Breach Opening Characteristics and Dam Failure Due to Overtopping

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Abstract

Earth Embankment dams are highly exposed to failure due to overtopping especially with the changing climate worldwide. The failure progress and breach profile are very important characteristics that are reflected on the resulting downstream hazard. A cohesive earth mixture embankment was used in this study to explore the breach parameters' correlation with dam failure progress. To achieve the study objectives, a dam model in small scale flume was directed to flop under hydraulic controlled conditions. Three pilot channel shapes were considered in this study. The effect of the pilot channel shape, breach characteristics in addition to the compaction percentage on the breach morphology and discharge were investigated. The erosion was found to develop from vertical to mostly lateral in nature. It was found that the shape affects the failure progression and time to breach. The results confirm the importance of dam compaction in resisting the failure with increased water level.

Keywords**:** Dam failure, breach characteristics, pilot channel, breach time, breach width.

1. INTRODUCTION

Dams are hydraulic structures constructed across channels to impound water in the upstream reservoir formed to supply water to irrigation, hydropower generation, domestic and industrial water supply. The determination of dam breach properties as breach width, shape, peak outflow, and failure time is important to understand the breaching mechanism that supports the mitigation and adaptation strategy in the case of dam failure. The erosion process can potentially initiate at any point of the slope but usually takes place at the toe of the dam.

Dam failure may result from extreme flood events with increasing siltation rates upstream reducing the storage capacities, wave attack and recently due to global warming causing a.o. increased precipitation rates. It also could be due to an unexpected increase in water levels caused by intense rainfall or due to inadequate design and construction of the embankment [1]. Dam failure is defined according to [2] as partial or catastrophic failure leading to uncontrolled release of enormous flood to the downstream.

The earth embankment failure may be due to overtopping or internal cracking due to piping. According to [3] the most common type of failure in earth and rockfill dams is overtopping (31% as a primary cause, 18% as a secondary cause). Dam overtopping can also cause a flood pulse downstream of a dam without the dam failing due to the stage discharge relationship of the reservoir. Dam overtopping and dam failure are very difficult processes to understand, predict, analyze, or model due to the inherently complex and relative nature of the overtopping and failure processes and lack of existing data relevant to dam failure.

The peak discharges were analyzed [4] under different failure modes and concluded that the overtopping failure mode had the smallest peak discharge, followed by the slope failure mode. In the overtopping mode, the stress happens by the increased water level causing the downstream dam face to start erosion and initiating the breach, [5]. A study [6] evaluated the effect of breach shape on dam failure due to overtopping.

Failure happens usually as a result of hydrodynamic forces on the downstream resulting in soil removal and formation of a head cut. The breach happens due to the increased water level in the upstream pushing water in the breach pilot channel, increasing the shear stress above the critical limit. Then consequently the erosion starts gradually. The soil removal takes place in the downstream, known as cover failure, and headcut starts to develop at the downstream toe. Then it spreads upward with lateral widening until the headcut reaches the dam crest. By reaching the dam crest the breach opening increases, then the failure progresses dramatically due to flow swelling in the crest breach pening. Different research studies are available tackling the earth embankment and levee breach failure using either physical models, or physically based numerical models [7-14].

Some of the main governing parameters that could resist the failure is the soil type, characteristics, erodability and compaction percentage, as was investigated by [15], [16]. According to [17], the clay, silt sand and sand earth dam material time breaching varies between rapidly to very rapidly breach (3 hours to day). It was observed [18] that increases in compaction effort and water content for the same soil material increased the erosion resistance of small earth embankment flume tests significantly.

In a breaching process, it is very important to determine the lag time, time to peak, breach time, peak outflow. The resulted breach width and depth depend on dam characteristics. A study defined breach initiation time [19] as the time that spans from the first flow over the dam initiating warning, evacuation, or heightened awareness of dam failure, to the breach formation phase. The breach formation phase is the span of time from the first lowering of the upstream earth embankment crest, to the point at which the upstream face is eroded to near full depth of the earth embankment dam.

According to [20], in the breach process, the very initial stages of levee failure include vertical erosion which is similar to dam failure. In later stages, horizontal advancement of levee breach starts increasing after the deepening process reaches a certain state.

[19] Stated that existing information is limited to final depth, final breach width, final shape, total eroded volume, estimated peak discharge, maximum overtopping depth, and failure time. According to [21] the breaching process and the failure progress still needs more work to get more in-depth with the process. [22], [23] argued that there is still lack of phenomenological insights on the processes that occur during breach growth, although there have been several small and large scale laboratory studies on earth embankment failures by overtopping that provided useful discharge hydrographs for model validation.

Several assumptions were made about the shape of the breach and an empirical coefficient was used to calibrate the model [24]. Although a lot of work has been executed tackling the failure process, but still more work needs to be done as stated by the previous investigator, especially in studying the effect of the pilot channel shapes on the failure process. [25] Executed experimental study to examine the impact of the pilot channel effects on the breach characteristics to fill the missing gap as there is not much work on this topic. [26] Stated that even though we have latest technologies in design methodologies and construction techniques, failure of dams still occurs. This calls for extra work to be done to understand the different reasons and parameters affecting the dam break progress.

