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Developing a mathematical framework in preliminary designing of detention rockfill dams for flood peak reduction

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ABSTRACT

Hydraulic designing of rockfill detention dam is based on the treatment of nondarcian and non-linear turbulence flow in coarse porous media. Previous literature focused only on the regular outlet ponds, and there is a shortcoming in the design methodology for detention rockfill dams. So, this paper develops a simple novel design framework by combining the governing equation of non-linear and non-darcian flow through rockfill dams with the hydrologic flood routing in reservoirs and hydraulic rules of storage dams. An innovative mathematical framework developed for preliminary designing of detention rockfill dams. The effects of type and size of rock fill materials, the shape of reservoir, shape, and intensity of inflow hydrograph on the peak of outflow, the volume of a stored flood, coefficients of flood peak and storage are investigated by parametric study in 36000 simulations. A simple design equation for preliminary designing of detention rockfill dams is provided and its applications in two design examples are presented. Its results indicate that the developed design equation (with $R^2 = 0.996$, MAE = 0.008, and RMSE = 0.0041) is superior to the previous equations and can be used in preliminary designing of detention rockfill dams for flood peak reduction.

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KEYWORDS
Flood control; detention rockfill dam; preliminary designing; mathematical model; non-darcian flow

1. Introduction

Flood events are common natural hazards over the world also in Iran, due to uneven spatial and temporal patterns of rainfall, climate change, loss of water and soil resources, poor watershed management operations. Because of the social and economic damages of floods,flood peak attenuation is crucial (Kanani-Sadat, Arabsheibani, Karimipour, & Nasseri, 2019). On the other hand, mortal effect and damages of flood,reveal the necessity of flood control and flood damage reduction operations. Furthermore,catastrophic effects of flash floods and storm water in urban and catchments areas are the other problems of flood hazards which also require flood management systems (Fotovatikhah et al., 2018; Sivakumar, 2009).

There are several methods for flood control and peak discharge reduction such as structural or non-structural methods and some early warning methods (Erpicum, Dewals, Archambeau, Detrembleur, & Pirotton, 2010; Takamatsu, Barrett, & Charbeneau, 2009). The structural methods use physical activities to control or reduce flood peaks and the non-structural methods used flood forecasting, early warning systems, flood management to reduce the flood damages (Chuntian & Chau, 2002; Li, Chau, Cheng, & Li, 2006; Mosavi, Ozturk, & Chau, 2018; Wang, Chau, Xu, Qiu, & Liu, 2017; Wu & Chau, 2006; Yaseen, Sulaiman, Deo, & Chau, 2019). Using detention rockfill dams is one of the best methods as it increases the time of flood routing while reducing the temporary peak of flood discharge due to the use of natural porous materials, simple and fast design construction (Samani, Moknatian, & Heidari, 2013). Detention dams operate as storage reservoirs which store high flood flows and gradually deplete this flow through reduced and safe discharge. The outflow discharge is a reduced design discharge, which is determined based on the downstream conditions of the river and riverbank (Riahi Madvar, Samani, & Ayyoubzadeh, 2009). Rockfill dam is a common and fast tool for flood peak reduction where rocks are available at the site. Rockfill dams are constructed from pebbles and rock fills (Samani, Samani, & Shaiannejad, 2003) and because of their porous media, the risk of liquefaction and slope failure is smaller than the risk of dam breach in earthfill dams or erodible embankments (Hooshyaripor &

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Tahershamsi, 2015; Hooshyaripor, Tahershamsi, & Razi, 2017). Using these structures, the flood is temporarily stored in the reservoir of rockfill dams which then discharges to the downstream at a safe discharge automatically by seepage flows without needs for operational management. Since the body of these types of dams are constructed through the use of the coarse rock particles, the flow through these coarse pores will deviate from Darcy's law and generally be turbulent and the variation of flow velocity (V) with hydraulic gradient (i) will be a non-linear relation (Legrand, 2002; Sarkhosh, Samani, & Mazaheri, 2017). Where the flow in coarse porous media of rockfills is non-Darcian and turbulent, determination of seepage discharge, seepage force, flow net, and outlet discharge requires the use of non-linear relations of gradient hydraulic with flow velocity (Qian, Zhan, Zhao, & Sun, 2005). Classical detention ponds or dams have an impervious body with single or multiple outlet facilities, and there are several methods and frameworks for designing these types of Best Management Practices (BMP).

The first step in the design of these structures is to determine the volume of detention reservoir in such a way that the peak of outflow discharge reduces to the allowable peak of flood discharge that has minimized damages. The sites that have the proper potential for detention dam construction are determined based on the allowable peak of flood discharge (related to the downstream conditions). After determining the suitable sites, the second step will involve preliminary designing of the detention dam and finally, the optimized size and shape of the detention dam are determined (Riahi Madvar et al., 2009). Another interesting topic of detention rockfill dams is the da breach risk and its effective factors that should be considered in design and construction of these ponds (Eghbali, Behzadian, Hooshyaripor, Farmani, & Duncan, 2017; Hooshyaripor, Tahershamsi, & Behzadian, 2015).

