Analysis of Measured Seepage Rate of Rockfill Dams
Affected by Changes in Rainfall for Dam Safety in Korea

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ABSTRACT
In Korea more than 60% of annual rainfall is concentrated in the short term from June to August because of the climate characteristics of the East Asian Monsoon (Lee et al, 2005). In this period the reservoir water level rises sharply and the risk of leakage problem increases but the detection of abnormal leakage problem and emergency response are more difficult because the amount of rainwater into the seepage rate is increased. In this paper, rainwater rate is filtered out from the measured seepage rate of 6 large rockfill dams, operated and managed by Korea Water Resources Corporation using digital filtering method. For the purpose of this paper, dams are named A to F. F dam was not affected by rainwater significantly because the seepage water through F dam was collected in inside and the collected seepage water was transferred to seepage meter located in downstream of the dam through the steel pipe. The permeability of core zone was evaluated that the estimated seepage rate by numerical seepage analysis fit to the corrected measured seepage rate by varying the permeability by trial and error method. Generally seepage rate through the 5 dams in Korea were dominant in the measured seepage rate but it was confirmed that the measured seepage rate greatly influenced by rainfall in rainy season. The rate of rainwater in the measured seepage rate was in the range from 4.5 times to 9.2 times of the seepage rate through the dams after filtered out by the digital filtering method. Seepage behavior through 6 large rockfill dams in Korea were estimated as stable condition because certain correlation between the seepage rate and the reservoir water level as the seepage rate rise and fall correspond to the reservoir water level rise and fall. From the evaluation results, evaluated permeability of core zones of 6 large dams in Korea were in the range from $6.0 \times 10^{-6}$ to $8.5 \times 10^{-5}$ cm/sec. It shows that water tightness of the core zones have no problem.

Keywords: Rockfill dam, Seepage rate, Filter out of rainwater, Water tightness of core zone

1. INTRODUCTION
Seepage rate through a rockfill dam is correlated with the reservoir water level of the dam. Abnormal seepage problem, such as piping in the core zone of the dam, can be determined to analyze carefully relationships between reservoir water level and seepage rate. In Korea, according to the design standards of dam (Korea Water Resources Association, 2005), construct a catchment wall and a triangular weir in the downstream side of a dam and continuously measure and analyze seepage rate through a dam is required to be used as a basis of a seepage stability evaluation. Therefore, most of multipurpose dams in Korea have facilities to monitor seepage rate through dams as shown in Fig. 1.

However, most of rockfill dams have a problem that rainwater affects into the seepage rate measurement as shown in Fig. 2, because a catchment wall and a triangular weir constructed in the downstream outside of dams. To find out relationships between reservoir water level and seepage rate, the volume of rain water is removed from the measured seepage rate.

In Korea more than 60% of annual rainfall is concentrated in the short term from June to August because of the climate characteristics of the East Asian Monsoon (Lee et al, 2005). In this period the
reservoir water level rises sharply and the risk of leakage problem increase than ever, detection of abnormal leakage problem and emergency response are more difficult because the amount of rainwater into the seepage rate is increased.

In this paper, rainwater rate is filtered out from the measured seepage rate of 6 large rockfill dams (see Table 1), that are operated and managed by Korea Water Resources Corporation using digital filtering method. The permeability of core zone was evaluated by adjusting the estimated seepage rate from numerical seepage analysis to fit the corrected measured seepage rate by varying the permeability with trial and error method.
Table 1. Characteristics of 6 large rockfill dams in Korea

