Design and manufacturing of flume apparatus to investigate the failure mechanism of riverbanks

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Cogent Engineering (2019), 6: 1655234
CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

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Abstract: To improve the experimental activities in the field of hydraulic and Geotechnical engineering, flume apparatus was designed, manufactured, and tested in the laboratories of the faculty of engineering at Wasit University, Iraq. The flume apparatus was designed precisely based on the principles of physical modeling in order to achieve the simulation of natural rivers problems in terms of water entry to the flume in a realistic way that happens in natural rivers, and the possibility of controlling water discharge, which produce a good opportunity to study many hydraulic and Geotechnical problems in natural rivers and open channels. This paper presents the details of the manufacturing process of the flume apparatus as well as the result of preliminary test. The test was to study the failure mechanism in riverbank which showed a very good prediction of the failure mechanism types that observed. The circular failure and planar failure as well as the initial tension cracks that appeared during short term condition of streaming flow are inspected. It was concluded also that the failure of the river banks during the water flow in the flume in prototype scale is consistent with what had been observed in the model scale.

Subjects: Water Engineering; Water Science; Hydraulic Engineering

ABOUT THE AUTHOR

Asad Aldefae has a PhD in civil engineering/geotechnical engineering from the University of Dundee/Scotland/UK at the end of 2013. He is interested in earthquake engineering, environmental engineering, riverbanks stability, physical and numerical modeling, geotechnical centrifuge, and seismic performance of soil-structure interaction and slope stability analysis. More than 13 paper were published in high ranking journal by Dr. Aldefae like Géotechnique, Soil Dynamic and Earthquake Engineering, Geotechnical and Geoenvironment Engineering, ASCE as well as many international conferences like a series of international conferences of physical modeling in geotechnic (ICPMG) in both Perth, Australia (2014) and London, UK (2018) and Greece. Results of this paper are important to improve the lab experimental activity and most of the obtained results from the preliminary tests of all designed machines are compatible with those of well-known outcomes in very big research Centres.

PUBLIC INTEREST STATEMENT

The experimental tests in geo-environmental laboratories witnessed a great development recently and in the last few decades. This research article describes designing, manufacturing and testing of flume apparatus that is widely used to investigate the open channel and water streaming behave under different water flow circumstances. The apparatus was tested under different water velocity through an open channel model that was prepared from clayey soil. The initial tension cracks, settlement and the collapsibility of the riverbanks are inspected carefully under short-term conditions of flow. The settlement and the tension cracks are both strongly influenced by the rising up of the water level in the channel. The failure mechanism of the riverbanks was inspected during the different conditions of flow and was circular failure. This failure was identical with the failure shape mode that occurs in real open channel.
Keywords: flume; riverbanks; failure mechanism; tension cracks

1. Introduction

Stability of the river banks is one of the main important factors that must be taken into account by government agencies and municipal office because of their importance of stability of the built structure close to these banks. The erosion due to collapsibility of the river bank's soil leads also to increase the sediment transport that affects the velocity of the sediment discharge along the open channel and the capacity of the water storage in the upstream of the irrigation dams and barrages.

Researches in Geotechnical engineering field and water resources engineering field have witnessed a remarkable evolution in the methods and techniques of studying the phenomenon that occurs in rivers which affects riverbank stability. The physical modeling is one of these techniques that can be used to study the stability of riverbanks, which has been widely used in many studies carried out on different rivers in the world.

Many attempts have been done to investigate different water resources problems and phenomena using small-, medium- and even large-scale flume or channel model. Khalaf, 1999 used 10 m long idolized channel model with 180° bend to study the Tigris river attitude (hydrodynamic and morphological) under a certain circumstance. Samadi, Amiri-Tokaldany, Davoudi, and Darby (2013) conducted an experimental study on the stability of overhanging riverbanks, using a physical model (tank) with dimensions of 200 cm length, 100 cm width, 100 cm height. (Jianfar, 2014) designed an erosion measurement device which contained an acrylic flume with dimensions of 243 cm long, 10 cm wide, and 5 cm height and an extensive experimental work is done to estimate the erosion rates and their effect on the stability of riverbank. (Patsinghasanee, Kimura, Shimizu, & Nabi, 2015) used small-scale flume model with dimensions of 100 cm long, 30 cm wide, and 20 cm high with 1/500 slope to investigate the cantilever failure mechanism in cohesive riverbank and the fluvial erosion in a rectangular channel. Xiaolong (Song, Xu, Bai, & Xu, 2016) carried out 12 m flume in length, 3 m in width and 0.5 m and preliminary experimental study on the impact of primary channel bend, width, and water discharge on the fluvial process in short intervals is done. (Chen, Hsieh, & Yang, 2017) conducted an experimental study to investigate the impact of the change in water level and the tension crack on the stability of riverbank, using a flume of 170 cm long, 50 cm wide, and 60 cm deep. Their study investigated three elements, decline of river levels, primary water elevation, and the slope angle of the riverbank. The model gave a good forecast in the analysis of riverbank stability when it was verified using modified tentative formula. Wang and Lai (2018) conducted an experimental erosion test using a sloping flume of 75 cm long, 25 cm wide, and 25 cm deep, and a strip laser device to estimate the changes in the topography of soil surface and the erosion practicability.