Several investigations emphasized on detention pond design or detention dams with single outlet facilities such as orifice outlet type or weir outlet type (Akan, 1990, 2010; Basha, 1995; Chen, Tsai, & Tsai, 2007; Emerson, Welty, & Traver, 2005; Froehlich, 2009; Graber, 2009; Guo, 1999, 2001; Harrell & Ranjithan, 2003; Hong, 2008; Konrad & Burges, 2001; McEnroe, 1992; Meredith, Middleton, & Smith, 1990; Nascimento, Ellis, Baptista, & Deutsch, 1999; Park & Roesner, 2009; Osorio, Muhaisen, & García, 2009; Powell, Khan, & Aziz, 2008; Tullis, Olsen, & Gardener, 2008; Tung, 1988), or urban storm water control, susceptibility analysis and management (Ahmad & Simonovic, 2006; Al-Hamati, Ghazali, & Mohammed, 2010; Cheng & Chau, 2004; Darsono & Labadie, 2007; Elliott & Trowsdale, 2007; Galelli & Soncini-Sessa, 2010; Girona, Roesner, Rossman, & Davis, 2010; Guo, 2009; Khosravi et al., 2018; Kumar & Reddy, 2006; Kumar, Baliarsingh, & Raju, 2010; Scholz & Yazdi, 2009; Sivakumar, 2009; Sreeja & Gupta, 2007; Zoppou, 2001). One of the simple and applicable methods for designing detention dams was developed and analyzed by Akan (1990), McEnroe (1992), Abt and Grigg (1978), Wycoff and Singh (1976). There are some methods and equations for designing detention dams for flood control. All these methods have been derived for the concrete or earth fill storage detention dams. Although some experimental and theoretical studies are done on flow over Gabion Weirs (Mohamed, 2010); Discharge through a Permeable Rubble Mound Weir (Chanson, 2006; Michioku, Maeno, Furusawa, & Haneda, 2005); Numerical modeling of 3-D flow on porous broad crested weirs (Mohammadpour, Ghani, & Azamathulla, 2013). None of these methods counts for the rockfill detention dam designs (Hansen, Garga, & Townsend, 1995; Riahi Madvar et al., 2009; Samani & Shaiannejad, 2004). In this topic, some researchers developed simple graphical methods for preliminary designing the detention non-rockfill dams that relate linearly with the volume of the reservoir to the depth of water and single bottom orifice outlet device (Akan, 1990; Froehlich, 2009; Guo, 2001). In another methodology, several designing curves were developed to design detention dams with double bottom orifice outlet (Akan, 1990).

A graphical standard method is presented by SCS, which designs the detention dams in by geographical method. In this approach, two curves are presented; one for storage coefficient (ratio of the peak of storage discharge to the total volume of the flood) and another for peak flood coefficient (ratio of peak outlet discharge to the peak of inlet discharge) (McEnroe, 1992). Another graphical method is presented,which determines the size of the outlet structure based on the flood conditions and reservoir characters. In this method, inlet flood hydrograph is the non-dimensional SCS hydrograph (Akan, 1990; Li & Gowing, 2005). There are several equations that determine the required volume of detention dam with free outlet device based on the allowable conditions of downstream and inlet hydrograph conditions (Graber, 2009; Harrell & Ranjithan, 2003; Scraggs & Lemckert, 2004; Tullis et al., 2008). In these equations, the required volume of the reservoir (S_f) is determined based on the volume of the flood (V_f), outlet discharge peak (Q_p), and inlet hydrograph peak (I_p). A simple equation in this case for inlet and outlet triangular hydrograph shape is developed (Baker, 1979):

$$\frac{S_f}{V_f} = 1 - \frac{Q_p}{I_p} \tag{1}$$

Where S_f/V_f is the flood storage coefficient and Q_p/I_p is the flood peak coefficient. Another equation for triangular inlet hydrograph and trapezoidal outlet hydrograph with maximum value in crossing with inlet hydrograph is developed (Abt & Grigg, 1978):

$$\frac{S_f}{V_f} = \left(1 - \frac{Q_p}{I_p}\right)^2 \tag{2}$$

Based on 50 numerical flood routings from 10 different inlet hydrographs and 5 sizes of outlet orifice another equation is developed (Wycoff & Singh, 1976):

$$\frac{S_f}{V_f} = \frac{129(1 - Q_p/I_p)^{0.753}}{(T_b/T)^{0.411}} \tag{3}$$

Where t_b is the base time and T is the time of the peak of the flood. In this equation, the base time of the hydrograph is the time when the rising limb of hydrograph of the inlet discharge reaches less than 5% of inlet peak discharge.

