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Effect of Soil Type and Geometry on the Peak Flow and Depth of Breach Resulting from Overtopping Failure of Embankment Dam

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ABSTRACT

Experiments were conducted in a hydraulic laboratory for eight physical models representing homogeneous embankment dams using two types of soil: silty sand and clayey sand. The models were exposed to overtopping flow, which causes the overtopping failure. The models of the embankment were constructed with a width of 0.6 m, a crest height of 0.3 m, and two different side slopes, 1:2 and 1:1. Two different inflows, 15 L/min, and 30 L/min, were used as a hydraulic variable. Two stages were conducted for the tests; at the first one, silty sand was used to build the embankment consisting of four experiments, and four other experiments were conducted at the same hydraulic and geometric conditions, but with a clayey sand embankment. The necessary calculations were made to calculate the outflow, the depth of the breach, and the breaching process. The analysis and comparison of the results of the eight tests revealed that the breaching process consists of three stages. The first is the stage of breach initiation, while the other two stages are the feature of breach development, during which the two peak discharge phenomenon occurs. The first peak is a result of the beginning of the flow of the stored water upstream, while the second peak occurs as a result of the continuing process of erosion and breach growth. Finally, the clayey sand soil delayed the timing of the first peak discharge, shortened the time interval between the first and second peak discharges, and delayed the breach initiation time by (73.33% and 58.82%) with a slope of 1:2, while when the slope is 1:1, the percentage of delay decreases and becomes (33.33% and 13.33%). In addition, the breach depth (Hf) for clayey sand soil has lower values. Generally, the embankment slope of 1:1 decreased the impact of the variation in soil type, and the embankment slope ratio is considered the primary factor influencing the depth of the breach. The experimental results show that the stability breakdown in clayey sand occurs later than in silty sand, and the dam's geometry has a significant and clear impact on breach depth and failure-resistant stability.

Keywords: Embankment dam, Breach depth, Overtopping failure, Soil type, Flooding risk, Peak discharge.

INTRODUCTION

An embankment dam is built from locally sourced or excavated natural materials. Earth-fill and rock-fill embankment dams are the two primary types of dam. An earth dam is made of appropriate soil excavated or borrowed from designated places, which is then layered and mechanically compacted. The rock-fill material provides enhanced strength and resistance to erosion, making it suitable for constructing large-scale dams that must withstand high water pressures (Sánchez-Martín et al., 2020).

Concrete face dams and homogenous zoned fill dams are the two types of dam studied by Mohamed et al. RWS(2023) at both high and medium erodibility rates. According to the results, the homogeneous zonal fill dam is less dangerous in both scenarios, whereas in the worst-case scenario, the concrete face dam with a high erodibility rate allows it to convey a significant flood flow.

Embankment dams are essential infrastructure for flood control and irrigation, retaining water during flooding and facilitating agricultural activities (Neupane et al., 2019). They impound large volumes of water during intense rainfall or snowmelt events, reducing downstream flooding risk. They also regulate the release of stored water during water scarcity, ensuring a sustainable supply for irrigation. In agricultural practices, embankment dams transform surrounding areas into fertile and productive agricultural lands, enabling farmers to cultivate crops during dry seasons or in arid regions (Debnath et a., 2020). Dam failures cause flooding, requiring flood management and risk analysis. Erosion breaching is a significant cause, but historical data on erosion, breach parameters, and discharge is limited. More research is needed to estimate breaching time and understand erosion mechanisms Costa and Schuster (1988) assessed fifty-five cases of dam failure and discovered that overtopping occurred in more than fifty of the analyzed cases. The other five failed due to piping or unstable slopes. According to Zhong et al. (2017), there have been 3530 cases of dam breaches; over 50% of these accidents were the result of overtopping, and homogenous cohesive dams accounted for over 85% of all failures. Significant downstream flooding may occur from the overtopping-related release of enormous volumes of water. Because of the failure's double-peak structure, the flood event may last longer and cause more damage to nearby houses, infrastructure, and life. The size of population centers located downstream of an impacted dam and its outflow hydrograph directly determine the subsequent tragedy that results from a dam breach (Ahmadi & Yamamoto, 2021).

This research proposal aims to contribute to this body of knowledge by studying homogeneous earthen dams and their response to varying discharge rates, types of soil, and dam geometry. The findings will enhance design criteria, maintenance practices, and risk assessment strategies associated with earthen dams, contributing to the overall resilience of flood control and irrigation systems. The study will examine two soil types (silty sand and clayey sand) commonly used in laboratory-scale models to facilitate the failure process analysis. Finally, the results and recommendations are provided.

Overtopping Failure

It occurs when the water overflows the dam's crest. Due to the increasing water volume behind the dam, one of the most important factors in the structural and safety assessment of the dam structure is the embankment dam's tendency for erosion during periods of severe flooding.

The main causes of overtopping of embankments (whether dams, levees, or flood protection structures) are:

1- Extreme Flood Event: When water levels rise due to exceptional rainfall, snowmelt, hurricanes, or other natural events, they can exceed the embankment's design capacity.
2- Insufficient Freeboard: Freeboard is the height between the normal water surface and the top of the embankment. If it's too small, even moderate floods or wave action can cause overtopping.
3- Wave Action: Wind-driven waves can splash over embankments even if the main water level is below the crest.
4- Settlement of the Embankment: Over time, embankments can settle (especially in soft soil foundations), lowering their effective height and making overtopping more likely.
5- Erosion or Structural Damage: Surface erosion, animal burrows, or cracks can weaken the embankment, allowing water to breach it more easily.

The overtopping flow is shown in Figure 1. Overtopping occurs when the reservoir's water level rises over the dam's crest and overflows to the downstream side. The probability of an embankment overtopping collapse can be decreased by increasing the width of the auxiliary spillway or the reservoir's storage capacity (Hunt et al., 2005).

The likelihood that a hydraulic structure fails at some point in its operational life is known as the dam risk. Throughout their lives, dams are always at risk of failing to perform their intended duties. A hydraulic structure's design flood is the highest flood that it can safely pass through without overtopping (Ruan et al., 2021).

