SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage: https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Experimental Tests of Slope Failure due to Rainfall using Physical Slope Modelling

Jayant Raut[1,*], Prashant Pande[1], Avinash Vasudeo[2], Rajesh Bhagat[1], Boskey Bahoria[1], Atul Kurzekar[1]

[1] Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India
[2] Department of Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, India

ARTICLE INFO

Article history:
Received 23 August 2024
Received in revised form 25 September 2024
Accepted 1 October 2024
Available online 30 October 2024

Keywords:
Slope, stability, rainfall, experimental model

ABSTRACT

In order to investigate the damage due to slope failure is very important. The main aim of this study is to found experimentally the effects of slope and rainfall intensity on stability of slope. We performed number of experimental tests using our varying slope model. To understand the failure mechanism of slopes there are various methods and also some models are been prepared for testing purpose. Slope failure can be occurred due to increase in pore water pressure, weathering of soil, cracking, decomposition of clayey rock fills, intensity of rainfall, duration of rainfall. By considering all these causes analysis of slope stability is most important to protect the slopes from failures. Slope stability analysis can be static, analytical methods to evaluate the stability of hills, natural slopes, excavated slopes etc. Analysis is generally done to understand the causes of failure or factors which affect the movement of slopes etc. Model development is also one of the ways to analyse the slope failure because of some specific reason. So understanding the rainfall effect on the slopes in hilly region is the major aspect to study. Our experimental result shows that vegetation is the effective and economical way of improving stability of slope. It increases that stability of slope by 15 to 25 %.

1. Introduction

Disastrous damage due to slope failures triggered by heavy rainfall is great concern. People all around the world have been extremely concerned about slope failures triggered by heavy rainfall. India has not had the different story and witnessed number of landslides. This catastrophe landslide is dangerous because of heavy losses of public property, government property as well as human life. On 30th July 2014 in the village of Malin in the Ambegaon taluka of the Pune district in Maharashtra, India, landslides occurred [1]. This landslide has buried at least 140 people under soil debris and destroyed infrastructure. In India, catastrophic damage from sediment disasters like slope failures and debris floods is becoming a more serious problem as the frequency of heavy rains

* *Corresponding author*
E-mail address: jmrv100@gmail.com

https://doi.org/10.37934/aram.126.1.4959

rises year after year. This is the outcome of climate change which is significantly affecting our way of life and living conditions. Governments, businesses, and universities have all come to the conclusion that global warming is major reason behind it. Numerous studies on climate change and the means of reducing its consequences have been done due to the urgency of the issue and the scope of its effects. Rising temperatures are anticipated, along with more intense and sparse rainfall. It is seen that due to heavy rainfall there is change in water table. This change in water table causes decrease in metric suction and shear parameters are also get affected by heavy rainfall. By taking into consideration the slope failure there are several aspects which effects on slope of the hills. Rainfall is one of the major aspects causing failure of slope so in this paper further we had covered the information regarding the model which we tried to prepare for studying the effect of rainfall on soil slopes. We tried to develop the instrument for slope stability analysis by understanding the variation in rainfall effect on the slopes. Rainfall-induced slope failures are reported to occur during or immediately after the long period of intense or prolonged heavy rainfall. These slope failures most frequently occur on natural slope, hilly region in a variety of material and on a varying climate. This change in water table causes damage due to sediment disasters, knowledge about how slopes fail due to rainfall is indispensable. The main objective of this project is to investigate experimentally effect of rainfall on the different types of soil and observe their failure patterns. As we can see that rainfall is one of the main reasons behind the most of the slope's failure in hill region. It is necessary to analyses the effect of rainfall on slopes. Soil failure pattern can be understood from studying rainfall effects. How various type of soil responds to the rainfall can also be seen. Change in the properties of soil due to rainfall these some factors can be taken into consideration if we study the rainfall effect and proper measures can be given.