2. OBJECTIVES

Breach characteristics are very vital; they deviate due to the earth embankment characteristics and the start of the overtopping process. This research study was therefore implemented to investigate the differences in the resulted breach parameters due to changing pilot channel shape, depth and width. The impact of the carved pilot channel was also inspected. The significance of the compaction percentage of the earth embankment material was also explored in the study.

3. EXPERIMENTAL WORK

The experiment study was executed in Hydraulics Research Institute (HRI), in flume of 20 m length, 1.4 m width and 1.0 m height, Fig. 1. The test's main condition was to conserve a constant water level upstream the earth embankment. To achieve this condition, a large reservoir was constructed upstream the earth embankment in the available area. Water was supplied to the main channel using centrifugal pump with constant discharge to maintain the water level constant. The reservoir was filled at a rate 0.3 l/s until it reached the level of the pilot channel. The discharge was measured on the delivery pipe of the pump using ultrasonic clamp on instrument. The flow rate downstream the earth embankment was measured using 0.49 m calibrated wide sharp crested weir. Two ultrasonic water level sensors were installed to measure the upstream water level and to measure the water head over the sharp crested weir in the downstream.

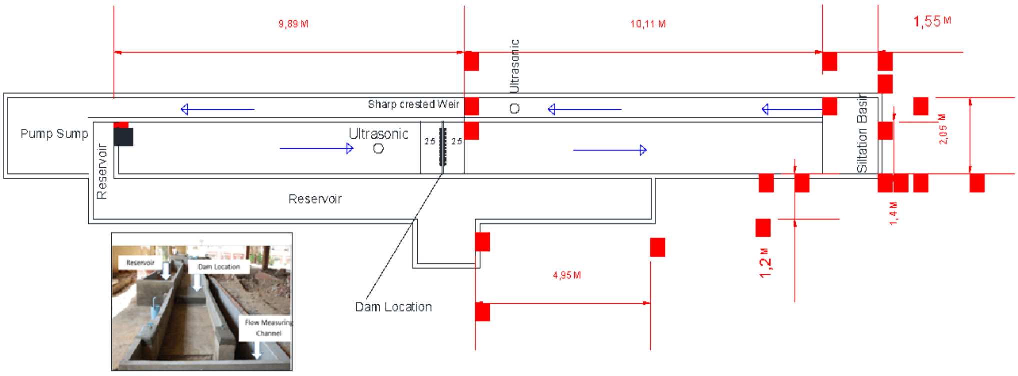


Figure 1: Experimental setup

A trapezoidal cross section was selected for the earth embankment with side slope 1:2.5 (V:H) for side slope stability. The construction for one test takes from 3 to 4 days, the embankment was constructed in layers, each layer of 15 cm thickness. The earth mixture embankment was constructed from cohesive soil of 58% sand, 30 silt% and 12% clay (Fig.2), the soil properties are shown in table (1); according to AASHTO soil classification system, the soil is classified as (A-2-6). The mixture D_{50} is 0.14 mm and D-mean of 0.36 mm with water contents of 11%. A Pilot channel was carved at the middle dam crest in order to initiate the overtopping process.

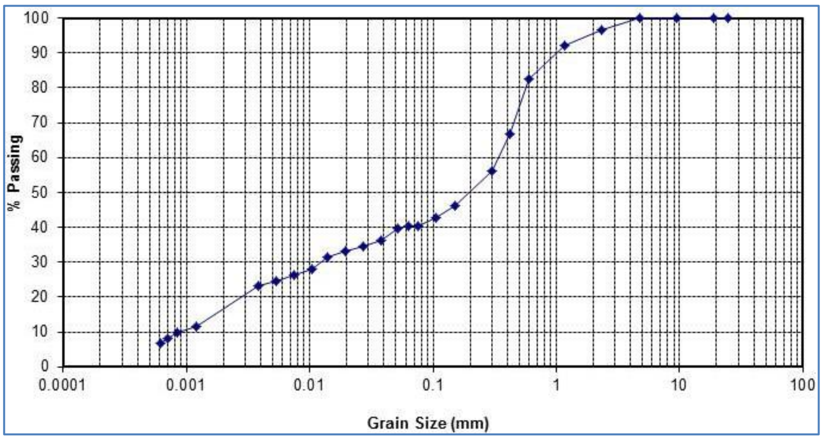


Figure 2: Grain Size Distribution Curve

Table 1: Soil Properties

Parameter of Tested Soil	Results
Soil type	**Clayey Sandy Silt**
Specific gravity m^2/s	9.81
Liquid Limit (L.L) %	38.9
Plastic limit (P.L) %	150
plasticity Index (P.I) %	23.9
Maximum Dry Density (γd) (gm/ cm3)	2.01
Optimum moisture content (O.M.C.) (%)	11%
Bulk Density (γ) (gm/ cm^3)	2.21
Dry Density (γ_d) (gm/ cm^3)	2.01
Water Content W_c (%)	10.0
Critical Length Without Tension Cracks (Z_o) (cm)	122.5
friction angle (φ)degree	30.3
cohesion (C) kg/ cm^2	0.065

The failure progress was considered to start once the water reached the level of the pilot channel at the crest, and then the breach discharge was recorded in addition to the breach morphology. The breach evolution was monitored using scaled rods, a sliding-rods setup was used, as shown in Fig. 3. The setup consisted of two rows of rods, with rod intervals of 10 cm. The setup was placed on the downstream slope of the earthen dam with the first row aligned with the end of the crest (US) and the second in the middle of the downstream (DS). The breach evaluation was measured by defining rods movement, recorded using digital camera fixed in the upstream and the downstream with recording at 20s frames.