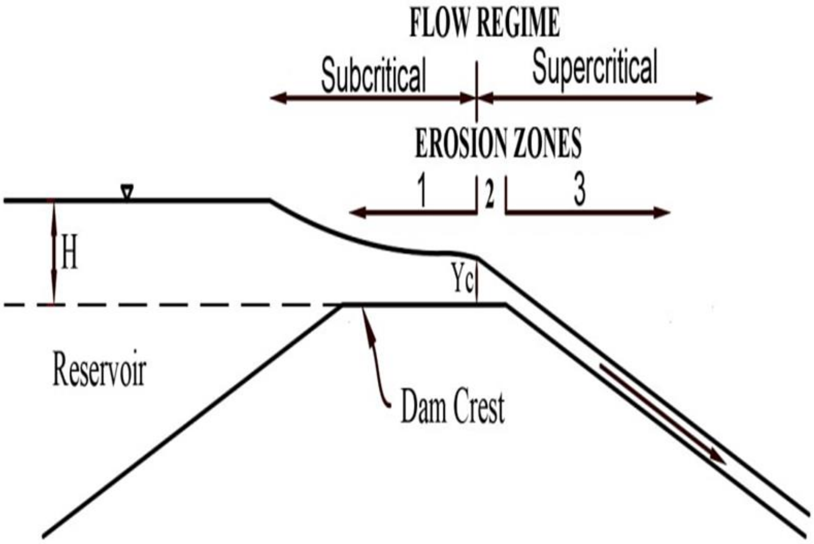


Figure 1. Embankment overtopping: erosion zones and flow regimes (Powledge et al., 1989)

Visser (1999) outlined a five-phase breaching process for a sand dike breached by overtopping. The process includes steepening the inner slope, decreasing the crest's width, lowering the top, a critical flow stage where flow is critical, and a sub-critical stage where the breach continues to grow due to sub-critical flow. The process is illustrated in Figure 2.

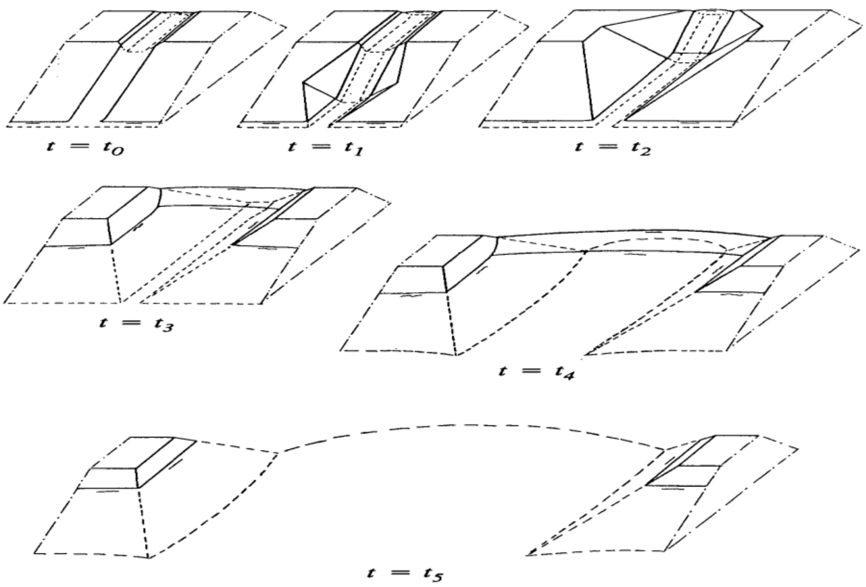


Figure 2. Process of breach growth in a sand dike (Visser, 1999)

RESEARCH DESIGN AND METHODOLOGY

The present research involves the following steps:

The experimental tests of the physical model have been conducted in a hydraulic laboratory to ascertain the homogeneous embankment failure mechanism caused by overtopping. The tests show that the erosion process and soil type have a substantial impact on the timing and rate of discharge during overtopping events after observing the emergence of an overall process or steps that gradually proceed toward the upstream face (Verma et al., 2023). The following is a description of the observed processes. Firstly, different types of soil were prepared. Two types of soil were used in the experiments: silty sand (soil-1) and clay sand (soil-2). Before conducting the experiments, basic tests of samples taken from each type of the selected soil were performed in the soil laboratory to determine the soil properties. These tests include measuring parameters, such as density, granular gradation, and specific gravity (Gs), the main parameters for soil(Aymen et al., 2024). The test results are listed in Table 1. Soil parameters give good information for the analysis and interpretation of experimental results.

Table 1. The properties of soil

Properties	**Soil 1**	**Soil 2**	**Specification**
Type of Soil	Silty sand (SM)	Clayey sand (SC)	(USCS)
Maximum dry unit weight (kN/m³)	17.50	1743	ASTM D 4253
Minimum dry unit weight (kN/m³)	12.54	13.62	ASTM D 4254
Specific gravity Gs	2.63	2.65	ASTM D 854
Sand %	84.3	70.58	
Silt %	14.36	9.217	
Clay %	1.34	20.203	

A total of eight experiments were conducted, with four experiments for each type of selected soil. The trials were conducted in a controlled laboratory setting. Each experiment involves constructing a scaled-down model of the homogeneous embankment dam using the respective soil type.

Two discharge rates, 30 L/min and 15 L/min, were used for the test and were chosen according to previous studies and as a limitation of flume size. The inflow rates simulate different flow conditions and allow for the evaluation of the dam's performance under varying water volumes.

For the embankment geometry, two side slopes were considered: 1 V: 2 H and 1 V:1 H. Table 2 shows the details of the variables and the dimensions of the dams. The dam geometry's influence on stability and failure mechanisms was analyzed by testing different slope ratios, as shown in Figure 3.

The experiments provide valuable data on homogeneous earthen dams' behaviour and failure mechanisms under different conditions by systematically varying the discharge rates, dam dimensions, and failure scenarios. The findings contribute to understanding dam performance and guide improvements in dam design and construction practices.

