Technical Note

Localizing and Quantifying Leakage through CFRDs

J. S. Jia[1]; Y. Xu[2]; J. T. Hao[3]; and L. M. Zhang, F.ASCE[4]

Abstract: Large leakage occurred in several concrete-face rockfill dams (CFRDs) around the world recently, resulting in economic losses and safety problems. To rehabilitate these dams, it is necessary to identify leakage locations on the concrete face slabs and understand the severity of leakage at each location. This technical note presents a method for localizing and quantifying leakage through CFRDs. Analysis models are developed to estimate the leakage rate from horizontal and vertical leakage sources. The relationship between water level and leakage is described for these two leakage sources. Based on a monitored water level-leakage relation, the elevations of leakage are determined, and the leakage rate at each elevation is estimated using these models. A case study on the Buxi CFRD is presented to illustrate the method. The calculated water level-leakage relation is in good agreement with the measured one before rehabilitation, and the leakage has decreased over 80% after rehabilitation. **DOI:** 10.1061/(ASCE)GT.1943-5606.0001501. *© 2016 American Society of Civil Engineers.*

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Introduction

The concrete-face rockfill dam (CFRD) has become a popular and competitive dam type because of its excellent performance in safety, economy, and environment. A CFRD relies on the weight of rockfill to withstand the force of water and uses the concrete face slab as an impervious layer to prevent leakage. The concrete face slab has vertical joints and peripheral joints with waterstops. For high CFRDs, horizontal construction joints are often used when it is necessary to place the concrete face slab in two or more stages. Leakage from a CFRD mainly occurs through defective joints and waterstops, or cracks and ruptures in the concrete face slab (e.g., Sherard and Cooke 1987; Won and Kim 2008; ICOLD 2011). In recent years, large leakage occurred in several CFRDs around the world, such as Barra Grande and Campos Novos in Brazil, Mohale in Lesotho, and Gouhou in China, resulting in economic losses and even potential safety problems (e.g., Chen and Zhang 2006; Pinto 2007). To reduce excessive leakage through a CFRD, it is necessary to identify the leakage locations on the concrete face slab, understand the severity of leakage at each location, and take proper rehabilitation measures to repair the face slab.

The objectives of this note are to develop a simple analysis method for localizing and quantifying leakage through CFRDs. Firstly, two basic analysis models are developed to estimate leakage from horizontal and vertical leakage sources. Then, based on a site-specific monitored water level-leakage relation, the elevations of leakage are determined, and the leakage rate at each elevation is estimated with the analysis models. A detailed case study on the Buxi CFRD is presented to illustrate the application of this method.

[1]Professor, State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China; Honorary President, International Commission on Large Dams (ICOLD), Paris, France.

[2]Senior Engineer, State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China (corresponding author). E-mail: xuyao@iwhr.com

[3]Professor, State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China.

[4]Professor, Dept. of Civil and Environmental Engineering, Hong Kong Univ. of Science and Technology, Hong Kong, China.

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Development of Models for Estimating Leakage Rate

Casinader and Rome (1988) summarized two approaches for estimating leakage through concrete facings of CFRDs, including the apparent permeability method and the crack flow method. Both approaches involve the assumption of laminar flow through the concrete slab. In fact, the leakage areas due to defective joints and waterstops or ruptures in the concrete face slab can be very large. For instance, peripheral joints of high CFRDs may experience large three-dimensional displacements because of large settlement of the rock fill; large damaged areas may result from ruptures of the concrete face slab. In this case, the leakage through the defective concrete face slab, $Q(\mathrm{m}^3/\mathrm{s})$, cannot be considered as a laminar flow; instead, the flow is governed by a general orifice equation

$$Q = \mu A(\Delta p)^m \tag{1}$$

where μ = flow coefficient; A = leakage area (m^2); Δp = pressure loss across the leak (Pa); and m = orifice shape coefficient, $m = 1$ for a slender orifice ($L/d > 4$), $m = 0.5$ for a thin-wall orifice ($L/d < 0.5$), and $0.5 < m < 1$ for a thick-wall orifice ($0.5 < L/d < 4$). Note that L and d represent the length and diameter of the orifice, respectively. Fig. 1 shows the leakage rate versus the pressure loss across the leak for different sorts of orifices. The leakage rate of a thin-wall orifice is larger than that of a slender orifice when the pressure loss is small, and the trend reverses when the pressure loss is large. When the pressure loss is small, the leakage through either the thin-wall orifice or the slender orifice is a laminar flow with a small velocity, and the frictional water head loss of the thin-wall orifice is less than that of the slender orifice because of its shorter flow distance, resulting in a larger leakage rate through the thin-wall orifice than that through the slender orifice. When the pressure loss becomes large, the frictional water head loss of the slender orifice is still larger than that of the thin-wall orifice because of its longer distance. However, the presence of a contracted cross section of flow in the slender orifice forms a vacuum area with a significant suction effect, which increases the

