METHODS FOR CONTROL OF SEEPAGE IN RCC DAMS WITH WATERTIGHT AND DRAINAGE MEASURES

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Abstract

The technologies for construction of roller-compacted concrete (RCC) dams have been considerably developed during recent years in China. At the time being, they have been successfully applied to the constructions of even extreme-high gravity dams and medium to high arch dams. There are a few of hundreds of RCC dams (RCCD) under design and/or construction in China. One of the main concerned technical problems according to the construction is about the understanding of the property of seepage in RCCDs and the relevant theory and methods for the control of the seepage. In order to overcome the problem, the senior author has been engaged in a wide study on the property and methods for control of seepage in RCCDs for more than 10 years. The property of seepage, measures for watertightness and drainage, optimal design and construction schemes for control of seepage in the dams have been essentially understood either in theory and practice. The results have been applied for the construction and the backanalysis of several dams. The paper describes the research findings in detail with respect to the theoretical fundament and their application for a high RCC gravity dam.

Keywords

gravity dam, Roller-compacted concrete, RCC, seepage, anisotropic permeability, drainage

1 INTRODUCTION

The Horizontal Layer Method used in roller-compacted concrete (RCC) construction has been replaced by the Slope Layer Method, which importantly reduces the area of exposed young RCC and increases RCC placing rates. The intrinsic permeability of RCC is very low (it equals 1.0×10^{-9} to 1.0×10^{-12} cm/s), whilst the permeability of the lift surface including the joint lift surface is proportional to the cubic width of a hydraulic joint. Theory and engineering practice have proved that the lift surface is the main pathway of seepage, in which leakage generally occurs. According to the present technology for constructing of RCC dams, the body of a RCC dam is considered to be a strong anisotropic medium with more than 2 to 4 or even 6 to 7 orders of magnitude (for example Willew Creek RCC gravity dam, USA) of ratio of the tangential major coefficient of permeability to the normal major coefficient of permeability of the layer and lift joint surfaces. This causes the seepage properties of RCC dams to be totally different from those of conventional concrete dams.

Since the early development stages of RCC dam construction, there have been a lot of problems with seepage due to the lack of knowledge about the property of seepage in RCC dams. One problem, for example is an extremely high position of the exit point on the downstream face, so that exit-flowing discharge may be higher than expected. This is caused by the anisotropic hydraulic resistance according to the dam structure constructed by layers. So, a lot of dams were required to increase their waterproof capability by grouting during the beginning period of operation. Such was the case with Willew Creek RCC dam and Chinese Shimantan RCC gravity dam of the height of 40.5 m.

This paper analyses in detail optimal design schemes for the control of seepage. The analysis is based on a wide and in-depth study on the property and methods for the control of seepage in RCCD and on the senior author's experiences in studying characteristics of permeability and control techniques to handle problems of seepage for RCC dams.

2 PROPERTIES OF SEEPAGE OF RCC AND RCCD

The system of RCC or RCCD consists of body layer of concrete with homogeneous and isotropy property, a layer and a lift interface of anisotropy property which becomes an inhomogeneous multi-laminated medium. Actual properties of seepage of RCC and RCCD are influenced by the properties of the body of concrete, which can be described by Darcy's coefficient of permeability k_{RCC}, and the properties of the layer and the lift interface which is related to the width of a hydraulic joint, roughness of the joint, connectivity of the joint, stress and strain behaviour of the layer surface, load history, etc. The engineering practice has already proved that the layer and the lift interface are the main pathway of seepage and represent weak surfaces according to tension and sliding. In general, RCC and RCCD can be considered as strongly anisotropic medium.

An experiment recorded in literature [1, 2] presents the model of an in-situ concrete block connected in parallel and in series within the Longtan RCC project, which is shown in Fig. 1. The experiment shows that the ratio of average coefficient of permeability in the parallel model to that in the series model is about 1 to 4 orders of magnitude. And the seepage flow mainly exits through the layer and the surrounding region of great skeletal material, which proves that the layer and the lift interface are main pathways of seepage [3].

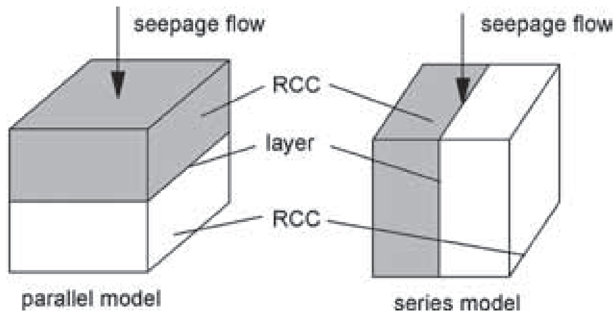

Figure 1. Parallel and series models of a rectangular RCC block in the permeability test.

