EXPERIMENTAL BREACH AND OVERTOPPING STUDY IN EARTH DAMS BY PHYSICAL MODELS

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ABSTRACT

Overtopping and Internal erosion are two major threats that affect the safety of earth dams during emergency events like floods or earthquakes or even during normal operation. Both of these defections cause failure and piping throw dam body and progressive failure of the main dam. In numerical simulation of dam breaks and flood routing at downstream of dams in Emergency Action Plan (EAP) studies and preparation of inundation maps; usually a simple non progressive pattern is considered for dam breach. It seems that the progressive nature of the damage mode affected by dam body material and geometry, and hydraulic gradient; should be considered more precisely. In this paper main affecting parameters of the phenomena are reviewed and the preliminary planning for some physical model tests to be conducted on model dam bodies with intentional induced breaches or over topping, are presented.

Keywords *: overtopping, breaching, physical model, hydraulic gradient, earth dams*

1. INTRODUCTION

The increasing human population and the consequent need for drinkable water is an important issue for governments, and the construction of dams as a way of collecting surface water is considered to be the most efficient way. Dams can also be hazardous in addition to numerous concessions, because in the event of a dam failure in addition to the loss of an important water source, it can cause irreparable financial and life loss by damaging downstream.

Dam breaches can occur gradually or suddenly. Gradual failure occurs more often in earthen dams due to the phenomenon of overtopping or piping. Sudden breaks often occur in concrete dams due to overtopping or sliding bearing. For instance, the failure of the Johnstown Dam in Pennsylvania in 1889 (Figure 1), it is noted that there were 2,200 casualties.

Figure 1 : Johnstown after the 1989 flood and failure of upstream Johnstown dam (Johnstown Area Heritage Association).

The failure of the dam will lead to the release of large quantities of water in the form of floodwaters and mud in addition to the life-threatening risks of water loss in a country.

Therefore, completing our information on the process of dam failure could be very useful and necessary. In this study, our main focus will be on failures in earth dams.

The gradual failure of embankment dams is accompanied by a progressive crack in the body of the dam. The way of creation of a crack in the body, the duration of its creation, as well as the final geometry of the fracture section (generally the fracture parameters), will have a significant impact on the flooded area downstream and the extent of the damage.

Accurate prediction of dam breach characteristics is one of the most important and complex issues to analyze for failure problems in the earth dams and it has a lot of uncertainties. (McDonald 1994), If we cannot accurately predict dam breakdown parameters, we need to be more cautious in shield design, which will lead to higher costs, and with today's global community moving towards more accurate computation and optimization of designs is inevitable. In this study, we intend to work on practical solutions in addition to examining the dam breakdown theory.

It is worthwhile mentioning that the importance of this issue in dams' safety is due to the fact that it can give us a better understanding of the dam breach process by obtaining a failure rate, and by moving the terms towards more practical ones, they can be used in software and instructions. As these issues become more precise, it is possible to address the dam's emergency action plans and reduce the ramifications of dams' failure in addition to achieving a meticulous design.

2. THE CHALLENGE

The first issue to be discussed is the type of material, it should be noted that regarding materials, unmatched gradation and their properties can lead to different behaviors when dam fails. For example, the erosion of a clay core dam differs from the erosion of a homogenous sand and gravel dam.

In broad terms, low erodibility materials show head cut, whilst more erodible materials show surface erosion or, as particles get even more coarser (gravels, rocks), forms of slumping (Alves, Toledo, & Morán 2016, Toledo, Alves, & Morán 2015).

Many researchers have proposed models for each of these materials, but there is no integrated standard for where to use these models and further studies are needed in this area. Our focus in this research will be on aggregate materials, and in particular, we have attempted to focus on overtopping and piping by controlling the time and optimizing models.

In the next step, the subject is the variation of failure parameters. Until now, all designs and softwares have considered a final breakdown stage and time of fracture for computation, and according to geometrical and temporal characteristics of the fracture time, the design studies are performed. The main focus of this study is to investigate the damages development in earth dams from the moment of inception to the moment of dam breach.

