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Evaluation of Earthen Dam-Breach Parameters and Resulting Flood Routing Case Study: Aidoghmosh Dam

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***Abstract* — Dams are constructed for a specific purpose such as agricultural water supply, flood control, irrigation, navigation, sedimentation control, and hydropower. Using the most recent publication of the World Register of Dams, irrigation is by far the most common purpose of dams. Simulation of dam breach events and the resulting floods are crucial to characterize and reduce threats due to potential dam failures. The studies of dam breach are necessary and important in academic studies, the government's planning and investment in downstream of the dams. In this research, considering the importance of the dam breach studies and resulting flood routing, based on the previous studies, new equations were presented for estimating dam breach parameters (breach width, side slope, time of failure and peak outflow) by collected data from 142 broken dams. Dimensional analysis and multiple regression were used to predict maximum outflow from earth dam breach. The uncertainty of equations was evaluated. In this way, geotechnical equation of the BREACH model was adapted. This modification was evaluated by the data of pervious broken dams and revealed better results. Finally as a case study, Aidoghmosh dam breach was analyzed using the presented equations of breach and a flood routing model. According to the results obtained from the examined dam breach, equipment of wastewater refinement, four connective bridges of the railway and some parts of the town near the railroad are exposed to the danger of the flood resulting from the dam breach.**

***Keywords* — Dam Breach, Flood Routing, Dam Break, BREACH Model, FLDWAV Model, Aidoghmosh Dam.**

I. Introduction

In ancient times, dams were built for the single purpose of water supply or irrigation. As civilizations developed, there was a greater need for water supply, irrigation, flood control, navigation, water quality, sediment control and energy. Flood resulting from dam breach caused many damages in last two centuries for rural and agricultural lands. Today, there are numerous tools available to analyze dam failures and the resulting flood planning. One important step in dam breach modeling is the accurate prediction of the outflow hydrograph of breach. Some efforts have been made in developing models that accurately predict breach characteristics; still, many uncertainties related to breach modeling are still existent [1]-[2]-[3]. Due to the incomplete understanding of breach formation process and the limited capabilities of mathematical description of dam breaching mechanisms, the presently available models rely on several assumptions. The U.S. Bureau of Reclamation [4] suggested that for earthfill dams the ultimate width of a rectangular dam breach shape equals three times the initial water depth in the reservoir measured to the breach bottom elevation assumed to be at the stream bed elevation. This relationship was used as a guideline in the National Weather Service Simplified Dam Break Model [5]. Hagen [6] analyzed 18 historical events of dam failures due to overtopping. MacDonald and Langridge-Monopolis [7] analyzed 42 dams: 30 earthfill and 12 non–earthfill dam breaches (rockfill and other dams with protective concrete surface layers or core walls). The height of the dams varied from 6 to 93m. Singh and Snorrason [8]-[9] analyzed some historical earthfill dam failure events due to overtopping. One finding of this analysis was the identification of a strong correlation between breach width and dam height. US Army Corps of Engineers HEC-1 and National Weather Service BREACH [10] models are usually used for predicting the peak outflow. Costa [11] analyzed 31 historical dam failure events. The heights of the dams considered in the analysis varied from 1.8m to 83.8m, while the volume of the reservoir at the failure time ranged from 3.8×103 m3 to 7.0×108 m3. No distinction was made between different failure modes and dam types. There is no significant difference between the regression equations obtained by Mac-Donald and Langridge-Monopolis [7] and Costa [11], though the first authors included only earthfill dams in the analysis, the second author considered both earthfill and non–earthfill dams. Froehlich [12] analyzed 22 embankment dam failures with height of water ranging from 3.4m to 77.4m and volume of water ranging from 0.1 to 310 million m3. Wahl [13] carried out an uncertainty analysis of the empirical equations using a compiled database of 108 dam failure events. In the analysis no distinction was made between different failure modes (the same stands for Costa [11]). It is clear that for peak outflow prediction based on dam height and reservoir storage, the failure mode is important. The water depth in the reservoir can be lower than the dam height in case of a piping failure mode, and higher than the dam height during an overtopping. Webby [14] used dimensional analysis to develop a similar equation for peak outflow using Froelich's data. An early example of such a model is the work of Cristofano [15], which can be argued to be the first physically based dam breach model. The model related the rate of erosion of the breach channel to the discharge through the breach, using an equation that accounted for the shear strength of soil particles and the force of the flowing water [16]. Recently, artificial intelligence tools were used to estimate parameters of earthen dams breach. Babaeyan et al. [17] used artificial intelligence tools to estimate peak outflow from earth dam breach. Nourani et al. [18] implemented artificial neural network technique for simulation of dam breach hydrograph using laboratory experiments and a physically based model (BREACH). In the current study, 142 embankment dam breach data were collected from reliable references and dam breach equations were