Gong et al. [3] show the results of in-situ water pressure test, which includes the tests on Willew Creek RCC dam in the USA, Chinese Guanyinge and Tongzijie projects. The tangential major coefficient of permeability of the layer in Willew Creek RCC dam in the USA even surpasses 3×10^{-3} cm/s, and the average value of the tangential major coefficient of the layer permeability is in the range of 1×10^{-3} to 1×10^{-8} cm/s. So, heavy leakage occurs through layers and the location of the exit-flowing line is very high. Compared to the tangential major coefficient of layer permeability, the normal major coefficient of layer permeability is the same as the coefficient of permeability of the body of RCC. The properties of seepage of RCC and RCCD mainly depend on the tangential property of seepage. The system of RCC and RCCD should be considered as strongly anisotropic, and the ratio of anisotropy may reach 1 to 4 or even more orders of magnitude.

Theoretically, the properties of flow through layer and lift joint surfaces agree with the properties of fissure flow. The properties of seepage flow through layer and lift joint surfaces in RCC and RCCD can be usually described by the cubic law of an advective fissure flow, which has been proved by home and foreign engineering experts and which is in accordance test with results in various countries [3, 4].

The property of RCC considered as inhomogeneous multi-laminated medium can be described by tangential and normal major coefficients of the permeability of the layer which depend on the body coefficient of permeability, cubic law and the thickness of the layer. Eqs. (1) and (2) show the tangential and normal major coefficients of the permeability of the layer.

$$k_t = \frac{1}{B}[(B-d_f)k_{RCC} + \frac{g}{12\mu}d_f^3] \qquad (1)$$

$$k_n = \frac{Bk_{RCC}}{B-d_f} \qquad (2)$$

where k_t and k_n are average tangential and normal major coefficients of permeability of the layer, respectively, B denotes the thickness of the layer including the body thickness of the layer and the width of the hydraulic joint d_f, k_{RCC} denotes body coefficient of permeability of RCC, μ denotes the kinematic viscosity of water with $\mu \approx 0.013$ cm²/s at 10° C.

Because d_f is much smaller than B, the normal major coefficient of the permeability of the layer mainly depends on the body coefficient of permeability of RCC and also on the coefficient of bedding cushion, when there is one, whilst the tangential major coefficient of permeability mainly depends on the width of a hydraulic joint.

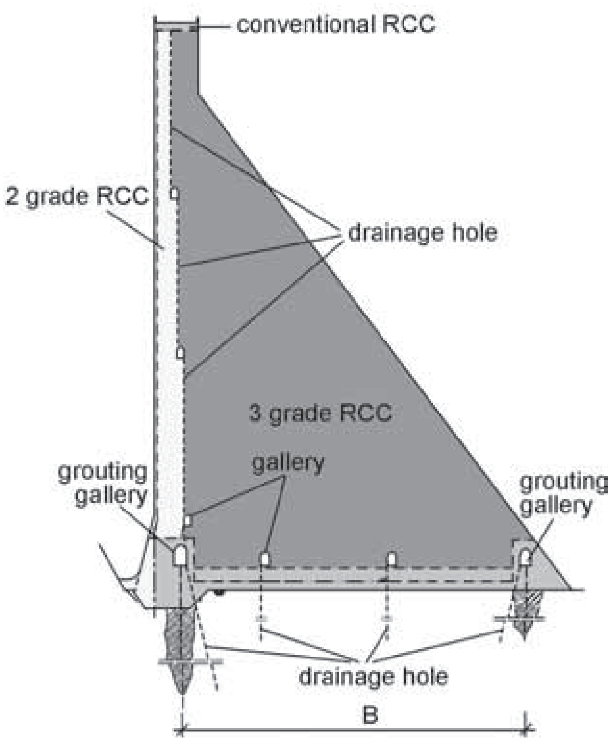

Figure 2. Cross section of seepage control measures for RCCD.

Due to a strong anisotropic property of RCC, the seepage control measures for RCCD become more difficult than conventional concrete. Fig. 2 shows the general layout of measures for watertightness and material zones. It will be a reliable anti seepage structure of a distorted concrete layer with a thickness of 0.3 to 1.0 m on the upstream face, which plays an important role of water-resistance in the front of the dam. Other forms of anti seepage structure on the upstream face of RCCDs are available, such as a RCC layer, a reinforced concrete slab, an asphalt concrete layer, and a combination of different anti-seepage structures. The majority of all projects under construction or under design adopt a distorted concrete layer as the anti seepage structure. Some infiltrating flow through the anti-seepage structure will be drained by drainage holes behind a distorted concrete layer, in which the uplift pressures in the layer and lift surface are almost zero. In order to prevent the seepage flow from exiting on the downstream face, a thin distorted concrete layer is also required on the downstream face. When the upstream water level is very high, a curtain of drainage holes hanging upward the datum plane is needed. Sometimes horizontal drainage holes are alternatively arranged in the layer and the lift surface additionally helps drainage and pressure relief. The principles of seepage control for RCCDs foundation mostly agree with conventional concrete dams which mainly depend on a curtain of watertightness and drainage holes.

3 NUMERICAL ANALYSIS ON THE RCCD SEEPAGE FIELD WITH FEM

3.1 NUMERICAL MODEL OF SEEPAGE FIELD

Due to special inhomogeneous and strongly anisotropic multi-laminated structures in RCCDs, the system of RCC should be considered as fractured rock masses medium according to the property of the layer seepage, which can be simulated by an equivalent continuum model, a discrete fractured network model and a dual porosity model [4-7].