Until now there is very few models developed for analyzing the effect of rainfall on slopes. Experimental investigation has been done on how surface sand layer depth and rainfall intensity affect slop failures and study failure mechanism using 1g physical model using Kasumigaura sand and DL clay and observed two types of failure slide failure and retrogressive failure [2]. Eckersley, J.D.,[3] Conducted experimental model test in which he increased water table in soil slope and concluded that excess pore water pressure in shear zone is responsible for slope failure. A Tohari [4] conducted centrifuge experimental test and examine impact of increase of water level and concluded that there is difference in failure mechanism in dense soil and loose soil. Beddoe [5] tried to study liquefaction failure in loose saturated soil observed that presence of a loose granular base layer with reduced hydraulic gradient leads to liquefaction-prone soil triggered from monotonic loading region at the base of the slope leads to slope failure. R.P.Orense [6] examined the impact of infiltrating water in a physical 1g slope model and discovered that the failure of the slopes happened at their toes, where the soil became almost saturated. A.Tohari [7] in his laboratory studies found that slope failure started because of full saturation of soil at toe. While there is full saturation achieved at toe and still majority of sliding soil is still in unsaturated stage. Many researchers have investigated slope failures in the field [8'9] in order to create warning systems and preventative measures as given in Table 1 [10,11]. The results of the field surveys revealed that the majority of failed slopes shared the following characteristics: the failure depths were less than 2 m, the slopes' inclinations ranged from 30 to 50 degrees, and the slopes were made up of porous residual layers on comparatively stable rock foundations.

Table 1
Case Histories of Slope Failure in India

Sr. No.	Year	Location	Rainfall	Slope	Causalities
1	2022	Noney District, Manipur	375	40°	62
2	2022	Kalimpong, West Bengal	62.6	25°	nil
3	2022	Siliguri	54.8	28°	Nil
4	2020	Pettimudi, Kerala	229.4-261	30°	50
5	2019	Puthumala, Kerala	500	30°	17
6	2014	Malingoan Village, Maharashtra	600	35°	151
7	1968	Darjeeling landslide in West Bengal	1000	45°	1000+
8	1948	Guwahati Landslide, Assam	2000	35°	500+
9	1998	Malpa landslide, Pithoragarh, Uttarakhand	5.3-113 mm/day	60°	380
10	2001	Amboori Landslide, Thiruvananthapuram District, Kerala	82.4	35°	50

The mechanism of slope failure owing to rainfall has been the subject of numerous prior attempts, but it is still not fully understood. Therefore, the following were the primary goals of this investigation:

i. to conduct an experimental investigation into the relationship between rainfall intensity, duration and slope failure
ii. to elucidate failure behavior by continuously monitoring both saturation level at every point of soil.
iii. Effect of intensity of soil as well and sloping angle of soil
iv. infiltration through soil as well as vegetation effect on stability of slope.

2. Methodology
2.1 Experimental Program

In this experimental program we have made soil slope arrangement with permeable soil over the strong base like rock foundation which is structure which is likely prone to failure. Rectangular box is fabricated using aluminum sheet of 3 mm thick having dimensions 60 mm length and 40 mm wide. The box is kept open in a upper larger side and one of shorter side. The height three side of box was increase with the help of transparent fiber glass to observe failure pattern as shown in Figure 1. Two rectangular frames were fabricated having similar dimension of aluminum box with the mild steel angles 15 x 15 x 2 mm. These two rectangular frames were connected by hinges at one end and other ends kept free. The rectangular aluminum box is fixed over the upper frame. So, by keeping one rectangular frame horizontal and lifting another frame form free end, we can make the different angles. The bottom of the box is made rough by sticking soil & coarse aggregate by glue to aluminum sheet as shown in Figure 2. Also, small holes created at bottom of box to have permeability effect. The shorter side at hinge end kept open so that slope can be made unsupported. The soil is filled into that aluminum box in layers of 5 cm each. Each layer is compacted well to achieve desired dry density specified in Table 2. Pore-water pressure and displacements were measured during the experimental testing as shown in Figure 3 with the help of four pore water pressure transducers with a 200 kPa capacity were used to monitor the pore water pressure as per positing shown in Figure 4. These four transducers were attached to a ceramic cup with a fine tube of around 3 mm outer diameter with de-aired water filled. Each ceramic cup measured 25 mm in length and 12.5 mm in diameter, with an air entrance value of roughly 100 kPa. These four ceramic cups were positioned into the slope model and used for all the experiments and shown in Figure 4. To track the slope deformation, pictures were taken from the transparent glass side with a fixed digital camera and displacement was calculated form it.