When the anticipated erosion of the earth embankment was reached (reduction 10% in the reservoir water level), flow through the breach was rapidly halted shutting down the pumps. Any remaining water in the earth embankment upstream was drained using a bypass drain under the embankment base.

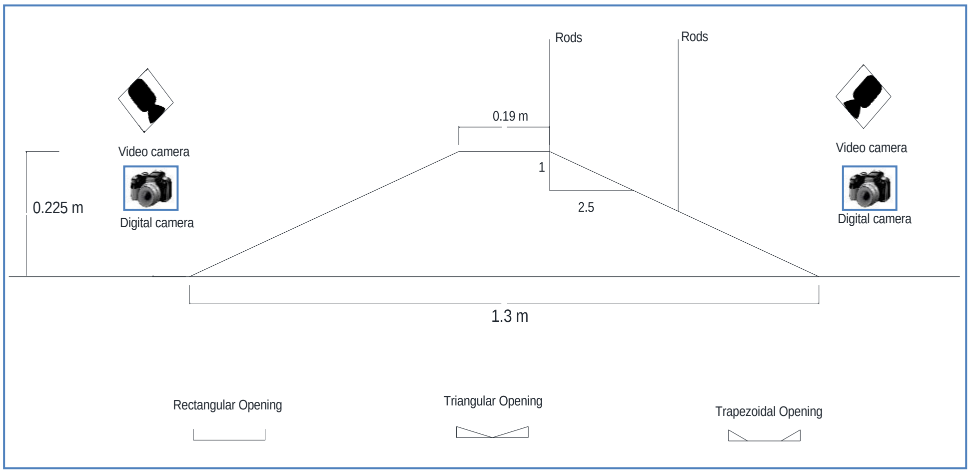


Figure 3: The Embankment cross section and Monitoring Tools

After each test, the earth embankment was totally rebuilt, the reservoir was refilled, and breaching process from the initial breach to the failure was recorded for each experiment, and the above mentioned process was repeated.

4. RESULTING BREACH PROGRESS AND DAM FAILURE DUE TO OVERTOPPING

The failure development process was monitored using a high resolution video camera and digital camera to capture snapshots with fixed intervals. To distinguish between the different failures modes, the breach dimensions and time of development were recorded for the different scenarios in addition to the outflow hydrographs. The breach location for the different cases was determined, which depended on different parameters related to the dam characteristics and the failure mode.

Six earth embankments were constructed from the same earth mixture material with the composition specified in the test program illustrated in Table (2), with crest width of 0.19 m and bottom length of 1.3 m and total soil volume of 0.236 m^3 for each dam. The width of the pilot channel was selected as 10 % of the flume width, and with changing the opening shape and dimension the area reserved constant for all cases except case triangular (2). Five tests were under the low compact condition and one test was well compact. The dam was compacted using controlled moisture content throughout construction to ensure that optimum moisture content was used. This was verified through Standard Proctor Tests as illustrated in Fig. 4. Optimum compaction was done using a small mechanical compactor, while the low compaction test was achieved without any static load.

Table 2: Test Program

No.	Material Composition			Pilot channel shape	Dimension (cm)	Compaction
	Sand	Silt	Clay			
1	58%	30%	12%	Rectangular	15 * 2	Low compacted
2	58%	30%	12%	Triangular 1	15 * 2	Low compacted
3	58%	30%	12%	Triangular 2	30 * 2	Low compacted
4	58%	30%	12%	Triangular 3	15 *4	Low compacted
5	58%	30%	12%	Trapezoidal	7.5 *15 * 2	Low compacted
6	58%	30%	12%	Rectangular	15* 2	Well compacted

In selecting the dam height and reservoir size, it was considered that the final breach width would not reach the side walls before stopping the test and not be influenced by wall effects. The breach and failure progress were identified by collecting data on water level variation upstream the dam, flow discharge measured in the downstream over the sharp crested weir, and breach cross-sectional area.