Table 2. The variables and dimensions

Test No.	**Type of soil**	**Height of Crest (cm)**	**Width of Crest (cm)**	**Slope**	**Inflow (L/min)**
1	Silty sand (S1)	30	20	1/2	30
2	Silty sand (S1)	30	20	1/2	15
3	Silty sand (S1)	30	20	1/1	30
4	Silty sand (S1)	30	20	1/1	15
5	Clayey sand (S2)	30	20	1/2	30
6	Clayey sand (S2)	30	20	1/2	15
7	Clayey sand (S2)	30	20	1/1	30
8	Clayey sand (S2)	30	20	1/1	15

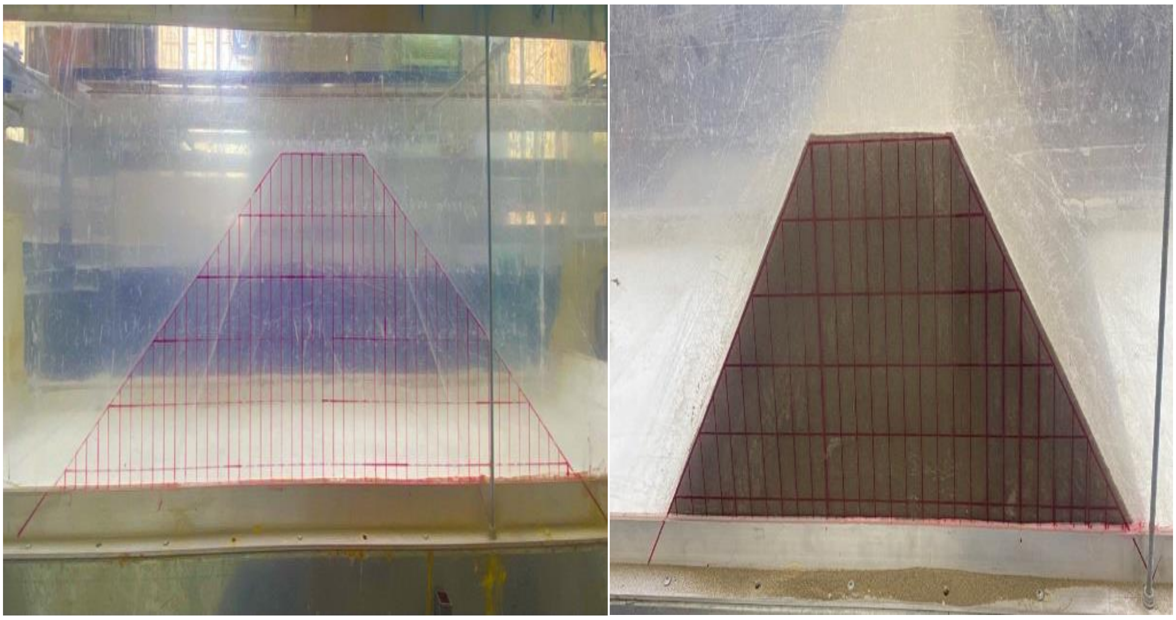


Figure 3. Preparation of dam dimensions and side slopes in the flume

For each test, three cameras, positioned at various angles, were used to monitor the inspection process. The features of the breaches that occurred as the embankments overtopped were more easily seen thanks to acrylic panels on the side walls of the flume. With the aid of digital cameras, the breach mechanism was documented on a film. Discharge measurements were recorded during the experiments. The flume implemented in this study is shown in Figure 4. As can be seen in this Figure, the flume's width is 60 cm, and its depth is 45 cm. A water pump with a 40 L/min discharge capacity, a flowmeter, and three cameras type Sony Hx1 with 1440 x 1080 pixels of resolution were used.

There are two tanks in the flume: an inlet tank at the upstream and a sump tank at the downstream. Water is moved upstream by pipes from the water pumping tank. Additionally, the washed sediments pass through the trap basin at the downstream of the flume, so that they can settle and then collect to ensure that the sediments do not rotate with the flow and thus keeping a clear water flow through the pump.

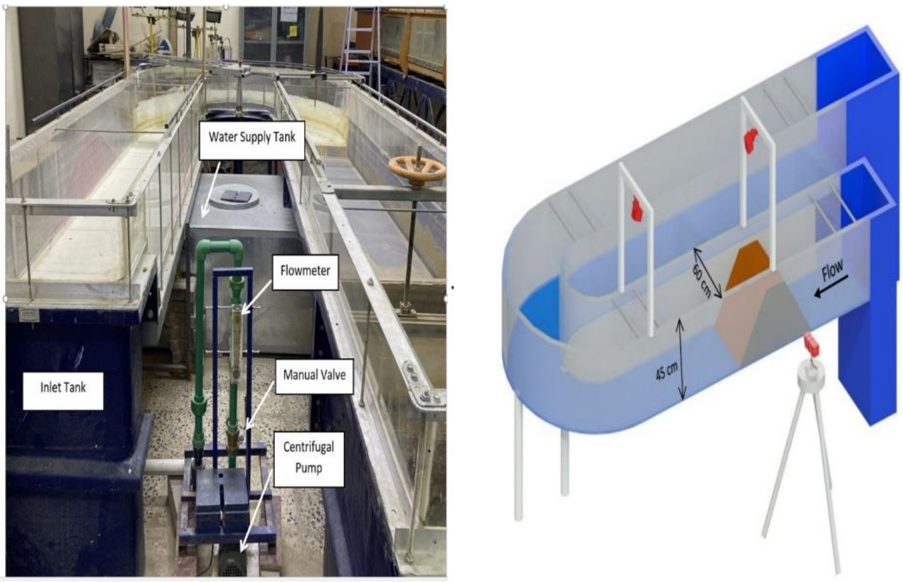


Figure 4. The flume channel and monitoring cameras

The Comparative Analysis of the Study

The provided charts, supported by a grid to determine the dimensions of the breach, are used to analyze the results. The analysis involves measuring changes in dam dimensions and breach dimensions over time. Key parameters, such as flood wave, Q_p, time to final failure, failure mechanism, failure stages, and the dam's final form after failure, are calculated; their results are listed in Table 3. From the results of the tests mentioned above, a comprehensive comparison was made between the results obtained from the two soil types and the different variables used in the experiments.

