An Experimental Study on the Influence of Water-Level Fluctuation on Stability of Slope of Model River Bank Composed of Cohesionless Material

Md. Firoz Ali, Supia Khatun, and Yasser Arafat

1 Introduction

The stability of a slope is utterly governed by soil properties, stress conditions, and slope geometries. Any change taking place of at least one of these factors, means slope stability conditions being potentially affected [1]. At a micro-scale, the inherent properties of a soil are governed by its history; no matter if the soil is processed (crushed, filled, etc.), or if it is naturally occurring; i.e., formed by weathering of rock, transported by erosive processes, and finally deposited from water, wind, or ice. Also, at a larger scale—considering the soil skeleton—many different processes are governing the properties of the soil; e.g., particle-size distribution, soil-profile homogeneity, denseness, etc. The properties of soil are continuously affected by long-term processes, including, e.g., transport and depositing (i.e., erosion and land-form development), and aging (i.e., weathering or other changed chemical or physical conditions). Any soil volume is continuously affected by the hydrological conditions prevailing; present water is either influencing or completely governing the actual soil properties. At the scale of bank slopes and embankment dams, the structures are influenced by external water loads, development of pore pressures, and hydrodynamic impact from internal and external water flow [2] (Fig. 1).

Md. F. Ali (✉)
Department of Civil Engineering, Dr. Sudhir Chandra Sur Degree Engineering College, Kolkata 700074, India

S. Khatun · Y. Arafat
Department of Civil Engineering, Aliah University, Kolkata, West Bengal 700156, India

C. N. V. Satyanarayana Reddy et al. (eds.), *Stability of Slopes and Underground Excavations*, Lecture Notes in Civil Engineering 185,
https://doi.org/10.1007/978-981-16-5601-9_17

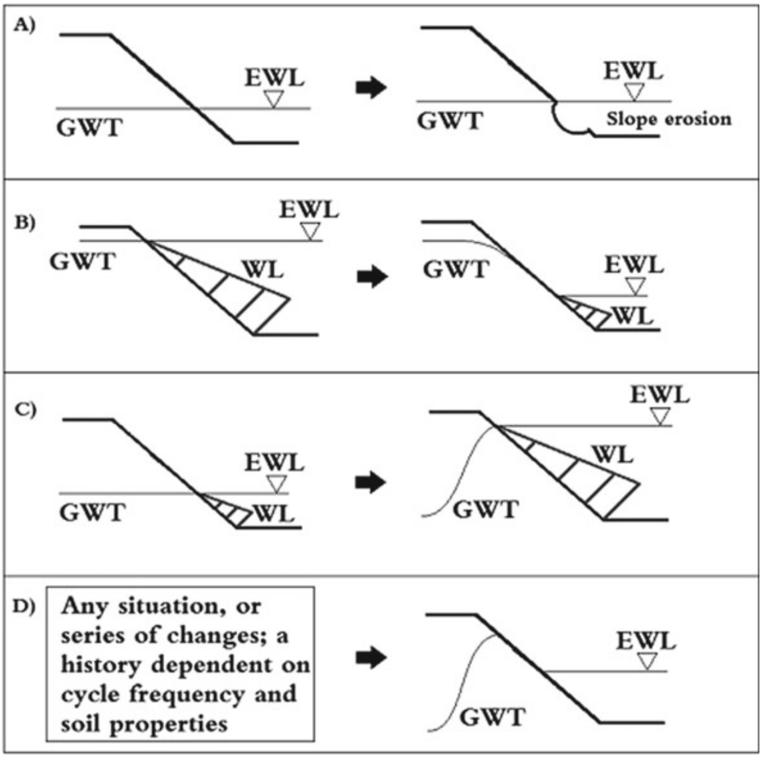


Fig. 1 Basic modes of water level change; streaming water (**A**), water level drawdown (**B**), raised water level (**C**), and fluctuating water level (**D**). Water loads (WL), positions of the ground-water table (GWT), and the external water level (EWL) are shown

2 Objective

2.1 Aim and Objectives

The aim of this study is to identify and enlighten the potential impacts on waterfront slopes subjected to water-level fluctuations, including evaluation of factor of safety by strength reduction method.

The summary of the objectives of this study is as follows:

1. Experimental model analysis of the stability of a bank simulating a river bank during post-flood condition.
2. Determination of factor of safety by strength reduction method.
3. Study of the influence of drawdown rate and ratios on the stability of a bank.
4. To study the variation of pore pressure with water level fluctuation and its effects on stability.