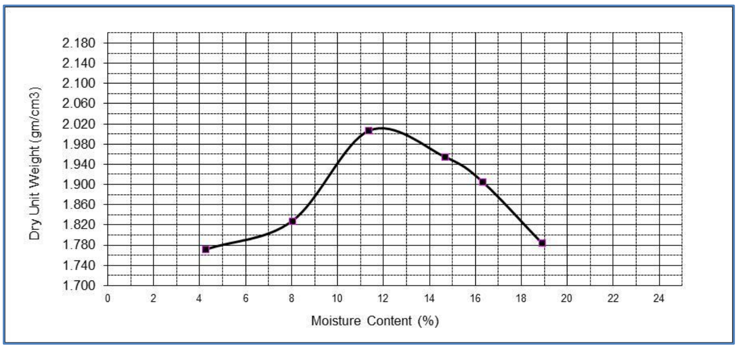


Figure 4: Compaction Proctor Test

From observation of the failure progress, it was found that the erosion started in the downstream face going to the dam toe, then the process completes vertically upwards to the crest forming the headcut at the crest. Then, it takes the lateral widening trend until the channel widens causing breach flow to increase and pushing it towards total dam failure. This confirms the work of [6], [27].

For all cases, staircase was created on the downstream face of the dam.. The shape of the breach width is almost parabolic shape. Example of breach development during the failure processes is illustrated in Fig.5 below. Table (3) shows the maximum breach depth and width for each test.

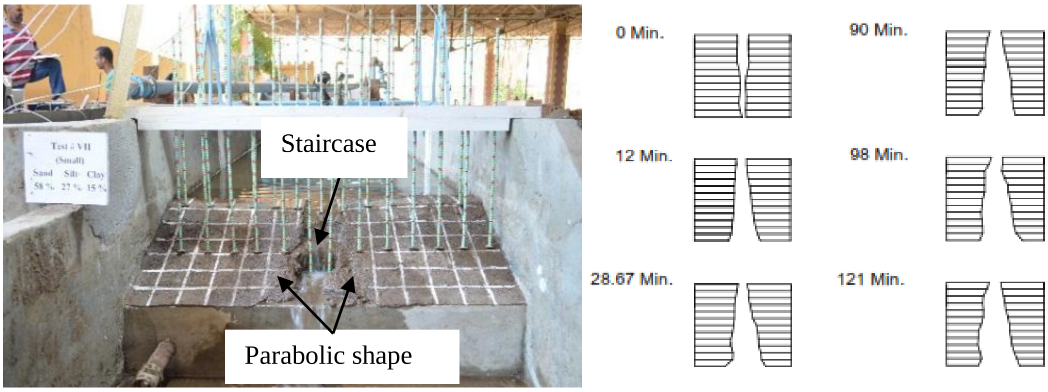


Figure 5: Breach Progression over D.S face for compacted dam

Table 3: Breach Depth and Width

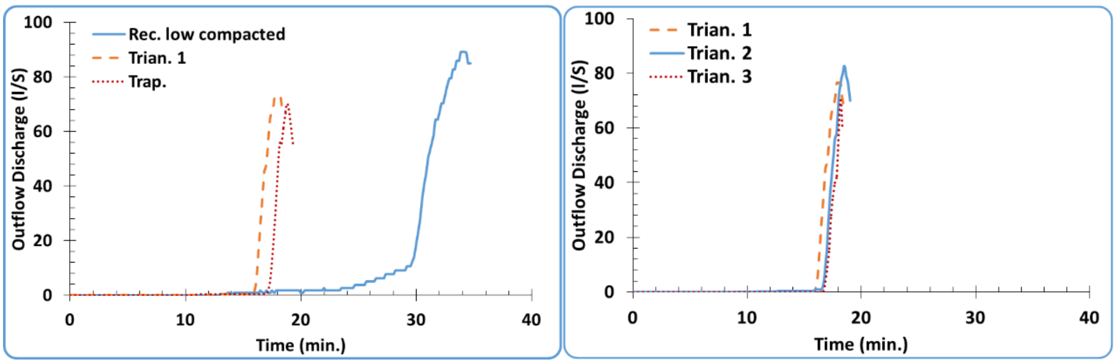
Case	Max. depth (US) (m)	Max. width (US) (m)	Max. depth (DS) (m)	Max. Width (DS) (m)
Rec. Low compacted	0.22	0.85	0.10	0.99
Rec. Well Compacted	0.03	0.15	0.01	0.59
Trian. 1	0.20	1.07	0.10	0.84
Trian. 2	0.22	1.01	0.11	0.92
Trian. 3	0.20	0.74	0.11	0.81
Trapezoidal	0.21	0.73	0.12	0.68

4.1. Breach Hydrograph Observations

It should be mentioned that the lag time (from the test start to the moment there is a significant discharge through the pilot channel) was found to be almost the same for all the low compacted tests with about 16 minutes, and the time for breach was then recorded for all tests. To assure constant reservoir water level, the inflow was adjusted continuously, the tests thereby simulating the failure of an embankment dam impounding a very large upstream reservoir. The hydrograph's recording started once water reached the end of the flume where the sharp crested weir was installed. The peak outflow was also identified per test run. In the case of full breach and complete dam failure, outflow through the breach was increased as the breach section enlarges until the peak is reached.

It was observed that the breach hydrograph had the same trend for the three tests with different channel shape, as illustrated in Fig. 6(a). At the beginning, the breach discharge was minimal, then it increased at nearly a fixed rate until reaching the peak discharge, and then starts to decrease but the test at this moment was stopped due to reaching the set condition (decrease of reservoir level by 10%). *[8] Reported similar observations*.