Two equations for detention dams with bottom orifice outlet and dams with overflow weir are developed (McEnroe, 1992). For bottom orifice or gate outlet:

$$\frac{S_f}{V_f} = 0.97 - 1.42\frac{Q_p}{I_P} + 0.82\left(\frac{Q_p}{I_P}\right)^2 - 0.34\left(\frac{Q_p}{I_P}\right)^3 \tag{4}$$

And for overflow weir:

$$\frac{S_f}{V_f} = 0.97 - 1.17\frac{Q_p}{I_p} + 0.77\left(\frac{Q_p}{I_p}\right)^2 - 0.46\left(\frac{Q_p}{I_p}\right)^3 \tag{5}$$

Reviewing the available studies and equations for designing detention dams indicates that all of these methods are focused only on detention dams with an impermeable body that have bottom orifice or overflow weirs for outlet structure. Whereas detention rockfill dams have a permeable body constructed from rockfill with large macro-pores, different hydraulic mechanism, and requires appropriate designing methods, there isn't any methodology for designing detention rockfill dams and based on the authors' queries; it is the first study that developed a preliminary design procedure for detention rockfill dams. In this paper, a hybrid novel method is extended for the preliminary designing of detention rockfill dams hybridizing the reservoir flood routing with non-darcian, nonlinear flow in coarse porous media of rockfill dams. There are no equations, method or study on designing detention rockfill dams and based on knowledge of the authors this study is the first one in this particular case. Therefore, in this study, we have developed a new approach for preliminary designing of detention rockfill dams innovatively and presented some applicable design and analysis of the developed model in design examples as a case study. The current study deals with the one-dimensional hydrologic routing combined with the non-darcian flow and reservoir routing simulation of the detention rockfill dams. The remainder of the present paper is arranged as follows: in the material and methods of the study, the mathematical basis of model equations are presented, and their coupling with routing presented. After that, the design procedure is provided. In the results section, the numerical, regression-based design equation, comparisons with previous equation and flood control of some example rockfill dams are discussed respectively.

2. Material and methods

In this study, by combining hydrologic flood routing equations with the equations of depth -volume of the reservoir, non-darcian based stage-discharge in rockfill dams, stage-discharge of downstream and inlet flood hydrograph, a mathematical flood routing method for flow in detention rockfill dams is developed and numerical preliminary designing technique is presented. Due to the lack of knowledge regarding the design of detention rockfill dams in order to attenuate the flood peak, a parametric analysis is done by assuming several conditions for inlet hydrograph shape and intensity, reservoir shape, rockfill dimensions, and downstream river conditions. Finally, a simple designing equation for preliminary sizing of detention rockfill dams is presented. All equations that have been used in this study take their general form and the results of the developed model can be used for several application conditions. The development of the mathematical model and governing equations are presented in the following subsections.

2.1. Continuity equation for hydrologic flood routing in reservoirs

The continuity equation, which is used for hydrologic flood routing in reservoirs, is (Al-Humoud & Esen, 2006):

$$\frac{dS}{dt} = I - Q \tag{6}$$

Where t is the time, Q is the outlet discharge from the reservoir, I is the inlet flood discharge, and S is the volume of water inside the reservoir. Hydrologic flood routing method in reservoirs, usually assumed that the outlet discharge and the storage volume inside the reservoir haven't affected by the downstream conditions, but in detention rockfill dams, the downstream level of water and tailgate significantly affects the outlet discharge and storage volume of water inside the reservoir. So the reservoir routing equations should be modified in such a way that they take into account the non-darcian regime of flow in coarse porous media of rockfill.

2.2. Inflow flood hydrograph

In this study, the inlet flood hydrograph into the reservoir is produced by Gamma Probability Distribution Function (Machajski & Kostecki, 2018). The PDF of the gamma distribution is:

$$I = I_p\left(\frac{t}{t_p}\right)^m \exp\left(-m\left(\frac{t}{t_p}-1\right)\right) \tag{7}$$

Where m is the dimensionless shape factor of the inlet hydrograph, t_p is the time of inlet flood hydrograph to reach the peak value; I_p is the peak of input hydrograph. Several researchers have used this function to simulate inlet flood hydrograph in hydrologic studies (Aksoy, 2000; Gray, 1961; Machajski & Kostecki, 2018; Nash 1959). For example, Nash (1959), Gray (1961), Bhunya, Ghosh, Mishra, Ojha, and Berndtsson (2005) and Singh, Mishra, and Jain (2014) used this equation to derive unit hydrograph model of the flood. This equation gives an average shape of inlet flood hydrographs in hydrology. Figure 1 shows the inlet dimensionless hydrograph for several values of m coefficient. From this figure, it is clear that when m increases, the peak of flood hydrograph is sharper, and the rising limb becomes shorter; hence the shorter, the tail will be. Increasing the m parameter will decrease the flood volume. In these conditions, the volume of inlet flood is derived by integrating this equation over the base time of the inlet hydrograph and equals to:

$$V_f = I_p t_p m^{-(m+1)} \exp(m)\Gamma(m+1) \tag{8}$$

Where: $\Gamma()$ is the gamma function.