3 Literature Review

Mehmet M. Berilgen (2006): This paper presents an investigation of slope stability during drawdown depending on the soil permeability, drawdown rate, and drawdown ratio, considering the nonlinear material and loading conditions.

Jens Johansson, (June 2014): Water-level fluctuations have been reviewed; sources, geotechnical effects on slopes, and approaches used for modeling have been focused on. It has been found a predominance of research focused on coastal erosion, quantification of sediment production, bio-environmentally issues connected to flooding, and effects on embankment dams subjected to rapid drawdown.

Qin Rong, Pan HaiZe, Han LingFeng, Chen MengJie, (2014): Using SEEP/W, SIGMA/W and SLOPE/W Module of GEO-SLOPE software, we studied the slip mass change rule with the water level lifting, variation of the stress field and displacement fields of action under the reservoir water level lifting, and on the basis of the results of seepage and stress–strain calculation results, considering finite element method and limit equilibrium method to calculate the landslide stability analysis and comprehensive evaluation.

4 Experimental Programme and Methodology

4.1 Laboratory Model Study

The model river bank and hydro-fluvial conditions were defined simulating a river bank subjected to rapid drawdown based on the field condition of the bank of river Ganga at the upper region of Murshidabad district in West Bengal, India. The laboratory model study was done for the following reasons:

1. The socioeconomic losses are at alarming condition due to bank failure in West Bengal, India, which demands the scientific analysis of bank failure.
2. The bank consists of composite material, loamy sand in the lower layer, and thin silty clay at the top.
3. Most of the failure occurs during post-flood drawdown of water.

A series of trial experiments have been carried out to study the responses of model banks for varying bank geometries, different drawdown rates and ratios and hydrograph conditions. The slope of the model bank has not been perfectly represented as the actual bank slope as the site slope is not perfectly uniform. The slope of the model bank was chosen as 1 V:2H, 1 V:1.5H, respectively. This slope has been adopted in the field for protection work which has also failed experience.

4.2 Test Procedure and Program

A model river bank was built inside the tank with slope geometry as mentioned above. In each experiment, the initial bank slope 1 V:2H, LWL, and HFL have been kept constant. The model bank has been prepared by a uniform compaction energy of 0.209 kg/cm^2 to achieve 15.965 kN/m^3 unit weights of the bank materials. This density has been chosen based on pre-monsoon density obtained from the actual field. All the experiments have been recorded using a digital video camera. Three different hydrograph cases were undertaken by controlling two outlets of diameters 50.8 mm and 76.2 mm. Each run was continued for 3 h to record the observations. The water level in the model river course has been increased gradually from a low water level to a high flood level, i.e., 0.8H for this model study. The experimental program and variations of drawdown rate and ratios are presented in the following Table 1 (Fig. 2).

The pore pressure variations along the cross-section of the model river bank after each drawdown have been measured with the help of a tailored pressure measuring device (Fig. 3). It consists of eight numbers of transparent P.V.C. tubes (3 mm dia.); one end of which has been installed at different locations of the bank during the construction of the model river bank and other ends of the pipes are attached at the lower ends of the series of labeled manometers fixed on the Perspex wall of the model flume. The positions of the manometers inside the bank were shown in Fig. 3 and the planimetric and vertical positions of manometers are listed in Table 2.

The schematic diagram of the experimental setup has been presented in Fig. 4 (2.00 m long, 0.90 m wide, and 0.60 m deep). Two sets of pumps have been installed in the setup; 5L/s capacity pump has been assigned for maintaining the water level in the seepage tank. A 10L/s capacity pump was used to produce the required drawdown rates and ratios. The capacities of the pumps have been fixed after trial tests to achieve a drawdown rate from the high flood level to observe the failure condition. The high flood level (HFL, 0.8H cm) and low water level (LWL, 0.3 cm) for this particular research works have been selected based on the actual HFL at that particular site during monsoon and LWL during summer and adjusting with the model flume size.

4.3 Materials Used in the Study

It has been found that the major part of the river bank comprises a layer of sands which is vulnerable to failure. To represent the similar kind of bank material fine-grained local sand having similar grain size distribution has been used. The angle of internal friction and coefficient of permeability for horizontal flow for the three different unit weights are tabulated in Table 3.