This paper explains a research program consisting of laboratory physical model tests and numerical modeling examines the issue of dam failure in earthen dams and attempts to find a simple method to exploit in the industry.

3. TERMINOLOGY

In this part it is aimed to elaborate on the notions of earth dam failures, and then some results of the available researches are presented.

3.1 Types of earth dam failure

Overtopping Failure: It is simulated as a rectangular, triangular or trapezoidal fracture and is calculated at each moment using the equation governing the broad-crested weir.

Piping failure: In this case, the fracture develops over time. Output flow is calculated at each moment using the Orifice equations.

3.2 Equations governing erosive failure of earth dams

Equations governing non-permanent currents in open streams and rivers, as well as waves caused by dam failure are presented by St.Venant in 1871. To obtain this equation, the assumptions of hydrostatic pressure distribution, uniform velocity distribution in the vertical section or neglecting the vertical component of fluid particle acceleration are considered.

- Water Flow Consistency Equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial A_d}{\partial t} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

- Water Flow Dynamic Equation:

$$\frac{\partial Q}{\partial x} + \frac{\partial (\frac{Q^2}{A})}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{2}$$

in which Q is flow rate, A is flow area, A_d is deposition area, z is water surface height, g is gravity acceleration, S_f is energy line's slope. Also, t and x represent time and space, respectively.

- Sedimental Consistency Equation:

$$\frac{\partial G_s}{\partial x} + \gamma_s(1-\lambda)\left(\frac{\partial A_d}{\partial t}\right) + \frac{\partial (A.C_s)}{\partial t} = 0 \qquad (3)$$

In the above equation, G_s represents the specific gravity, C_s is the concentration of suspended matter, γ_s is the specific weigh of the solids and λ is the porosity of the sedimentary material.

The sediment transport equation can also be obtained by using one of the most common formulas in sediment hydraulics. The above equations can only be solved analytically if there is a very specific and limited state of the waves that can be simplified by assumptions. Nowadays, due to the advancement of computers, equations are solved by numerical methods and various numerical methods are used depending on accuracy, speed, stability and convergence of the case.

3.3 Dam Breach Parameters

As mentioned before, the failure parameters scrutiny and the development of breakdowns have always been very important and have involved many uncertainties. In recent years, researchers have used parameters that have been used to control dam failures. In the following we examine these parameters.

3.3.1 *Geometric properties of cross section*

Figure 2 shows the geometrical characteristics of the broken section of the earth dam, with the following parameters:

Depth of Break (h_b & h_w): The vertical height of the fracture is measured from the dam's crest to the fractured bottom (h_b). In some references, the distance from the surface of the water head is considered (h_w);

Fracture width (B): This parameter is equal to the final width of the fractured cross section. The expansion rate of this width can have a significant impact on the maximum outflow rate of the fracture cross section and the flooded area in the downstream areas.

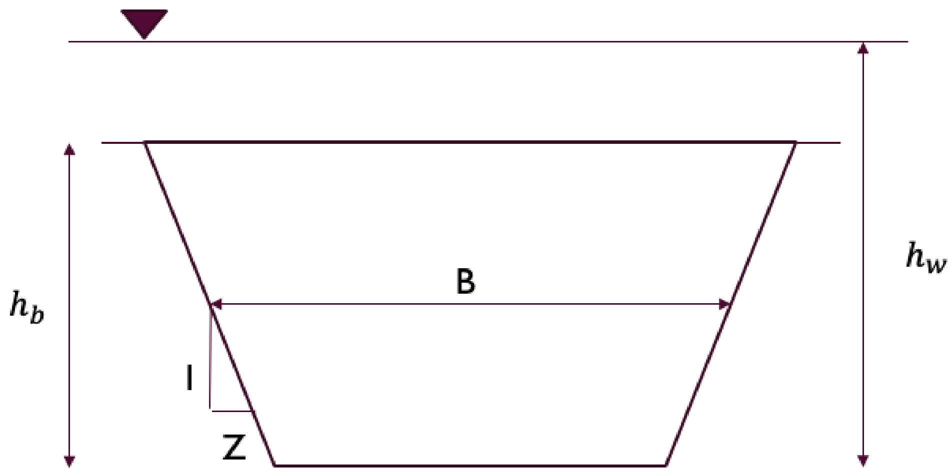

Figure 2 : Schematic cross section of dam failure.