Equivalent continuum models based on the balance equation of mass consider layer and lift surfaces as equivalent continuum porous media, which are analyzed by a mature theory of continuum porous media. But the equivalent seepage discharge and seepage pressure cannot be obtained with this method. A discrete fractured network model assumes that the body of RCC is impervious, so that the properties of RCC mainly depend on the widths of hydraulic joints, location and connectivity of the layer, and the coefficient tensor of permeability is determined by the cubic law and Darcy's law. This method is able to actually simulate the behaviour of seepage flow between layers, but due to the uncertainty of the joint and lift surface, it is more difficult to simulate fractures. The objects within a dual porosity model involve seepage behaviour both in porous media and fractured media.

Combining the merits and faults of three models mentioned above, the authors proposed inhomogeneous multi-laminated media elements model, which unifies the equivalent continuum model and the non-continuum mixed model, and which has the advantages of an equivalent continuum model involving fewer elements needed in the calculation [8].

3.2 INHOMOGENEOUS MULTI-LAMINATED MEDIA ELEMENT

An inhomogeneous multi-laminated media element model assumes that the dam body consists of a body layer of roller-compacted concrete, a lift interface, a lift joint interface of the course of one continuous construction of lifts, a bedding plane and normal concrete materials, which become inhomogeneous multi-laminated media elements. The element conductivity matrix is expressed with Eq. (3).

$$k_{ij}=\int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1}B_i^T K B_j |J| d\xi d\eta d\zeta=\sum_{k=1}^{N}\int_{\xi_{k-1}}^{\xi_k}\left(\int_{-1}^{1}\int_{-1}^{1}B_i^T K_k B_j |J| d\xi d\eta\right)d\zeta \quad (3)$$

Here we introduce the integral variable transformation shown in Eq. (4).

$$\zeta=\frac{\zeta_k-\zeta_{k-1}}{2}\zeta^{'}+\frac{\zeta_k-\zeta_{k-1}}{2} \quad (4)$$

So we have Eq. (5).

$$k_{ij}=\sum_{k=1}^{N}\int_{-1}^{1}\frac{\zeta_k-\zeta_{k-1}}{2}\left(\int_{-1}^{1}\int_{-1}^{1}B_i^T K_k B_j |J| d\xi d\eta\right)d\zeta^{'} \quad (5)$$

Here N is the number of layers of inhomogeneous multi-laminated media, K_k is the coefficient tensor of permeability of the k th layer, Eqs. (9), (10) and (11), B_i, B_j and $|J|$ are functions of the local coordinates of ξ, η and $\zeta^{'}$.

3.3 PLANAR ELEMENT WITHOUT THICKNESS FOR FISSURES

Bearing in mind numerous lift interfaces and lift joint interfaces and occurrence of horizontal cracks and cleavage cracks in case of emergency of a dam, the authors proposed the planar element without the thickness model ([9] and [10]), which can be used to simulate the exact behaviour of the seepage flow in RCC and which has been proved to be a successful model up to now.

Because the normal major coefficient of the permeability of a RCC body and the width of the joint are so small that normal head loss in the joint lift surfaces is almost zero, the seepage flow through joint lift surfaces can be considered as a two dimensional flow model (index f). We then have Eq. (6).

$$-\frac{\partial}{\partial x_i^f}\left[k_{ij}^f\frac{\partial h}{\partial x_j^f}\right]=0 \qquad i,j=1,2 \quad (6)$$

where x_i^f is the corresponding local coordinate, k_{ij}^f is a two dimensional coefficient tensor of permeability in the planar element without the thickness model, and k_{rs}^{fe} is the element conductivity matrix which can be calculated from the below Eq. (7):

$$k_{rs}^{fe}=\int_{s^f}\left[k_{11}^f\frac{\partial N_r}{\partial x_1^f}\frac{\partial N_s}{\partial x_1^f}+2k_{12}^f\frac{\partial N_r}{\partial x_1^f}\frac{\partial N_s}{\partial x_2^f}+k_{22}^f\frac{\partial N_r}{\partial x_2^f}\frac{\partial N_s}{\partial x_2^f}\right]ds \quad (r,s=1\cdots m) \quad (7)$$

where s^f is a subdomain of a joint lift surface element, N_r and N_s are interpolating functions of the joint lift surface element, m is the number of nodal points in the joint lift surface element.

According to balance equation of mass [11], we obtain the below FEM governing equation for a seepage field

$$\sum_e(Q_i^{RCC}+Q_i^f)=0 \qquad i=1,2,\cdots,n \quad (8)$$

where n is the total number of nodal points, Q_{RCC} and Q_F are nodal fluxes of the point i which are contributed by a 3-D equivalent continuum media element of RCC and a 2-D planar element without the thickness element.