Due to the large number of hydraulic and morphological problems that occur in natural rivers or in open channels, thus, founding a flume apparatus is important to increase the lab facilities and researchers capabilities. This paper focuses on clarifying the details of the manufacturing process of the flume device, which was conducted at the laboratories of the engineering faculty at Wasit University.

2. Design of flume apparatus

The main structure of the flume device consists of a steel frame, storage tank, pacification tank, pump, conveyance pipes, a control valve to set the discharge, and vitreous flume with dimensions of 247 cm long, 80 cm wide, and 44 cm high. The water that spins in the flume device is contained in the storage tank which is 1 cubic meter in volume, with a transverse barrier in the center of the tank acting as a filter to prevent the sediment particles from crossing to the other side of the tank and causing damage to the pump. The water that is withdrawn from the storage tank by the pump is transported through the pipes and enters the pacification tank which is 0.225 cubic meters in
volume, and contain a baffle system which is opposite transverse barriers, the purpose of the baffle system is to increase the flow path to keep away as much as possible from the pumping source to restrict the flow before entering the flume. The height of the front side of the pacification tank extends to the level of the flume height for the purpose of storing the water until it reaches the level of the water entry hole to the flume, so the water will come out in a realistic way, as happens in the rivers, and at the end of the flume there is a vertical gate to control the tail-water depth. There is another pipe connecting between the storage tank and the pacification tank, called the relief pipe which allows controlling the discharge by a valve. Figure 1 shows the details of the designed flume.

3. Actuator specification (The pump)
The pump was chosen with a certain capacity to achieve the required velocity, which is the average velocity of the Tigris River. To achieve the average actual velocity of the stream flow, the pump was provided by a volume to decrease the rotation (i.e. RPM of the pump). By this way, the water flow velocity (discharge) can be controlled easily, alongside the baffles in the pacification tank. The pumping system makes the water flow under simple mechanical action, composed of three sections, an inlet, a casing, and an outlet. Through the operation, water enters the pump through the inlet, the pressure of the liquid is lowest at this point. The water that enters the pump is contained in the casing section during the operation. The liquid leaves the pump through the outlet, this section of the pump is also called the discharge part, the pressure of the liquid is higher at this point. Inside the pump, there is a part that physically moves the liquid through the pump called a paddle, the type of the paddle defines the type of the pump.

4. Designed channel specification
The main purpose of designing this flume apparatus is to study and investigate many phenomena concerning with water flow along the river (i.e. scouring, sediments and hydraulic jump). The failure mechanism that occurs in the banks of natural rivers (Tigris river as a case) using similar soil specimen in the field used in the model, as a result of the effect of water flow velocity and the amount of settlement occurring in riverbank soil (which will be discussed later in this paper).

Dimensions of the upper part of the flume are 2.4 m in length, 0.8 m in width and 0.4 m height. These dimensions allow achieving the minimum requirements of the steady flow in the open channel model. Transparent sidewall is provided from perplex glass so that the model can be inspected during the test. Figure 2 shows the designed flume apparatus with the channel specification.
In order to reflect the reality of natural rivers using the physical model, a trapezoidal channel was constructed within the flume and was tested under short-term condition to investigate how the water flow affects the river bank models and the failure mechanism of these banks.

The trapezoidal channel was designed using manning equation, where the design velocity and the normal depth of specified discharge were calculated (Chaudhry, 2007) (not involved in this paper).

Then the side slope of the designed channel was testified by slope stability analysis in order to calculate the factor of safety in static condition using two methods, Slices method and Taylor method, the calculated value of safety factor was within acceptable limits in each of the two cases (not mentioned in this paper).

5. Preliminary test of the flume

5.1. Material properties

The soil that was used in the physical modeling for the preliminary test is a specimen of Tigris riverbank soil. The specimens were collected from both sides of the river banks close to Al-Kut barrage and then transported to the laboratory for model preparation under similar field conditions (i.e. density and water content). To achieve the in-situ density, many trials were performed on specimens using medium size contained to investigate how many layers, how many blows and the mechanism that can capture the desired density. The model was prepared according to the calibrated procedure and the tests were carried out to specify the physical modeling whereas the physical properties of the soil sample have been determined before model preparation. Table 1 shows the physical properties of the collected samples from the river banks.