Table 1 Summary of experimental program

Details of different geotechnical and fluvial conditions under which various runs of the experiment have been carried out:							Hydrograph cases	Initial bulk density (kN/m^3)	Bank slope 2 Types
Drawdown ratios	0.0	0.2	0.3	0.5	0.6	0.8	I (when the outlet pipe is 50.8 mm)	15.965	1:2 & 1:1.5
	0.0	0.2	0.3	0.5	0.6	0.8			
	0.0	0.2	0.3	0.5	0.6	0.8			
	0.0	0.2	0.3	0.5	0.6	0.8	II (when the outlet pipe is 76.2 mm)		
	0.0	0.2	0.3	0.5	0.6	0.8			
	0.0	0.2	0.3	0.5	0.6	0.8			
	0.0	0.2	0.3	0.5	0.6	0.8	III (when the outlet pipe is both 50.8 mm and 76.2 mm)		
	0.0	0.2	0.3	0.5	0.6	0.8			
	0.0	0.2	0.3	0.5	0.6	0.8			

Fig. 2 The gauging system to measure deformation in the profile

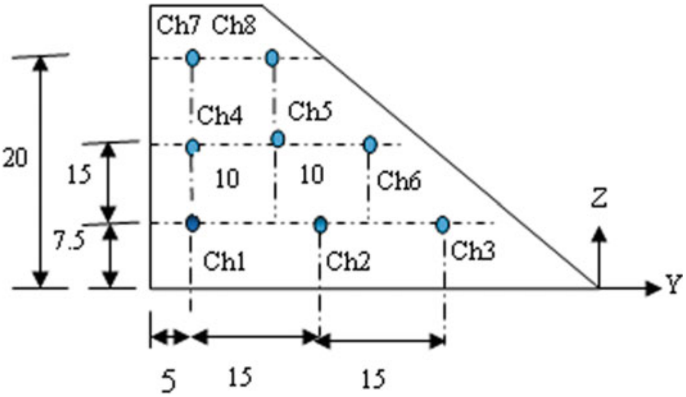


Fig. 3 Configuration of pressure monitoring manometers (Bank Slope 1 V:2H dimensions are in cm)

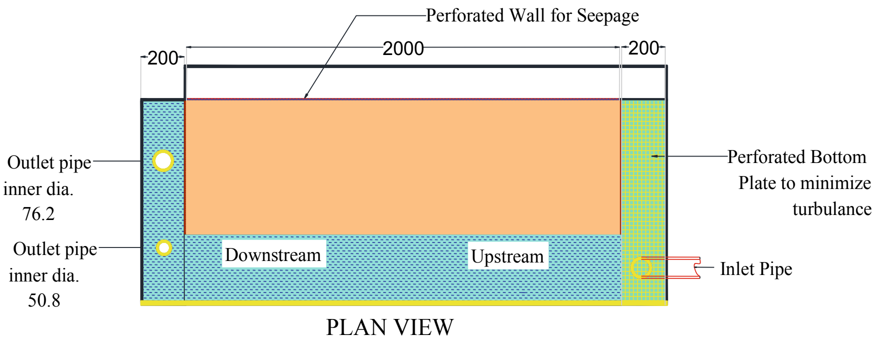


Fig. 4 Experimental setup plan view (all dimensions are in mm)

Table 2 Positions of pressure measuring channels, bank slope 1 V:2H

Manometer channels	Position in x-direction (along the length of bank (cm)	Position in y-direction (cm)	Position in z-direction (cm)
Ch1	48	5	7.5
Ch2	48	20	7.5
Ch3	48	35	7.5
Ch4	48	5	15
Ch5	48	15	15
Ch6	48	25	15
Ch7	48	5	20
Ch8	48	15	20

Table 3 Geotechnical Properties of bank material used in the experiment

Unit weight of bank material (γ) (kN/m^3)	Optimum moisture content (%)	Angle of internal friction (φ°)	Coefficient of horizontal Permeability
15.965	3	34.5	0.0675

4.4 Embankment Geometry

In this laboratory model study, a linear scale of 1:25 was selected to simulate the prototype bank geometry of river Ganga in Murshidabad District of West Bengal. The height of the bank was selected based on field observation and slope of bank 1 V: 2H and top width of the bank as 0.1 m as shown in Figs. 5 and 6 is the photographic view of the experimental setup along with the model bank.

5 Experimental Result and Discussion

As it is not possible to control the drawdown rate for each drawdown ratio manually, so the three average drawdown rates have been assigned that are named as Hydrograph case-I (2″ dia.), Hydrograph case-II (3″ dia.), and Hydrograph case-III (2″ + 3″ dia.). In case of results discussion, we prepared the tables and drew the curves of pore pressure variation with respect to time at different drawdown ratios and shear strength variation with respect to time at different drawdown ratios after drawdown. And at last, we prepared tables and draw curves on factor on safety variation with respect to drawdown rate and drawdown ratio on different hydrograph cases (Tables 4 and 5) (Figs.7, 8, 9, 10, 11 and 12).