3.4 COEFFICIENT TENSOR OF PERMEABILITY IN THE RCCD SEEPAGE FIELD

In the study of seepage properties in RCCDs, if the layer of RCC is horizontal, the coefficients of permeability can be described by major coefficients of permeability shown in Eqs. (1) and (2). In a sloped layer the direction of major coefficients of permeability are not the same as a coordinate axis and the properties of seepage should be expressed by the coefficient tensor of permeability shown as Eqs. (9), (10) and (11). Eq. (9) is suitable for the layer incline to the upstream, whilst Eqs. (10) and (11) are suitable for the layers' incline to the left bank and the right bank, respectively.

$$[K]=k_n\begin{bmatrix} r\cos^2\theta+\sin^2\theta & 0 & \frac{1}{2}(r-1)\sin 2\theta \\ 0 & r & 0 \\ \frac{1}{2}(r-1)\sin 2\theta & 0 & r\sin^2\theta+\cos^2\theta \end{bmatrix} \quad (9)$$

$$[K]=k_n\begin{bmatrix} r & 0 & 0 \\ 0 & r\cos^2\theta+\sin^2\theta & \frac{1}{2}(1-r)\sin 2\theta \\ 0 & \frac{1}{2}(1-r)\sin 2\theta & r\sin^2\theta+\cos^2\theta \end{bmatrix} \quad (10)$$

$$[K]=k_n\begin{bmatrix} r & 0 & 0 \\ 0 & r\cos^2\theta+\sin^2\theta & \frac{1}{2}(r-1)\sin 2\theta \\ 0 & \frac{1}{2}(r-1)\sin 2\theta & r\sin^2\theta+\cos^2\theta \end{bmatrix} \quad (11)$$

where θ is the slope angle, k_t and k_n are tangential and normal major coefficients of permeability, respectively, $r = k_t / k_n$ is the ratio of tangential major coefficient of permeability to normal major coefficient of permeability, $[K]$ is the coefficient tensor of permeability.

4 THE DESIGN METHODS FOR WATERTIGHT AND DRAINAGE MEASURES

4.1 WATERTIGHT STRUCTURES ON THE UPSTREAM FACE

Lift surfaces on the upstream face are probably a pathway of leakage, so it is important to take watertight measures in the upstream. The distorted RCC and 2-grade RCC are mostly used as watertight measures on the upstream face in present RCCDs. 2-grade RCC represents a defined RCC quality, which is higher than the 3-grade RCC. Based on the authors' experiences about methods of seepage control in RCCDs, the following schemes for the control of seepage are proposed. First, a thin layer of distorted RCC and additional 2-grade RCC are arranged on the upstream face, and seepage control treatment is done on the lift surfaces within the width of 2m. Second, a thin layer of distorted RCC and additional 3-grade RCC are arranged on the upstream face, and seepage control treatment is done on the lift surface within the width of 2 m (i.e. to spread a layer of mortar of the thickness of 1.0 ~ 1.5 cm in time). Different projects will take different schemes of control of seepage. Temperature control and crack prevention are very important on the upstream face to prevent the occurrence of penetrating cracks. Quality of structure of seepage control is more important than its width.

Uplift pressure tolerances in the lift surface, the joint lift surface and the datum plane are shown in Figs. 3 and 4, where H_u and H_d are depths of upstream and downstream respectively and γ unit weight of water.

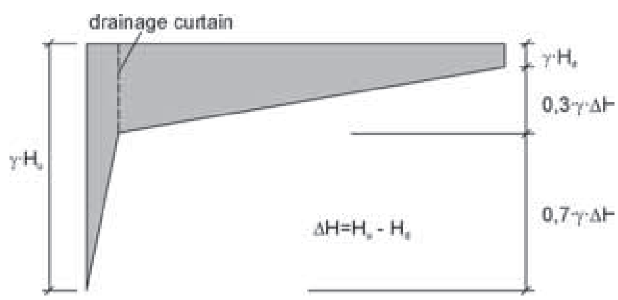

Figure 3. Cross section of design uplift pressure in the dam body.

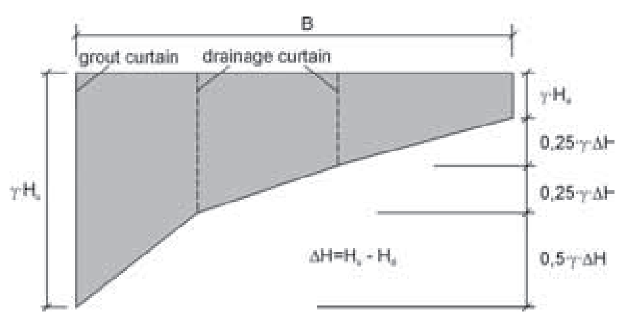

Figure 4. Cross section of design uplift pressure on the datum plane.

4.2 WATERTIGHT STRUCTURES ON THE DOWNSTREAM FACE

Due to the strong permeability of the lift surface on the downstream face of RCCDs, the location of the exit-flowing line may be very high and the leakage of seepage may be so great that it will endanger stability safety of the dam. A layer of distorted RCC with a thickness of 0.30~0.50 m will be arranged on the downstream face. Inside the distorted RCC layer, the seepage control treatment will be performed to the depth of 1 to 2 m of the lift surfaces below the water level of downstream; alternatively; 2-grade RCC can follow inside the distorted RCC layer.