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presented according to the previous researches. Dimensional analysis and multiple regression were used to predict maximum outflow from earth dam breach. Uncertainty of empirical relations was determined using appropriate statistically method. For this purpose, the method of eliminating out of range data using Rousseeuw algorithm [19] was employed. In this way, geotechnical equation of the BREACH model was adapted. This modification was tested on pervious broken dams which revealed better results. FLDWAV [5] model was then used to simulate flood routing and evaluate efficiency of dam breach parameters. Finally, probability of floods due to Aidoghmosh dam break was studied using different methods.

II. Uncertainty Analysis of Empirical Methods

Different empirical methods were assessed using 142 embankment dam breaches data. Minimum mean square errors are usually used for determining accuracy of estimation equation. Because of inaccuracy of observed data (Table I), existing unnecessary data and also uncertainty of estimation equations, uncertainty analysis must be applied to the empirical equations. If estimation equation is more strong, it will have good coefficient of determination, low minimum mean square error, low uncertainty range and low unnecessary parameters, and it can be used for suitable estimation.

A step-by-step description of the uncertainty analysis method used herein is as follows [13]:

1. Plot predicted versus observed values on log–log scales.
2. Compute individual prediction errors in terms of the number of log cycles separating the predicted and observed value, where is the prediction error, is the predicted value, and is the observed value.
3. Apply the outlier-exclusion algorithm to the series of prediction errors computed in Step 2. The algorithm was described by Rousseeuw [19].
   - Determine, the median of the values is the estimator of location.
   - Compute the absolute values of the deviations from the median, and determine the median of these absolute deviations ( ).
   - Compute an estimator of scale the 1.483 factor makes comparable to the standard deviation, which is the usual scale parameter of a normal distribution.
   - Use and to compute a score for each observation, , where the 's are the observed prediction errors, , expressed as a number of log cycles.
   - If the samples are from a perfect normal distribution, this method rejects at the 98.7% probability level. Testing showed that application to normally distributed data would lead to an average 3.9% reduction of the standard deviation.
4. Compute the mean, and the standard deviation, of the remaining prediction errors. If the mean value is negative, it indicates that the prediction equation underestimated the observed values, and if positive the equation overestimated the observed values. Significant over or underestimation should be expected, since many of the breach parameter prediction equations are intended to be conservative or provide envelope estimates, e.g., maximum reasonable breach width, fastest possible failure time, etc.
5. Using the values of and, one can express a confidence band around the predicted value of a parameter as, where is the predicted value. The use of approximately yields a 95% confidence band.

Table I : Data of Embankment dam breach

References	Number of breach cases
Babb (1968) [20]	1
ICOLD(1974) [21]	35
SCS(1981) [22]	1
Singh and Snorrason(1982) [8]	19
Jansen (1983) [23]	1
Graham (1983) [24]	25
MacDonald and Monopolis (1984) [7]	42
Costa (1985) [11]	26
Singh and Scarlatos (1988) [25]	51
Ballentine (1993) [26]	1
Baker and Bliss (1996) [27]	1
Wahl (1998) [21]	108
Froehlich (2008) [28]	74

III. Results and Discussion

In this part, estimation of breach width, maximum discharge, breach time, breach slope and modified BREACH model are discussed.

A. Breach Width Estimation

Following general results could be derived from collected data by studying 142 embankment dam breaches (Table I):

$$2h_d \le \bar{B} \le 3h_d \quad (1)$$

$$B_{top}/B_{bottom} = 1.13 - 1.64 \quad (2)$$

Where, $\bar{B}$: average breach width (m), h_d : dam height (m), B_{top} : breach width at crest of the dam (m), B_{bottom} : breach width at the bottom (m). Equation 3 was presented after analyzing parameters of embankment dam breach and comparing existing correlation using multiple regressions:

$$\ln(\bar{B}) = 0.8259 + 0.0635\ln(V_w) + 0.8481\ln(h_b) \quad (3)$$

Where, $\bar{B}$: Average breach width (m), Vw : Water volume above break point of bottom (m^3), h_b : Water depth above breach bottom (m). Equation 3 can be presented as:

$$\bar{B} = 2.2839 V_w^{0.0635} h_b^{0.8481} \quad (4)$$

Coefficient of determination of equation 4 is 0.918. Uncertainty analysis of proposed equation is demonstrated in Table II using Rousseeuw algorithm (Rousseeuw, 1998). Estimation coefficient of breach width is listed in Table II with % 95 probabilities.