Fig. 5 Model for the experiment in Lab

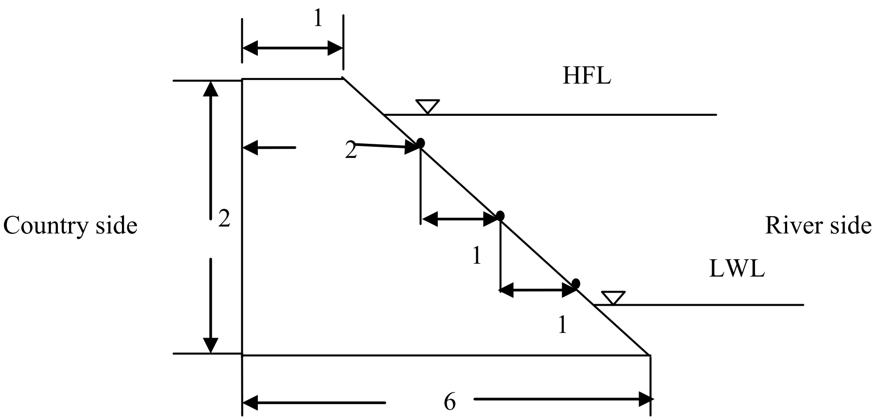


Fig. 6 Model geometry: Dimensions, Low water level (LWL), high flood level (HFL), and A, B, C are manometer positions (three rows as shown and six columns @280 mm c/c) are shown in the figure. (All dimensions are in mm)

Table 4 Experimental result of pore pressure variation at different times after drawdown from 0.3H to 0.0H (Bank Slope = 2H: 1 V)

Drawdown ratio = 0.3		Hydrograph Case: I		Pipe diameter: 2″		Date: 03–23-2019		
Data measurement of pressure from manometers								
Time interval after drawdown (Sec)	Height of water in cm in pipe number							
	Ch.1	Ch.2	Ch.3	Ch.4	Ch.5	Ch.6	Ch.7	Ch.8
t = 0	6.0	5.5	7.0	5.6	8.2	5.9	0	0
t = 5	5.9	5.0	6.5	5.6	8.2	5.8	0	0
t = 10	5.7	4.0	6.4	5.4	8.0	4.8	0	0
t = 15	5.5	3.8	5.8	5.3	7.8	4.2	0	0

Table 5 Experimental result for the determination of shear strength at different times after drawdown from 0.3H to 0.0H (Bank Slope = 2H: 1 V)

Hydrograph case: I			Pipe diameter: 2″	Date: 03–23-19	
Condition	Shear strength calculation				
	Initial reading of the vane	Final reading of Vane	Torque (kg-cm)	Shear strength (kPa)	Shear strength reduction (%)
Before flow (0.0H)	250	209	0.586	14.04	
After drawdown; t = 2 min	250	226	0.343	8.22	41.46
t = 4 min	250	224	0.371	8.91	-8.33
t = 6 min	250	223	0.386	9.25	-3.85
t = 10 min	250	220	0.429	10.28	-11.11

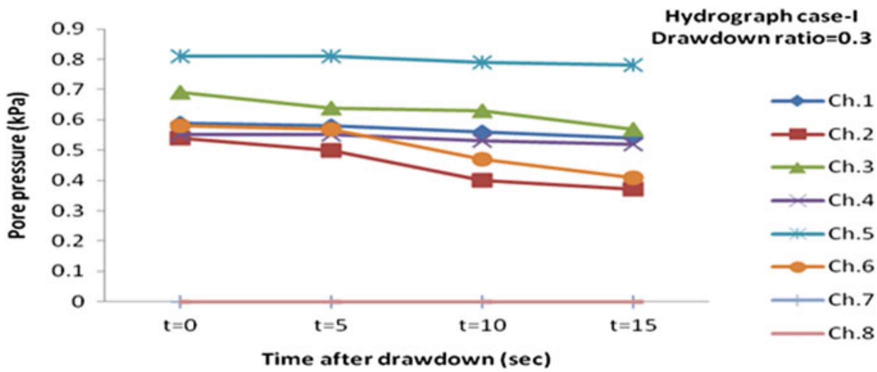


Fig. 7 Plot of pore pressure variation with time after drawdown from 0.3H to 0.0H (Bank Slope = 2H: 1 V)

