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Simulation of flow through dam foundation by isogeometric method

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ABSTRACT

This research introduces a numerical approach called IsoGeometric Analysis (IGA) to solve the Laplace equation. Non-Uniform Rational B-Splines (NURBS) basis function is applied for approximation of the anisotropic saturated porous media of dam foundation field, as for description of the geometry. The discretized form of the governing Laplace equation is obtained using the standard Galerkin method. The present results consist of uplift pressure, seepage discharge and exit gradient which are validated with existing experimental data based on a physical model. The obtained data are also compared with empirical data. The computed results show a satisfactory agreement with the experimental measurements in the wide ranges of upstream flow conditions. In addition, it was found that the mentioned numerical method improves the convergency and accuracy of parameters compared to traditional methods.

1. Introduction

Dams usually are built on permeable foundations. Seepage through the dam foundation occurs due to the difference in water levels between the upstream and downstream sides and its effects on permeable foundations include the uplift force, seepage discharge and exit gradient. The uplift force reduces the shear resistance between the dam and its foundation. In addition, this process can provide strain, tension and finally decreasing safety factor against sliding or overturning of the dam structure. The exit gradient is the main design criterion in determining the safety of hydraulic structures against the piping phenomenon. Bligh (1910) introduced the creep length theory of the flow passing under hydraulic structures. He defined the creep length as the route of the first line of seepage which is in contact with the dam foundation. Also, Bligh stated that hydraulic gradient is constant along the creep line and energy loss along this path varies linearly with creep length. Thus, uplift pressure distribution is linear under the dam foundation [1,2].

Lane (1935) investigated the exit gradient for more than 200 damaged hydraulic structures and reported that there is a difference between horizontal and vertical creep paths. Consequently, he presented weighted creep theory in which coefficients of 0.33 and 1.0 for total horizontal and vertical percolation lengths were assigned, respectively (Fig. 1). Therefore, according to Lane's weighted creep theory, the equivalent creep length is defined in form of [2]:

$$L_{eq} = \frac{1}{3}\sum L_H + \sum L_V \tag{1}$$

in which L_{eq} is the total equivalent length, $\sum L_H$ is the total horizontal percolation length (walls with slope less than 45°) and $\sum L_V$ is the total vertical percolation length (walls with slope more than 45°). According to the Bligh's method, the uplift pressure distribution under the dam foundation is linear. To prevent undermining phenomenon at downstream toe of the structure, the available exit gradient (i_x) should be less than the allowable exit gradient (C) in following term:

$$i_x = \frac{\Delta h}{L_{eq}} \le C \rightarrow \frac{L_{eq}}{\Delta h} \ge \frac{1}{C} \Rightarrow L_{eq} \ge \frac{\Delta h}{C} \tag{2}$$

where Δh is difference between upstream and downstream heads:

Khosla et al. (1936) presented a method to estimate the distribution of uplift pressure under foundations through solving complex potential functions. They investigated the flow network under a hydraulic structure which was constructed on a permeable foundation. Khosla assumed that flow and potential lines are concentric ellipses and hyperbolic, respectively. Considering no

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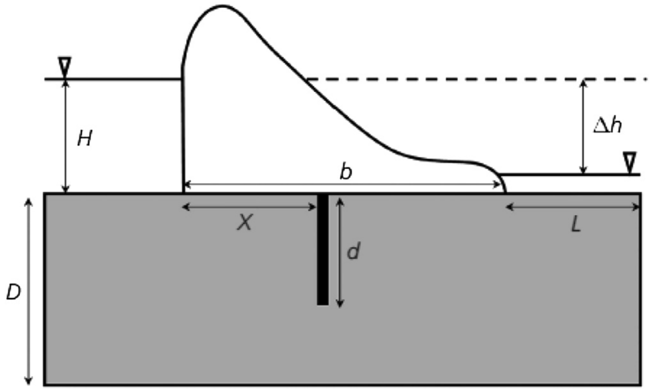

Fig. 1. A schematic definition for characterization of parameters in creep theory (Tokaldani and Shayan, 2012).

cutoff wall, the relationship of Khosla to estimate the uplift pressure distribution along the floor is [2,4].

$$P = \frac{H\,\gamma_w}{\pi}\cos^{-1}\frac{2x}{b} \quad \text{for } -\frac{b}{2} \le x \le \frac{b}{2} \tag{3}$$

and the exit gradient as:

$$i_{exit} = \frac{H}{\pi d\sqrt{Y}} \tag{4}$$

Here, H is upstream head and the parameters $Y = 1 + \sqrt{1+\alpha^2}/2$ and $\alpha = b/d$ varied by the length of foundation (b) and the length of cutoff wall(d) [2].