4.3 DRAINAGE HOLES CURTAINS IN THE DAM BODY

Drainage holes are required both in a conventional dam and a RCC dam to discharge the seepage flow. The curtains of exit-flowing drainage holes will be arranged in the zone of 3-grade RCC following 2-grade RCC in the upstream region, in which the intervals of drainage holes are about 4 to 5 m. In the downstream region of a 2-grade RCC zone or within the RCC, treated by seepage control, a curtain of exit-flowing drainage holes can be also arranged, in which the interval between drainage holes is recommended to be 6 m. For a high dam with a wide datum plane, the curtains of overflowing drainage holes are needed on the datum plane near the upstream region.

4.4 BEDDING PLANE OF CONCRETE ON THE DATUM PLANE

Due to cracks generated frequently, difficulties in construction and more cement used in conventional concrete, the bedding plane built of conventional concrete has been replaced by bedding plane built with 2-grade RCC of the thickness of 0.5 m to play the role of providing flat and resisting water. The bedding plane and watertight structures together form a watertight structure.

4.5 WATERTIGHT STRUCTURES AND DRAINAGE MEASURES ON THE DATUM PLANE

Watertight structures and drainage measures are also required in the zones of the dam heel and the dam toe on the datum plane. Engineering practices have proved that curtain's relative watertightness just needs to be 3 times lower than of the surrounding rock masses. The grout curtain must be complete and the curtain drainage holes should be unblocked. The interval of drainage holes on the datum plane is 4 to 5 m, the same as in the dam body.

4.6 TRANSVERSE JOINT SEAL AND WATERTIGHT STRUCTURES ON SIDES OF JOINTS

Compared to conventional concrete dams, the RCCDs need better transverse joint seal because there are lift surfaces in RCCDs. In order to prevent water from infiltrating into the dam through the sides of the transverse joint, watertight structures on the sides of the joint are strongly required. This can be realized by a distorted concrete layer of a thickness between 0.3 and 0.5 m and should be connected very well with the bedding plane.

4.7 DESIGN PRINCIPLES FOR THE WATERTIGHT STRUCTURE AND DRAINAGE MEASURE

Briefly, the design principle of a watertight structure and the drainage measure is to resist in front and to drain at the back in the upstream region of the dam as well as in the zone of the dam toe in dam foundation, whilst in the downstream region of the dam the principle is to drain in front and to block at the back as well as in the zone of the dam heel in dam foundation. Here, to resist in front in the upstream region means to arrange a layer of distorted RCC and 2-grade RCC or the zone of lift surface and lift joint surface treated by seepage control method of the width of 2 to 3 m; and to drain at the back means to arrange the main curtain of drainage holes. To drain in front in the downstream region means to arrange the main curtain of drainage holes near the upstream, and to drain at the back means to arrange a layer of distorted RCC.

In the zone of the dam toe in dam foundation, to resist in front means to arrange the main grouting and the watertight curtain, and to drain at the back means to arrange the main curtain drainage holes behind the grouting and watertight curtain. In the zone of the dam heel in dam foundation, to drain in front means to arrange the curtain of drainage holes behind the watertight curtain near downstream, and to resist in the back means to arrange the watertight curtain near downstream.

In fact, the function of water-resisting of the watertight curtain and the function of drainage and pressure relief of the curtain of drainage holes are not independent. If there is only a watertight curtain and no curtain of drainage holes in dam foundation, the uplift pressure will be very high unless the permeability of the watertight curtain is very small, for example 2 orders of magnitude smaller than that of surrounding rock masses. This is difficult to perform in engineering practices. If there is only a curtain of drainage holes and no watertight curtain in dam foundation, though the uplift pressure can be greatly reduced, the rock masses in foundation may be destroyed by a great hydraulic gradient surrounding the drainage holes, which is absolutely irrational for the long-term safety of dam.

5 APPLICATION

5.1 STUDY ON THE ENTIRE SEEPAGE FIELD

We have taken the 6th segment of Guangzhao RCCD as a case study, which is located in the middle reaches of the Longtan River in the Guizhou province. On the face of upstream, there is a layer of distorted concrete of different thickness along the height, 0.8m above the elevation of 615.0 m and 1.0 m below the elevation of 615.0 m. The watertight structure in the upstream region is composed of a layer of distorted concrete and additional 2-grade RCC and 3-grade RCC, except for the zone above the elevation of 710.0 m, where there is a layer of distorted concrete and an additional 3-grade RCC. The depth of 2-grade RCC is in the range of 3 to 13m according to the water head on the face of upstream. There is a drainage curtain in the dam body, and the watertight curtain and the main drainage curtain are arranged in the zone of the dam toe because the water level in downstream is lower than the elevation of the datum plane. The normal water levels are 745.0 m and 583.5 m in the upstream and downstream, respectively. Empirical coefficients of permeability of various watertight materials in the dam, the watertight curtain in dam foundation and the grout curtain are shown in Table 1.

According to the seepage control methods proposed in this paper, Fig. 5 and Fig. 6 show the distributions of water head contour lines and uplift pressure head contour lines, respectively, in a short form.