Fracture side slope (Z): lateral slope of the crack

By using the lateral slope of the crack width and its depth, the geometry of the fractured cross section can be obtained. In general, the effect of lateral slope is of secondary importance. The value of this lateral slope parameter depends on the friction angle and water content of the soil through which the fracture is created.

3.3.2 *Required time for completion of the erosion and demolition of dam body*

As mentioned before, the failure of the earthen dams is gradual, and the expansion of the failure crossings in the body of the earth dams is a time-dependent process, with variable increasing rate. This erosion occurs at two time intervals. In the early moments of the overtopping from dam body, dam destruction has not started and the outflow from the dam is low. Outlet of the dam reservoir in this phase can be due to a small amount of overtopping or a small amount of leakage from the piping. After this phase the fractured cross section begins to fail in a time dependent manner. Outflow and erosion are increasing rapidly from now on, and dam demolition is not expected to stop.

The total failure time of the dam can range from a few minutes to several hours. The two phases of the time frame are discussed below.

Failure Starting Time: The failure begins with the first blade crossing over or through the dam, which in fact should begin with an emergency alert and discharge. This phase ends when the crack expansion time begins.

Crack Expansion time (t_f) : This time can be achieved with the help of the researchers proposed equations. This time is equal to the time interval between the crack formation upstream of the dam until the crack is fully formed.

3.4 Popular equations for estimating breach parameters

So far, many studies have been conducted to investigate the failure parameters that can be summarized in the Table below. These results are more consistent and agreed by researchers.

Table 1 : Some available and popular equations for estimating breach parameters.

Reference	Piping	Overtopping
Fread (1985)	$B = 9.5 * 0.7(V_w h_w)^{0.25}$ $t_f = 0.3{V_w}^{0.53}{h_b}^{-0.90}$	$B = 9.5 * 1.0(V_w h_w)^{0.25}$
Froehlich (1995)	$B = 0.18034{V_w}^{0.55}{h_b}^{0.19}$ $t_f = 0.00254{V_w}^{0.55}{h_b}^{-0.90}$	$B = 0.2524{V_w}^{0.32}{h_b}^{0.19}$
Von Thun and Gillette (1990)	$B = 2.5h_w + C_b$ C_b depends on V $t_f = 0.020h_w + 0.25$ (erosion resistant) $t_f = 0.015h_w$ (easily erodible)	
US Bureau of reclamation (1988)	$B = 3h_b$ $t_f = 0.11B$	
MacDonald and Langridge-Monopolis (1984)	$t_f = 0.0179(V_{er})^{0.364}$ $V_{er} = 0.0261(V_{out}\ h_w)^{0.736}$	

NOTE: V_W in Fread equation is in acre-ft and h_w in ft
V_w in Froehlich equation is volume of water above breach invert elevation at time of breach, m^3
V is the reservoir capacity, m^3
V_{er} is the volume of embankment material eroded, m^3
V_{out} is the volume of water discharged through breach, m^3

4. PROPOSED PROGRAME OF THE RESEARCH

The proposed program for this research consists of laboratory scrutiny of the phenomena and development of laboratory physical models and the study of a numerical models and finally comparison of the results.

Certainly, a large-scale case study can be a great help in comprehending the subject and conducting a large-scale experiment is one of our goals, if possible.

Both phases of research focus on examining the extent of damage to the body of homogenous earth dams, and the main point of the experiments is to examine each failure separately. At the end of the research, terms are established to explain how the assumed earths dams eroded from the beginning of the breakdown to the moment the dam breach.