Fig. 1. Rectangular Aluminium Box

Fig. 2. Aluminium box made rough at bottom

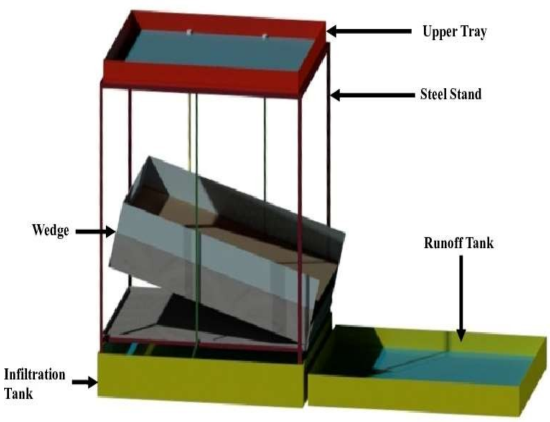


Fig. 3. Experimental model Measurement

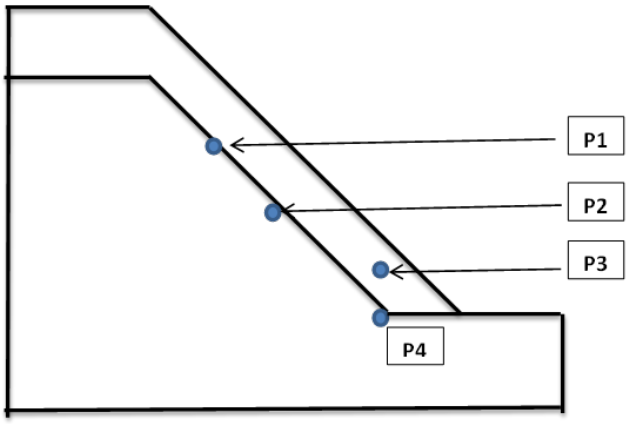


Fig. 4. Pour water pressure transducers position

In this study, every slope model was constructed over aluminium sheet of the rectangular box having small holes for collecting and measuring infiltration. Also, top surface of the aluminium sheet was made rough by sticking the stones of small size with the help of glue for making interlocking between sheet and soil material from which artificial slope was constructed. So, every slope model was constructed consist of permeable soil layer having strong rock foundation. While constructing the slope model, maximum care was taken that our artificially constructed model should replicate, relate and similar to existing natural slope vulnerable to failure. Infiltration tank is provided for collecting and measuring infiltration and runoff. The size of the tank is 77 cm x 63 cm x 18 cm enough for collecting expected water flow. Important variables impacting the erosion processes include slope and rainfall amounts. In our experimentation we have considered both variables and study its effect on stability of slope. As shown in figure and discussed earlier we have made arrangement to change slope angle and also change duration and intensity of rainfall over the slope. For the purpose of creating a artificial rain, tray having nozzles are placed over the distance of 75 (average) over the artificial slope. The distance of nozzle and tray is so placed that water drops are equally pour over the artificial slope. In this the nozzles are provided of 2 mm diameter in a square pattern of 2.5 cm x 2.5 cm centre to centre. Dimensions of the upper tray are 62 cm x 46 cm x 10 cm. To keep this upper tray over the slope stand was made up of structural steel as shown in Figure 3, Figure 5 and Figure 6. Dimensions of the stand are 70cm (length) x 49cm (width) x 100cm (height).

Fig. 5. Experimental Model front View

Fig. 6. Experimental Model Side View

2.2 Procedure of Slope Model Test under Rainfall

Every slope consists of shallow soil layer over the comparatively hard foundation having different angles like 15, 30 and 45 degrees as shown in Figure 7. The detail experimental procedure is explained below. The exact dimensions of the experimental test setup with sensor locations were shown in Figure 4, Figure 5 and Figure 6. All the details were presented in Table 2. The physical properties were determined and presented in Table 3.

Table 2
Dimensional details of Experimental Setup

Sr. No.	Apparatus	Length (cm)	Breadth (cm)	Height (cm)	Area (cm^2)	Volume (cm^3)
1	Upper Tray	61	46	6	2806	16836
2	Steel Stand	70	49	120		
3	Wedge	60	40	31	2400	74400
4	Runoff Tank	72	56	19	4032	76608
5	Infiltration Tank	76	61	18	4636	83448

Slope 150 Slope 300 Slope 450

Slope 150 Slope 300 Slope 450

Fig. 7. Failure situations of all the slopes after mulching & after the rainfall test

Table 3
Soil properties of materials used in slope model tests

Soil Properties	Values
Cohesion	21.42 kN/m^2
Angle of Internal friction	4.62^0
Specific Gravity (G)	2.32
Unified Soil Classification	CH
Shrinkage Limit	12.77 %
Liquid Limit	53.23 %
Plastic Limit	23.22 %
Initial water content	12.51 %
Permeability	8. 11x 10-4cm/sec