<table>
<thead>
<tr>
<th>Dam</th>
<th>Construction Completed Year</th>
<th>Height (m)</th>
<th>Length (m)</th>
<th>Volume of Dam Body ($10^4$ m$^3$)</th>
<th>Crest Elevation (EL.m)</th>
<th>Analyzed Measured Seepage flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1992</td>
<td>99.9</td>
<td>562.6</td>
<td>496.5</td>
<td>115.0</td>
<td>JAN. 2002 ~ DEC. 2008 (84 Month)</td>
</tr>
<tr>
<td>B</td>
<td>1992</td>
<td>58.0</td>
<td>330.0</td>
<td>157.3</td>
<td>115.0</td>
<td>JAN. 2002 ~ DEC. 2006 (60 Month)</td>
</tr>
<tr>
<td>C</td>
<td>1993</td>
<td>73.0</td>
<td>515.0</td>
<td>342.3</td>
<td>168.0</td>
<td>JAN. 2002 ~ DEC. 2008 (84 Month)</td>
</tr>
<tr>
<td>D</td>
<td>2000</td>
<td>50.0</td>
<td>291.0</td>
<td>111.6</td>
<td>79.0</td>
<td>JAN. 2007 ~ DEC. 2009 (36 Month)</td>
</tr>
<tr>
<td>E</td>
<td>2002</td>
<td>48.5</td>
<td>205.0</td>
<td>67.5</td>
<td>184.0</td>
<td>JAN. 2004 ~ DEC. 2005 (24 Month)</td>
</tr>
<tr>
<td>F</td>
<td>1981</td>
<td>52.0</td>
<td>131.6 (496.0)</td>
<td>123.4</td>
<td>83.0</td>
<td>JAN. 1981 ~ DEC. 1985 (60 Month)</td>
</tr>
</tbody>
</table>

2. ANALYSIS OF MEASURED SEEPAGE RATE

2.1. DIGITAL FILTERING METHOD

Digital filtering method was applied to filter out rainwater from the measured seepage rate. It is one of the base flow separation methods for hydrograph, widely used in the field of hydraulic engineering. The digital filter based on the principle used in signal processing by regarding rainwater as high-frequency signals. This method was applied to the time series of seepage rate measured at regular time interval.

Many researchers have proposed digital filters. The methods using a number of parameters are difficult to apply because the difficulty to determine objectively the parameters needed in general. Although the digital filter by Chapman and Maxwell(1996) using single parameter, exhibit unrealistic results when the seepage rate through dam body is greater than rainwater over 50%. It is confirmed that Nathan and McMahon(1999)’s digital filter has not such a problem(Stephen et al, 2009).

Therefore, the rate of rainwater were filtered out of the seepage rate measured from 6 large rockfill dams in Korea using Nathan and McMahon(1999)’s digital filter. Nathan and McMahon(1999)’s digital filter is as shown in Eq. 1 and Eq. 2. The parameter($\beta_d$) of the filter is equal to recession constant(k) of the seepage rate recession curve.

\[
Q_{d,i} = \beta_d \cdot Q_{d,i-1} + \frac{1+\beta_d}{2} (Q_i - Q_{i-1}) \quad (1)
\]

\[
Q_{b,i} = \frac{1-k}{2} (Q_i + Q_{i-1}) + k \cdot Q_{b,i-1} \quad (2)
\]

Where, \(Q=\)measured seepage rate(\(Q=Q_b+Q_c\)), \(Q_b=\)seepage rate through dam body, \(Q_d=\)rainwater rate, \(i=\)time step, \(\beta_d=\)filter parameter(\(\beta_d=k\)), \(k=\)recession constant.

The recession constants (k) of the recession curve of measured seepage rate were determined from exponential decay function as shown in Eq. 3, is using in the field of Heat flow, diffusion and radioactivity. Eq. 3 and Eq. 4 are obtained by taking the natural logarithm on both sides of Eq. 1.
The recession constants to be applied for each target dams were determined by general method (Stephen et al., 2009) that the recession curves at each target dams after the rain stopped were plotted in semi-logarithmic plot. This method was as shown in Fig. 3 where the lowest slope ($\alpha$) of recession curves is obtained by plotting the natural logarithm of the measured seepage rate hourly. Recession constant ($k$) was determined as Eq. 5 using $\alpha$ obtained by Eq. 4. Average value of the recession constants determined applied as the parameter of the digital filter.

$$Q_t = Q_0 \cdot e^{-\alpha t} = Q_0 \cdot k^t$$  \hspace{1cm} (3)

$$\ln Q_t = \ln(Q_0) - \alpha \cdot t$$  \hspace{1cm} (4)

$$k = e^{-\alpha}$$  \hspace{1cm} (5)

Where, $Q_0$=measured seepage rate at a time, $Q_t$=measured seepage rate after a time $t$ from $Q_0$, $\alpha$=slope of recession curve of measured seepage rate, $k$=recession constant($k<1$), $t$=time.

