Seepage Analysis of The Structure with Cracks Based on XFEM

Zhong-Yan Huo*,1, Guang-Xuan Qian2 and Dong-Jian Zheng3

1College of Port and Waterway Engineering, Zhejiang Ocean University, Zhoushan, Zhejiang, 316000, China
2Environmental Health Management Office of Dinghai District, Zhoushan, Zhejiang, 316000, China
3College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098, China

Abstract: For the difficulty of applying classical fracture criteria to the actual hydraulic engineering and simulating the process of cracking by conditional FEM, the XFEM is introduced into the analysis of the seepage field in hydraulic structures in this paper. Firstly, analyze the enriched forms of nodes in elements intersecting with cracks, and then build the enriched functions, which could either reflect the features of conductivity matrix within cracks, or satisfy the conditions of that osmotic pressure is continuous across the crack. Thus obtain the XFEM approximation form. Finally, combining with the initial conditions and boundary conditions, the discrete equations and workflow of XFEM for solving the seepage field is established. Case study shows that the method is reasonable and reliable.

Keywords: Crack, Seepage filed, XFEM, Enriched function.

1. INTRODUCTION

As the characteristics of the structure itself and its construction and operation environment, many hydraulic concrete structures run with cracks. Obviously, the existence of cracks is seriously undermined the integrity of a structure, having a significant impact on the structure itself and its morphology, and is not conducive to operate the structure safely. Therefore, monitoring and analyzing the deformation of cracks is one of the important contents for safety evaluation of a hydraulic concrete structure. Meantime, hydraulic concrete structures are always operated under the effect of Hydro-Mechanical (HM) interaction.

In this paper, based on analysis of the properties of hydraulic concrete structure, analysis and monitoring method of the security status of hydraulic concrete structure crack under the effect of HM interaction is studied by using extended finite element method (XFEM).

Infiltration of the reservoir water will change the distribution of the flow field in structures, thereby causing changes of its stress field, displacement field and the crack behavior. Conversely, the seepage boundary condition in cracks will change by the structural stresses and the geometry features of the cracks; thereby affecting the distribution of the permeability and the seepage pressure within cracks, and changing the seepage field of the crack area in structures. Therefore, in order to analyze the crack behavior of hydraulic concrete structures under the interaction of the seepage and water pressure, the changes of the seepage field, displacement field, and the interaction law between them should be studied at first.

Currently, the most versatile and mature mean solving the problems related to the fields of seepage and displacement is the FEM. However, for the structures with cracks, as the crack-size changes, it is necessary to mesh and remesh the discontinuity surfaces, thus increasing the computational costs and projection errors associated with conventional finite element methods. Recently, the development of the numerical analysis for solving discrete mechanics, such as XFEM, facilitates the building of the deformation monitoring methods for those with non-stable cracks.

The extended finite element method (XFEM), first introduced by U.S. Northwestern University Study Group headed by Prof.Belytschko [1], provides a convenient and effective way for problems with discontinuities. It models the discontinuity in a displacement field along the crack path, wherever this path may be located without respecting to the mesh. This flexibility enables the method to simulate crack growth without remeshing. XFEM has been developed rapidly and applied widely in only a few years [2-12]. Thus, the XFEM is a optimum method to study the dynamic expansion of cracks under the interaction of the seepage field and stress field. Considering that there is no precedent in solving seepage problems with this method, in order to analyze the interaction of the two fields under the framework of XFEM, one should first study the XFEM approximation and solving method of the seepage field. Therefore, the XFEM is introduced to stable seepage analysis in the structures with cracks. According to the characteristics of seepage field with cracks, the XFEM approximation form

*Address correspondence to this author at the Changzhou Road, Zhoushan, Zhejiang, China. Postcard: 316000; Tel: + 86 188570931601; E-mail: hhuhzy@yahoo.com
and discrete equations of the seepage field is studied by analyzing the basic theory of seepage and building the enriched functions of crack related elements, and finally, the XFEM for solving the seepage field is established.

2. MATERIALS AND METHODOLOGY

2.1. The Extended Finite Element Discretization

The basic idea of XFEM is to make the crack path been located without any respect to the mesh by using some additional function to improve classical FEM. XFEM models the discontinuity in a displacement field along the crack path by incorporating some local enrichment functions into the classical finite element approximation. The displacement field approximation can be expressed as [3]:

\[ \mathbf{u}_r = \mathbf{N} \mathbf{u} + N(H - H(x))\mathbf{a} + N(\phi - \phi(x))\mathbf{b} \]  

(1)

Where, \( N \) is the array of shape functions; \( \mathbf{u}, \mathbf{a} \) and \( \mathbf{b} \) represent the vectors of displacement and enriched variables related to nodes. \( H \) involves the Heaviside function, and \( \phi \) is used to model the displacement field around the tip of the discontinuity.