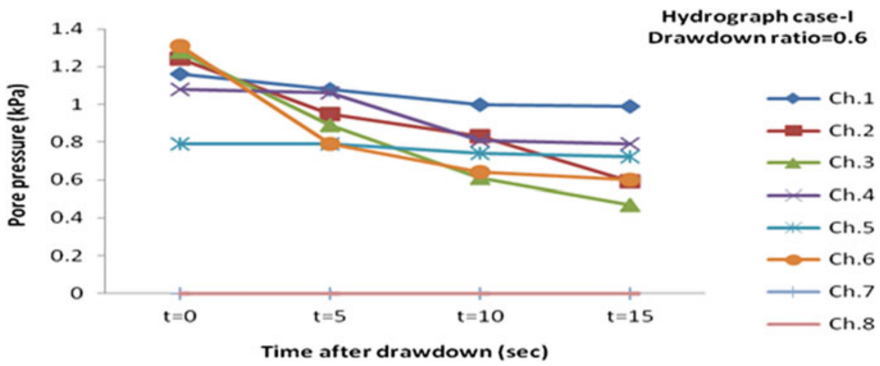


Fig. 8 Plot of pore pressure variation with time after drawdown from 0.6H to 0.0H (Bank Slope = 2H: 1 V).

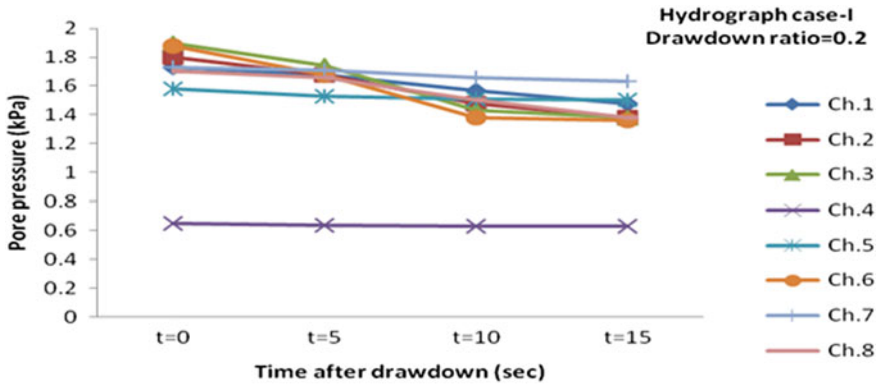


Fig. 9 Plot of pore pressure variation with time after drawdown from 0.8H to 0.6H (Bank Slope = 2H: 1 V).

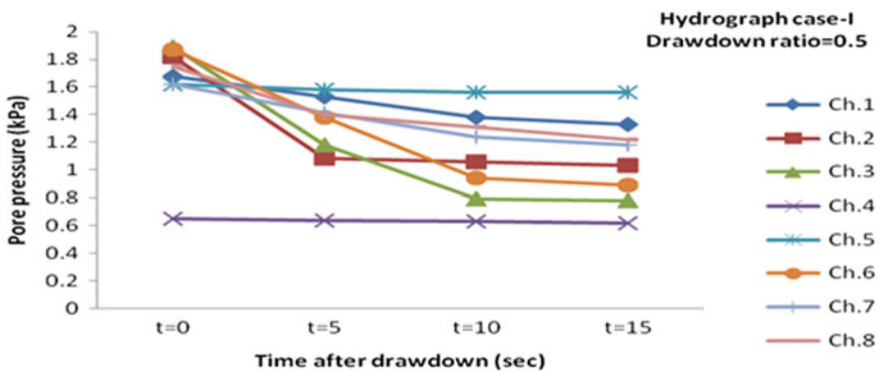


Fig. 10 Plot of pore pressure variation with time after drawdown from 0.8H to 0.3H (Bank Slope = 2H: 1 V)

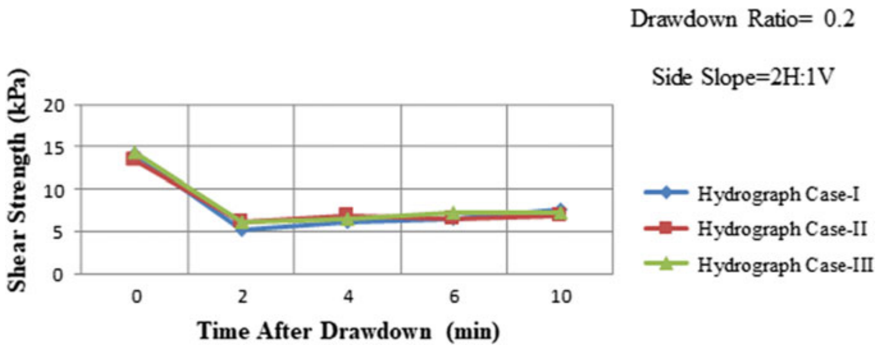


Fig. 11 Plot of Shear strength variation with time after drawdown for different hydrograph case conditions for drawdown ratio 0.2 (Bank Slope = 2H: 1 V)