B. Estimation of Maximum Discharge

Some equations were presented for estimation of maximum discharge due to dam breach in different

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researches. Following Webby's [14] work, suitable equation can be presented for estimating maximum discharge using collected data. The procedure is as follows:

$$Q_p = f(g, V_w, h_w) \quad (5)$$

Where, Q_p: maximum discharge (m^3/s), g: gravity acceleration (m/s^2), h_w: Water height above breach bottom (m). According to Equation 5, there are two basic dimensions of length and time and totally four parameters for estimation. So, it can be mentioned that two non-dimensional parameters should be considered as:

$$\Pi_1 = Q_p g^{-1/2} V_w^{-5/6} \quad (6)$$

$$\Pi_2 = h_w V_w^{-1/3} \quad (7)$$

Therefore Equation 8 could be presented between non-dimensional parameters:

$$Q_p / \sqrt{g V_w^{5/3}} = F\left(h_w / V_w^{1/3}\right) \quad (8)$$

Equation 9 was presented using non-linear regression and based on existing data:

$$Q_p / \sqrt{g V_w^{5/3}} = 0.0657\left(h_w / V_w^{1/3}\right)^{1.7053} \quad (9)$$

Equation 10 was obtained after simplification of equation 9:

$$Q_p = 0.06577\, g^{1/2} h_w^{1.7053} V_w^{0.2649} \quad (10)$$

Comparison between predicted and observed data of peak outflow for Eq. 10 is demonstrated in Fig. 1. The results of uncertainty analysis are presented in Table II

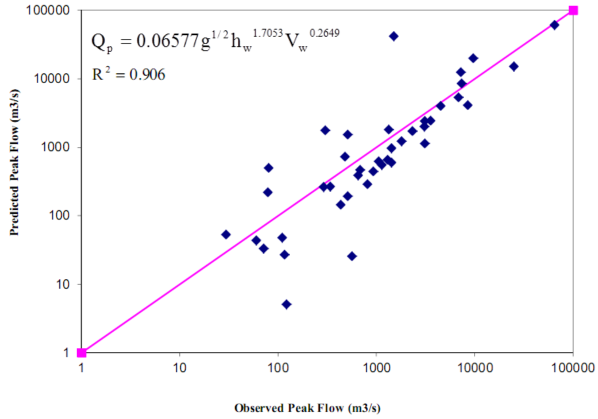

Fig.1. Comparison between observed and predicted peak outflow.

It is worth noting that the ranges are with % 95 probability for estimating maximum discharge unit and maximum or minimum of estimation coefficient of maximum discharge.

Table II : comparison of uncertainty and accuracy of proposed equation for estimation of breach width and maximum discharge.

Equation	Average square errors	Number of unnecessary data	Mean prediction error (log cycles)	Width of uncertainty band (log cycles)	Prediction interval around hypothetical predicted value of 1.0
breach width (Eq. 4)	241.62	3	0.01	±0.272	0.55-1.92
Peak outflow (Eq. 10)	1.08×10^7	4	– 0.11	±0.586	0.33-4.95

The first column identify the method being analyzed, the next two columns show the average square errors and number of unnecessary data, and the next two columns give the prediction error and the width of the uncertainty band. The last column shows the range of the prediction interval around a hypothetical predicted value of 1.0. The values in this column can be used as multipliers to obtain the prediction interval for a specific case.

C. *Estimation of Breach Time*

According to analysis done in this research, uncertainty of previous models [13] for estimating breach time is high, so that, using these models practically is not logical. Results of uncertainty analysis of collected data related to breach time is as follows:

1) Average of breach time is 3.08 hour.
2) The range of breach time is 0.97 to 5.19 hour with confidence of % 95.
3) The minimum and maximum breach times calculated 0.1 and 48 hour, respectively.

It is proposed to use minimum amount or BREACH model in studying breach time in order to satisfy safety management in downstream of dams.