The maximum time to peak was recorded for the rectangular opening at about 34 minutes, and the least was recorded for the triangular with 17 minutes. The breach time was almost the double (34 minute) for rectangular compared to the other shape openings. For triangular and trapezoidal breach opening the peak discharge of about 75 l/s was reached faster than the rectangular case as shown in Fig. 6(a). The width and depth of the opening does not seems to have remarkable effects. The lag time and the time to peak and breach time were found to be almost the same with little difference, Fig. 6(b).



(a) Effect of breach opening shape **(b) Effect of opening dimension**

Figure 6: Effect of breach opening shape and dimension on the hydrograph

For the same channel shape, in low compact test, the breach discharge was found to increase slowly until 30 minutes then rapidly increase with high rate during initiation of failure until peak discharge was recorded. Fig.7 shows that peak discharge for well compacted test is less than the low compact, while the time to breach increased in agreement with[28].

The time to peak was 34 minutes for the low compacted dam, with lag time (from the test start to the moment there is a significant discharge through the pilot channel) almost of 15 minutes and 10 minutes for the well compacted. The breach time was 34 minutes for the low compacted, while for the well compacted the full breach was not reached.

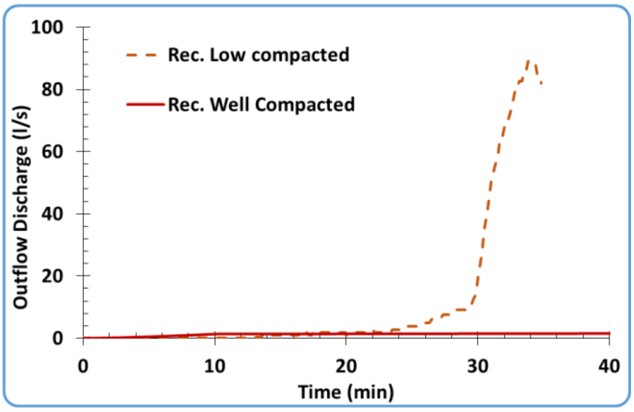


Figure 7: Compaction effects on the hydrograph

4.2. Breach-Shape Observations

The measured breach profile by the weight grid and the moving rods captured by high resolution digital cameras enabled the production of longitudinal-section and cross-section geometry during breach development stages.

The breach growth had the same trend throughout the whole domain. First, the breach developed in the vertical direction, until steps were formed within the eroded area. Then, the breach started to widen due to slope failure of the breach sides. The breach widening was almost symmetrical along the centerline of the pilot channel and the downstream face for the different cases. From the observation, it was established that the breach is widest at the downstream toe while it is smallest at the crest.

From the tests observations, the breach depth development was found to have almost three phases, starting by erosion, then a faster breach development, then development gets either slow or at constant rate until reaching maximum depth with the total failure. As for the breach width the development started gradually and the rate increased to reach the maximum value by total failure. This was found to be the case in the US and DS in all tests except the compacted damwhich hadn't reach the total failure and stopped in the constant phase.

The breach final form was almost the same for the different cases, which meant that the geometry of the pilot channel does not influence the breach final form as shown in Fig.8. *This confirms[10]*, but has an influence on the failure progress, time and breach development mechanism.