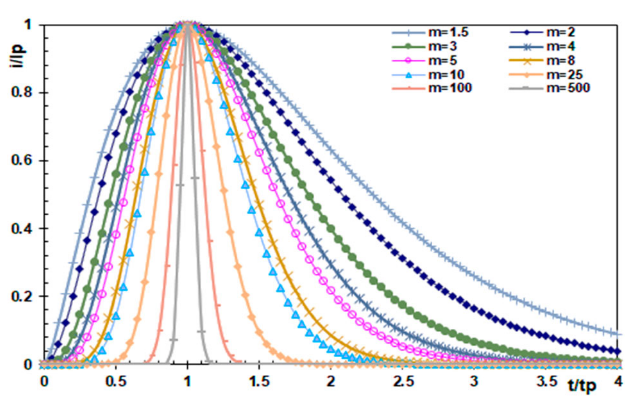

Figure 1. The effects of m factor on inflow hydrograph shape in dimensionless form.

2.3. Depth – volume equation in reservoirs

The general form of depth-area relation in reservoirs (for positive depths, $H > 0$) is:

$$A = k(H + z_o)^n \tag{9}$$

Where A is the area of the water surface in the reservoir, k, z_o, and n are the constant coefficients of the reservoir shape or the factor of bank slopes. Using this equation and integration of $A = ds/dh$, the volume-depth relation of the reservoir is derived:

$$S = \frac{k}{n+1}[(H + z_o)^{n+1} - z_o^{n+1}] \tag{10}$$

Where S is the volume of the reservoir. In these equations k and z_o are the shape factors of the reservoir and n is the factor of bank slopes of the reservoir which varies between 1 and 2, for vertical banks, the n value equals zero.

2.4. Seepage discharge through detention rockfill dam

Rockfill detention dams are built by coarse porous media, rockfill and rock dumps. In Figure 2 a schematic illustration of detention rockfill dam parameters is shown. Since these types of detention dams are constructed by coarse media, the flow through them deviates Darcy's law and follows turbulent non-linear law (Samani & Shaiannejad, 2004). The non-darcian equation of flow velocity in coarse porous media is described by the following power law:

$$i = a'V^{b'} \tag{11}$$

Where i is the hydraulic gradient, V is the velocity, a' and b' are constants which depend on the media and fluid characteristics. Also, in this case, the relation between

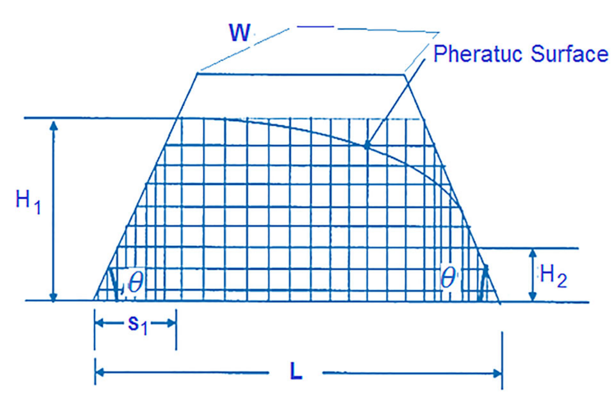

Figure 2. The hydraulic performance of detention rockfill dams in flood control.

Darcy-Weisbach friction factor (f) and Reynold's number (Re) can be written as:

$$f = a\mathrm{Re}^b \tag{12}$$

By considering $i = dh/L$, $D - \sigma$ as length scale, and using Darcy-Weisbach equation, we can derive the following equation for i in rockfill materials:

$$dh = f\frac{L}{D-\sigma}\frac{V^2}{2g} \tag{13}$$

$$i = f\frac{1}{D-\sigma}\frac{V^2}{2g} = (a\mathrm{Re}^b)\frac{1}{D-\sigma}\frac{V^2}{2g} \tag{14}$$

By using the continuity equation and $i = -dh/dx$ we have

$$-\frac{dh}{dx} = a\left(\frac{Q(D-\sigma)}{hW\upsilon}\right)^b \frac{1}{D-\sigma}\frac{Q^2}{2g(hW)^2} \tag{15}$$

By integrating this equation over the water table differences at upstream and downstream of the dam H_1 to H_2 for dh; and integrating for 0 to $L-0.7\,H_1\mathrm{Cot}\theta$ for the dx we can derive the analytical equation seepage discharge equation for detention rockfill reservoirs

$$Q = W\left[\frac{H_1^{b+3} - H_2^{b+3}}{L - 0.7H_1\cot\theta} \times \frac{1}{\alpha(b+3)}\right]^{\frac{1}{b+2}} \tag{16a}$$