The research program during the project might be modified based on the findings of each experiment.

5. RESEARCH IMPLEMENTATION

Laboratory experiments and all stages of this research are carried out for answering the following questions:

1. How the expansion of the failure can be described as a function of time
2. Critical failure locations can be categorized
3. Provide a numerical model suitable for earth dam failure
4. Provide an appropriate practical proposal and safety measurements for dam safety

5.1 Laboratory experiment plan

Experimental investigation for overtopping and piping failure modes is performed by constructing two experimental models. Examination of the failure expansion in each of the two models is performed as a function of time to obtain the failure expansion attributes.

5.1.1 *Overtopping*

For the purpose, according to the phenomenon under study, a model with a length of 5 meters, height of 1 meter and a width of 1 meter is considered (Figure 3). For this model, a water pump is designed to stabilize the water level behind the dam, and 2.5 meters of water is used to model the water behind the dam. According to previous studies, it is important to investigate this phenomenon behind the dam model. Therefore, a distance of 1.5 meters in front of the dam has been established to investigate the impact of this distance and to investigate the sediment resulting from dam failure.

The dam that will be used is 1 meter wide and has the height of 1 meter, and after the dam impoundment, we will investigate how to examine the dam failure expansion with the built-in cameras. It is noteworthy that new methods of particle motion monitoring are used to investigate the spread of the breakdown, which is similar to the case study of the Waktola method (2017) that can be found in the references for those interested in further information. It is worth stating that in this experiment, the inalterability of water level is controlled by a laser.

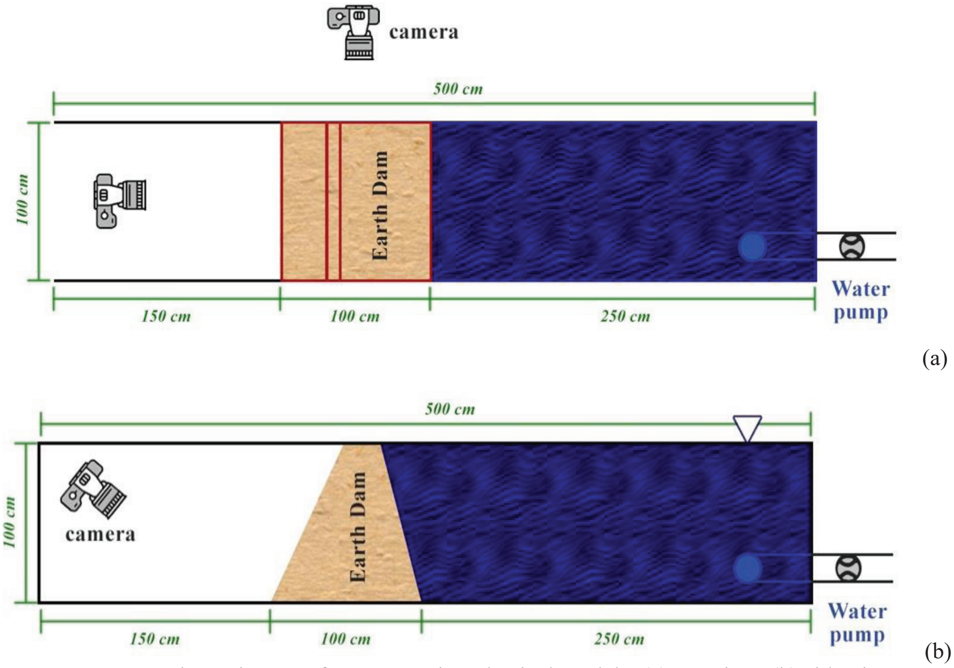

Figure 3 : Schematic setup for overtopping physical models: (a) top view; (b) side view

5.1.2 *Piping*

In this section, a model with a length of 1.4 meters, width of 1 meter and a height of 1 meter is used (Figure 4). The model uses a water source behind the modeled dam that has a larger water head than the height of the dam, which is embedded in the dam body to increase the rate of water seepage, separated by a reticular plate between the two reservoirs. A pipe is embedded in the body to observe piping, and the changes around the pipe are controlled by cameras. In this case, a water reservoir is also used to keep the water level constant. The bottom of the model also uses a special section for sediment analysis.