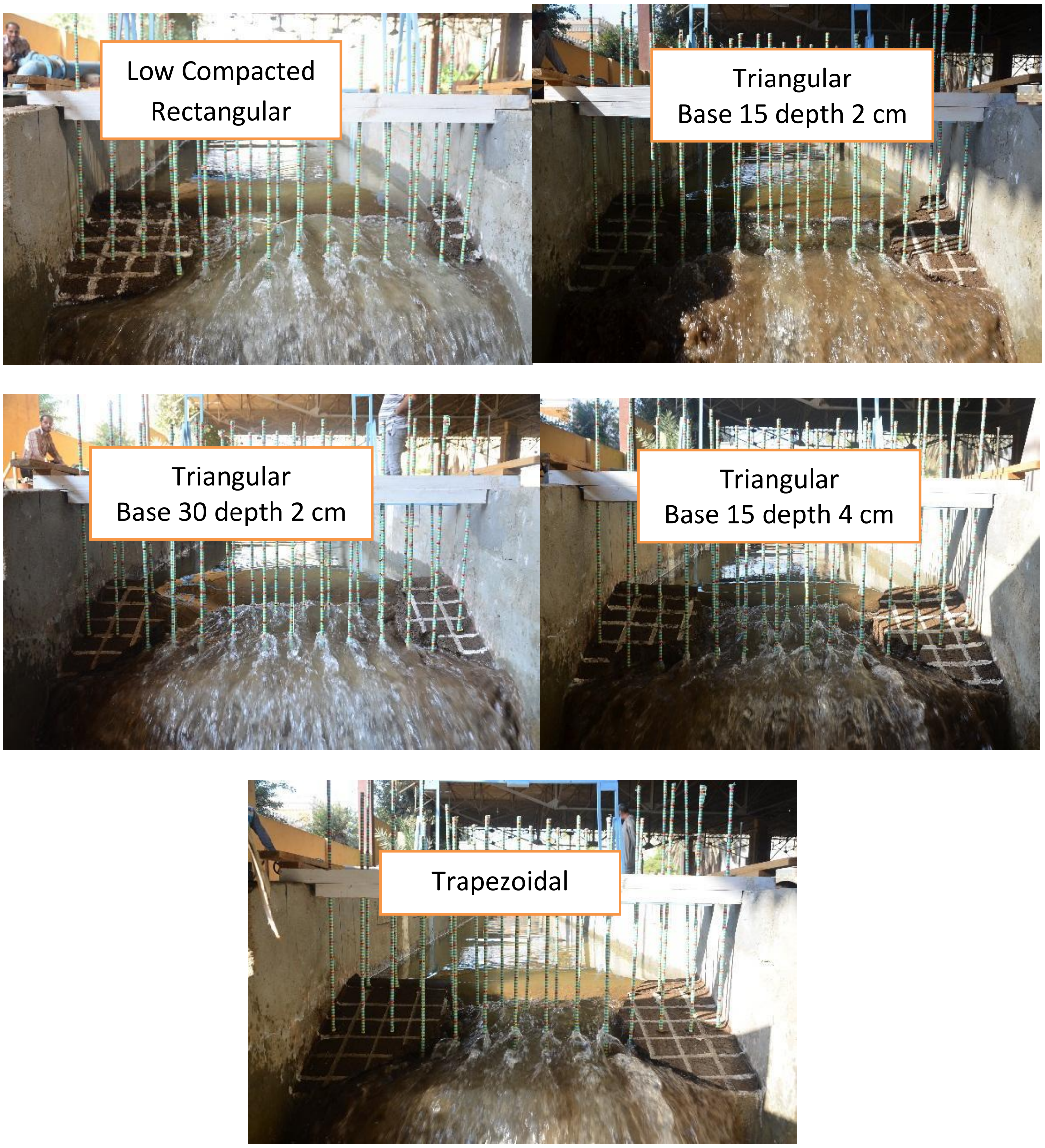
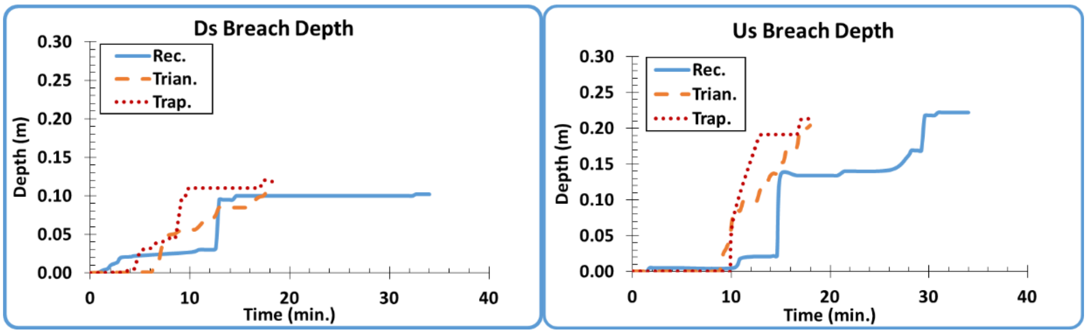


Figure 8: Final breach for the different cases

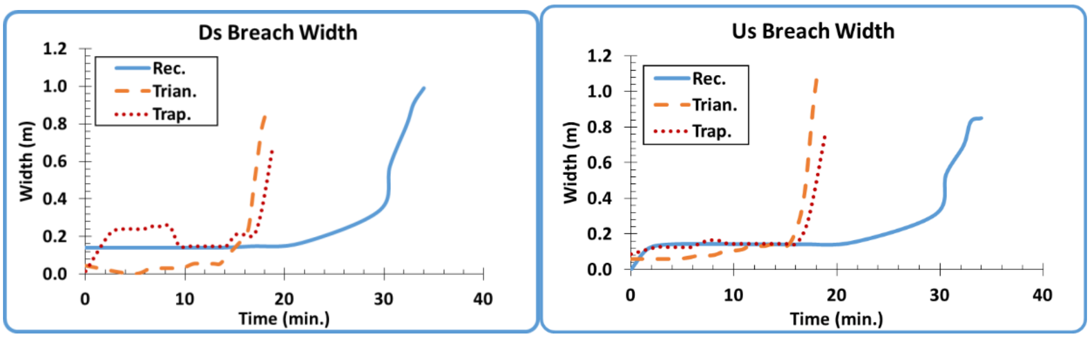
4.2.1. Effect of the breach opening shape

For various breach opening shapes, the progress in the failure process almost starts approaching 40 % (5 min.) of operation time as seen in Fig.9(a) for US and DS breach depth. The development in breach depth was found to be faster than the breach width in the US and DS. The US breach depth has a sharp increase trend for all the pilot channel shapes after 10 min from the beginning. For triangular breach opening, the DS breach depth increases gradually until the end. For the rectangular opening a sudden failure occurred at around 5 minutes and then at 12 minutes from start then it continues increasing to the end of the operation test. The maximum values were recorded in the case of triangular opening with about 0.12 m DS breach depth and 0.22 US breach depth.