![Fig. 3 Method for determination of $\alpha$](image)

**2.2. RESULTS OF ANALYSIS**

Time series data of reservoir water level (EL.m) and seepage rate (ℓ/min) measured daily at 24:00 and cumulative rainfall in one day (mm/day) were used for the analysis. F dam was not expected to be affected by rainwater significantly because the seepage water through F dam was collected in inside of F dam and the collected seepage water was transferred to seepage meter located in downstream of the dam through a steel pipe with diameter 300mm as shown in Fig. 4. The measured seepage rate of F dam was not filtered out of rainwater.

The recession constants of 5 target dams except for F dam were in the range from 0.986 to 0.993 from the analysis results. Generally seepage rate through the dams were dominant in the measured seepage rate but it was confirmed that in some cases the measured seepage rate is greatly influenced by rainfall in rainy season.

The rate of rainwater in the measured seepage rate was up to the range from 4.5 times to 9.2 times of the seepage rate through the dams after filtered out by the digital filtering method.

Fig. 6 and Fig. 7 show one of $\alpha$ value of recession curves of A dam and the results of filtering out of rainwater of A dam each. Seepage behavior through 6 large rockfill dams in Korea were evaluated as stable condition because certain correlation between the corrected measured seepage rate and the reservoir water level as the corrected measured seepage rate rise and fall correspond to the reservoir water level rise and fall. Fig. 8 shows variations of the seepage rate with the reservoir water level.
Table 2. Summary of analysis results of measured seepage rate of 6 large rockfill dams in Korea

<table>
<thead>
<tr>
<th>Dam</th>
<th>Recession constant ((k))</th>
<th>①Max. of Measured Seepage flow (ℓ/min)</th>
<th>②Max. of Adjusted Seepage flow (ℓ/min)</th>
<th>③Max. Amount of Rainwater (①-②, ℓ/min)</th>
<th>Ratio(③/②)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.9908</td>
<td>2584.8</td>
<td>337.9</td>
<td>13.1</td>
<td>6.7</td>
</tr>
<tr>
<td>B</td>
<td>0.9925</td>
<td>2455.3</td>
<td>321.7</td>
<td>13.8</td>
<td>6.7</td>
</tr>
<tr>
<td>C</td>
<td>0.9859</td>
<td>1734.6</td>
<td>221.3</td>
<td>12.8</td>
<td>6.8</td>
</tr>
<tr>
<td>D</td>
<td>0.9929</td>
<td>792.2</td>
<td>142.8</td>
<td>19.3</td>
<td>4.5</td>
</tr>
<tr>
<td>E</td>
<td>0.9924</td>
<td>766.7</td>
<td>75.4</td>
<td>9.8</td>
<td>9.2</td>
</tr>
<tr>
<td>F</td>
<td>0.8430</td>
<td>280.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 4 Layout of seepage water measuring system of F dam
Fig. 5 Time series graph of measured seepage rate with daily cumulative rainfall and reservoir water level of F dam

3. EVALUATION OF PERMEABILITY OF CORE ZONE

3.1. ESTIMATION METHOD OF SEEPAGE THROUGH DAM BODY

The estimated seepage rate was determined with numerical analysis to evaluate the permeability of core zones of 6 large rockfill dam using the corrected measured seepage rate. First, seepage rate per unit width (\(\text{q}_{ci,j}\)) at each reservoir water levels was determined with 2D seepage analysis on the representative cross-sections of divided each portion of longitudinal section of target dam as shown in Fig. 9(A dam case). Second, Seepage rates of each divided section with reservoir water levels were determined as shown in Eq. 6(A dam case). Finally, total seepage rate was determined as shown in Eq. 7.

Filter zone and rock zone surrounding core zone were not included in 2D seepage analysis because the permeability of filter zone and rock zone was significantly higher than core zone’s. Table 3 represents upper and lower elevation and width of core zone and slope of upstream and downstream to model finite element mesh of the 6 dams. Fig. 10 shows finite element mesh of A dam.
Fig. 6 Determination of $\alpha$ of A dam for event on May 24, 2007

$$\ln Q = 5.0975 - 0.0088 t$$

$R^2 = 0.8263$

Fig. 7 Time series graph of measured and adjusted seepage rate of A dam
Fig. 8 Seepage rate variation with reservoir water level of A dam