After the determining physical properties the soil sample made a specific slope by filling the soil in the aluminum box. The slope is made by filling the soil in 4 layers with the proper compaction in each layer of soil to achieve proper slope and to make it more realistic. Artificial rain is created over the slope like natural rain and spread uniformly over the slope. The rainfall was continued still the failure of each slope. The intensity of rain changed to 25 mm/hr, 50 mm/hr, 75 mm/ hr and the 100 mm/ hr for each slope angle i.e. 15^0,30^0,45^0. The complete set of reading is 12 and called them 12 cases which are tabulated in Table 4. It has been observed that for 25 mm/hr and 15^0 slope we observed for failure to happen for long time and no failure observed. So it may be due small slope angle and lesser quantity of rainfall intensity. After increasing the intensity from 25 mm/ hr to 50 m/hr time require to around 145 minutes and the major reason of failure may be soil erosion due to runoff water as time duration of rainfall is more.

As the intensity of rainfall increased to 75 mm/hr the failure of slope is surface failure but taken longer duration for failure. As the rainfall intensity increases to 100 mm/hr the time required for failure is less and it was surface failure. It has been observed that as the intensity of rainfall increases the time required for slope failure decreases. The same procedure of 15^0 slope was repeated for the 30^0 and 45^0 slopes. As expected, the same results obtain as when we increase rainfall intensity as was slope angle, time required for failure was decreases and the failure pattern changes form surface failure to retrogressive as mentioned in Table 5.

Table 4
Failure Conditions of slope model test

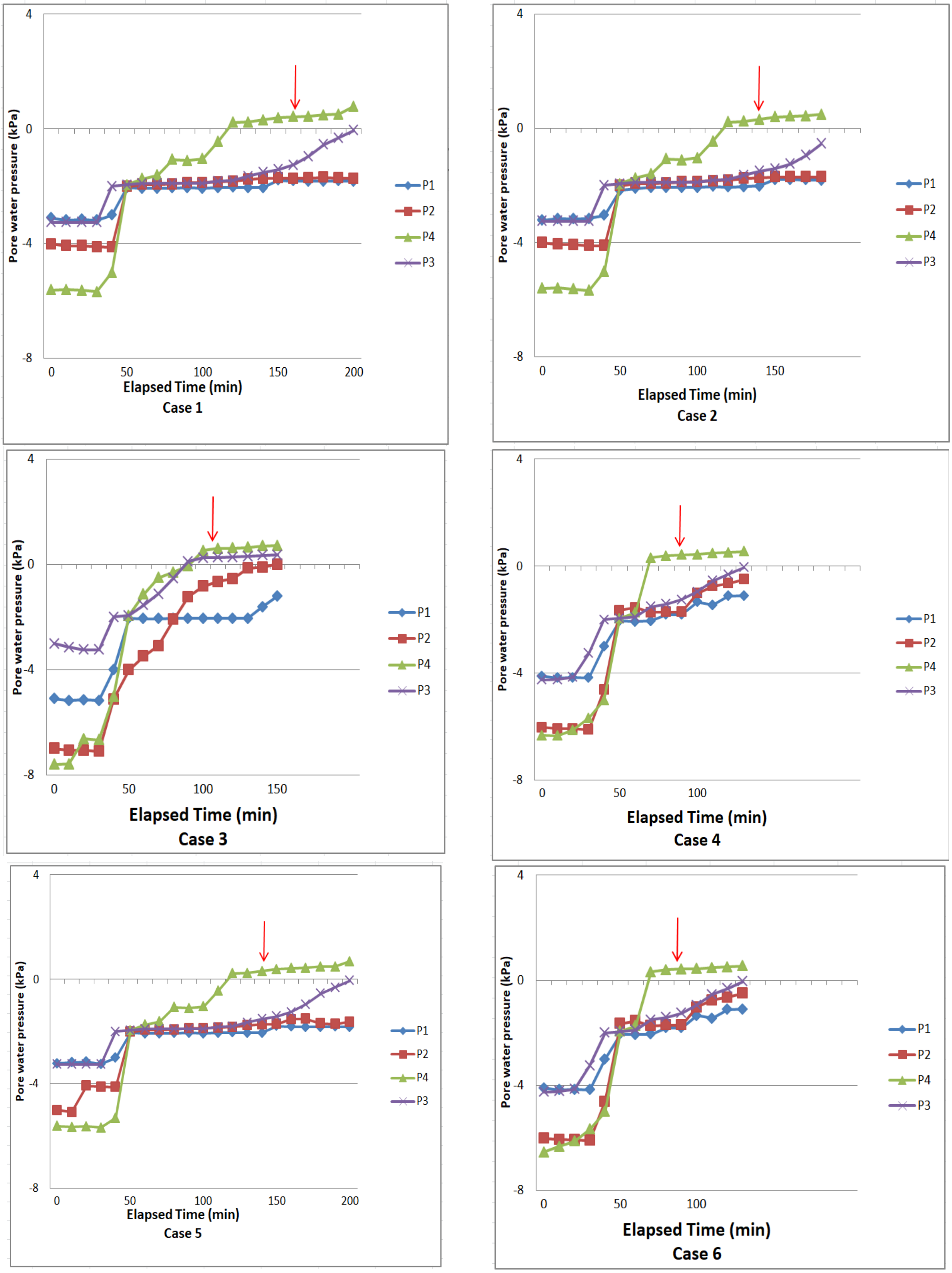
Case	Rainfall intensity, I (mm/h)	Slope Angle	Initial Water Content (%)	Dry density, ρd (g/cm^3)	Degree of saturation Sr (%)	Initial Void ratio, e0
1	25	15	10.32	1.230	27.8	0.9504
2	50	15	10.3	1.452	29.8	0.9263
3	75	15	10.6	1.498	33.24	0.8546
4	100	15	11.4	1.220	29.8	1.0252
5	25	30	10.8	1.431	30.54	0.9477
6	50	30	9.7	1.495	33.65	0.7725
7	75	30	11.10	1.210	30.15	0.9867
8	100	30	12.6	1.430	31.25	0.9869
9	25	45	10.20	1.487	32.47	0.8419
10	50	45	11.5	1.220	30.85	0.9990
11	75	45	9.9	1.422	31.05	0.8545
12	100	45	10.00	1.490	33.38	0.8029