According to the westergaard base of asymptotic crack-tip field in the linear elastic fracture mechanics, \( \phi \) is taken as:

\[ \phi = \left[ \phi_1, \phi_2, \phi_3, \phi_4 \right] = \\
\left[ \sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2}, \sqrt{r} \sin \frac{\theta}{2} \sin \theta, \sqrt{r} \cos \frac{\theta}{2} \sin \theta \right] \]

(2)

Because the displacement field nearing crack-tip for cohesive cracks no longer has the singularity, and according to the asymptotic analysis [13-14] of the mechanical fields in a cohesive zone for very large structure, then \( \phi \) is taken as:

\[ \phi = \left[ r \sin \frac{\theta}{2} \right] \]

(3)

Where \((r, \theta)\) is the local polar coordinates at the tip.

2.2. Solving the Seepage Field with XFEM

It is different that using XFEM to solve the seepage field in the structures with cracks to that of discontinuous displacement field. The key to the problem is how to describe the characteristics of conductivity coefficient matrix within cracks effectively and reasonably, and then construct the enriched functions of crack related elements. The functions should either allow the osmotic pressure to be continuous, or make flow balancing at nodes. Because although the distribution of seepage water-head is continuous, while the conductivity coefficient matrix within its cracks are different from the rest of the structure, which reflects the impact of cracks on the seepage field. Therefore, the enriched functions of crack related elements should be studied first, and then the XFEM approximation and discrete equations of the seepage filed be finally built.

2.2.1. Enriched Functions

Similar to the method for describing the displacement field by XFEM, the level set method (LSM) is also used to simulate the seepage field of structures with cracks, and it is used to select the enriched nodes. There are two forms of enriched node, namely split-element enriched node and tip-element enriched node. Once the mesh generation are the same in the two fields, then the enriched nodes are exactly the same, which make the analysis on the interaction of seepage, stress and deformation to be easier. Despite the above similarities, the enriched functions should be different in seepage field and displacement field. As the water-head, unlike the crack deformation, will not discontinuous for the existence of cracks, so the enriched nodes adopted in the seepage field should be separately studied in detail. It is specifically described in two cases as follows.

(1) Enriched Nodes in Split-Element

LSM is adopted to track the crack interface, whose change is expressed as the equation of function \( \phi(x,t) \). And the dimension of \( \phi(x,t) \) is higher one dimension than that of the crack interface. Mobile interface \( \gamma(t) \subset R^2 \) could be assumed as the LSM curve: \( R^2 \times R \rightarrow R \), where:

\[ \gamma(t) = \left\{ x \in R^2 : \phi(x,t) = 0 \right\} \]  

(4)

The movement of \( \gamma(t) \) could be obtained by the evolution equation of \( \phi [15] :\)

\[ \begin{cases} \phi + F \| \nabla \phi \| = 0 \\ \phi(x,0) \text{ is given} \end{cases} \]  

(5)

Where, \( F \) is the speed in normal direction of the point \( x \in \gamma(t) \) outside the interface.

Define LS \( \varphi \) as the signed distance function, and LS zero describe the crack interface.

\[ \varphi(x,t) = \pm \min_{s \in \gamma(t)} \left\| x - x_s \right\| \]

(6)

When the point \( x \) is above the crack \( \gamma(t) \), and the sign is taken positive; otherwise, it is taken negative.

The water-head enriched function \( \psi^w(\phi) \) in split element should be the function of the LS \( \phi(x,t) \). Considering that water-head is continuous within the crack, \( \psi^w(\phi) = |\phi| = \left| \sum_i N_i(x)\phi_i \right| \) is first proposed. However, the enriched function only exists in the enriched-node domain of support, that is, only the functional values of one-layer elements in both sides of the crack related elements should be calculated, but the function exists in the whole solving domain. In order to meet the above requirements and to improve the convergence rate, some optimization and adjustment should be conducted on this function. The adjustment strategy is as follows: define \( M \) as enriched node set, and define \( \phi_i \) as the value of LS function at each enriched node, and assume \( \psi^w(\phi) = \phi_i \). The sets enriched node near
split element are defined as $M_w = \{n_{p+1}, n_{p+2}, \ldots, n_q\}$, where the nodes are arranged in ascending order by node value, and its LS value is taken as initial value. Thus, the optimization algorithm of enriched function of nodes in $M_w$ is as follows:

For $J = p+1, q$

Build the set $G_J = \{\text{nod}_i \in M_w : |\mathbf{n}_i| < |\mathbf{n}_{\text{nod}}|\}$,

Where the node $\text{nod}_i$ and $\text{nod}_j$ have the same element edge; $\psi_J(\mathbf{n})$ is solved by minimizing the following equation:

$$\min \sum_{\text{nod}_i \in M_J} \left(\frac{\psi_J - \phi}{d_{ij}}\right)^2,$$

where $d_{ij}$ is the distance between node $I$ and $J$.

End for

The result of solving the problem of the minimum value is expressed as follows:

$$\psi_J = \sum_{\text{nod}_i \in M_J} \alpha_i \phi_i, \alpha_i = \sum_{\text{nod}_i \in M_J} \frac{1/L_i^2}{L_i^2},$$

(7)

Known from the above derivation, The desired enriched function should be expressed as:

$$\psi(\phi) = \psi_J = \left[\sum_{J} N_j(x)\psi_j\right]$$

(8)

Referring to the definition of displacement field enhanced mode $\mathbf{u}^{\text{enr}} = \sum_{J} \alpha_i N_j(x)(\psi(x) - \psi(x)_j)$; define the enriched function of enriched nodes in seepage field as [15]:

$$\psi^\text{enr}(X) = \sum_{J} \theta_j N_j(x) - \sum_{J} \theta_j N_j(x)$$

(9)

One-dimensional schematic of the above enriched functions $\psi^0(\phi)$, $\psi^1(\phi)$ and $\psi^2(X)$ is as Fig. (1), where the convergence rate of $\psi^2(x)$ is highest and close to the optimum convergence rate of the FEM. There is a ridge at the position of crack within the two-dimensional schematics of $\psi^2(x)$ (Fig. (2) and Fig. (3)). The value of function $\psi^2(x)$ is zero within the elements do not contain cracks.

Fig. (1). Several choices for the enrichment function.

Fig. (2). Enrichment function $\psi^2(x)$.

Fig. (3). Enrichment function $\psi^2(x)$.

(2) Enriched Nodes in Tip-element

If the crack terminates within element, and the above enriched function is used, then the crack tip will be treated as extending to the edge of element, so that the result will no longer accurate. While there is a tip enriched function, selecting the analytic solution of asymptotic crack-tip field as enriched function, could ensure that the crack terminates exactly within the element. The main items of asymptotic expansion of the water-head and flow velocity are as follows:

$$H = -\frac{K_n}{k} \sqrt{\frac{\pi}{2}} \cos \left(\frac{\theta}{2}\right), v = -\frac{K_n}{\sqrt{2\pi} r} \left(\cos \left(\frac{\theta}{2}\right)\right)$$

(10)

According to the above expansion items, second item of the formula (2) should be used as the enriched function of crack tip: $\varphi = \sqrt{\frac{\pi}{2}} \cos \left(\frac{\theta}{2}\right)$. Since the value of LS at the crack interface is zero, it has no effect on the situation that crack is set as boundary.

In summary, the XFEM approximation of seepage field can be expressed as follows:
The governing equation of steady seepage field of cracked structure should be given first. Assume the fluid is incompressible and of no endogenous. There is a seepage field in the two-dimensional plane (Shown in Fig. (4)).

\[
H^i(x) = \sum_{i=1}^{N_e} N_i(x)H_i + \sum_{j=1}^{N_e} N_j(\phi(x) - \phi) e_j + \sum_{k=1}^{N_k} N_k(x)(\phi(x) - \phi_k) f_k
\]

Where, \( x \) is the coordinate vector of point, \( N_i(x) \) \( i \) \( j \) \( k \) \( m \) \( p \) \( \phi \) \( \phi_k \) \( f_k \) \( e_j \) \( e \) \( \phi \) \( \text{shape function} \) \( \text{node ID} \) \( \text{node ID} \) \( \text{DOF} \). The equation of \( H(x,z) = f(x,z) \) should be satisfied at the boundary of \( \Gamma_1 \) and \( \Gamma_2 \); meantime, the equation of

\[
k_x \frac{\partial H}{\partial x} \cos(n,x) + k_y \frac{\partial H}{\partial y} \cos(n,y) = q
\]

should be satisfied at the boundary of \( \Gamma_2 \), where \( n \) is the normal direction of the overflow section. The value of \( q \) is determined in iterative process. The equation of \( \frac{\partial H}{\partial n} = 0 \) should be satisfied at the boundary of \( \Gamma_3 \) and \( \Gamma_4 \), where \( n \) is the outer normal direction of the boundary. Water level on both sides of the crack surface \( \Gamma_c \) should be continuous.