For breach width, the three breach opening shapes have the same gradually increasing trend at the beginning until the erosion of the dam crest, then the breach width dramatically increases to the maximum values, as shown in Fig. 9(b). The maximum value for the DS width was in the case of rectangular opening about 1 m while in the US it was recorded for the trapezoidal with about 1.1 m. For the trapezoidal breach opening, the erosion takes place first on the surface and widens, after that the erosion starts to take place in the inner area until it reaches the outer outline and complete until the full failure occurs.



(a) The impact on the breach depth



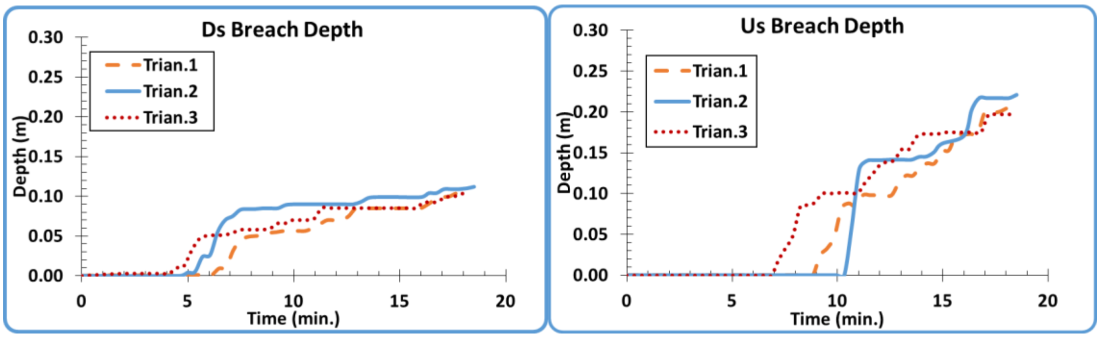
(b) The impact on breach width

Figure 9: Effects of the breach opening shape on the progress of US and DS breach depth and width

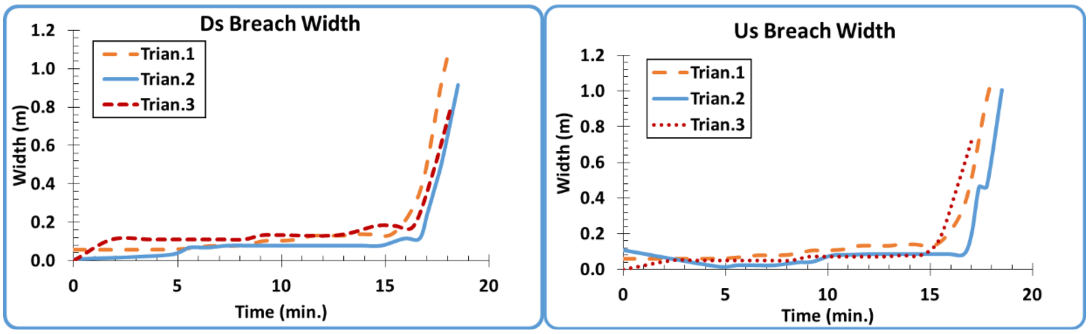
4.2.2. Effect of the breach opening dimension

Fig. 10(a) shows that with increasing the breach opening depth (case of Trian. 3), the erosion starts earlier and the breach depth is higher at the beginning in both US and DS, while with increasing the breach opening width (case of Trian. 2) a sharp increase at 55% of the operation time for the US depth, and then continue gradually until the total failure occurs. The breach depth development rate in the DS was found to be faster than the US while the breach width's development was almost the same in US and DS. The maximum breach depth was recorded in the case of Trian. 2 with values of about 0.1 m Ds and 0.22 m US.

For the breach width US and DS, the different tested dimensionswere found to have the same trend until the total failure, Fig. 10(b). The maximum values for breach width were recorded for case Trian. 1 with values of about 1.1 m in the DS and 1.0 m in the US.