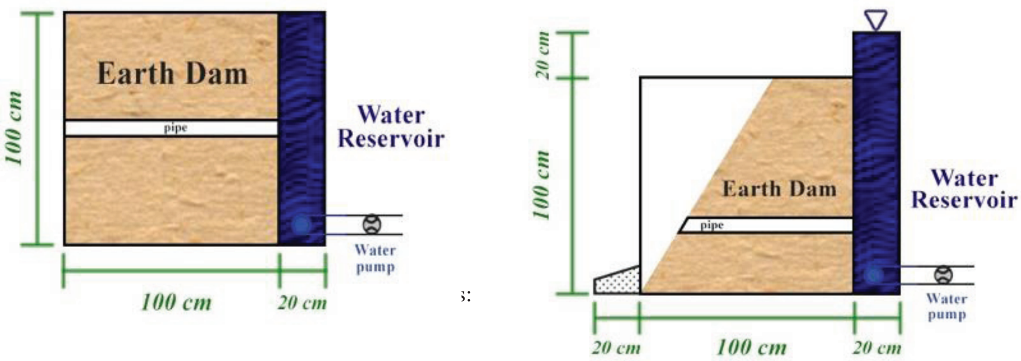

Figure 4 : Schematic setup for piping physical models: (a) top view; (b) side view

5.2 Numerical model

For the numerical model, the "breach erosion process modeling" approach will be used, and the EMBREA model (Mohamed, 2002 and Morris, 2011) will be used to evaluate the failure progression from inception to complete breakdown. The model is a commercial model for dam breach and models the failure procedure.

An example of the experimental investigations is given in Figure 5. This model will help to refine the geometric properties of the laboratory models during the research and will also be used as a guide.

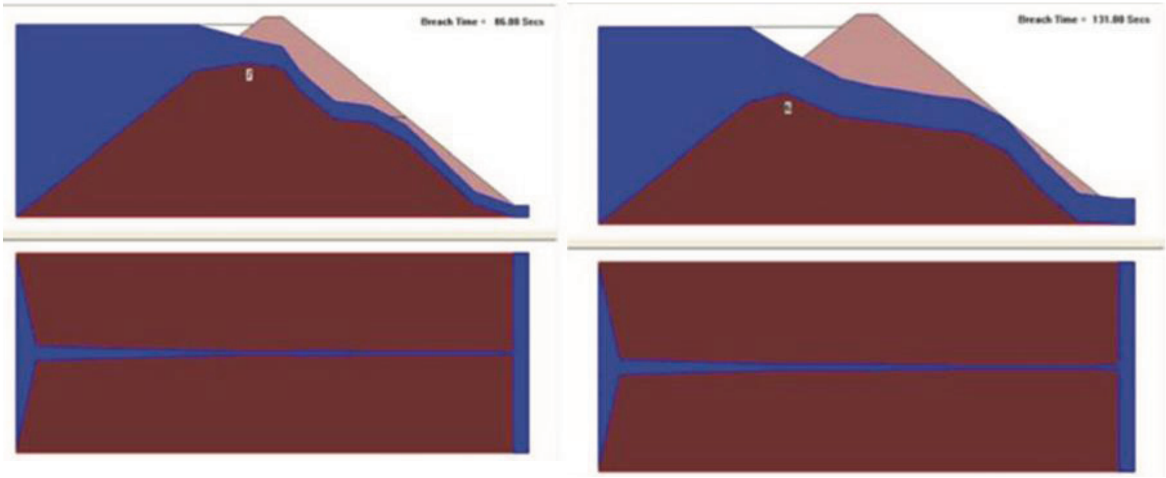

Figure 5 : Examples of using EMBREA code for modelling of breach erosion process showing breach erosion progression with different zones of erodibility (Morris et al.,2019).