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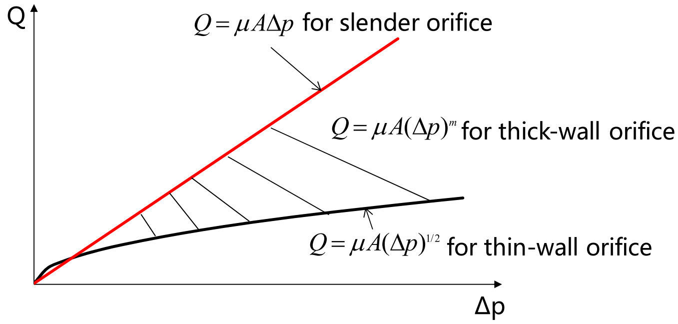

Fig. 1. Leakage rate versus pressure loss across the leak for different sorts of orifices

flow rate substantially and overwhelms the negative effect of the frictional water head loss, resulting in a larger leakage rate through the slender orifice than that through the thin-wall orifice.

For CFRDs, the water head loss through impervious barriers mainly consists of two parts: the loss through the facing and the loss through the bedding materials. The pressure loss across the facing, Δp, should be proportional to the water head at the leakage location, H (m)

$$\Delta p = \lambda \rho g H \tag{2}$$

where λ = coefficient of proportionality, $0 < \lambda < 1$; ρ = water density (kg/m^3); and g = gravity acceleration (m/s^2). The value of λ is determined by not only the geometry and the relative roughness of the orifice through the facing but also the permeability of the bedding materials under the facing. Therefore, Eq. (1) can be rewritten as

$$Q = \mu A(\lambda \rho g H)^m \tag{3}$$

According to the longitudinal direction of the leakage area, two common sorts of leakage sources can be identified: horizontal leakage source and vertical leakage source (Fig. 2). For a horizontal leakage source of width b (m) and length l (m), the leakage rate can be calculated based on Eq. (3) as follows:

$$Q_1 = \mu(bl)(\lambda \rho g)^m H^m \tag{4}$$

Let $K_1 = \mu(\lambda \rho g)^m$, Eq. (4) is simplified as

$$Q_1 = K_1(bl)H^m \tag{5}$$

For a vertical leakage source, the leakage rate is estimated by

$$Q_2 = \begin{cases} \dfrac{\mu b}{m+1}(\lambda \rho g)^m H^{m+1}, & H < l \\ \dfrac{\mu b}{m+1}(\lambda \rho g)^m [H^{m+1} - (H-l)^{m+1}], & H \geq l \end{cases} \tag{6}$$

Let $K_2 = \mu(\lambda \rho g)^m/(\mathrm{m}+1)$, Eq. (6) is simplified as

$$Q_2 = \begin{cases} K_2 b H^{m+1}, & H < l \\ K_2 b[H^{m+1} - (H-l)^{m+1}], & H \geq l \end{cases} \tag{7}$$

If a leakage source is inclined with length l and inclination angle α, it can be converted into an equivalent vertical leakage source with length $l \sin \alpha$. Therefore, the leakage rate equation for an inclined leakage source is not specified here.

Figs. 2(a and b) show the relationships between reservoir water level and leakage rate for horizontal leakage sources and vertical leakage sources, respectively. In general, the leakage rate tends to increase with the water level for both sorts of leakage sources. However, the increasing rates with the water level are different for these two sorts of leakage sources. For the horizontal leakage source, the increasing rate becomes slower as the water level rises except for the case of $m = 1$ [Fig. 2(a)]. For the vertical leakage