5.2. Model preparation

In order to prepare the designed channel model within the flume, the disturbed soil specimen that was brought from the site to the laboratory was used in constructing the channel, where the soil was placed by three layers, each layer was compacted by human force using a small manufactured hammer with a weight of 2 kg based on the calibrated procedure that was mentioned earlier. To make sure that the desired density was satisfied; a small tube was used to measure the density.
(according to procedures of field density test by core cutter method BFC 31703). Two LVDTs were installed in two different positions to measure the vertical displacement which represents the settlement in riverbank. A flow velocity was measured using mini-water flowmeter device of precision ±2%. The behavior of failure mechanism was recorded by taking pictures and short videos using high-speed camera under short-term condition (i.e. 5 hr). Figure 3 shows the designed and prepared open channel section.

To prevent the erosion from the banks at the begging of the channel, fractions of small size rock are used as a lining of the banks and were fixed in a way where no banks soil is contactable with water (i.e. collocation as in-site). This method is very important as the lining will prevent the water flow at the beginning to be turbulent as well as making the water stream to flow at steady state after the lining with uniform velocity as much as possible (Habsen and Cook, 1998).

6. Failure mechanism
In the finite slope, where the value of critical height \( H_{cr} \) approaches the height of the slope, for analyzing the stability of this finite slope, an assumption should be made about the general shape of the failure slip surface. After an extensive investigation of slope failure since 1920s, a Swedish geotechnical commission recommended that the actual surface of sliding may be approximated to

| The Property                  | Grade |
|------------------------------|-------|
| Liquid Limit                 | 33.29 |
| Plastic Limit                | 26.31 |
| Plasticity Index             | 6.98  |
| Specific Gravity, \( \gamma_i \) | 2.67  |
| USCS                         | CL-ML |
| Maximum Dry Density, \( \gamma_d \) | 16.2  |
| Field Density, \( \gamma_f \) | 15.1  |
| Cohesion, \( C \)            | 27.4  |
| Angle of Friction, \( \Phi \) | 5.2   |

Figure 3. The physical modeling of open channel.
be circularly cylindrical for cohesive soil (Al-Bahdli et al, 2009). Since that time, most conventional stability analysis of slopes has been made by assuming that the curve of potential sliding is an arc of a circle. Circular failure may occur in one of three modes, when the failure occurs in such a way that the surface of sliding passes above the toe of the slope, it is called a slope failure, when the surface of sliding passes at some distance below the toe of the slope, it is called a base failure, and if the surface of sliding passes at the toe of the slope, it is a toe failure.

From Figure 4, it can be seen that the failure mechanism is very close to what has been mentioned above (i.e. arc or semi-arc slip surface). The actual slip surface of the Diyala river (i.e. Figure 4(b)) was completely simulated during and after the test. It should be noticed also how the banks collapsibility affects the increase of the sediment discharge in the streaming flow.

It is necessary to understand the causes of slope failure in order to avoid repeated failure and to take the necessary steps to repair the slopes so that they remain stable and safe. The main requirement for slope stability is that “the shear strength of the soil must be greater than the shear stress required for equilibrium”—that means the instability occurs in two ways, decreasing the shear strength of the soil and increasing the shear stress required for equilibrium (Duncan, Wright, & Brandon, 2014).

The failure modes that were observed in the results of our preliminary test could be discussed according to the decreasing in the strength of the soil along the slip surface and the increasing in the shear stress. The cracks that were observed on the surface represented the tension in the soil, which exceeded the soil strength. The increasing in the shear stress recognized by three signs, firstly, when the tension cracks were filled with water, additional pressure would be generated on the slope, if these cracks stay filled with water for long enough, the pore water pressure would increase and lead to failure. Secondly, the excavation at the toe of the bank, when the water level was rising due to centrifugal force, so it was highest at the outer bends, and as the water comes down due to gravity, there was a helical spiral that occurred which causes erosion at the toe of the bank (Pastinghasanee et al, 2017). The last sign was that the sudden drawdown in the water level, where the external water pressure provides a positive effect on the slope, and when the water level decreased without decreasing in pore water pressure in the same consistency, so the shear stress within the soil increased, which caused the slope failure.