Table 3. The main parameters for the failure mechanism

Test No.	Type of soil	Time of breach T_f (s)	Height of breach H_f (mm)	Q_{p1} (L/min)	Time of Q_{p1} (s)	Height of breach at Q_{p1} (mm)	Q_{p2} (L/min)	Time of Q_{p2} (s)	Height of breach at Q_{p2} (mm)
1	Silty sand	245	166	89.9262	95	45	50.46408	210	140
2	Silty sand	220	171	59.9946	110	45	103.563	195	150
3	Silty sand	140	210	202.7054	85	76	172.4738	110	153
4	Silty sand	160	210	184.1032	105	80	153.1629	140	175
5	Clayey sand	255	163	84.96141	155	42	85.98621	200	130
6	Clayey sand	255	169	109.4266	165	57	100.9739	210	142
7	Clayey sand	150	208	186.21	95	55	157.2299	130	175
8	Clayey sand	160	204	171.2770	100	50	164.6268	135	160

Two-peak Discharge

Table 3 shows two columns representing the flow rate (discharge). These two values of flow rate are recorded for the same test and represent two peaks of flow across the breach that occur at specified two times. The initiation of the overtopping failure occurs when water just flows over the crest of the dam. The term "two-peak discharge phenomena" may pertain to two discrete phases or stages of the overtopping failure's discharge. The most hazardous flood for a given return period is the design flood. As a result, the design flood needs to take into consideration the hydrograph's peak discharge, shape, and volume. When there are two peaks, the design flood should specifically take into consideration the locations of the two peaks (Gioia, 2016); Martínez-Carreras et al., 2016).

As the water level begins to rise and cross the dam's crest, the first peak discharge, which is frequently characterized by a swift and powerful flow, may be caused by the first surge of water over the dam and is considered the “First Peak Exhaustion”. The dam structure may deteriorate further after the initial breach or overtopping, and the breach may enlarge or change. This could result in a longer-lasting and more powerful secondary or sustained peak discharge than the first surge. The features of the breach, ongoing erosion, and structural breakdown of the dam all have an impact on the secondary peak discharge denoted as “Secondary Peak Emission”.

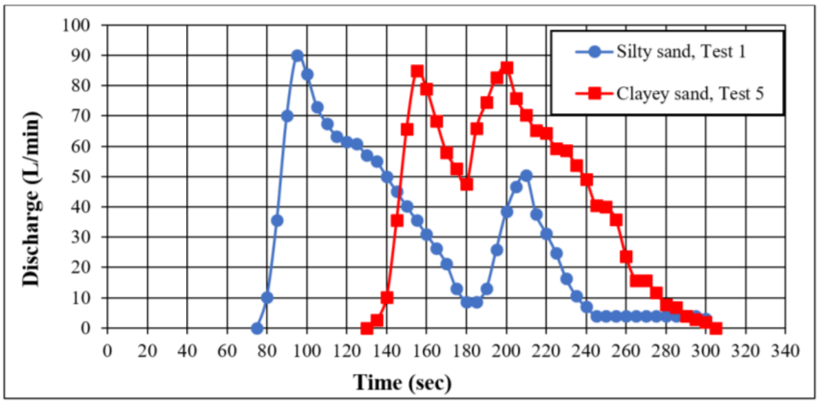
Comprehending the two peak discharge phenomena is crucial for evaluating the safety of dams and devising emergency responses. It assists authorities and engineers in foreseeing possible overtopping failure outcomes and implementing suitable countermeasures, such as bolstering the construction of the embankment dam, enhancing spillways, or putting early warning systems in place to lessen the effects (Martínez-Carreras et al., 2016; Froehlich, 2016).

The Impact of Soil Type and Slope of the Embankment Dam on Outflow Discharge

The investigation has been conducted for two types of soil and two different slope ratios; namely, 1:1 and 1:2. Four tests have been conducted for both silty sand and clayey sand to demonstrate (experimentally) the effects of soil type and slope on the outflow discharge and breach configuration. The experiments were conducted using two inflow rates of 30 L/min and 15 L/min. The experiments commence when the inflow commences to pass through the crest of the dam. The breach creation process commences at the downstream edge of the crest and proceeds until it reaches the upstream edge. Subsequently, the water stored behind the embankment dam starts to release, and the rate of this discharge is determined as shown in the following part.

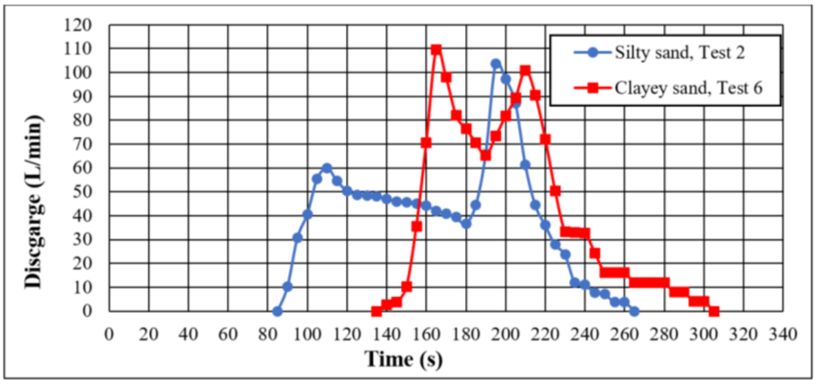
Figure 5 is the illustration of release discharge *versus* time for silty sand (Test-1) and clayey-sand (Test-5) embankment at a side slope of 1:2. The collapse occurs during Test-1 at t = 75 sec. from the beginning of the run. This time was marked after the path of breach over the crest had completely eroded, and the water stored in the reservoir had started to be released. The first peak of discharge, Qp1, which refers to the maximum rate of water flow, was recorded at t = 95 sec. and measured to be 89.92 L/min. The second peak of discharge, Qp2, was recorded at a rate of 50.46 L/min and occurred at t = 210 sec.