Where the coefficient equals:

$$\alpha = \frac{a(d-\sigma)^{b-1}}{2g\upsilon^b n^{b+1}} \tag{16b}$$

Where a and b are constant coefficients, d is the grain size (mm), σ is the standard division of grain size (mm), g is the gravity acceleration (m/s^2), ris the porosity of medium, υ is the viscosity of fluid (m^2/s), L is the thickness of dam (m), W is the dam width perpendicular to direction of flow (m), θ is the angle of the upstream face of the dam with the horizontal direction, n is the porosity, H_1 and H_2 represent downstream and upstream water depths, respectively. The authors derived values of a and b coefficients by using an experimental model setup and optimization technique. The optimized values of a and b equals to 54 and -0.077, respectively (Samani & Shaiannejad, 2004).

2.5. Numerical nonlinear flood routing in detention rockfill dams

Combining the Equations (7–16) with Equation (6) gives a non-linear ordinary differential equation of unsteady flow in detention rockfill dams and its reservoir as follows:

$$\frac{dS}{dt} = I_p\left(\frac{t}{t_p}\right)^m \exp\left(-m\left(\frac{t}{t_p}-1\right)\right) - K_Q\left(\frac{((A_0S+A_1)^{B_1}-Z_0)^{B_2} - H_2^{B_2}}{L - A_2((A_0S+A_1)^{B_1}-Z_0)}\right)^{B3} \tag{17}$$

Where A_i and B_i are constant parameters, and they are equals to:

$$K_Q = W\left(\frac{\alpha}{b+3}\right)^{\frac{1}{b+2}},\ B_1 = \frac{1}{n+1},\ B_2 = b+3,$$

$$B_3 = \frac{1}{b+2}$$

$$A_0 = \frac{n+1}{k},\ A_1 = z_0^{n+1},\ A_2 = 0.7\frac{\cos(\theta)}{\sin(\theta)}$$

In a compacted form Equation (17) can be written as:

$$\frac{dS}{dt} = F(t, S, H_2) \tag{18}$$

Equations (17) and (18) show that the governing differential equation of flood routing through detention rockfill dams is non-linear such that the storage volume of water is a non-linear function of the storage volume of water in the reservoir, downstream and upstream depths of water in the reservoir. Simulating and flood routing in detention rockfill dams requires an iterative numerical procedure. The algorithm of solving the derived Equation (17) is as follows: at first, initial guesses for the downstream water depth are taken (usually equal to values at previous time step), and through the use of the Range-Kutta Forth Order Scheme (RKFOS), the governing ODE is solved numerically using Visual Basic Programming. After this, the storage volume S, depth of water in reservoir H_1, and outlet discharge of flood Q_P are determined. Through the use of the derived outlet discharge and stage-discharge equation of downstream channel (in this study manning equation), the depth of water at downstream is determined and a comparison done with the initial guess. If necessary, the new iterations are done until the convergence is derived. This process is continued for all-time steps on the inflow flood, and finally, the maximum storage volume and peak of outlet discharge are derived, and the storage and peak coefficient are determined. This is the numerical algorithm for one specific dam.

This study is based on the wide range of m, n, z_o, k, I_p, t_p, d, L, θ and s parameters, published in previous literature (Graber, 2009; McEnroe, 1992; Samani & Shaiannejad, 2004). This numerical solution was conducted on 36000 different compositions of these parameters. Finally, the derived results are investigated and a practical design equation for detention rockfill dams presented, and its results are compared with similar studies for other types of detention dams. The developed code can be accessed from the first author.

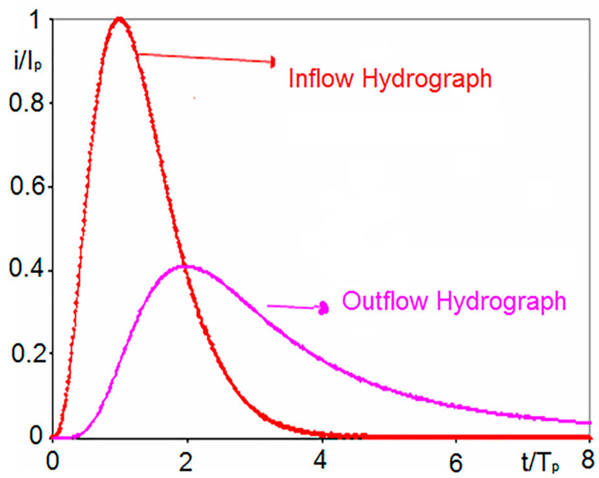

Figure 3. The hydraulic performance of detention rockfill dams in flood control.