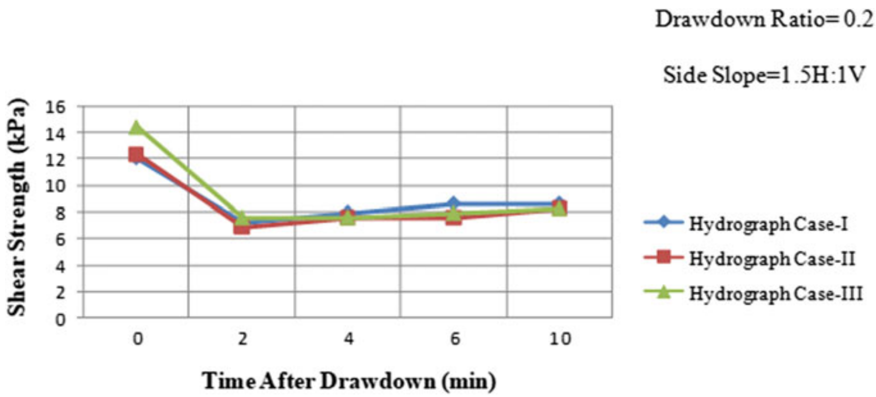
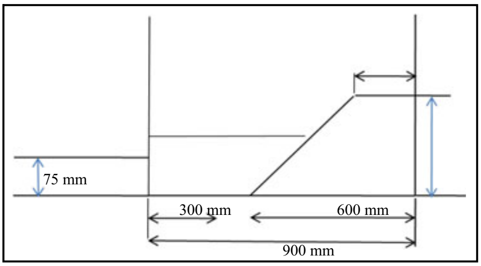


Fig. 12 Plot of Shear strength variation with time after drawdown for different hydrograph case conditions for drawdown ratio 0.2 (Bank Slope = 1.5H: 1 V)

5.1 Experimental Data of Pore Pressure and Shear Strength After Drawdown for Hydrograph Case-I

5.1.1 For Drawdown from 0.3H to 0.0H (Bank Slope = 2H: 1 V)



Initial water content = 3%

Bank Material: Homogeneous Sand

Bank Geometry

Side Slope = 2H: 1 V

Height of Bank = 250 mm

Base width = 600 mm

Top Width = 100 mm

Hydraulic Data

Height of bank up to which water level to be raised (a) = 0.3 H = 75 mm

Time required to fill up the tank up to desired level (b) = 84.00 s

Rate of filling of tank (a/b) = 0.90 mm/s

Volume of water collected (c) = 5.60 L

Time of collection (d) = 4.00 s

Flow rate (c/d) = 1.4 l/s

Area of Flow = 28,125 mm^2

Velocity of flow = (Flow rate*10ˆ6)/Area of flow = 49.78 mm/s

Drawdown Data

Initial Height of water (L) = 0.3 H = 75 mm [Here, H = 250 mm]

Final Height of water after drawdown (F) = 0.0 H = 0 mm

Time required to drawdown from 0.3 H to 0.0 H (t) = 26.00 s

Drawdown Rate [(L–F)/t] = 2.88 mm/s Drawdown Ratio (L/H) = 0.3.

5.2 Calculation of Factor of Safety by Strength Reduction Method

5.2.1 Factor of Safety for Bank Slope 2H: 1 V

See Table 6 and Fig. 13

Table 6 Experimental results of factor of safety (FoS) after drawdown for different drawdown rates and drawdown ratios for hydrograph case-I

Hydrograph case: I		Pipe dia.: 2″						Side slope: 2 H:1 V	Date: 23-03-19	
Variation of shear strength with time and calculation of FoS										
DD ratio (L/H)	DD rate (R) mm/s	Time (min)	t = 0	2	4	6	10	Minimum shear strength or failure shear strength (kPa)	FoS	Failure condition
0.3	2.88	Shear Strength (kPa)	14.04	8.22	8.91	9.25	10.28	5.14	1.60	Minor mass failure
0.6	2.5		14.04	7.19	7.19	7.88	8.56		1.40	
0.2	2		14.04	5.14	6.17	6.51	7.54		1.00	
0.5	1.32		14.04	5.14	6.17	6.85	6.85		1.00	
0.8	3.28		14.04	6.17	6.85	6.85	7.19		1.20	