6. CONCLUSION

Safety of earth dams could be threatened due to dam body breach caused by overtopping or pipping, during heavy floods, strong ground motions or any structural damage or defection. In this paper some affecting parameters on the phenomena are introduced. Also based on the experience of various cases, a comprehensive research plan was explained based of physical model tests and numerical modeling of both failure mechanisms.

REFRENCES

Asghari Tabrizi, A., Elalfy, E., Chaudhry, M.H., Kahn, I.B., and Imran, J., 2015. Experimental Modeling of Levee Failure Process due to Overtopping.

Bureau of Reclamation. 1988. 'Downstream hazard classification guidelines. ACER Tech. Memorandum No. 11, U.S. Department of the Interior, Bureau of Reclamation, Denver, 57.

Do, X.K., Kim, M., Nguyen, H.T., Jung, K. 2016, Analysis of landslide dam failure caused by overtopping , 10.1016/j.proeng.2016.07.587 .

Fread, D. L. 1985. Dam breach erosion modeling. Proc., Conf. on Delineation of landslide, flash flood, and debris flow hazards in Utah, Utah State Univ., Logan, Utah, 281–310

Froehlich, D. C. 1995a. Embankment dam breach parameters revisited. Water Resources Engineering, Proc. 1995 ASCE Conf. on Water Resources Engineering, New York, 887–891.

Froehlich, D. C. 1995b. Peak outflow from breached embankment dam. J. Water Resour. Plan. Manage. Div., Am. Soc. Civ. Eng., 121(1), 90–97.

Güney, M. S., Tayfur , G., Bombar, G., and Elci, S.,2014. Distorted Physical Model to Study Sudden Partial Dam Break Flows in an Urban Area, 10.1061/(ASCE)HY.1943-7900.0000926. American Society of Civil Engineers.

Larese, A., Rossi, Oñate, E., Toledo, M.A, Morán, R., and Campos, H., 2014. Numerical and Experimental Study of Overtopping and Failure of Rockfill Dams. 10.1061/(ASCE) GM.1943-5622.0000345. American Society of Civil Engineers.

MacDonald, T. C., and Langridge-Monopolis, J. 1984. Breaching characteristics of dam failures. J. Hydraul. Eng., 110(5), 567–586.

Mohamed, M. A. A. 2002. Embankment breach formation and modelling methods. PhD., The Open Uni- versity, England.

Monteiro-Alves, R., Toledo, M.A., and Morán, R., 2019. Characterization of the Overtopping Flow through the Downstream Shell of Rockfill Dams , 10.1061/(ASCE)HY.1943- 7900.0001598. American Society of Civil Engineers.

Morris, M.W. 2011. Breaching of earth embankments and dams. PhD. The Open University, England.

Morris, M.W., Courivaud, J.R., Morán, R., Toledo, M.Á., Picault, C., 2019. Levee and dam breach erosion through coarser grained materials, Sustainable and Safe Dams Around the World – Tournier, Bennett & Bibeau Eds Canadian Dam Association, ISBN 978-0-367-33422-2 .

Toledo, M. A., Alves, R. M., & Morán, R. 2015. Structural failure of the clay core or the upstream face of rockfill dams in overtopping scenario. In Proc., 1st International Seminar on Dam Protections.

Waktola, S., Bieberle, A., Barthel, F., Bieberle , M., Hampel , U., Grudzień, K., Babout, L., 2018 , A new data-processing approach to study particle motion using ultrafast X-ray tomography scanner: case study of gravitational mass flow, https://doi.org/10.1007/s00348-018-2523-2 . Springer Experiments in Fluids 59:69 .

Wu, W., 2013. Simplified Physically Based Model of Earthen Embankment Breaching,10.1061/(ASCE)HY.1943-7900.0000741. American Society of Civil Engineers.