Fig. 2 illustrates the uplift distribution predicted by Bligh and Khosla theories. Although the theory of Khosla is generally more reliable than the creep theories of Bligh and Lane, in cases dealing with a compound foundation it is required to solve very complicated equations and also has a low accuracy when applied to anisotropic foundations [3].

The other methods for estimation of the uplift pressure under hydraulic structures are suggested based on solving the governing equations on problem condition. During the past century, various efforts were conducted to develop numerical modeling using the Darcy law and Richard equation. In a case study, Abedi Koupaei (1991) predicted the distribution of uplift pressure using the finite difference method [5].

In the recent decades, due to the high complexity of flow in porous media and in most cases, all domains of porous media were considered as a control system to be possible measuring the different hydraulic parameters between the particles. In this way, several investigators proposed the empirical relationships between hydraulic gradient and flux rate based on experimental data sets [6–10].

Also, due to the essential needs for investigations of 2D-(or 3D) dimensional problems and limitations of previous empirical models, applications of improved models have been studied by few researchers [11,12]. The IGA is a recently developed computational approach that offers the possibility of integrating finite element analysis (FEA) into conventional NURBS-based Computer Aided Design (CAD) tools. The IGA-based approaches have constantly developed and shown many great advantages on solving many different problems in a wide range of research areas such as fluid–structure interaction, shells, structural analysis and so on [14–18]. The concept of the IGA in mechanic problems is pioneered by Hughes and his co-workers as a novel technique for the discretization of partial differential equations [13]. Within recent years, the IGA has been applied to various flow problems and proved its value within the field of fluid mechanics. The first studies were in field of steady-state incompressible Stokes flow in the benchmarking lid-driven square cavity [14]. Subsequent analysis of the full time dependent Navier-Stokes equations using the IGA has shown its advantages for both variables continuity and complicated dynamic flow domains [15,16]. The basic idea of the IGA method is to utilize the basis functions that are able to model geometries exactly from the CAD points of view for numerical simulations of physical phenomena. It can be achieved using the B-splines or Non Uniform Rational B-splines (NURBS) for the geometrical description and invoke the isoparametric concepts to define the unknown field variables. The IGA-based approaches have constantly developed and shown several important advantages in solving different problems such as fluid-structure interaction, shells, and structural analysis [17–20]. Imposing essential boundary conditions in time dependent problems are applied in IGA with Hughes et al. [21].

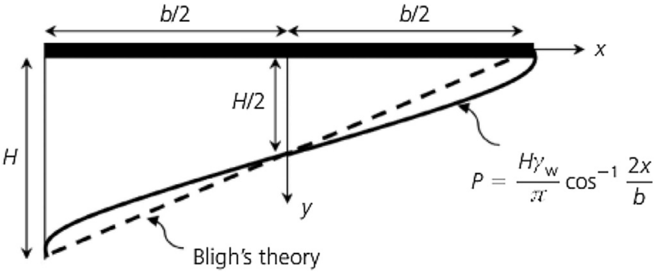

Fig. 2. Comparison of uplift distribution according to the Bligh and Khosla et al. Theories (Tokaldani and Shayan, 2012).

In this paper, the numerical algorithm based on the IGA has been used to estimate the solution of the Laplace equation in anisotropic porous media. The results of the numerical model was compared with those obtained using the physical model based on experimental conditions and traditional methods.

2. Specifications of experimental model

In this study, data reported from experimental set up were applied to validate the proposed numerical model. The experiments were carried out in a flume with a length of 1.70 m and width of 0.18 m. The flume was located in the Hydraulic Laboratory of the Department of Irrigation and Reclamation Engineering, University of Tehran. To obtain hydraulic parameters and also the accuracy and the convergency of the proposed method, the experimental set consisted of an upstream impervious bed, an impervious wall as a dam body, various cutoff walls and a piezometric network. A schematic sketch of physical model was illustrated in Fig. 3. The length of cutoff walls varied from 2.5 cm to 30 cm and were located in different positions beginning from 40 cm upstream to 115 cm downstream from the impervious wall. The upstream head water was taken from 2.5 cm to 20 cm and the upstream water level was fixed by using a floating body. The downstream water level was set to zero. Distribution of uplift pressure was measured by the piezometric network, which consisted of 39 piezometers (13 rows with each row including 3 piezometers, Fig. 3) [3].

To prevent uncontrolled piping, a gravel filter ($D_{50} = 2$ mm) was dumped in both upstream and downstream beds. Beach sand, classified as the most unsuitable type of soil from the point of view of stability of hydraulic structures, was selected as pervious bed material. The hydraulic conductivity of the soil was measured using