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Numerical analysis of rubber dams using fluid–structure interactions

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ABSTRACT

Rubber dams are flexible cylindrical inflatable structures attached to a rigid base and inflated by air and/or water. Due to elasticity of the structure and continuous variation of its shape during operation, a rubber dam structural and hydraulic analysis is more complicated than a rigid dam.

This paper deals with numerical analysis of the rubber dams for solving the flow based problem and static and dynamic structural analysis, simultaneously. The three dimensional fluid–structure interactions are analyzed both under the stationary hydrostatic and overflow conditions, based on different internal pressures, and upstream and downstream water depths. The water free-surface was obtained based on two-phase air–water flow interface. The flow separation downstream of the dam was modeled using shear stress transport turbulence model. The results describing height, cross-sectional profile and cross-sectional area of the dams were compared with these of former studies and good agreement was obtained. Altogether, the fluid–structure interaction analysis provides two new correlations to predict the equilibrium height of the rubber dam and its discharge coefficient based on the dam equilibrium height and the total upstream head. It was found that the rubber dam equilibrium height is a function of its thickness, modulus of elasticity, internal pressure and foot width.

1. Introduction

The interest in rubber dams is increasing because of the ease of placement, construction and operation. They are used for various purposes such as diverting water for irrigation, flood control, tidal defense, recreational purposes, preventing contamination, and raising the height of existing dams to increase reservoir capacity [1]. They could be deflated when not needed, and then inflated when flooding is imminent. However, this requires some research to predict the hydraulic characteristics of the structure based on fluid–structure interaction which is the objective of the present study. Rubber dams are relatively easy to install, do not corrode, require little maintenance, and can handle extreme temperatures. This type of structure is considered as more economical compared with the rigid types of control structures constructed from concrete, masonry, and steel (Anwar [2], Tam [3] and Zhang et al. [4]). The cross sectional configuration of a rubber dam is depicted in Fig. 1. Where h_u and h_d are the up- and downstream water depths, D_h is the equilibrium dam height, B is the dam foot width, P is the air and/or water internal pressure, and W_d is the weight of the structure.

Several investigations have performed 2D and 3D numerical studies on rubber dams (Anwar [2], Alwan [5], Al-shami [6], Abd-alsaber [7], Song and Chen [8], and Alhamati et al. [9]). Former numerical simulations were focused on determining the dam's dynamic response and stability. Alwan [10] performed modal analysis of a rubber dam subjected to a flood. Two-dimensional analyses on rubber dams were carried out by Watson et al. [1]. The tube was modeled as an inextensible and weightless membrane. They obtained closed-form solutions for the cross-sectional shape and the circumferential tension. Some studies focused on their cross-sectional static profiles, both for cases when the dam impounds water and when overflow occurs (Watson et al. [1], Alhamati et al. [2], Haßler and Schweizerhof [11], and Ghavanloo and Daneshmand [12]). A number of published works focused on experimental modeling of flow hydraulics over rubber dams (Anwar [2], Tam [3], Al-shami [6], Chanson [13], and Alhamati et al. [14]). However, little attention has been paid on the overflow hydraulics [15]. The relationship between the overflow head and the discharge over the inflatable dams is more complex than traditional structures because the shape of the rubber dams may vary due to the change in the internal pressure, overflow head and the downstream water depth. For identical upstream head, rubber dams have larger discharge than broad- and sharp-crested weirs [14]. While the equilibrium shape of the rubber dam forms, it resembles as a rigid weir. Hence the weir general discharge coefficient is used to determine the discharge

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Nomenclature

B	foot width of the dam
C_d	discharge coefficient
D_h	dam equilibrium height
E	rubber modulus of elasticity
g	gravitational acceleration
H_u	total head upstream of the weir relative to the weir crest level
h_d	downstream water depths
h_u	up-stream water depth
P	air and/or water internal pressure
q	specific discharge over the rubber dam
R	Reynolds number
t	rubber thickness
W	Weber number
W_d	weight of the dam
γ	specific weight of water
μ	dynamic viscosity
ρ	fluid density
σ	surface tension

coefficient of a rubber dam as follows:

$$C_d = \frac{q}{\sqrt{2gH_u^3}} \tag{1}$$

where q, H_u and g are the weir specific discharge, total head upstream of the weir relative to the weir crest level, and the gravitational acceleration, respectively. Anwar [2] found that the discharge coefficient of an air and water inflated rubber dam ranges from 0.35 to 0.5 for the relative head H_u/D_h values between 0.2 and 0.7. He also presented a correlation for discharge coefficient of rubber dams depending on H_u/D_h as follows:

$$C_d = 0.361 + 0.188\frac{H_u}{D_h} \tag{2}$$

Stodulka [16] used Eq. (1) to calculate the discharge coefficient and found that C_d varies from 0.25 to 0.40. Alwan [5] found that C_d of water-inflated dams is dependent on the relative head H_u/D_h. He assumed the head-discharge relationship of a rectangular broad-crested weir and found that C_d varies from 0.2 to 1.1. Al-Shami [6] used Eq. (1) to calculate C_d of air and water inflated dams and found that it ranges from 0.35 to 0.4. Based on experimental data he presented two correlations for air- and water-inflated dams (Eqs. (3a) and (3b), respectively).

$$C_d = 0.4866\left(\frac{H_u}{D_h}\right)^{0.11} \tag{3a}$$

$$C_d = 0.4338\left(\frac{H_u}{D_h}\right)^{0.0694} \tag{3b}$$

Abd-alsaber [7] found an empirical relationship between the discharge Q and the ratio H_u/D_h for an air inflated rubber dam as follows:

$$Q = 110.205\left(\frac{H_u}{D_h}\right) - 5.9625 \tag{4}$$

Alhamati et al. [14] determined the discharge coefficient of air inflated rubber dams based on the experimental data under different overflow heads and internal pressures. They have used H_u as the upstream depth relative to the weir crest level and showed that C_d increases by increasing H_u/D_h and ranges between 0.22 and 0.38, when the ratio of H_u/D_h varies from 0.04 to 0.3. The results showed that the internal pressure has little effect on C_d. Based on their own experimental data and combining the data with these of Anwar [2] and Tam [3] they obtained Eqs. (5a) and (5b) respectively

$$C_d = 0.5066\left(\frac{H_u}{D_h}\right)^{0.2447} \tag{5a}$$

$$C_d = 0.5516\left(\frac{H_u}{D_h}\right)^{0.2697} \tag{5b}$$

In the present study, numerical analyses were performed on the rubber dams to determine the equilibrium shapes of such dams. The overflow is assumed to start with a uniform depth and velocity. This problem has two distinct parts including nonlinear free-surface flow, and structural responses. These two problems are coupled and must be solved simultaneously. Transient, fully nonlinear computations for the fluid flow are performed using a mixed Eulerian–Lagrangian formulation. The effects of the internal pressure, external water head and flow velocity on the equilibrium shapes of the rubber dam was studied and then the results were compared with the previous experimental/numerical results. The fluid dynamics program determines the free-surface elevation and calculates the external pressure acting on the dam surface at each time step. This pressure is then used as an input at each time step to determine the deformation and the velocities along the dam surface and the stresses in the dam. The structural results were used in the next time step to continue the fluid dynamic analysis. The data of the free surface is translated to a coordinate frame moving with the structure to show how the free surface develops over time. The simulation was run over ranges of H_u and Q. Accordingly all the significant parameters of fluid–structure interactions were attained in a comprehensive dimensional analysis resulting in a more accurate correlation for the discharge coefficient of rubber dams to be used in practical purposes.

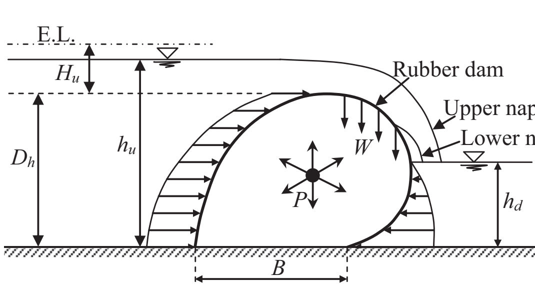

Fig. 1. Geometric and hydraulic features of a rubber dam.

2. Methodology

Three dimensional numerical models of rubber dams were created in ANSYS Workbench environment using ANSYS CFX code for solving the flow based problem and ANSYS Mechanical for static and dynamic structural analysis. The structural physics is set up in the transient structural (ANSYS) analysis system and the fluid physics is set up in fluid flow (CFX) analysis system. However, both structural and fluid physics are solved together under the solution cell of the fluid system. The purpose of the present investigation is to determine the equilibrium shapes of the rubber