(a) The impact on the breach depth

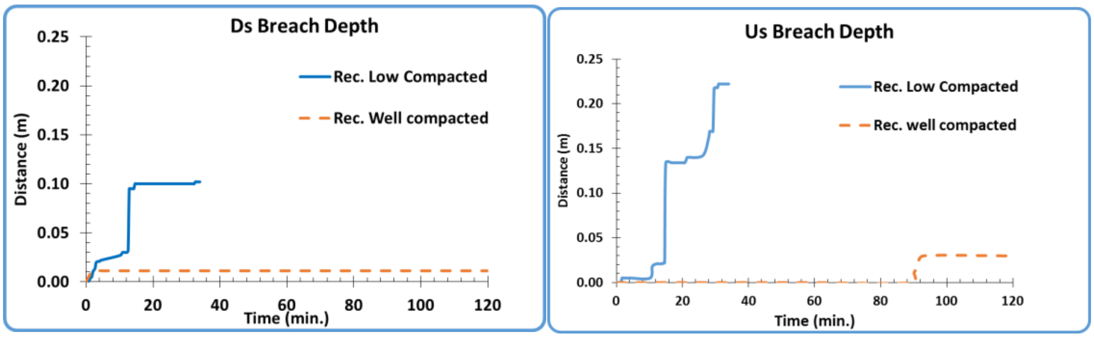


(b) The impact on the breach width

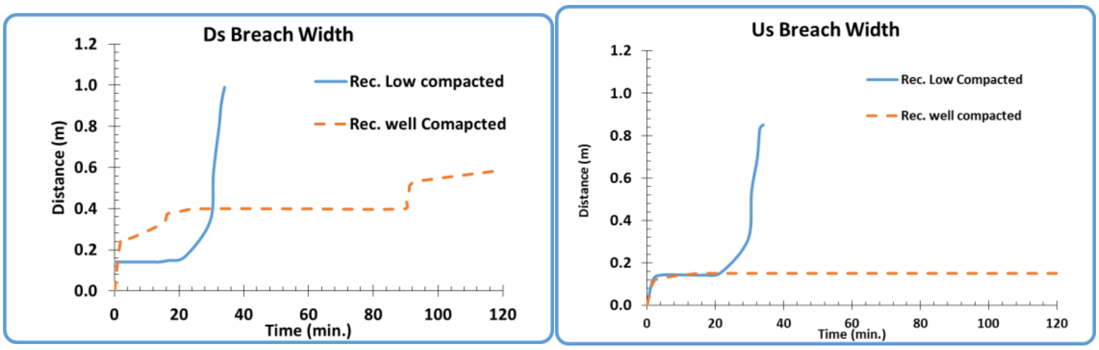
Figure 10: Effects of the breach opening dimension on the progress of US and DS breach depth and width

- **Effect of the Compaction**

The results of the optimum compaction test confirm the importance of achieving the designed compaction percentage to assure the hydraulic stability of the earth dam. As illustrated in Fig. 11(a) and Fig. 11(b) the low compacted dam reached the full failure after about 40 min. while the compacted dam didn't reach this status, this in agreement with [18]. Also for the breach depth and width, the development has faster increasing process in the low compacted dam compared with low development rate in the compacted dam.



(a) The impact on the breach depth



(b) The impact on the breach width

Figure 11: Effects of compaction on the progress of US and DS breach depth and width

5. SUMMARY AND CONCLUSION

The base for this experimental work is six earth embankments subjected to overtopping due to carved pilot channel in the dam crest. The tests involved both the well and low compacted conditions. The experiments were carried out in the Hydraulics laboratory of the Hydraulics Research Institute of Egypt. The investigations' tests were designed to study the effects of the breach opening shape and dimension, in addition to investigating the influence of the compaction on breach morphology and outflow characteristics. The temporal changes of the embankment surface profiles and the downstream hydrographs were measured for all cases. The erosion started vertical and progressed lateral afterward, and headcut processed upward until it reached the crest. Based on the study results and analysis, the following conclusions could be drawn:

1. The rectangular breach opening shape increases the initiation to breach time, giving more time for evacuation of the population in the downstream threatened arena.
2. The triangular and trapezoidal breach opening shapes have a faster rate in the breach depth and width development.
3. The different breach opening shapes have almost the same failure development trend, but affect the progression and the breach time.
4. The tested breach dimension has a great effect on the breach depth, with no or little impact on the breach width.
5. The step-case was dominant in all tests, the breaching process was almost symmetrical around the dam centerline.
6. The critical situation starts when the headcut approaches the dam crest and the widening rate increases.
7. Development of the headcut and erosion rate are much higher in the low compacted test compared with the optimum compacted test. The same was observed for the triangular and trapezoidal breaches opening compared to the rectangular opening.
8. The study results confirmed that the compaction condition is a vital parameter. Achieving the "designed" compact condition protects the earth embankment and the area in the downstream from flooding, due to the high ability to resist the erosion and breach process giving more time for evacuation compared to the low compacted dam.

Building on the study results, it is recommended to investigate more in-depth the effect of the breach opening profile and try to develop a functional relationship (s) to predict the breach peak flow and the resulting breach morphology, which supports the evacuation plan development of the dam downstream areas. Also the location of the breach opening may affect the breach process and this is an important point to study in future research work.

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7. NOTATIONS

Bulk Density (γ)	(gm/ cm^3)
Critical Length Without Tension Cracks (Zo)	(cm)
Cohesion (C)	(kg/ cm^2)
Dry Density (γd)	(gm/ cm^3)
Friction angle (φ)	(degree)
Liquid Limit (L.L)	(%)
Maximum Dry Density (γd)	(gm/ cm^3)
Plastic Limit (P.L)	(%)
Plasticity Index (P.I)	(%)
Optimum moisture content	(O.M.C.) (%)
Water Content Wc	(%)
Specific gravity	(m^2/s)