3. Results and discussion

3.1. Hydraulic performance of detention rockfill dams

In this section, a summary of derived numerical model results is presented. At first, the hydraulic performance of detention rockfill dams is shown in Figure 3. In this case, the L equals 100 meters, d_{50} equals 2 cm, $W = 2$ m, I_p equals 100 (m^3/s), and p equals 3. From this figure, it is clear that the peak of flood hydrograph is reduced significantly due to detention rockfill dams. Also, in Figure 4, stage-discharge relations upstream and downstream of detention rockfill dams are presented. It shows that detention dams reduce output water level and flood stages. Comparing model results with the observed hydrograph values requires measure flood downstream of detention rockfill dams and these data were not accessible to the authors at this time. It is an interesting issue for future studies over rockfill dams. But the developed model is based on the well-known procedure of SCS detention dam designs and its validity is accepted internationally. However to evaluate the accuracy and reliability of mathematical model results the basic idea of reservoir routing is used: the peak outflow occurs when the outflow hydrograph intersects the inflow hydrograph and The peak outflow must lie on the recession limb of the inflow hydrograph, this is verified in the model developments as shown in Figure 3 the theoretical and physical validity of model results are approved. Also in unsteady flows the stage-discharge in the rising and falling stages

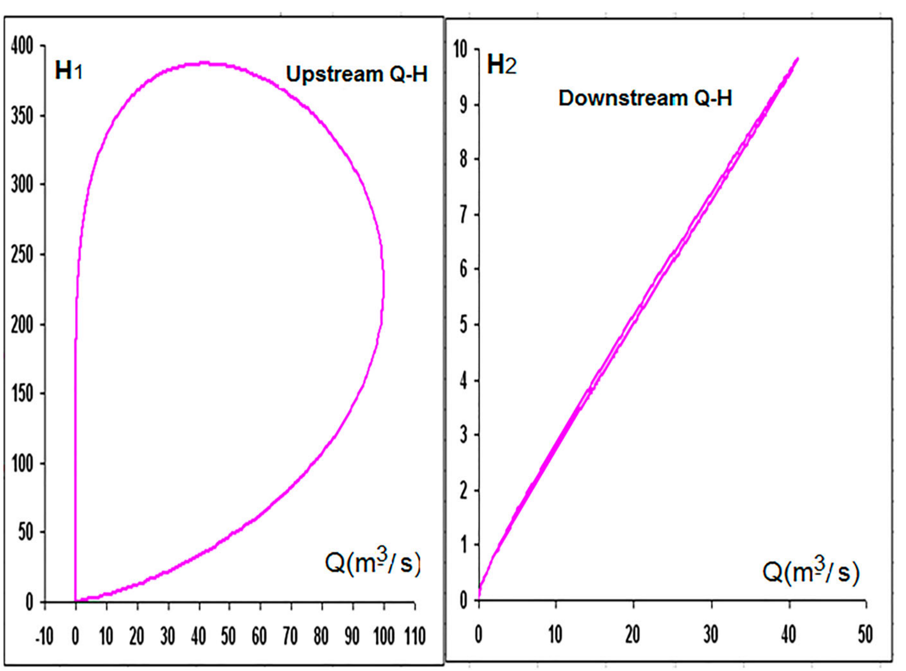

Figure 4. Stage-discharge upstream and downstream of detention rockfill dams.

of flood hydrograph are different and produce a loop-shaped stage-discharge curve. The loop curve of model results are also approved upstream and downstream of the detention rockfill dam based on the model results in Figure 4 and this proofs the acceptable accuracy of model results in this stage of the study.

3.2. Comparing model results with measured data

In this section the results of developed model are compared with the results of measure routed hydrograph in a detention rockfill dam reported by Samani and Shaiannejad (2004). In this respect, the numerical model results are used to calculate the flood routed hydrograph and compare with the results reported by Samani and Shaiannejad (2004). In this case the following input model parameters are used: $L = 3$ m, dam width, $w = 5$ m, $d_{50} = 50$ mm, side slopes = 90°, Manning's coefficient of the downstream channel = 0.014, slope of downstream channel = 0.001, and the reservoir length = 2000 m. the results of developed model are compared with the observed values in Figure 5. This figure shows well agreement between the observed values of hydrograph outflow from the dam and the observed results. The developed model accurately predicts the peak of outflow from the detention rockfill dam, the shape and the real values of outflow discharges. The differences between the model results and observed values in the rising limb and in the first stages of falling limb are negligible and only in the final stage of the hydrographs there is a very little difference, overall the model have errors smaller than 4.3% I regard with the observed routed outflows.