In Test-5 for the clayey-sand embankment, the failure occurred at t=130 seconds, as denoted in Figure 5, and the first peak of discharge, Qp1, is 84.96 L/min recorded at t=155 seconds. Meanwhile, the second peak of discharge, Qp2, reached a value of 85.98 L/min at a time of 200 seconds.



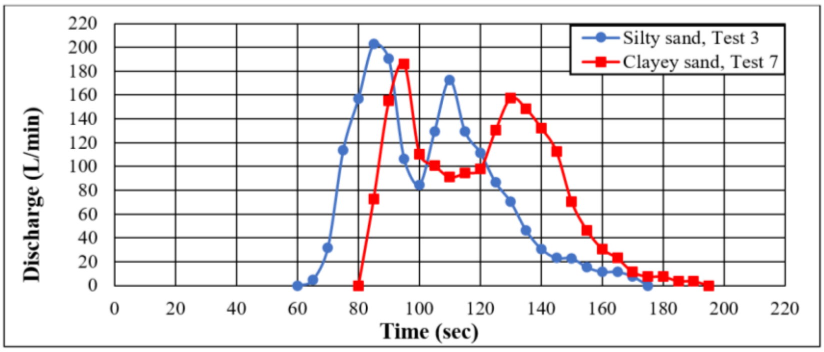
Qin = 30 L/min, slope 1:2

The same trend context has been observed using a lower inflow rate, entering the reservoir at 15 L/min, exerted on the same two embankment models as mentioned above, as depicted in Figure 6. In Test-2, which involved silty sand soil, failure occurred at t=85 sec, and the first peak of discharge (Qp1) was 59.99 L/min, which occurred at t=110 sec. Subsequently, the second peak of discharge, Qp2, reached a value of 103.56 L/min at a time of 195 seconds. While in Test-6, the failure of the clayey sand occurred at t=135 sec. and the first peak of discharge of 109.42 L/min was observed at t=165 sec. with little decrease in the value of flow rate for the second peak of discharge recorded as 100.97 L/min when the run time reaches t=210 sec.



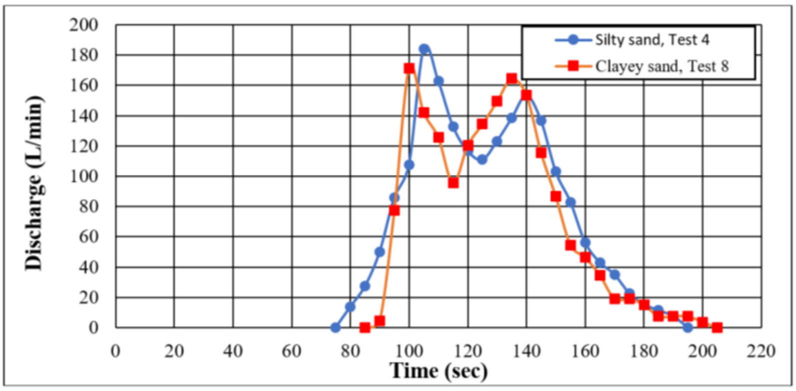
Qin= 15 L/min, slope 1:2

Figure 7 illustrates the discharge hydrograph for silty sand (Test-3) and clayey sand (Test-7) embankment at a side slope of 1:1. The tests were conducted with an inflow rate of 30 L/min. The failure time for the silty sand (Test -3) occurred at t=60 sec. The first peak of discharge Qp1= 202.70 L/min was observed at t=85 sec. Subsequently, the second peak of discharge Qp2 = 172.47 L/min was attained at t=110 sec. In Test-7 for clayey sand embankment, the failure occurred at t=80 seconds, and the first peak of discharge, Qp1, occurred at 95 seconds and had a value of 186.21 L/min. Meanwhile, the second peak of discharge, Qp2, attained a value of 157.22 L/min at a time of 130 seconds.



Qin= 30 L/min, slope 1:1

In Figure 8, the same trend context has been observed using a less inflow rate, entering the reservoir at 15 L/min, exerted on the same two embankment models as depicted in Figure 7. In Test-4, which involved silty sand soil, failure occurred at t=75 sec. The first peak of discharge (Qp1) of 184.10 L/min occurred at t=105 sec. followed by the second peak of discharge (Qp2) of 153.16 L/min at a time of 140 sec. In the clayey sand model (Test-8), Figure 8 indicates that failure occurred at t= 85 sec. The first peak of discharge, Qp1, was 171.27 L/min, and the second peak of discharge, Qp2, was 164.62 L/min. These peaks occurred at times of 100 sec. and 135 sec., respectively.



Qin= 15 L/min, slope 1:1

Based on the comparative analysis, when the characteristics of the soil of the embankment, as it is the only parameter that can change with the geometrical parameters of the dam and the hydraulic conditions affecting it, remain constant, it was clearly observed that the peak occurs at a somewhat longer time with clayey sand soil compared to the second type of soil (i.e., silty sand) in addition to reducing the period between the two peaks of flow rate through a breach. The disparity in discharge values between the first and second peaks is small in clayey sand soil, whereas there is a significant disparity in discharge values between the two peaks in silty sand soil.

When conducting experiments with a 1:1 slope, we observed that the steepness of the slope decreased the impact of the variation in soil type. Figures (7 and 8) depict the outflow discharge hydrograph for the two soil types used in the experiments with a 1:1 slope, and they appear very similar. In contrast, the outflow discharge charts for clayey sand soil and silty sand soil show a noticeable disparity when a 1:2 slope is used, as shown in Figures (5 and 6). When the slope of the embankment dam has a ratio of 1:1, the two peaks of discharge occur earlier, as seen in Figures (7 and 8). Furthermore, the stability failure of the clayey sand embankment dam takes more time than that of the silty sand. Furthermore, the gentle slope of the embankment dam with a ratio of 1:2 provides increased resistance to potential failure.

The Impact of Soil Type and Slope of Embankment Dam on the Height of the Breach

The influence of soil type and embankment slope on the depth of breach is well explained herein. Figure 9 shows Test-1, which has a mild side slope of 1:2 and is conducted on soil composed of silty sand. The breach reached a final height Hf of 166 mm after a total breach time Tf of 245 seconds. In Test-5, conducted on clayey sand soil for the same slope of 1:2, the breach height Hf rested at 163 mm at Tf = 255 sec.