Fig. 9 Divided longitudinal section of A dam

\[ Q_{1c} = \frac{1}{2} \times (q_{c1-2}) \times B_1 \]
\[ Q_{2c} = \frac{1}{2} \times (q_{c1-2} + q_{c2-3}) \times B_2 \]
\[ \vdots \]
\[ Q_{5c} = \frac{1}{2} \times (q_{c4-5}) \times B_5 \]

\[ Q = Q_{1c} + Q_{2c} + Q_{3c} + Q_{4c} + Q_{5c} \]
### Table 3. Dimensions of the core zones of 6 large rockfill dams in Korea

<table>
<thead>
<tr>
<th>Dam</th>
<th>Year</th>
<th>Height (m)</th>
<th>Length (m)</th>
<th>Core EL(m)</th>
<th>Core Width(m)</th>
<th>Core Slopes (V:H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1992</td>
<td>99.9</td>
<td>562.6</td>
<td>115.0</td>
<td>15.1</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>1992</td>
<td>58.0</td>
<td>330.0</td>
<td>114.5</td>
<td>56.5</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>1993</td>
<td>73.0</td>
<td>515.0</td>
<td>168.0</td>
<td>95.0</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>2000</td>
<td>50.0</td>
<td>291.0</td>
<td>78.5</td>
<td>28.5</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>2002</td>
<td>48.5</td>
<td>205.0</td>
<td>183.0</td>
<td>134.5</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>1981</td>
<td>52.0</td>
<td>143.0</td>
<td>83.0</td>
<td>34.0</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 10 Finite element mesh of the core zone of A dam for numerical seepage analysis

### 3.2. EVALUATED PERMEABILITY OF CORE ZONE

Inverse analysis was performed by varying permeability of core zone to fit estimated seepage rate to the corrected measured seepage rate by varying the permeability by trial and error method. The permeability of core zone was considered determined when the estimated seepage rate and the corrected measured seepage rate fit well. Fig. 11 shows the corrected measured seepage rate and the estimated seepage rate at each reservoir water level of A dam. Fig. 12 shows the measured seepage rate and the estimated seepage rate of F dam, is not affected with rainfall. From the evaluation results, evaluated permeability of core zones of the 6 large dams were in the range from $6.0 \times 10^{-6}$ to $8.5 \times 10^{-5}$ cm/sec. In general, criterion of permeability of core zone for water tightness is $1.0 \times 10^{-5}$ cm/sec. Therefore, the core zones of 6 large dams are considered to maintain water tightness to some extent.
Fig. 11 Comparison of the estimated and the corrected measured seepage rate with reservoir water level of A dam

Fig. 12 Comparison of the estimated and the measured seepage rate with reservoir water level of F dam

Table 4. Results of evaluated permeability of core zones of 6 large rockfill dams in Korea

<table>
<thead>
<tr>
<th>Dam</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>k (cm/sec)</td>
<td>1.5×10^{-5}</td>
<td>2.7×10^{-5}</td>
<td>6.0×10^{-6}</td>
<td>1.8×10^{-5}</td>
<td>1.0×10^{-5}</td>
<td>8.5×10^{-5}</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

Rainwater rate may be filtered out from the measured seepage rate of rockfill dams using digital filtering method. In this study the permeability of core zone was evaluated that the estimated seepage rate by numerical seepage analysis fit to the corrected measured seepage rate by varying the permeability by trial and error method. The following shows the results.

Generally seepage rate through the 5 dams in Korea were dominant in the measured seepage rate but it was confirmed that the measured seepage rate greatly influenced by rainfall in rainy season. F dam was not affected by rainwater significantly because the seepage water through F dam was collected in inside and the collected seepage water was transferred to seepage meter located in downstream of the dam through the steel pipe.

The rate of rainwater in the measured seepage rate was up to the range from 4.5 times to 9.2 times of the seepage rate through the dams after filtered out by the digital filtering method.

Seepage behavior through 6 large rockfill dams in Korea were evaluated as stable condition because certain correlation between the corrected seepage rate and the reservoir water level as the corrected measured seepage rate rise and fall correspond to the reservoir water level rise and fall.

From the evaluation results, evaluated permeability of core zones of 6 large dams in Korea were in the range from $6.0 \times 10^{-6}$ to $8.5 \times 10^{-5}$ cm/sec. In general, criterion of permeability of core zone for water tightness is $1.0 \times 10^{-5}$ cm/sec. Therefore, the core zones of 6 large dams are considered to maintain water tightness to some extent.

REFERENCES

Korea Water Resources Association, 2005, Design Standards of dam, Korea