3.3. Simple design equation

The final results of 36000 storage and peak coefficient values are used to evaluate a simple design equation for detention rockfill dams. The coefficients of regression equation are determined through minimizing least square errors. The final design equation with $R^2 = 0.996$, AME = 0.008 and RMSE = 0.0041 is as follows:

$$\frac{S_f}{V_f} = 1.0166 - 0.231\frac{Q_p}{I_p} - 2.2433\left(\frac{Q_p}{I_p}\right)^2 + 1.4661\left(\frac{Q_p}{I_p}\right)^3 \quad (19)$$

This equation can be used simply on preliminary designing of detention rockfill dams to reduce the flood peak of I_p to the desired values of Q_P. This equation is derived based on variation of effective parameters and is valid for $n < 1$; $z_o < 1.1$; $k < 1.2$; $p < 4$; $t_p < 45$; $i_p < 200$; $d < 4$; $L < 150$. Comparing this equation with Equations (1–7) indicates the apparent differences. Figure 6 shows the results of Equation (19) and the mathematical model. It is clear that the results of this simple designing equation are very close to the numerical results of

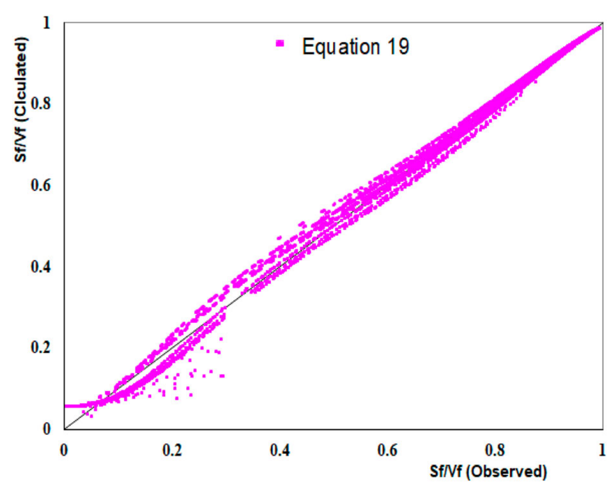

Figure 6. Comparing the results of the mathematical model with Equation (19).

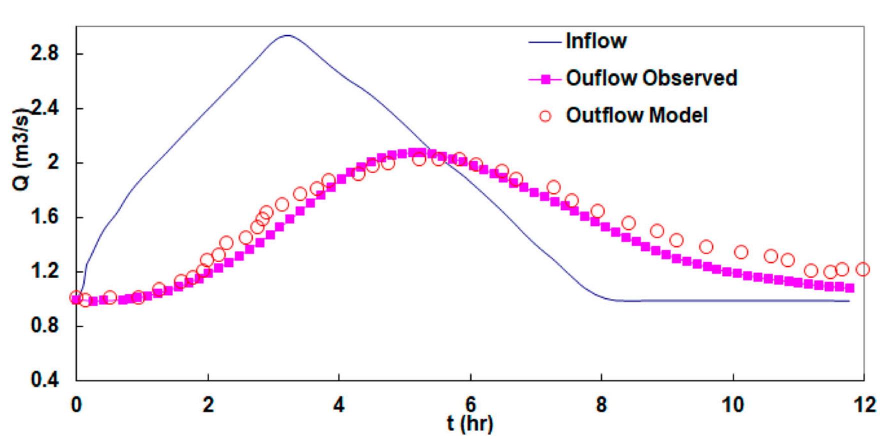

Figure 5. Stage-discharge upstream and downstream of detention rockfill dams.

the developed model. This equation is simpler than the mathematical non-linear flood routing in detention rockfill dams, and it can be used easily in real-world design projects. It is noticeable that the final results of the developed mathematical model can be presented as designing charts, but in this study, preferably the explicit design equation are developed and two deign examples are provided.

3.4. Comparing results of this study with previous studies

In this section, the results of Equation (19) derived based on detention rockfill dams, are compared graphically with the results of Equations (1–7), which were derived based on other types of detention dams. Figure 7 shows these comparisons. From this figure, it is clear that using results of Equation (1–7) produce significant errors in designing detention rockfill dams. From this figure, it is clear that the results of Equation (19) are in mediocre of these equations and detention rockfill dams show a combined operation between detention dams with bottom orifice outlet or overflow weir. It is noticeable that the results of this study in comparison with previous studies, are derived innovativelyfrom detention rockfill dam's analysis and have different parameters such as Shape of inflow hydrograph, reservoir shape and etc.

3.5. Design example

In order to provide the applicability of the derived design equation and the developed framework in determining the rockfill detention dam, the applicability and general design framework of developed model and equations can be illustrated through two examples.