The entire seepage field presents exact seepage property and obvious regularity, which indicates that the seepage control method proposed in this paper plays the role of

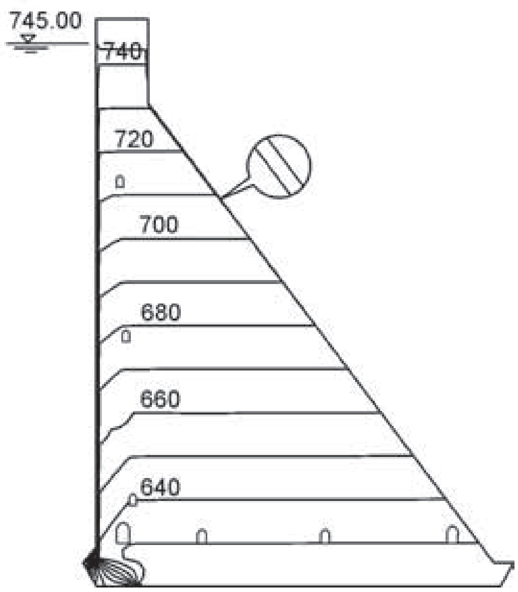

Figure 5. Water head contour lines.

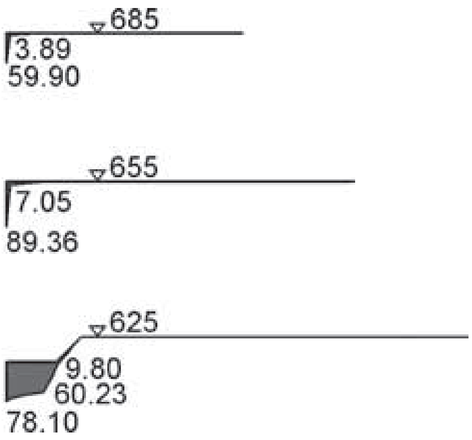

Figure 6. Uplift pressure head contour lines.

Table 1. Coefficients of permeability of body material and various watertight materials.

Type of concrete	Body coefficient of permeability (cm/s)	Normal coefficient of permeability of lift surface (cm/s)	Tangential coefficient of permeability of lift surface (cm/s)	notes
Conventional concrete	1×10^{-10}			anisotropic
Distorted concrete	1×10^{-9}			anisotropic
2 grade RCC	1×10^{-9}	1×10^{-9}	1×10^{-7}	
3 grade RCC	1×10^{-9}	1×10^{-9}	5×10^{-7}	
Watertight curtain	1×10^{-5}			isotropic
Consolidated grouting	1×10^{-4}			isotropic

resisting in front and draining at the back. In the dam body, the potential of high water head is mostly lost through the isotropic layer of distorted concrete. Though the coefficient of permeability of distorted concrete is the same as the normal major coefficient of permeability of 2-grade RCC and 3-grade RCC behind the layer of distorted concrete, it is watertight compared to the tangential major coefficient of permeability of 2-grade RCC, because the coefficient of permeability of layer of distorted concrete is 2 orders of magnitude smaller than the tangential major coefficient of permeability of 2-grade RCC. Contour lines in the layer of distorted concrete are probably parallel to the face of upstream. In the layer of distorted concrete above the datum plane about 1 m the potential of water head is reduced about over tens meters, in which the cracks always occur and quality of the layer of distorted concrete should be paid more attention. In the adjacent zone of 2-grade RCC and 3-grade RCC the contour lines have a distinctly horizontal kink towards downstream, which is caused by the fact that hydraulic gradients in 2-grade RCC and 3-grade RCC are much smaller than those in the layer of distorted concrete. Due to the easiness of seepage flow through 3-grade RCC, the quality of a watertight structure ahead 3-grade RCC should be paid more attention to ensure the safety of RCCDs.

Some seepage flow moves around the drainage holes, and it will exit from the face of downstream if there is no watertight structure arranged. Fig. 5 shows a layer of distorted concrete on the face of downstream shown in enlargement. Due to no resistance on this seepage flow in the lift surface and lift joint surface, the value of uplift pressure will be near zero. A drainage hole is another useful seepage control structure, by which almost all of the seepage flow is discharged. So, in order to ensure that the drainage hole performs successfully, the quality of the drainage hole should be paid more attention to the construction phase and the drainage hole should be checked regularly during the operation phase.

The uplift pressure contour lines at the elevation of 685.0 m, 655.0 m and 625.0 m are shown in Fig. 6. In these typical elevations, the uplift pressure is low, and the drainage curtain in the dam body, the grout curtain and the main drainage curtain in dam foundation play an important role for pressure relief.

Briefly, the seepage control methods proposed in this paper work very well. Different watertight structures play different roles and also depend on each other. From the results mentioned above we can see that the layer of distorted concrete and drainage holes play an important role of water-resisting and pressure relief. A big deal of discharge will be drained by the drainage holes. The uplift pressure will be very high if there are no drainage holes. From the distribution of uplift pressure on the datum plane, we can conclude that the grout curtain and the drainage curtain in dam foundation are very important for water-resisting.

