td>
<td>4.52</td>
<td>11.94</td>
</tr>
<tr>
<td>9#</td>
<td>55.76</td>
<td>92.41</td>
<td>3.76</td>
<td>/</td>
<td>28.28</td>
<td>14.98</td>
<td>4.69</td>
<td>12.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>(K)</th>
<th>(D_x (\text{cm}^2\text{/sec}))</th>
<th>(D_y (\text{cm}^2\text{/sec}))</th>
<th>(\mu_s)</th>
<th>(A)</th>
<th>(C_{\text{solid}} (\text{mol/m}^3))</th>
<th>(D(C) (\text{cm}^2\text{/sec}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir-water</td>
<td>3.557E-05</td>
<td>4.56 E-07</td>
<td>8%</td>
<td>0.2</td>
<td>0.439 E-07</td>
<td>0.196 E-07</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 1 Chemical compositions of the water (unit: mg/L)

Table 2 Hydro geological parameters of modeling area
Table 3 Geo-chemical reactions among water-rock-curtain and their thermodynamic parameters in the area

<table>
<thead>
<tr>
<th>Reactant</th>
<th>Chemical reaction equation</th>
<th>Log K</th>
</tr>
</thead>
<tbody>
<tr>
<td>calcite</td>
<td>CaCO₃=CO₃²⁻+Ca²⁺</td>
<td>-8.48</td>
</tr>
<tr>
<td>dolomite</td>
<td>CaMg(CO₃)₂=2CO₃²⁻+Ca²⁺+Mg²⁺</td>
<td>-17.09</td>
</tr>
<tr>
<td>calcium oxide</td>
<td>Ca(OH)₂+2H⁺=Ca²⁺+2H₂O</td>
<td>22.80</td>
</tr>
<tr>
<td>CaOH⁻</td>
<td>Ca²⁺+H₂O=CaOH⁺+H⁺</td>
<td>12.78</td>
</tr>
<tr>
<td>CaHCO₃⁻</td>
<td>Ca²⁺+CO₃²⁻+H⁺=CaHCO₃⁻</td>
<td>11.43</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>Ca²⁺+CO₃²⁻=CaCO₃</td>
<td>3.33</td>
</tr>
<tr>
<td>HCO₃⁻</td>
<td>CO₃²⁻+H⁺=HCO₃⁻</td>
<td>10.33</td>
</tr>
<tr>
<td>CO₂</td>
<td>CO₂+2H⁺=CO₂+H₂O</td>
<td>16.68</td>
</tr>
<tr>
<td>H₂O</td>
<td>H₂O=OH⁻+H⁺</td>
<td>-14.00</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The domain was divided into triangular mesh elements of 16258. As the head of the upstream and downstream is constant, the steady-state seepage is simulated for calculating the hydraulic head and fluid velocity within the domain. Secondly, chemical reactive transport module was used for describing the curtain behavior. Fig. 1 to Fig. 5 shows some results at different stress time from simulation of section 6. Traffic information is difficult to share. Traffic information collection, management, processing, and release system have not unified interaction interface, so it is difficult to integrate various systems. Due to the independence of the systems, each system has its own set of databases and data formats, resulting that the data cannot be shared between the systems. So there are numerous data "islands" in traffic system.

Fig.1: Distribution of Ca²⁺ concentration after 360 days in cross section 6 (unit: kg/m³)

Fig.2: The Distribution of Ca²⁺ concentration after 360 days along vertical direction in the domain (unit: kg/m³)
It is known from the figures that reaction extent differs in different parts of the curtain that the dissolution of Ca (OH)\textsubscript{2} accounts to 877.884 g/m\textsuperscript{3} near the bottom and is much higher than the other parts (Fig.1 and Fig.3). Aqueous calcium had been always in dissolution during the time stress period for simulation that leads to the increasing amount in groundwater reaching by 846.35 ~ 865.312 g /m\textsuperscript{3}(Fig.2 and Fig.4). The erosion is much more seriously near the bottom of the curtain than the other parts, which is the same from the upstream to downstream (Fig.5). Calcium dissolution mainly takes place at the bottom of the curtain and transports in three sub-zones. The highest concentration is behind the curtain and toward the downstream in 45 degree, and the secondly highest concentration is at the curtain bottom and toward the upstream in 45 degree, are the consequence of both hydraulic condition and dispersion The lowest concentration is behind the curtain and toward downstream in 135 degree, which is caused by the dispersion of calcium concentration nearby the upstream. Water-rock-curtain interaction is slowing in...
thermo-dynamics. However, at the bottom of the curtain the long-term reaction is more aggressive. It could be deduced that the anti-seepage efficiency of the curtain is weakening with time.

To analyze the variation of concentration field and velocity with time, Fig. 6 shows the calcium concentration that is 5m away from the curtain bottom, respectively.

![Fig.6: Distribution of Ca\textsuperscript{2+} concentration at 5m from curtain after different times(unit: kg/m\textsuperscript{3})](image)

Fig. 6 shows the variation of Ca\textsuperscript{2+} concentration with times at the curtain bottom along the river. It reaches the highest value at the bottom of the curtain, which is 0.558 kg/m\textsuperscript{3} at 30d and 0.637 kg/m\textsuperscript{3} at 7200d; And it increase much more slowly far away from the local, the most slow rate at the upstream according to the hydraulic condition.

**CONCLUSION**

(1) An analysis model was built for simulating water-rock-curtain interaction in this study, which could be used to describe the evolution of both a curtain and groundwater in components, which represents the physico-chemical damage of the curtain in both spatial and temporal scales.

(2) The curtain anti-seepage efficiency is weakening all the time. Aqueous calcium from the curtain had been always in dissolution during the time stress period for simulation that leads to the increasing amount in groundwater. The erosion is much more seriously near the bottom of the curtain than the other parts.

(3) Calcium dissolution mainly takes place at the bottom of the curtain and transports mainly in three sub-zones. The first is behind the curtain and toward the downstream in 45 degree with the highest concentration. The second is at the curtain bottom and toward the upstream in 45 degree. And the last is behind the curtain and toward downstream in 135 degree.

(4) The reaction between fluid and solid phase may lead to variation of curtain permeability, porosity and calcium leaching quantity, which represents the weakening trend of the curtain’s anti-seepage. And it’s of great significance in both theory and practice.

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