Table 5
Failure Type of slope model test with percentage increase in time

Case	Rainfall Intensity, I (mm/hr)	Slop Angle of soil wedge	Failure Type	Elapse time to first failure (min)	Elapse time to first failure after vegetation (min)	Percentage Increase in time
1	25	15	Erosion Failure	155.23	176	13.38
2	50	15	Erosion Failure	140.22	158	12.68
3	75	15	Surface Failure	101.35	119	17.41
4	100	15	Surface Failure	75.55	86	13.83
5	25	30	Surface Failure	145.87	164	12.43
6	50	30	Surface Failure	80.47	91	13.09
7	75	30	Surface Failure	62.23	74	18.91
8	100	30	Surface Failure	45.23	56	23.81
9	25	45	Surface Failure	125.11	147	17.50
10	50	45	Surface Failure	65.25	73	11.88
11	75	45	Surface Failure	40.56	51	25.74
12	100	45	Retrogressive	30.12	42	39.44

2.3 Slope Failure Mechanism

In this part we will discuss how slope failed during the rain. In all our set of experiments rainwater gather at bottom of the slope as no rainwater get drained from surface. This gathered rainwater increases the pore water pressure and make to decreases the effective stress results in failure of soil. We can watch the pore water pressure at toe can be seen in Figure 8. Before the failure pore water pressure is negative and after the failure of slope pore water pressure gets positive. The pore water pressure at failure is shown in Figure 8 by read mark. As in case1 pore water pressure is positive 0.4 at the slope failure and remains positive after failure. Same will be the situation in all the 12 cases. The similar results are found by the previous study [13-15].