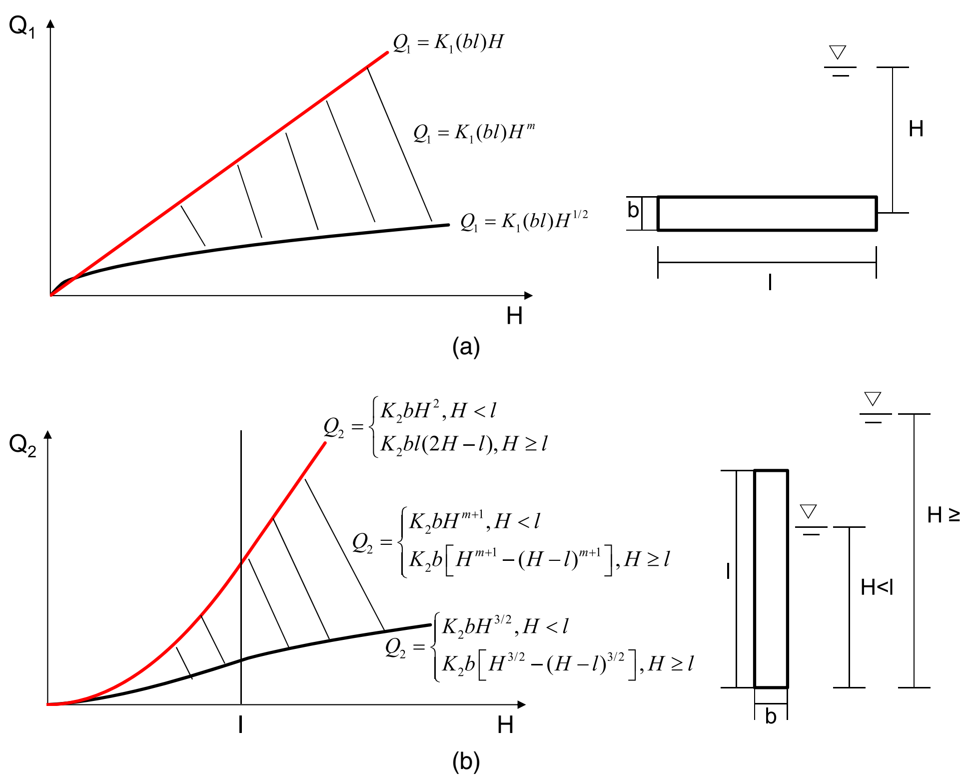

Fig. 2. Relationship between water level and leak rate: (a) for horizontal leakage sources; (b) for vertical leakage sources

source, the increase in leakage rate can be divided into two phases: the acceleration phase and the slowly increasing phase [Fig. 2(b)]. In the acceleration phase, the leakage rate increases not only because of the rising water level but also because of the enlarged leakage area. In the slowly increasing phase, the increase is only caused by the rising water level similar to that for the horizontal leakage source. In other words, when the water level is above the upper end of the vertical source, the vertical leakage source