Define \( H \) as water-head function, \( k_x \) \( k_y \) and \( k_z \) are respectively the permeability coefficients in the direction of \( x \) \( y \) \( z \). Then the basic equation to be satisfied for three-dimensional seepage field:

\[
k_x \frac{\partial^2 H}{\partial x^2} + k_y \frac{\partial^2 H}{\partial y^2} + k_z \frac{\partial^2 H}{\partial z^2} = 0
\]

For two-dimensional planar seepage field in Fig. (4), the following formula should be conformed:

\[
k_x \frac{\partial^2 H}{\partial x^2} + k_z \frac{\partial^2 H}{\partial z^2} = 0
\]

Combining with the boundary conditions, use the functional theory to solve the equation (13), the result is available:

\[
I(H) = \frac{1}{2} \int_{\Delta R} \left[ k_x \left( \frac{\partial H}{\partial x} \right)^2 + k_z \left( \frac{\partial H}{\partial z} \right)^2 \right] dxdz - \int qHd\Gamma
\]

By dividing the solving domain into finite elements, then function \( I(H) \) will be the integral sum of all elements:

\[
I = \sum I^e
\]

Where, \( I^e \) is the function of element \( e \) in the solving sub-region \( \Delta R \), can be expressed as:

\[
I^e = \frac{1}{2} \int_{\Delta R} \left[ k_x \left( \frac{\partial H}{\partial x} \right)^2 + k_z \left( \frac{\partial H}{\partial z} \right)^2 \right] dxdz - \int qHd\Gamma
\]

The XFEM discrete equation could be deduced from equation (16) in details as follows: assume the node IDs of elements in equation (11) are respectively \( i \) \( j \) \( m \) \( \ldots \) \( p \). Conventional water-head DOFs of each node are defined as

\[
[H] = [H_1,H_2,H_3 \ldots ,H_p]^T
\]

Enriched water heads of split elements are respectively \( [e] = [e_1,e_2,\ldots ,e_g]^T \), and the enriched water heads of split elements are respectively

\[
[f] = [f_1,f_2,\ldots ,f_p]^T
\]

Meantime, the equation of

\[
\int qHd\Gamma = Q
\]

should be satisfied, it means that the nodal flow is equivalent, and takes zero to all internal nodes and
boundary nodes of no flow. For two-dimensional seepage flow, $H^e(x, z)$ represents the water-head of any point in sub-region of elements. Then $H^e(x, z)$ is available by interpolating the water head of each node:

$$H^e(x, z) = N_i H_i + N_j H_j + N_m H_m + \ldots + N_p H_p$$

$$+ N \psi e_i + N \psi e_j + N_m \psi e_m + \ldots + N_p \psi e_p$$

$$+ N \varphi e_i + N \varphi f_j + N_m \varphi f_m + \ldots + N_p \varphi f_p$$

Where, $N_i, N_j, N_m, \ldots, N_p$ are the conditional shape functions of element nodes. $\psi, \psi, \varphi, \ldots, \varphi$ represent the values of enriched functions of the nodes in split elements. And $\varphi_i, \varphi_j, \varphi_m, \ldots, \varphi_p$ are the values of enriched functions of the nodes in tip elements.

The integral terms in formula (16) should be differentiated to any DOF while deriving the discrete equations. And the differentiator to $H_i$ is taken as example as follows:

$$\frac{\partial l^e}{\partial H_i} = \int \left[ k_e \frac{\partial H}{\partial x} \frac{\partial (\partial H)}{\partial x} + k_e \frac{\partial H}{\partial z} \frac{\partial (\partial H)}{\partial z} \right] dxdz$$

$$- \int q \frac{\partial H}{\partial t} d\Gamma$$

$$\frac{\partial H}{\partial x} = \frac{\partial N_i}{\partial x} H_i + \frac{\partial N_j}{\partial x} H_j + \frac{\partial N_m}{\partial x} H_m + \ldots + \frac{\partial N_p}{\partial x} H_p +$$