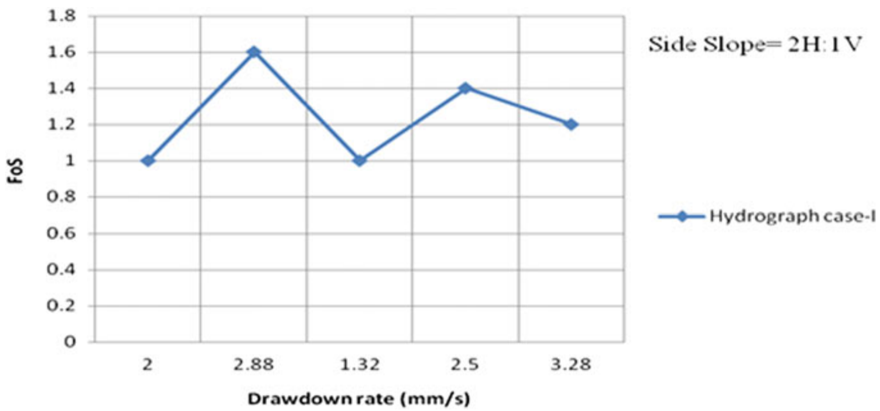


Fig. 13 Plot of FoS versus drawdown rate for bank slope 2H: 1 V and hydrograph case-I

5.2.2 Factor of Safety for Bank Slope 1.5H: 1 V

See Table 7 and Fig. 14

5.3 Results Discussion

It has been observed from the above data and the curve of pore pressure variations that immediately after drawdown the positive pore pressure is almost unchanged during the drawdown period, after that it is decreasing and becomes constant with respect to time. The change of pore pressure is maximum for maximum drawdown ratio and also it is varying for different hydrograph cases. Also, it is observed that after drawdown, the release of pore pressure is little bit slow in the case of 1:2 river bank slope compared to the 1:1.5 slope. In case of shear strength variation, it has been observed from the above data and the curve that immediately after drawdown the shear strength of the model river bank becomes minimum compared to the initial shear strength of the bank for different drawdown ratios, and after some time it is slowly increasing. It is also observed that the change of shear strength is maximums for maximum drawdown rate and also it is varying for different hydrograph case. At last, it has been observed from the above data and the curve of factor of safety (FoS) variation with respect to drawdown rate and drawdown ratio for different hydrograph cases that with the increase of drawdown rate and drawdown ratio, the factor of safety decreased and it became minimum for maximum drawdown rate and ratio. It is also observed that immediately after drawdown the factor of safety is minimum and it increases with respect to time (Figs. 15 and 16).

Table 7 Experimental results of factor of safety (FoS) after drawdown for different drawdown rates and drawdown ratios for hydrograph case-I

Hydrograph case: I		Pipe dia.: 2″			Side slope: 1.5 H:1 V			Date: 11-04-19		
Variation of shear strength with time and calculation of FoS										
DD ratio (L/H)	DD rate (R) mm/s	Time (min)	t = 0	2	4	6	10	Minimum shear strength or failure shear strength (kPa)	FoS	Failure condition
0.3	2.34	Shear strength (kPa)	11.99	6.51	6.85	7.54	7.88	651	1.00	Minor failure mass
0.6	1.90		11.99	7.54	7.88	8.22	8.56		1.16	
0.2	0.91		11.99	7.19	7.88	8.56	8.56		1.05	
0.5	0.83		11.99	6.85	7.54	7.54	7.88		1.05	
0.8	2.02		11.99	7.19	7.54	8.22	8.56		1.10	

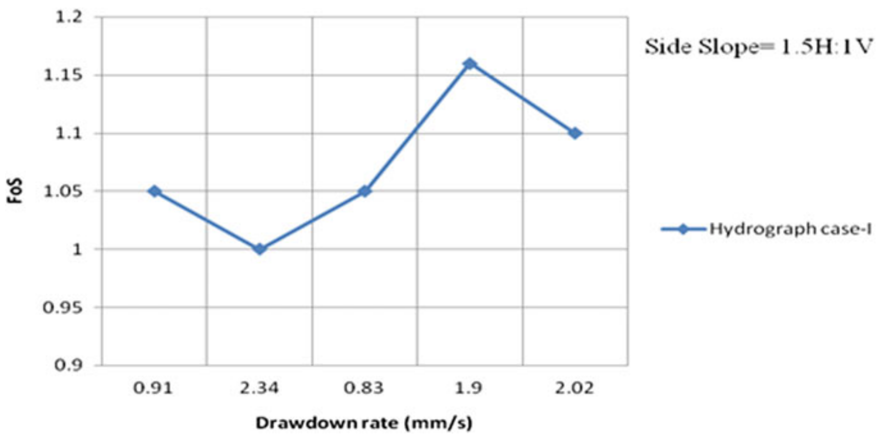


Fig. 14 Plot of factor of safety (FoS) versus drawdown rate for bank slope 1.5H: 1 V and hydrograph case-I