5.2 SENSITIVITY ANALYSIS ON SEEPAGE CONTROL METHODS

5.2.1 Water-resisting function of 2-grade RCC

Fig. 7 shows the computed result when the 2-grade RCC on the face of upstream is removed on the basis of seepage control structures mentioned above, from which we can conclude that there are no obvious changes in the entire seepage field. We can so come to the same conclusions as those obtained by engineering practice. First, the water-resisting function of 2-grade RCC can be ignored. Second, the layer of distorted concrete on the face of upstream only works in the function of water resisting. Third, the arrangement of 2-grade RCC will make the construction more difficult, reduce the construction rate and make the advantages of RCCD fade away. Fig. 8 shows the distributions of uplift pressure heads, from which the same conclusions can be obtained.

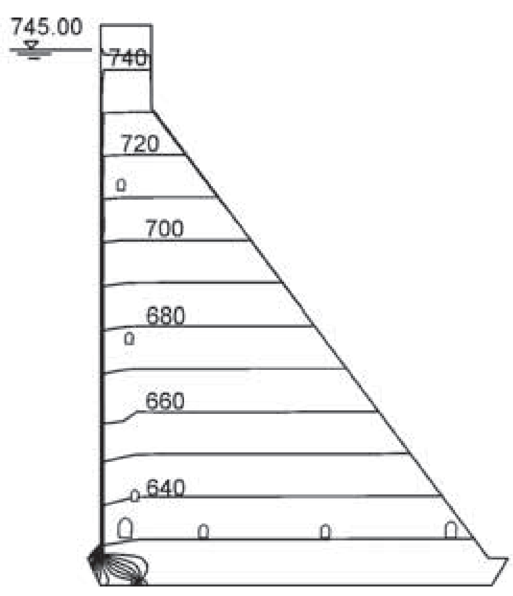

Figure 7. The contribution of hydraulic head contour lines in the dam body when 2-grade RCC is removed.

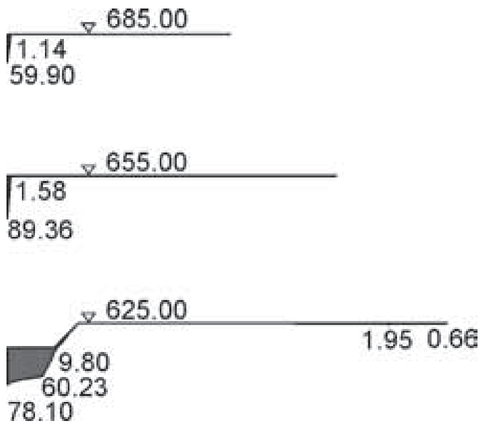

Figure 8. The distribution of uplift pressure head contour lines in different elevations when 2-grade RCC is removed.

5.2.2 The study of cracks in the Dam Body

Cracks in the dam body are of the key importance for the safety in hydraulic engineering. Figs. 9 and 10 show the computed results when there is a vertical cleavage crack in the layer of distorted concrete on the face of upstream. The width of this cleavage crack is 0.2 mm and it is located in the middle plane between two drainage holes. Figs. 11 and 12 show the computed results when there is a horizontal penetrating crack at intervals of 20 m only in the layer of distorted concrete on the face of upstream. The width of this horizontal penetrating crack is 0.1 mm.

When there is a vertical cleavage crack in the layer of distorted concrete on the face of upstream, the function of water-resisting of the layer of distorted concrete disappears and the main watertight structures are 2-grade RCC and drainage holes behind the layer of distorted concrete. The hydraulic head contour lines in 2-grade RCC are parallel to the face of upstream, and the uplift pressure head in the dam body is still small. But due to the anisotropic property of 2-grade RCC, the uplift pressure in 3-grade RCC is a somewhat higher compared to the distribution of uplift pressure shown in Fig. 6.

Fig. 11 shows the distribution of hydraulic head contour lines when there are several horizontal cracks on the face of upstream. The values of uplift pressure meet the demands desired. Except for the zones near the cracks, the influence of the cracks on the seepage field can be ignored. Under the watertight function of 2-grade RCC and drainage holes, the uplift pressure head contour lines are horizontal and small enough. Because there is a horizontal crack in the elevation of 685.0 m, the watertight function of the layer of distorted concrete vanishes, so the uplift pressure contour line is horizontal in the layer of distorted concrete.

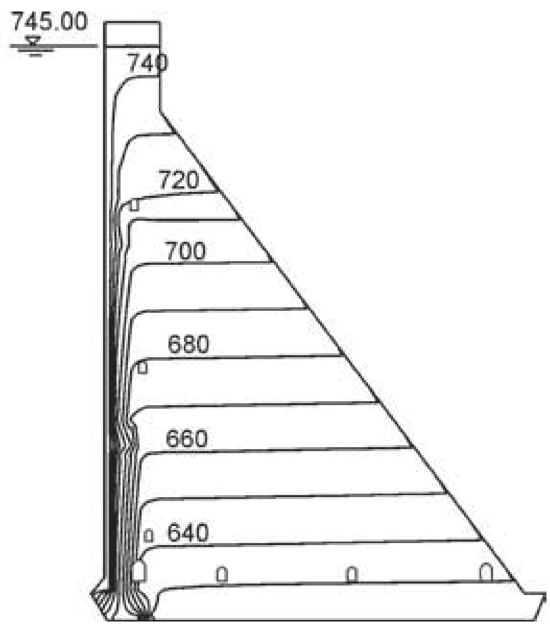

Figure 9. Distribution of hydraulic head contour lines when there is a vertical cleavage crack on the face of upstream.