D. *Estimation of Breach Time*

The best mode of determination of breach slope is using previous breached dam ranges. Analyzed results of uncertainty of dam breach slope are as follows:

1) Average of break slope is 0.98 (h:v).
2) The range of breach slope is 0.79 to 1.17 with confidence of % 95.

E. *Modified BREACH Model*

BREACH model, which is based on hydraulic, hydrology and geotechnical principles, is usually used to estimate embankment dam breach parameters and to determine hydrograph of output discharge due to dam breach. The size of the breach-pipe is growing depending on the flow velocity and material properties. This type of erosion process comes to its end, when a critical pipe radius is achieved (R_{crit}). The material above the pipe is dropping into the breach and the flow/erosion computation is continued similar to the overtopping failure. Using BREACH model in piping mode, to estimate outflow hydrograph for Aidoghmosh dam and some other dams lead to unreasonable results. So, in this research, Equation 11 [29] was adopted for critical conditions of piping in

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BREACH model. This modification was tested in pervious breached dams (e.g. Teton dam) [10]. and revealed better results.

$$R_{crit} = 2c/\rho'(tg\varphi+2)+tg\varphi/(tg\varphi+2)(H_{dam}-H_p) \quad (11)$$

In which, R_{crit} is critical pipe radius (m), c cohesion of the dam material (kPa), ρ' is submerged density of dam material (Kg/m^2), φ is friction angle of the dam material, H_{dam} is elevation of the top of the dam (m), H_p is elevation of the pipe center-line (m).

F. *Case Study*

Aidoghmosh dam was studied as the case study in this research (Fig. 2). Aidoghmosh dam is constructed in Miyaneh city of East Azerbaijan province in Iran. Residential region North West railways, bridges, water and wastewater refinement equipment and Azerbaijan steel factory are located at the downstream of this dam. The empirical equations (Equation 4, 10) and breach time limit, BREACH and FLDWAV models were used to study the breach of the dam. The FLDWAV model is a combination of the NWS DAMBRK and DWOPER models. It is based on the four-point implicit finite-difference numerical solution of the complete Saint-Venant equations of one dimensional unsteady flow along with appropriate internal boundary equations representing downstream dams, ridges, weirs, waterfalls, and other man-made/natural flow controls. The required information for breach analysis is included in Table III.

Table III. Physical properties of the Aidoghmosh dam

height of dam above ground(m)	67
width of dam crest(m)	12
inclination of dam slopes (dry/wet)	1:2/1:2.5
height of spillway above ground(m)	58.5
resource volume at the level of crest of spillway(MCM)	145.2
resource volume at the level of crest of dam(MCM)	212.5
cohesion of the core material(kg/cm^2)	0.28
friction angle of the core material(degree)	30
friction angle of the zone material(degree)	42.5
discharge of 100 years return period(m^3/s)	381
discharge of PMF(m^3/s)	5460
D_{50} of core materials(mm)	0.205
D_{50} of zone materials(mm)	3.35

Fig.2. The downstream of Aidoghmosh dam

Table IV. The results of breach parameters for Aidoghmosh embankment dam.

Breach parameters	Proposed Equation (Eq. 10)		BRECH Model	
	Overtopping	Piping	Overtopping	Piping
Maximum outflow (m^3/s)	43005	28243	55164	36438
Time (hour)	0.97-5.19	0.97-5.19	1.93	2.56

To study the earth dam breach, probable maximum flood (PMF) and 100-year or normal floods were used in overtopping and in piping mode, respectively. Maximum discharge rate was estimated 43005 and 28243 using proposed equation (Eq. 10) for overtopping and piping mode in the body of Aidoghmosh dam, respectively. These predictions are suitable as priming estimation from maximum discharge and show general view of importance of breach danger. Average of breach width was calculated using Eq. 4 for overtopping mode and using Froehlich equation [28] for piping mode in dam body 273m and 164.16m, respectively. Hydrographs of outflow discharge are shown in Fig. 3 for overtopping mode using BREACH model. Hydrographs of outflow discharge are shown in Fig.4 for piping mode using modified BREACH model. The results of breach parameters for Aidoghmosh dam are listed in Table IV.