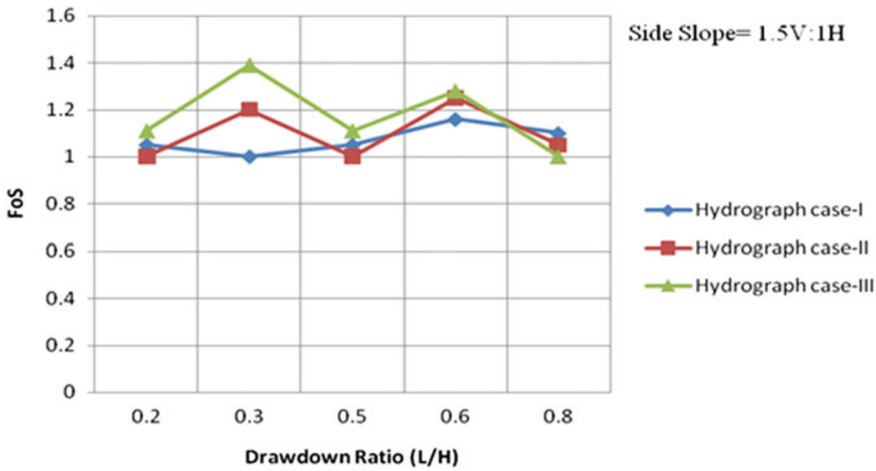


Fig. 15 Plot of factor of safety (FoS) versus drawdown ratios for bank slope 1.5H: 1 V and different hydrograph case conditions

6 Conclusions

After calculating the pore pressure variations with time after drawdown for different drawdown rates and drawdown ratios shows that the release rate of positive pore pressure increases with the increase of drawdown rate and ratios. And during major river bank failure, we observed that the release rate of positive pore pressure from the model river bank is minimum. In this model study of the stability of river bank, the effect of shear stress generated by the velocity of water flow has not been taken

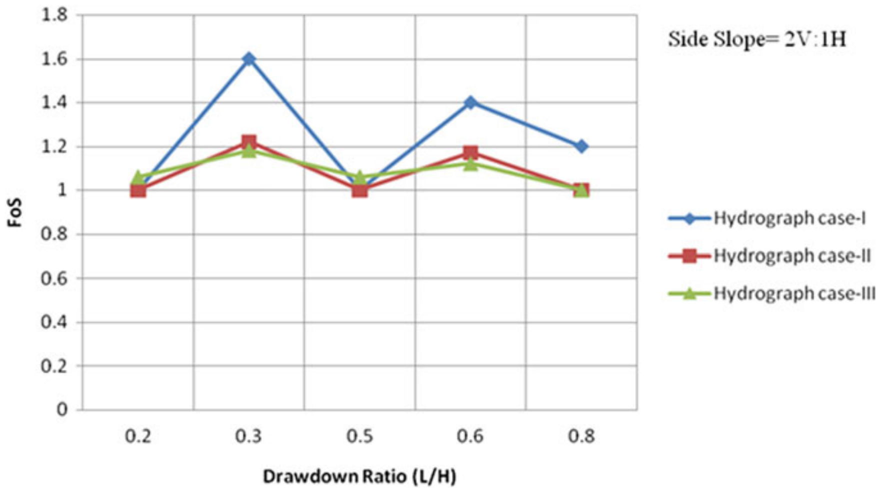


Fig. 16 Plot of factor of safety (FoS) versus drawdown ratios for bank slope 2H: 1 V and different hydrograph case conditions

into account, instead the river bank is subjected to rapid drawdown only, and from the experimental results, we may conclude that the water-level fluctuation is one of the dominating causes of bank failure for cohesionless soil. The factor of safety calculated for different drawdown rates and drawdown ratios shows that it decreases with an increase of drawdown rate and ratio, meeting the consequences of physical phenomenon associated with this condition. The effects of drawdown rate and drawdown ratio on the factor of safety reveals that it is rather than drawdown ratio which takes a leading role to make the river bank unstable in comparison to drawdown rate. And during major bank failure, we observed that the factor of safety of model river bank become minimum.

References

1. USACE, Engineering and Design: Slope Stability—Engineer Manual. US Army Corps of Engineers, EM 1110-2-1902 (2003)
2. Duncan, J.M., Wright, S.G.: Soil Strength and Slope Stability. John Wiley & Sons, New York, March (ISBN 0-471-69163-1) (2005)