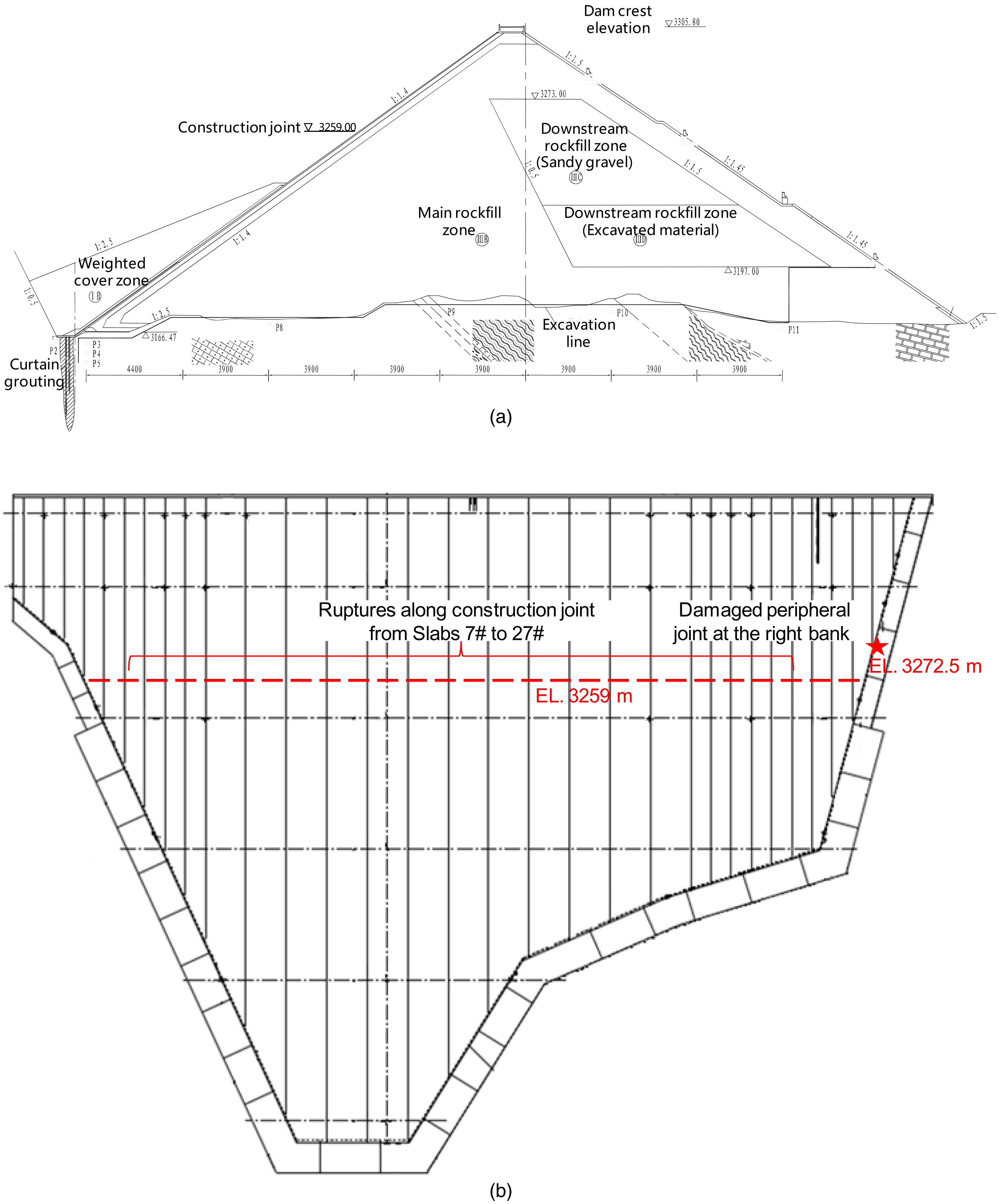

Fig. 3. (a) Typical cross section; (b) layout of concrete face slabs of the Buxi dam

becomes equivalent to the horizontal leakage source. Different sorts of leakage sources at different elevations can be differentiated based on the aforementioned characteristics of the relationship between water level and leakage rate.

Case Study on Buxi Highrise CFRD

The Buxi CFRD, 135.8 m in height, is located on the Yazhui River in Sichuan, China. The dam crest is at an elevation of 3,305.8 m, and the normal water level is at an elevation of 3,300 m. The dam was constructed between March 2008 and February 2011. The slabs were constructed in two stages with a horizontal construction joint at an elevation of 3,259 m. A typical cross section and the layout of the concrete face slabs of the dam are shown in Fig. 3.

Since the first reservoir impoundment started in September 2010, the dam had performed well until June 2012. In July 2012, the water level rose quickly in the flood season. At the end of July 2012, the leakage increased sharply, from 0.1 m^3/s to more than 1.0 m^3/s. Since then, the leakage increased continuously, reaching a maximum value of 1.982 m^3/s at a water elevation of 3,291 m on January 16, 2013. After that, the leakage decreased as the water level dropped. When the water level reached an elevation of 3,259 m on April 7, 2013, the leakage decreased to 0. In other words, no leakage occurred if the water level was below the construction joint of the face slabs. Fig. 4 shows the changes in the water level and the leakage rate with time. Improvement works for the flow-measuring weir were completed on January 15, 2013, as the dam seepage discharge exceeded the capacity of the previous flow-measuring weir. Therefore, the leakage data before January 15, 2013, might be underestimated. Considering this fact, the analysis in this note is conducted based on the data measured after the weir improvement. No significant leakage channels are found through the abutment foundations on both sides of the dam based on comprehensive analysis of technical documents on geological surveys, curtain grouting, and water pressure tests. Therefore, the leakage was primarily through the concrete face slab of the dam. The leakage channels through the abutment foundations on both sides of the dam are outside the scope of this study.

Fig. 5 shows the relationship between the measured leakage and water level after the weir improvement and before the dam rehabilitation. In Fig. 5, an obvious turning point at an elevation of 3,272.5 m is found on the curve; hence, two main sources of leakage can be identified: the first leakage at an elevation of 3,259 m, Q_{t1}, and the second leakage at an elevation of 3,272.5 m, Q_{t2}. The total leakage is the sum, $Q_t = Q_{t1} + Q_{t2}$. Here the first leakage and the second leakage are simply general terms for all leakage sources at an elevation of 3,259 m and an elevation of 3,272.5 m, respectively. Actually, the first leakage or the second leakage may be contributed by one or more defective locations of the concrete face slab at the same elevation.