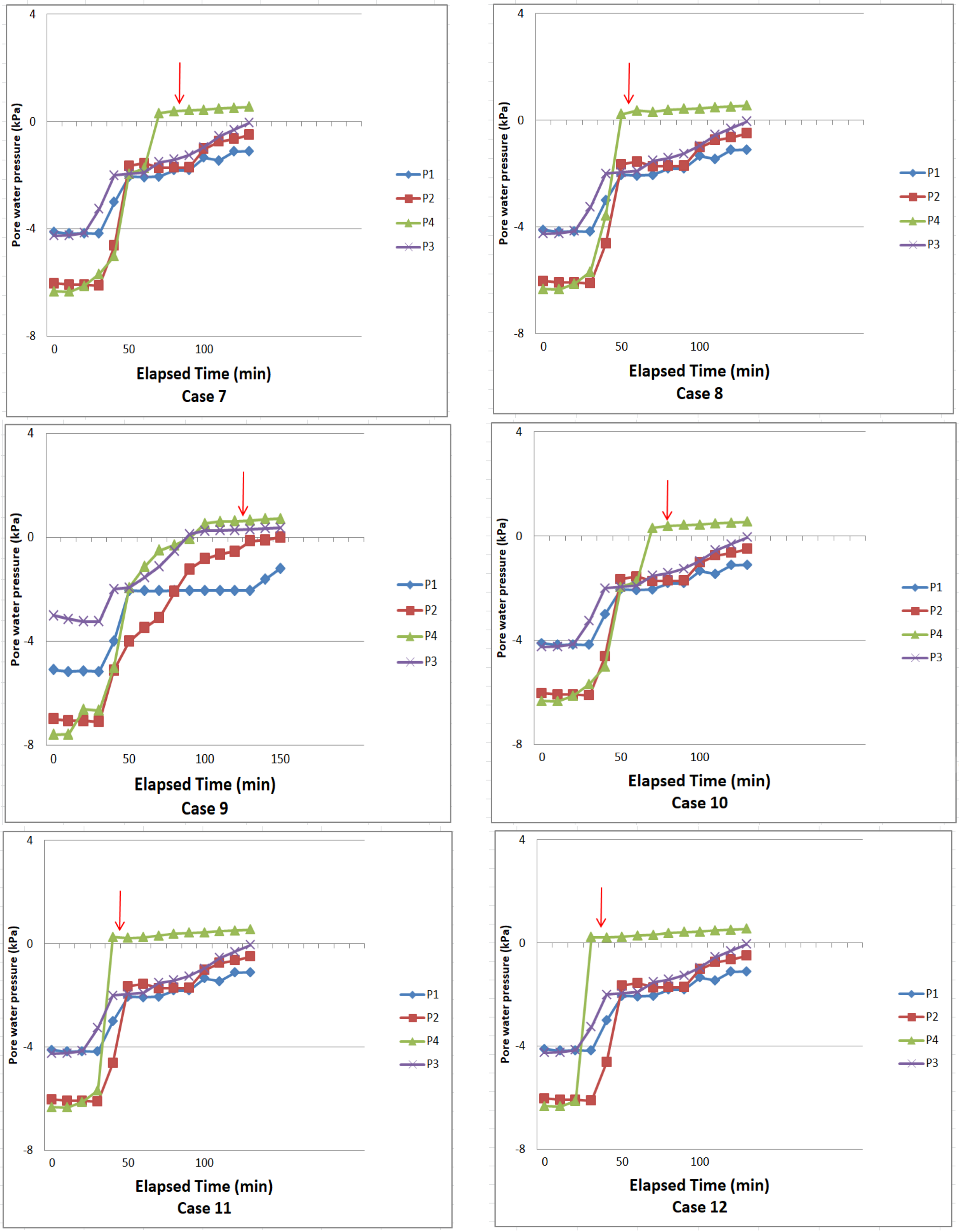


Fig. 8. Variation of pore water pressure during slope failure

It was main concern that how to improve slope stability. The solution applied must be economical also. So best method we can study was vegetation or plantation or mulching over the slope. The process of covering the open surface of the ground by a layer of some external material is called vegetation & the material used for covering is called as green plants. Vegetation is usually practiced when cultivating commercially important crops, fruit trees, vegetables, flowers, nursery saplings, etc. It is beneficial in yard gardening, containers & raised beds of home gardens. After vegetation it was observed that it takes time for the failure of the slope as the roots absorb water and they hold the soil. The strength of soil increases due to mulching. The observations after mulching can be seen below. As shown in table the stability of slope gets improved by around 10 to 40 %. There also number of methods available for stability of slope but vegetation is economical and sustainable construction methods. More improvements can be found in the previous study [16-20].

Also, for improving the stability of slopes all over the region first determine the maximum rainwater intensity form past histories and the determine the slope angle. So, from our experimental study we can judge the stability of that particular slope.