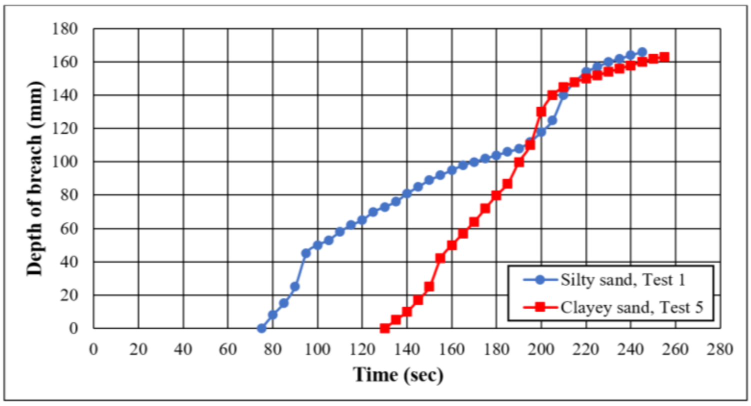


Figure 9. The impact of soil type and slope on the depth of breach for Qin= 30 L/min, slope 1:2

Figure 10 is the illustration of breach depth *versus* time for silty sand (Test-2) and clayey sand (Test-6) embankment at a side slope of 1:2 with an inflow rate of 15 L/min. In Test-2, the breach reached a final height (Hf) of 171 mm at a final breach time (Tf) of 220 sec. In Test-6, the final breach height (Hf) rested on 169 mm at Tf = 255 sec.

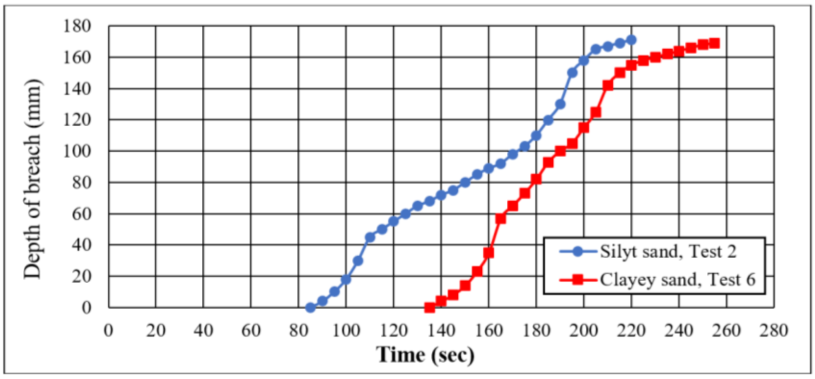


Figure 10. The impact of soil type and slope on the depth of breach for Qin= 15 L/min, slope 1:2

Figure 11 illustrates the results of Test-3 conducted on a model of silty sand with a side slope established at a ratio of 1:1. The final breach height Hf = 210 mm occurred at a final breach time Tf of 140 sec. For clayey sand embankment at Test-7, the final breach height (Hf) of 208 mm occurred at a final breach time Tf = 150 sec.

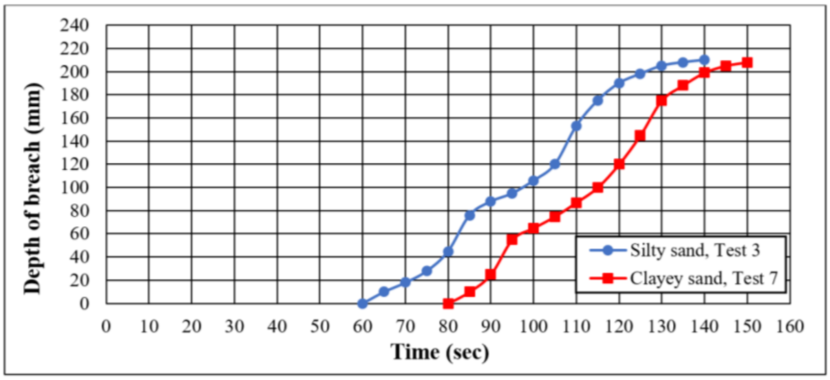


Figure 11. The impact of soil type and slope on the depth of breach for Qin= 30 L/min, slope 1:1

Finally, Test-4 was conducted on silty sand soil with a side slope of 1:1. The inflow rate was 15 L/min. The breach reached a final height (Hf) of 210 mm at a final breach time (Tf) of 160 seconds. In Test-8, using clayey sand soil with the same parameters, the final breach height (Hf) reached 204 mm at a final breach time (Tf) of 160 seconds, as seen in Figure 12.

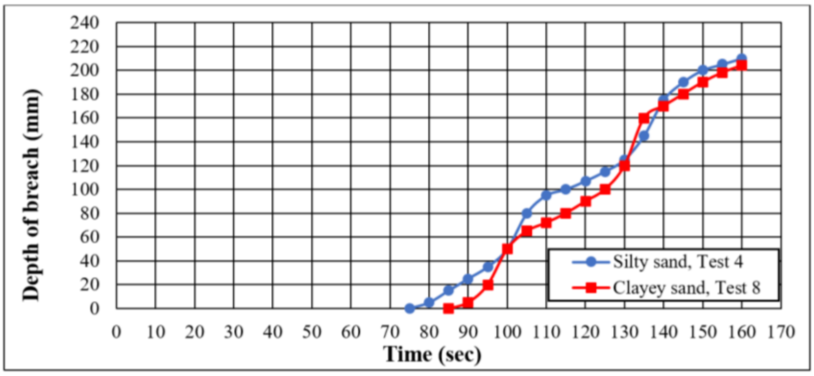


Figure 12. The impact of soil type and slope on the depth of breach for Qin=15 L/min, slope 1:1