$$\frac{\partial (N \psi e_i)}{\partial x} e_i + \frac{\partial (N \psi e_j)}{\partial x} e_j + \frac{\partial (N \psi e_m)}{\partial x} e_m + \ldots + \frac{\partial (N \psi e_p)}{\partial x} e_p +$$

$$\frac{\partial (N \varphi e_i)}{\partial x} f_j + \frac{\partial (N \varphi e_m)}{\partial x} f_m + \ldots + \frac{\partial (N \varphi e_p)}{\partial x} f_p$$

$$\frac{\partial H}{\partial H_i} = \frac{\partial N_i}{\partial x} = N_i$$

$$\vdots$$

$$\frac{\partial H}{\partial \varphi_i} = \frac{\partial (N \varphi e_i)}{\partial x} = N_i \varphi_i$$

Substitute the formula (18) into formula (19):

$$\frac{\partial l^e}{\partial H_i} \frac{\partial \varphi}{\partial t} = \frac{\partial l^e}{\partial \varphi}$$

$$\frac{\partial H}{\partial t} \frac{\partial \varphi}{\partial e_i} = \frac{\partial \varphi}{\partial (\varphi e_i)}$$

$$\frac{\partial H}{\partial t} \frac{\partial \varphi}{\partial f_j} = \frac{\partial \varphi}{\partial (\varphi f_j)}$$

$$= \left[ k^e \right] \left[ \{H\}^T \{e\}^T \{f\}^T \right]^T = \{Q\}^e = 0$$

Where $\{Q\}^e$ is the flow matrix of element, and $[k^e]$ is the conduction matrix of element. According to the formula (18), $k^e_{ij}$ and $Q^e_{ij}$ could be respectively calculated as follows:

$$k^e_{ij} = \int_{\Delta x} B_i^e \left(B_i^e\right)^T d\Omega \cdot (r, s = H, e, f)$$

$$Q^e_{ij} = \int_{\Delta x} B_i^e \{N\} \cdot (q) d\Gamma$$

Where,

$$B_i^H = \left[ \frac{\partial N_i}{\partial x} \frac{\partial N_i}{\partial z} \right], \quad B_i^e = \left[ \frac{\partial (N \varphi e_i)}{\partial x} \frac{\partial (N \varphi e_i)}{\partial z} \right] \ldots$$

represents permeation coefficient matrix.

There are some descriptions for $S_{rs}$ are as follows:

(1) Permeability coefficient matrices in the elements without intersecting with cracks are consistent with that of the conventional FEM. (2) In the elements intersecting with cracks, the permeability coefficient matrices includes two parts: permeability coefficient of the element and that of the crack. the former is consistent with that of the conventional FEM. while in the latter condition, the cracks are treated as medium, and the permeability coefficient is solved by the width of the cracks; and then the permeability coefficient should be converted from the spindle direction within cracks into the global coordinate system. The former is calculated as follows

$$S_{rs} = \begin{bmatrix} k_e & 0 & 0 \\ 0 & k_e & 0 \\ 0 & 0 & k_c \end{bmatrix} M_{rs} \begin{bmatrix} k_i & 0 & 0 \\ 0 & k_j & 0 \\ 0 & 0 & k_k \end{bmatrix}$$

$M_{rs}$ is the transformation matrix that converting the local coordinate system into the global coordinate system. As to the $S_{rs}$ in formula (21), it means permeability coefficient within cracks, while $r, s$ represent the enriched DOFs $e$ or $f$. If any one of the $r, s$ is taken as the conventional DOF, then the $S_{rs}$ is consistent with that of the continuous part of the structure. Thus, in the elements intersecting with cracks, the influence of crack is contained within the permeability coefficient matrix.

By integrating the results of all elements, the equations in solving region could be obtained:

$$\frac{\partial H}{\partial t} \{H\}^T \{e\}^T \{f\}^T = \left[ k \right] \{H\} - \{Q\} = 0$$

Where, $\{H\}$ is the water-head matix of all nodes INCLUDING the enriched nodes. $[k]$ is the total permeability coefficient
matrix, where the factor \( k_i \) could be integrated by the \( k_i^0 \) of each element related to node \( i \). \( \{Q\} \) is the flow array of nodes, and the water head of any point within elements could be calculated from formula (17).