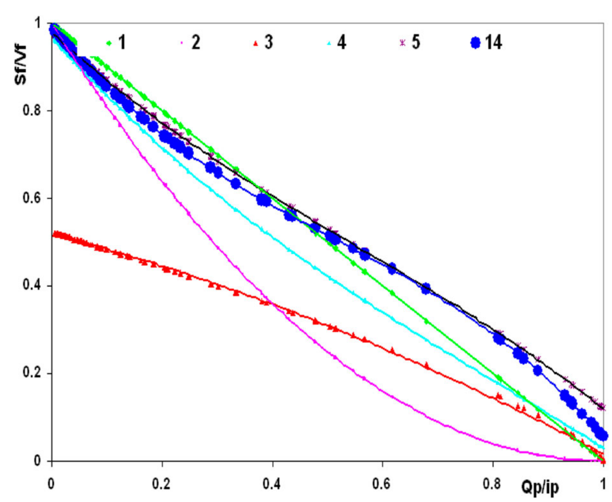

Figure 7. Comparing the results of the proposed equation with previous works.

Example 1

Suppose that the hydrologic analysis of a watershed revealed that the peak of a 25-year storm would be $I_p = 28$ (m^3/s), $t_P = 3600$ sec, with $m = 10$; allowable downstream discharge $Q_P = 11$ (m^3/s) which is the conveyance capacity of the downstream drainage system. The depth-volume relationship of a dam site location is in the form of Equation (10) with $n = 2$, $Z_0 = 0.0$, $k = 11000$. Rockfill dam width is equal to valley width 2 m; rockfill material havea uniform size of $d = 0.25$ m, $\theta = 90°$.

Using the parameters in Equation (8) results in $V_f = 80569.1\ m^3$. From Equation (19), the maximum required volume of a dam is calculated as $S_f = 53862\ m^3$. This is the required volume of dam storage. Using this in Equation (10), we can find the upstream depth as $H_1 = 3.76$ m. If the allowable downstream flood level is constrained to 1 m from Equations (16a) and (16b), we can find out the required thickness of detention rockfill as $L = 3.44$ m. Whenever the depth of 3.76 m upstream of the dam isn't allowable, we need to excavate the dam location and adjust the volume-depth relation to satisfy practical criterions. Otherwise, we can use successive detention rockfill dams. This example supposed that the side slopes of the rockfill dam are vertical, same as gabion dams, also can have any applicable side slopes.

Example 2

A detention rockfill dam is constructed, having $L = 6$ m, $W = 3.5$ m, $h = 4.5$ m, with rockfill material uniform size of $d = 0.52$ m, side slope of dam faces is $\theta = 45°$ a runoff hydrograph has a peak of $i_p = 15.6\ m^3/s$ with $t_p = 1.2$ h and $m = 5$ entered to the detention dam. The storage-depth parameters of the reservoir are $n = 3$, $Z_0 = 0.2$, $k = 350$, determine the outlet discharge peak for the detention dam. Using specified inflow hydrograph, the V_f is determined by Equation (8), $V_f = 76814\ m^3$. From Equation (10), the $S = 42697\ m^3$. Using these values in Equation (19), $Q_p = 7.435\ m^3/s$. Also from Equation (16a), downstream water depth $H_2 = 1.03$ m. This example illustrates that designing and construction of this dam will reduce the flood peak discharge from $15.6\ m^3/s$ to $7.435\ m^3/s$ and downstream water depth of 1.03 m, that can be compared with the desired downstream carrying capacity and allowable inundation depth of flood.

4. Conclusions

This study, by usingthe hydrologic flood routing equations in combination with governing equations of flow in coarse porous media of rockfill dams, the hydraulic performance of detention rockfill dams in reducing peak discharge of outlet flood is investigated.

A mathematical model is then developed andsolvediter-ativelyusing Range-Kutta Forth Order Scheme; the governing non-linear ODE is solved numerically for different values of the included parameters. Lastly, through the use of the results of 36000 model runs, a simple and applicableequation for preliminary designing of detention rockfill dams is then presented. A comparison done on the results of the proposed model with the results of the previous works shows the necessity of a new model. Using the proposed equation, the preliminary designing of detention rockfill dams for every flood with its return period can be done easily. For this purpose, first, the inflow hydrograph with its proper return period is determined based onthe watershed characteristicsafter which thedownstream flood allowable peak discharge is determined. After this, through the use of Equation (17), storage coefficient of the reservoir and its storage characters are determined, and finally, the preliminary site for detention dam construction and body materials is determined. One simple preliminary designing problem is presented. The final output of this study is the applicable framework for designing and the performance evaluation of detention rockfill dams. The developed framework has the capability of predicting the output flood from detention reservoir and routed hydrographs. Furthermore, the developed framework can also determine the dam dimensions, the rockfill sizes and characteristics required for the case of known inflow hydrograph, and downstream flow carrying capacity. This framework provides a sound basis on preliminary designing and sizing of detention rockfill dams in reducing peak discharge to the desired outlet peaks. The remaining topics in the field of detention rockfill dams that requires more studies are changes in the porosity and permeability of rockfill due to sediments, flash floods, leaves and etc., experimental and filed measuring of outflow hydrograph from detention rockfill dams and would be studied in future studies.

Disclosure statement

No potential conflict of interest was reported by the authors.

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