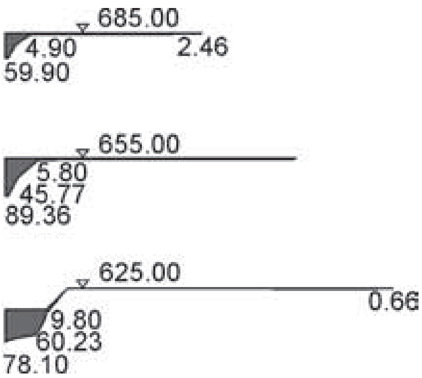

Figure 10. Distribution of uplift pressure head contour lines in different elevations when there is a vertical cleavage crack on the face of upstream.

Fig. 9 to 12 show the computed results which take into account of various adverse conditions. We can conclude that under the protection of other watertight structures there are no fatal uplift pressures in the seepage field, and the dam is in a temporary safe state. But we are all aware that the tendency of cleavage cracks and horizontal cracks is difficult to predict, so we have to pay more attention to the temperature control and cracks prevention measures, especially to the quality of the layer of distorted concrete.

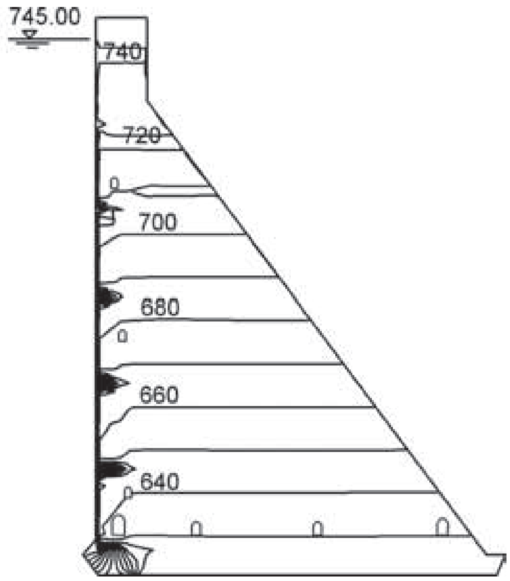

Figure 11. Distribution of hydraulic head contour lines when there is a horizontal penetrating crack at intervals of 20m in the layer of distorted concrete on the face of upstream.

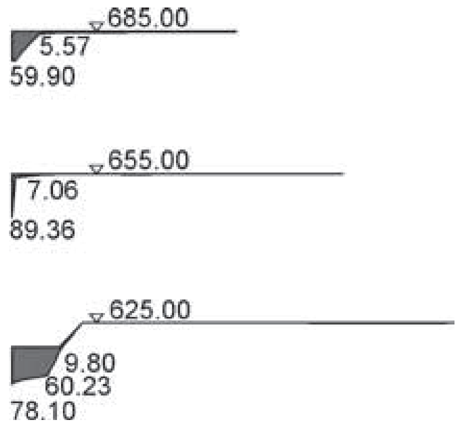

Figure 12. Distribution of uplift pressure head contour lines in different elevations when there is a horizontal penetrating crack at intervals of 20m in the layer of distorted concrete on the face of upstream.

6 CONCLUSIONS AND SUGGESTIONS

This paper generalizes the properties of seepage in RCC and RCCDs. Constructive suggestions of seepage control methods in various zones of the dam are proposed, and they have been applied to engineering practice. Because the RCC can be considered as inhomogeneous multi-laminated medium with strong anisotropy, the property of seepage of RCC are mainly depends on the property of the lift surface, in which the coefficient of permeability is 2 to 3 orders of magnitude higher than that of the RCC body. In construction stages the quality of the lift surface should be paid more attention.

Due to the anisotropy of RCC, the property of seepage of RCC is more difficult than that of conventional concrete. The design principles of watertight structures in RCCDs are to resist in front and drain at the back. On the face of upstream the arrangement of a watertight structure is strongly required, such as reinforced concrete slab, a conventional concrete slab and other forms. In present engineering practice the layer of distorted concrete and additional 2-grade RCC are recommended: the layer of distorted concrete plays the primary role in the watertight function, whilst 2-grade RCC plays the secondary role in the watertight function. In order to drain a small amount of seepage flow through watertight structures, drainage holes should be arranged behind the watertight structure in the upstream. In order to ensure that drainage hole play a permanent role in pressure relief, the diameter of a drainage hole should be greater and the distance between two drainage holes can reach 4 to 6m. In order to prevent the seepage flow from exiting too high on the face of downstream, a layer of distorted concrete is strongly required. The design of watertight control in the dam foundation is the same as that in conventional dam foundation, in which the grout curtain and main drainage curtain are absolutely needed. Based on the study of RCC for over ten years, the design of seepage control methods and the numerical model in RCCDs have been completely solved. The problem of temperature control and crack prevention is still to be researched in future.

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