7. The developed tension cracks
Tension cracks are one of the most important parameters that affect riverbank stability through two factors: the location and the depth of the crack, where the depth of tension cracks reduces the length of failure surface and thus reduce the stability of the bank. The tension crack depth calculated from Mohr-Diagram is symbolized as:
where \( Z_o \) is the tension crack depth, \( \gamma_s \) is the specific weight of the material, \( \varphi \) and \( C \) are the friction angle and cohesion, respectively (Amiri-Tokaldany, Darby, & Tosswell, 2003). Another equation to estimate the depth of tension cracks in a finite tensile strength soil was presented by Lohnes & Handy (1968):

\[
Y = Z_o \left(1 - \frac{\sigma_{TC}}{\sigma_t}\right)
\]

where \( Y \) is the depth of tension cracks, \( \sigma_{TC} \) is the soil tensile strength, \( \sigma_t \) is the tensile stress on the ground surface. Lohnes and Handy defined \( \sigma_t \) by using mohr diagram:

\[
\sigma_t = 2C \tan(45 + \varphi/2)
\]

where \( C \) is the cohesion of soil. At critical condition, the angle of the failure plane corresponds to the angle at which the cohesion, \( C \), is fully developed (Taylor, 1948). Depending on Taylor theory, Lohnes and Handy defined an equation to estimate the angle of the failure plane, \( \beta \), using a simplified geometric shape for the riverbank (see Figure 5):

\[
\beta = \frac{\alpha + \varphi}{2}
\]

where \( \alpha \) is the angle of the riverbank before failure. (Thorne & Abt, 1993) showed that the depth of the tension cracks equal to less than half of the height of the bank. An equation related between the current tension crack depth and its amount after the failure of the bank was presented by (Amiri-Tokaldany et al., 2003):

\[
\beta = \tan^{-1} \left( \frac{H_2}{B_w + \frac{H_1}{\tan \alpha}} \right)
\]

In this paper, the width of failure block, and the depth of tension crack were measured (see Figure 6), then the angle of failure plane was calculated using equation (5), which is illustrated in Table 2.

Figure 7 shows the developed tension cracks at the end of the test. It can be seen that these cracks are well captured the development of real behavior of the tension cracks at the crest of the river banks due water level drop in the river (i.e. prototype scale; Figure 8,7).

In general, there are four types of failure, hydraulic failure, gravitational failure, Geotechnical failure, and tectonic failure. In our preliminary test, the types of failures that were observed and discussed according to its causes and the shape of failure that was observed from the result of the
Figure 6. Locations of tension cracks.

Table 2. Calculation of failure plane angle

| Time (hr) | Bw (cm) | Y (cm) | H2 (cm) | β    |
|----------|---------|--------|---------|------|
| 1        | 1       | 15     | 5       | 21   | 42.4 |
| 2        | 2       | 5      | 5.6     | 20.4 | 57.5 |
| 3        | 2       | 2.5    | 4       | 22   | 64.5 |
| 4        | 2       | 8.5    | 13      | 13   | 38.2 |
| 5        | 2       | 5      | 3       | 23   | 60.5 |
| 6        | 4       | 3.5    | 5.5     | 20.5 | 60.7 |
| 7        | 5       | 4.5    | 8       | 18   | 55.2 |
| 8        | 5       | 4.5    | 3.5     | 22.5 | 60.9 |
| 9        | 5       | 3.5    | 9       | 17   | 55.9 |

Figure 7. Cracks at the crest of the bank; (a) model scale and (b) real river (Moayedi et al. 2010).
test, the hydraulic failure, which caused erosion at the toe of the bank. The gravitational failure or sliding failure, which is recognized by the tension cracks appeared on the surface of the bank, this appearance of the tension cracks indicates that the type of failure mechanism was a planar failure (in the locations of the tension cracks) (Gilliam, 2011).

8. Riverbanks settlement

The settlement of river banks model was measured using two lvdts as explained in the model preparation. It was observed that the total settlement at the end of the test (5 hr) was around 10.3 mm and 9.4 mm at both the right and the left bank model, respectively. The trend of the measured settlement at both banks replicated the short-term settlement of the river banks that has been observed and inspected settlement of the real river banks at threshold before the final collapsibility. Figure 8 shows the measured settlement at the crest of the river model.

9. Conclusion

The results of a preliminary test during short-term water streaming showed that the design of the flume apparatus has achieved the desired goal which is a physical model can simulate the natural rivers or open channels to a good extent. This means a good opportunity has been provided for future studies in the field of hydraulic and rivers engineering using the principles of physical modeling. The failure mechanism for the river banks is well captured during short-term condition streaming, the circular failure and the planar failure. The measured settlement of two banks (9 and 11 mm, respectively) leads to the formation of the initial tension cracks and the banks collapsibility that were observed in the model were very close to those in the actual rivers. The measured depths of the crack tension were predicted with the calculated values for art-of-literature equations. The riverbanks stability is strongly influenced by the cyclic flooding of the channel. The behavior was inspected when the channel water levels arise and then drop down leads to triggering of the tension cracks.

Acknowledgements

The authors would like to express their sincere gratitude to the technical staff at the engineering laboratories at Wasit University, faculty of engineering for their assistance in performing the experimental tests. The first author would also like to acknowledge the financial support for the postgraduate students from the Ministry of Higher Education and Scientific Research (MOHESR) of the Republic of Iraq.

Funding

This work was supported by the Wasit University [N/A].

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