For Q_{t1}, the curve in Fig. 5 shows that the increasing rate becomes slower as the water level rises between an elevation of 3,259 m and an elevation of 3,272.5 m, which is similar to Fig. 2(a). Therefore, it is judged that Q_{t1} is mainly contributed by the horizontal leakage at an elevation of 3,259 m. Assume $a = K_1(bl)$, Eq. (5) is simplified as

$$Q_{t1} = aH^m \tag{8}$$

where $a > 0$ and $0.5 \leq m \leq 1$. Note that Eq. (8) is just a slight modification of Darcy's law, in which some parameters for a specific problem such as the cross-sectional area, the hydraulic conductivity, and the hydraulic gradient are replaced by a single constant a herein; moreover, the relationship between the discharge and the energy loss is not linear but follows an exponential function. Based on the measured data, the values of a and m are determined using the least squares method in an Excel spreadsheet, leading to $a = 0.145$ and $m = 0.665$. Hence Eq. (8) is written as

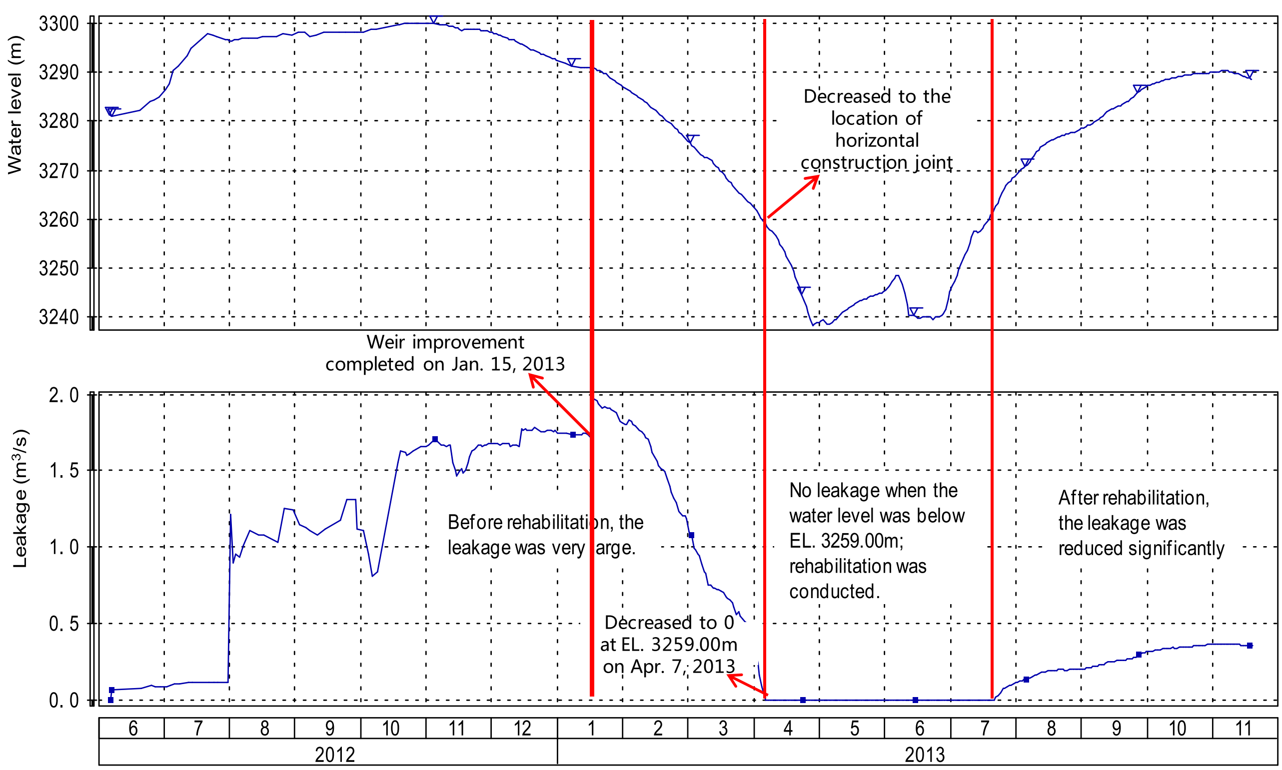

Fig. 4. Change of the water level and the leak rate of the Buxi dam with time

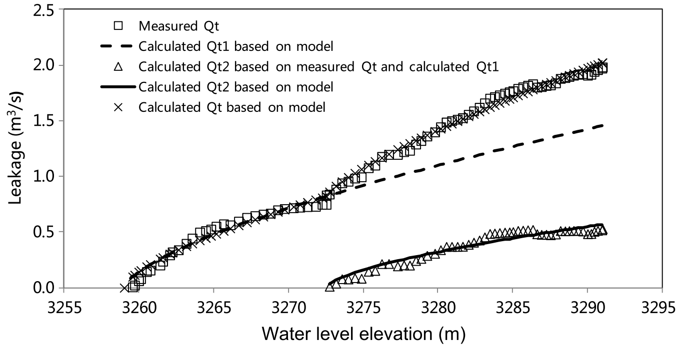

Fig. 5. Comparison of measured and calculated leakage values

$$Q_{t1} = 0.145H^{0.665} \tag{9}$$

By using Eq. (9), the value of Q_{t1} above an elevation of 3,259 m can be calculated, as shown in Fig. 5. Based on the measured Q_t values and the calculated Q_{t1} values, the other leakage component, Q_{t2}, above Elevation 3,272.5 m can be calculated. Like Q_{t1}, the curve for Q_{t2} has similar characteristics of Fig. 2(a). Hence, Q_{t2} is mainly contributed by the horizontal leakage at an elevation of 3,272.5 m. Following the same methodology for Q_{t1} by using the Excel spreadsheet, the coefficients for Q_{t2} are obtained as $a = 0.089$ and $m = 0.635$; and hence

$$Q_{t2} = 0.089\ H^{0.635} \tag{10}$$

By using Eq. (10), the value of Q_{t2} above an elevation of 3,272.5 m can be calculated, as shown in Fig. 5. Further, the calculated value of Q_t is obtained by adding the calculated values of Q_{t1} and Q_{t2}. In Fig. 5, the calculated leakage is in good agreement with the measured leakage.