2.2.3. Solving Steps for Seepage Field by XFEM

Solving seepage problems of free surface section is related to the procession of the elements intersected by infiltration line. In this study, initial flow method is adopted to determine the position of the free surface, and this constant mesh method is effective to solve the seepage problem of free surface. The basic idea is that the free surface is divided into two sub-domains by the infiltration line, and the two parts have no flow exchange, which could be basically achieved by adjusting the initial flow normal to the free surface.

For the initial flow method, the FEM equation [16] of the whole region could be expressed as:

\[
[k] \{H\} = \{Q\} + \{Q_0\} \tag{24}
\]

Where, \( [k] \) and \( \{Q\} \) are respectively the total penetration matrix and equivalent nodal flow matrix. \( \{Q_0\} \) is the nodal flow matrix caused by the increasing initial flow, its expression is:

\[
\{Q_0\} = \sum_e \left( [A]^T \right)^T \int_{e} [B] [k] [B]^T d\Omega \cdot H^e \tag{25}
\]

Where, \( F \) is a discontinuous function, and the values of \( F \) in unsaturated zone and saturated zone are respectively taken 0 and 1. \( [A]^T \) is the selection matrix for integrally assembling. \( [k] \) and \( [B] \) have the same means as formula (21).

Combined with the initial flow method, the solving steps for seepage field by XFEM is as follows:

1. Meshing for XFEM, calculating the water head of all nodes by the formula (17).

2. At first, according to the relationship between water head \( h \) and \( z \), determing the value \( F_i \) of each node, then the value of each Gauss integration point within element could be gotten by: \( F_i = \sum_i N_i F_i \). Secondly, by the convergence criteria, judging whether the difference \( \{\Delta H\} \) between the results of the adjacent two iterations is zero. If it is zero, then end computing; else, turning to the next step.

3. defining \( \{Q_0\}^n \) as the increment of water head at the right of the equation:

\[
[k] \{\Delta H\}^n = \{Q_0\}^n, \{\Delta H\}^{n+1} = \{H\}^n + \{\Delta H\}^n \tag{26}
\]

4. returning to the step (2), and keeping the iteration, until \( \{\Delta H\} \) meet the convergence conditions, then the results of each node are the desired water heads. Note that, the convergence criteria is: \( \max \|\{\Delta H\}\|^2 \leq \varepsilon \).

3. RESULTS

A typical sectional view of the non-overflow section of a concrete gravity dam is shown in Fig. (5). its crest width and height are respectively 10m and 65m. The width and elevation of the dam bottom are respectively 53m and 65m. The downstream slope is 1:0.7, and the impermeable curtain is below the surface 32m in-depth. The upstream water level is 112m, and the downstream water level is 68.5m. To simplify the analysis, the impact of the dam drainage is not considered here.

![Fig. (5). Typical profile of a gravity dam.](image)

Build the XFEM model of the dam section at first. And then calculate the seepage field under the action of 112 m water level respectively in the conditions that the dam section has upstream horizontal fracture and has no crack. Permeability coefficient of the dam is taken \( 8.0 \times 10^{-9} \) m/s, and that of the curtain and foundation are \( 5.0 \times 10^{-8} \) m/s and \( 1.5 \times 10^{-7} \) m/s. Assume that there is a horizontal construction, and it is 10m length. The average width and initial permeability coefficient are respectively 0.2mm and \( 1.0 \times 10^{-3} \) m/s (referring to the layer value of the RCC dam). XFEM model of the section is totally arranged 1240 nodes and 1159 elements, and the seepage water level distribution obtained are respectively as Fig. (6) and Fig.(7).

As shown in Fig. (6) and Fig. (7), the existence of crack has a great impact on the seepage field near the crack area, and the gradient of the water permeability within the crack is small, which is consistent with the actual situation. Thus, the
problem of different meshes could be avoided in dealing with the coupling problems. The computing efficiency also could be improved. For the hydraulic structures with crack, the XFEM of solving crack propagation problem has great potential. In this paper, only the method of solving seepage field by XFEM is proposed, but how to apply it to the analysis of crack extension needs further study.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

The Special Fund Support of Open Research Foundation of Chinese Yangtze River Scientific Institute (Grant Nos. CKWV2014215/KY) is gratefully acknowledged.

REFERENCES


Received: September 17, 2014  Revised: December 17, 2014  Accepted: December 23, 2014

© Huo et al.; Licensee Bentham Open.

This is an open access article licensed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/) which permits unrestricted, non-commercial use, distribution and reproduction in any medium, provided the work is properly cited.