Through the experimental observations, in the four cases with the same soil silty sand and different slopes, the final height of breach for the steep slope is bigger than that for the mild slope. On the other hand, the final breach time for the steep slope is smaller than for the mild slope. In addition, for different types of soil and the mild slope 1:2, the final height of the breach changes slightly, but there is a difference in the final breach time. In addition, for the steep slope 1:1, the depth of the breach value ranges between (20.4 -21) cm, as this is the greatest depth it can reach, and then, the flow becomes an open channel flow, and the height of the water at the upstream is equal to the tailwater level at the downstream with different soils, so there are slight differences in the breach heights and the breach times. From the previous results, the clayey sand dam has more stability than the silty sand dam. Therefore, the difference in soil type mainly affects the time of breach formation, and clayey sand soil delays the time of the onset of collapse due to the strength of adhesion and cohesion between its particles. In contrast to the slope of the dam, it is considered the main factor affecting the depth of the breach. In conclusion, the slope of the dam's sides can influence the stability of the dam during overtopping. Steeper side slopes may be more prone to erosion and failure, impacting the peak discharge (Walsh et al., 2021). In Figure 13, snapshots of two experiments (2 and 6) were taken at specific times, showing the effect of different soil types on failure time. In silty sand embankment (Test-2), due to the weak cohesive strength in this type of soil, the crest erosion process was fast compared to clayey sand embankment

(Test-6), where as we can see in the pictures, the time taken for crest erosion was 90 seconds for Test-2 and 140 seconds for Test-6. Also, note that the failure time at Test-6 was longer than the failure time for Test-2 due to the cohesive and adhesive strength of the clayey sand soil. Thus, Figure 13 clearly shows the effect of soil type on breach time.

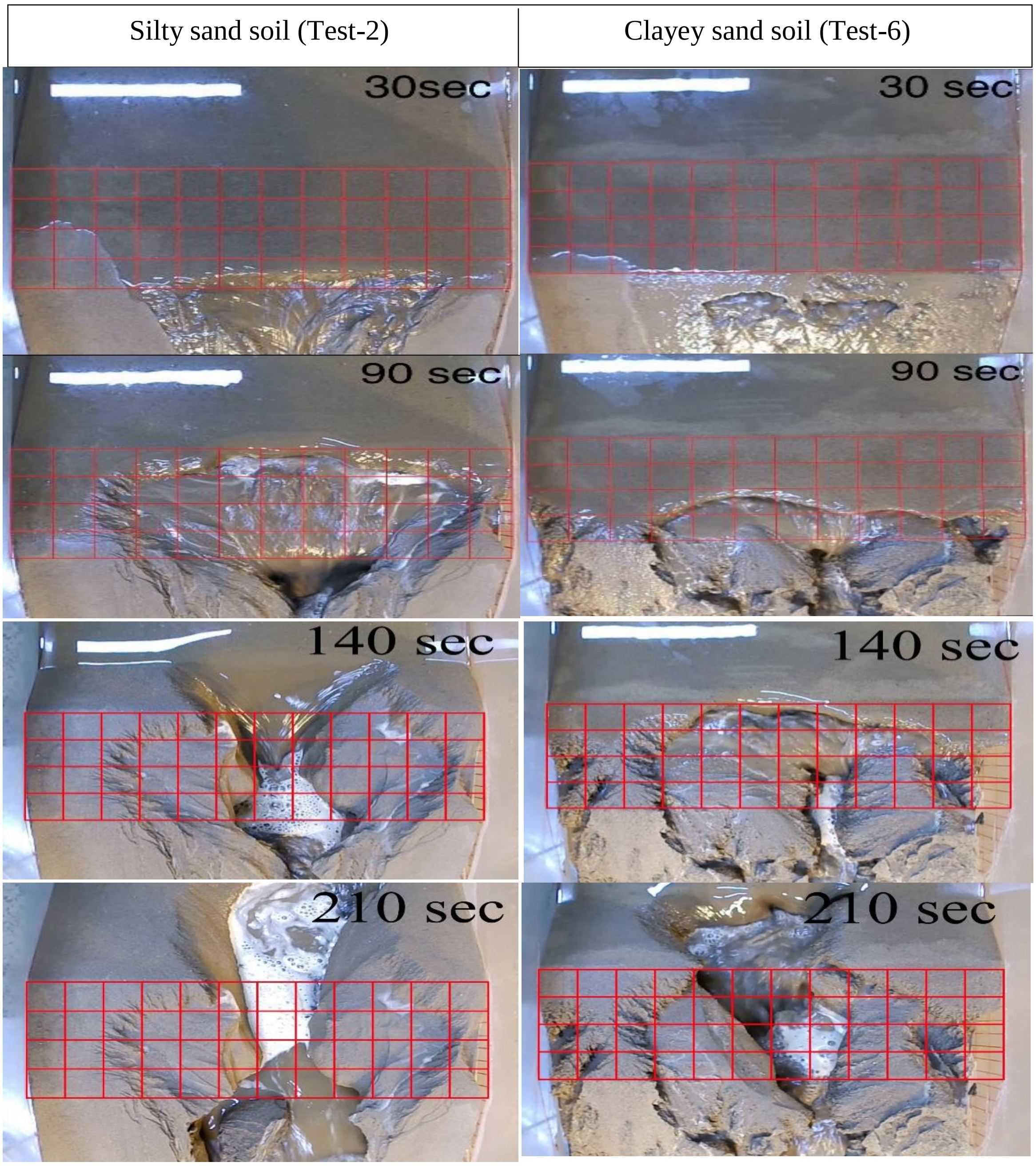


Figure 13. Snapshot of two tests (2 and 6) at the same time showing the impact of soil type on breach time

DISCUSSION

1- Erosion in an embankment formed by cohesive materials begins downstream and moves upstream. Headcut erosion is a kind of erosion that occurs in cohesive materials. The headcut consists of multiple stages. Eventually, they come together to create a single headcut. Multi-level headcuts resulted from an increase in the proportion of clay in the cohesive components of the embankment.
2- In comparison to the test on silty sand, the erosion process took a little longer after the addition of the

clay. The form of the headcut was entirely significant due to the highest percentage of clay in construction materials. In addition, the highest percentage of clay in construction materials shows the slowest breaching process.