For the maximum value of $Q_t = 1.982\ \mathrm{m^3/s}$ at the water elevation of 3,291 m, the contribution of the first leakage at an elevation of 3,259 m, Q_{t1}, is calculated as $1.452\ \mathrm{m^3/s}$, approximately 70% of the total amount. In fact, after the water level decreased to below the construction joint, serious ruptures were found along the construction joint at an elevation of 3,259 m, with a horizontal length of about 200 m and a width of about 1 m along the slab longitudinal direction. Therefore, the primary first leakage was caused by the seriously damaged construction joint. The second leakage at an elevation of 3,272.5 m was probably related to the peripheral joint on the right bank, where the maximum settlement of the face slab was as large as 300 mm and the waterstops were partially damaged. Therefore, Q_{t2} is treated as the contribution from the damaged peripheral joint on the right bank around an elevation of 3,272.5 m; Q_{t2} is about 30% of the total leakage at the water level of an elevation of 3,291 m.

In general, the damaged construction joint at an elevation of 3,259 m and the damaged peripheral joint on the right bank around an elevation of 3,272.5 m were the two main leakage sources for the Buxi CFRD (Fig. 3). Based on the analysis results, rehabilitation was conducted for repairing these two damaged locations on the concrete face slab. After the rehabilitation, the leakage was only $0.36\ \mathrm{m^3/s}$ when the water level reached the maximum level at an elevation of 3,290 m. Compared with the value of $1.92\ \mathrm{m^3/s}$ for the same water level before the rehabilitation, the leakage has decreased by over 80%. This practice again demonstrates the validity of the analysis outcome in this note, although minor leakage sources accounting for the remaining 20% of the total leakage before rehabilitation have not been identified through the simple analysis method presented in this note.

Conclusions

A simple analysis method has been developed for localizing and quantifying leakage through CFRDs. A case study on the Buxi CFRD is presented, which demonstrates that this method can be used to localize the elevations of leakage and to provide a general grasp of the main leakage sources through the concrete face slab of a CFRD. After identifying the leakage elevations, focal inspection can be conducted along certain horizontal lines of the concrete face slab to find the longitudinal positions of the leakage sources. By considering leakage locations and severities, proper rehabilitation measures can be taken to repair defective concrete face slabs.

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