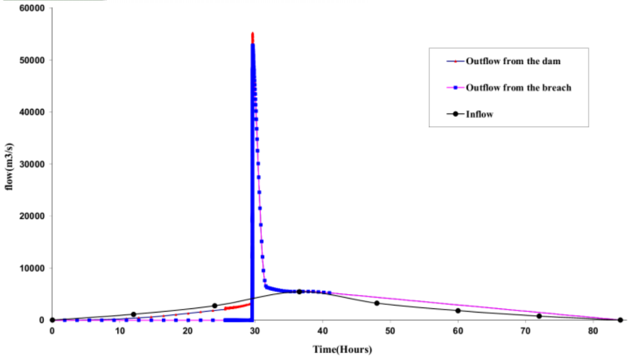

Fig.3. Outflow hydrograph of Aidoghmosh dam due to overtopping (calculated by BREACH model)

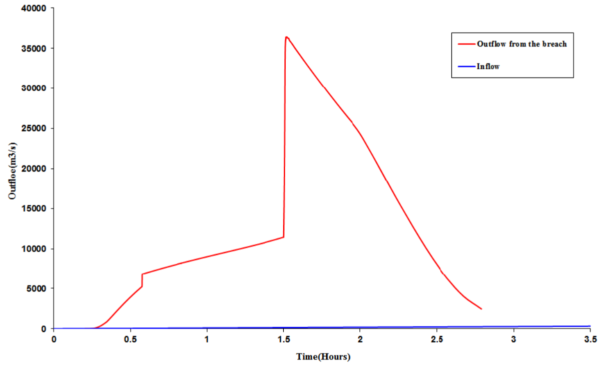

Fig.4. Outflow hydrograph of Aidoghmosh dam due to piping (calculated by modified BREACH model)

The results of empirical and BRECH models (initial breach width and breach time) were imposed to the FLDWAV model, outflow hydrographs were calculated as shown in Fig. 5 and 7 for overtopping and piping modes, respectively. The FLDWAV model was highly sensitive to breach time and led to considerable changes in outflow hydrograph. By changing breach time from 0.97 to 5 hour in FLDWAV model, maximum outflow discharge was ranged 84760 to 29630 m3/s for overtopping mode and 78490 to 31900 m3/s for piping mode. Simulated flow in downstream of the considered dam is demonstrated in Fig. 6 and 8 for overtopping and piping modes, respectively. Simulation of flow in the downstream of the dam was done by implicit scheme and LPI technique (Local Partial Inertia Technique) [5].

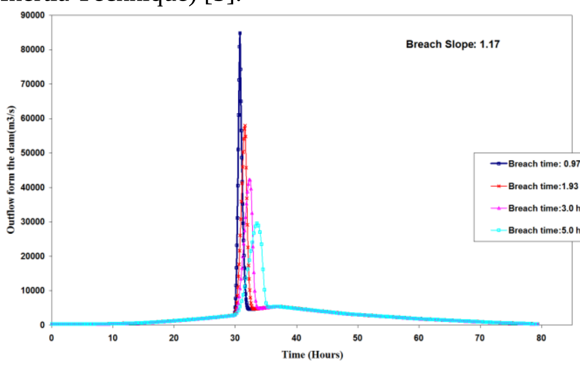

Fig.5. Outflow hydrograph for different amounts of breach time (FLDWAV-overtopping)

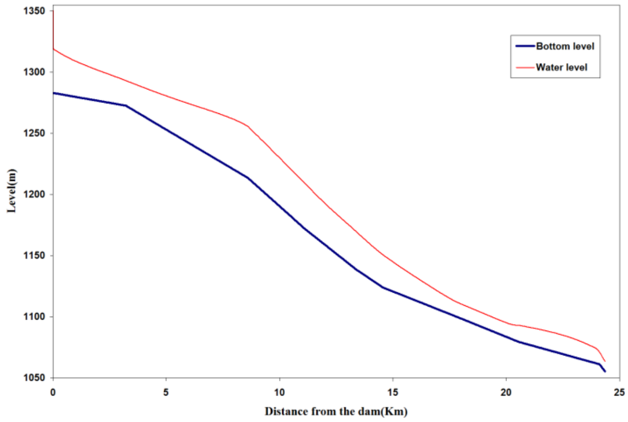

Fig.6. Profile of maximum water level in Aidoghmosh river (overtopping)