3- By following the experimental observations, there is a sudden increase in the erosion process (a sudden increase in the depth of the breach) and as shown in the diagrams at the times when the two peak discharges occur, this increase in depth causes an increase in discharge. According to Visser (1999) and Hahn et al. (2000), they found a unique failure mechanism in embankments compared with non-cohesive sands and cohesive sediment. The outflow hydrograph displays random peaks, initially causing damage to the embankment. Seepage before the pilot channel reached could have contributed to the irregularity of the breach outflow peaks and the duality of breach formation.

4- Several factors related to upstream dam geometry can influence the peak discharge during overtopping breaches in homogeneous embankment dams, and these factors can have implications for tailings dams: crest width, crest shape, freeboard, and the most important factor is the side slope. The slope of the dam body significantly impacts the final breach depth. As per the findings in dam breach studies, the slope geometry of the dam influences the breach hydrograph properties.

5- Wahl (2004) defines two stages for the breach process: the initiation stage and the development stage of the breach. The initiation stage ends when a breach has compromised enough of the reservoir's storage so that failure is imminent. The development stage concludes when the breach stops expanding. According to the observation of the experiments in this research, the failure process can be divided into three stages. The first stage is the stage of breach formation (the initiation of breach stage), which starts from the beginning of the water overflow in the body of the dam and ends when there is a complete erosion of the crest of the dam and the arrival of the breach to the upstream and the beginning of the moment at which the stored water flows behind the dam. The second stage begins from the moment at which the breach reaches the upstream side slope and the release of water stored behind the dam, during which the first flood wave occurs and ends when the behaviour becomes small and continues to decrease and becomes somewhat calm. The third stage begins with the beginning of the increase in discharge again and the occurrence of the second flood wave; then, the behaviour begins to decrease, and this stage ends with the end of the formation of the breach, the breach reaching its final depth, and the cessation of the vertical corrosion process, which is the time that can be known through charts for calculating the depth of the breach, as shown in Figure 14.

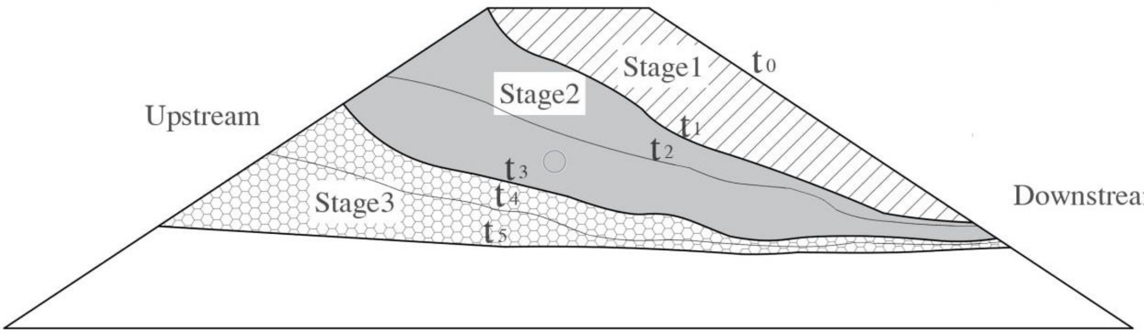


Figure 14. The three stages of the breach process

CONCLUSIONS

1- A breach in non-cohesive soil embankments due to overtopping and subsequent failures was attempted to be monitored within the breach parameters. In addition to reservoir and dam design, the location and rate at which the breach originates also affect dam failure conditions, final breach parameters, and flooding.

2- The slope of the embankment is one of the main variables. It has been shown through experiments that the difference in slope has a major effect on the final depth of the breach, whereas the type of soil only had a major effect on the time of breach formation and failure time.

3- As the cohesiveness of the soil increases, the embankment dam's resistance to erosion increases, which delays the process of breach formation, as observed in clayey sand soil.

4- In dams composed of silty sand, soil erosion starts in the higher portion of the downstream slope and eventually moves to the lower portion. The slope is marginally steeper and exhibits notable head-cut erosion in the top half.

5- As the water level starts to increase after the stored water behind the dam is released, the experiments demonstrate that the initial surge of water released may be the origin of the first peak discharge, which is often a quick and forceful flow. Then, after the first peak of discharge, the dam structure may continue to deteriorate, and the breach may grow or change. This continuity in eroding leads to a secondary or sustained peak discharge that is more powerful and lasts longer than the initial surge.

6- The characteristics of the breach, continuous erosion, and the structural deterioration of the dam influence the secondary peak discharge. We can conclude that clayey sand takes more time for stability failure than silty sand. Clayey sand soil causes a delay in breach initiation time of approximately 73.33% and 58.82% when the embankment slope is 1:2 at an inflow rate of 30 L/min and 15 L/min, respectively. However, the difference in soil type has a less impact on the breach time, with a delay of 4.08% and 15.91%.

7- Varying soil types result in small variations in the final breach height, so the variation in soil type mostly impacts the breach time rather than the depth of breach, while the slope of the dam is regarded as the primary factor influencing the depth of the breach.

8- The embankment dam with a slope of 1:2 tends to have a shallower breach depth ranging between 163mm and 171mm. while the embankment dam with a slope of 1:1 typically leads to a higher breach depth ranging between 204mm and 210mm. That effect can be attributed to a steeper slope, which has more inducement to accelerate the flow velocity of the water and increases its erosive power, resulting in a deeper breach.

Study's Limitations and Potential Future Research Directions

Limitations of the study include the following points:

- Homogenous embankments were used in this study.
- Two types of soil were used in this study (silty sand and clayey sand), with a maximum dry density of 17.5 kN/m³.
- The inflow rate used was (15 and 30) L/min.
- The slope ratios of the sides of the embankment used in this study were 1:1 and 1:2.

Recommendations for Future Works

- Studying the impact of locally-induced initial breaches at different locations on the embankment crest.
- Taking different soil types with different grain size distributions to construct the models.
- Studying the experimental measurement of sediment transport due to dam breach and analyzing of its effect on the downstream channel shape.
- Simulating the failure process due to embankment breach numerically using suitable CFD software.

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