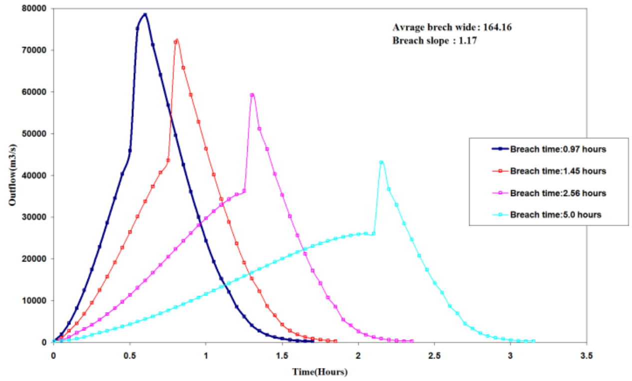

Fig.7. Outflow hydrograph for different amounts of breach time (FLDWAV-piping)

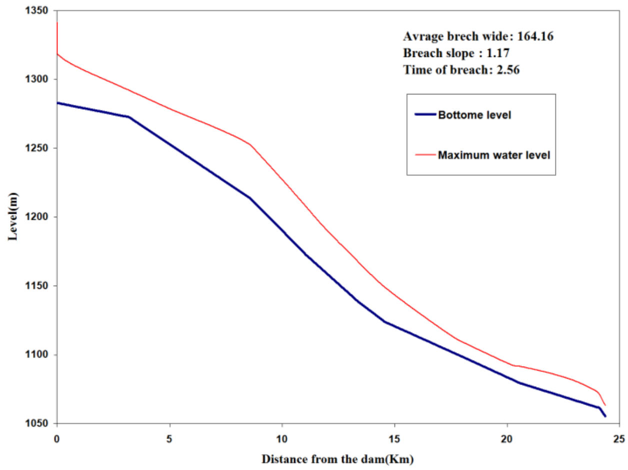

Fig.8. Profile of maximum water level in Aidoghmosh river (piping)

All presented models are included some degree of uncertainty in estimating earth dam breach parameters and should carefully be used in dam break flood studies. The analysis of 142 dam breaches data showed that mean of breach width in earth dams is 2-3 times of dam height and ratio of breach width in dam crest to breach width in the lowest part of breach is 1.13 to 1.64. Because of more data and lower uncertainty, proposed equations (Equations 4 and 10) and breach time limit for calculating breach width, maximum discharging flow and breach time are more accurate than earlier equations, which were proposed by Wahl [13], and it is recommended to use proposed equations as inputs to dam breach flood routing and comparison of flow simulation models. Earlier equations led to improper results for estimating breach time of earth dam and for this reason, BREACH model or uncertainty range of breach time (0.97 to 5.515 hour) can be used for estimating breach time. Upper and lower amounts of estimation can be used for the critical possible situation for determining breach width and maximum discharge and breach time, respectively. Sensitivity of BREACH model was not very significant to outflow hydrograph in overtopping mode with regard to properties of grain size classification. BREACH model in overtopping mode was markedly effected by initial depth of breach. In this study, depth of breach was considered 0.15 m according to the characteristics of Aidoghmosh dam. Maximum discharge and breach time were estimated as 52852m3/s and 1.93 hour, respectively due to overtopping mode. Modification of BREACH model as Equation 11 led to better results regarding pervious dams (e.g. Teton dam, Fread, 1988). In this case, maximum discharge and breach time were calculated as 36438 m3/s and 2.56 hour. According to Fig.s 6 and 8 maximum outflow of Aidoghmosh dam and maximum water level near the residential region (Km 24+300) were estimated 58327 and 1063.9 m for overtopping mode, and 59233m3/s and 1063.31m for piping mode, respectively. Considering obtained results from breach of studied dam, water and wastewater refinement equipment, four bridges beside railways and part of Rah-Ahan residential region are exposed to the risk of flooding due to dam break. Since a dam break is a very quick process, it seems essential to do necessary management and warn people when such disaster is occurred.

II. Conclusion

Results obtained from this research can be briefly presented as follows:

1) All estimations for embankment breach parameters include uncertainty and results of estimations were valid with a specific probability.
2) Proposed models were presented according to 142 broken earth dams. Because of more data and lower uncertainty, the accuracy and reliability of the models were better than previously presented models.
3) Better results coulde be gained using geotechnical conditions for BRECH model for determining collapse time of piping in the body of dam considering real broken dams.
4) BREACH model in overtopping mode was markedly effected by initial depth of breach. In this study, initial depth of breach was considered 0.15 m according to characteristics of Aidoghmosh dam.
5) The FLDWAV model was highly sensitive to breach time and made considerable changes at the outflow hydrograph.
6) FLDWAV model demonstrated high quantity for estimating maximum discharge in piping mode in dam body, because this model calculates collapse of formed pipe immediately and without conditions of sediment transfer.

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