4. Conclusions

Numbers of experiments were carried out on artificial slope with different intensity of rain. The following conclusions drawn on the outcomes of the model tests:

i. As the rainwater gets accumulated near the bottom of slope pore water pressure gets changed from negative to positive during the failure. So mostly slope failure occurs because of pore water pressure. If drainage is provided then there is more stability of slope.
ii. Two types of testing done on experimental model first testing on soil slope and another on soil slope with vegetation. The use of vegetation increases the stability of slope around 80 % to 120 %. So, vegetation is very economical and effective way of increasing stability of slope.
iii. Experimental data shows that for as the slope angle as well as intensity of rainfall increases stability of slope decreases and vice versa. In particular cases longer duration of rainwater there is slope failure because of erosion. So, erosion is one of the reasons for slope failure.
iv. Experimental data also shows that as intensity of rainfall increases then duration of slope failure decrease for all types of slopes.
v. Experimental data shows that for larger slopes and high intensity of rainfall the soil surface over the slope becomes mud and slope flows like liquid.

Acknowledgement
This research was not funded by any grant.

References
[1] Shah, Chetan R., Sandip S. Sathe, Prashant B. Bhagawati, and Santosh S. Mohite. "A hill slope failure analysis: A case study of Malingoan village, Maharashtra, India." *Geology, Ecology, and Landscapes* 5, no. 1 (2021): 1-6. https://doi.org/10.1080/24749508.2019.1695714
[2] Chueasamat, Anusron, Toshikazu Hori, Hirotaka Saito, Tomotaka Sato, and Yuji Kohgo. "Experimental tests of slope failure due to rainfalls using 1g physical slope models." Soils and Foundations 58, no. 2 (2018): 290-305. https://doi.org/10.1016/j.sandf.2018.02.003
[3] J.D. Eckersley, 1990,(2013). “Instrumented laboratory flow slides”. Geotechnique 40(3) 489-502 https://doi.org/10.1680/geot.1990.40.3.489
[4] Tohari, Adrin, Makoto Nishigaki, and Mitsuru Komatsu. "Laboratory Experiments On Initiation Of Rainfallinduced Slope Failure With Moisture Content Measurements." In *ISRM International Symposium*, pp. ISRM-IS. ISRM, 2000. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:5(575)

[5] Take, W. Andy, and Ryley A. Beddoe. "Base liquefaction: a mechanism for shear-induced failure of loose granular slopes." *Canadian Geotechnical Journal* 51, no. 5 (2014): 496-507. https://doi.org/10.1139/cgj-2012-0457
[6] Orense, Rolando P., Suguru Shimoma, Kengo Maeda, and Ikuo Towhata. "Instrumented model slope failure due to water seepage." *Journal of Natural Disaster Science* 26, no. 1 (2004): 15-26. https://doi.org/10.3208/sandf.44.2_15
[7] Rahardjo, Harianto, T. T. Lee, Eng Choon Leong, and R. B. Rezaur. "Response of a residual soil slope to rainfall." *Canadian Geotechnical Journal* 42, no. 2 (2005): 340-351. https://doi.org/10.1139/t04-101
[8] Rahardjo, Harianto, T. T. Lee, Eng Choon Leong, and R. B. Rezaur. "Response of a residual soil slope to rainfall." Canadian Geotechnical Journal 42, no. 2 (2005): 340-351. https://doi.org/10.1139/T04-101
[9] Orense, Rolando P., Suguru Shimoma, Kengo Maeda, and Ikuo Towhata. "Instrumented model slope failure due to water seepage." *Journal of Natural Disaster Science* 26, no. 1 (2004): 15-26. https://doi.org/10.2328/jnds.26.15
[10] Aleotti, Pietro. "A warning system for rainfall-induced shallow failures." *Engineering geology* 73, no. 3-4 (2004): 247-265. https://doi.org/10.1016/j.enggeo.2004.01.007
[11] Kamide, Sadayuki, Yasuyuki Dohi, Keigo Koizumi, Yasuo Hosoki, Masato Tonogakiuchi, and Keiji Nakatsuji. "Consideration of Slope Collapse Risk Assessment Considering Rainfall." *Journal Free* 5, no. 1 (2010): 159-168. https://doi.org/10.3208/JGS.5.159
[12] Take, W. Andy, and Ryley A. Beddoe. "Base liquefaction: a mechanism for shear-induced failure of loose granular slopes." *Canadian Geotechnical Journal* 51, no. 5 (2014): 496-507. https://doi.org/10.1139/cgj-2012-0457
[13] Rahardjo, Harianto, T. T. Lee, Eng Choon Leong, and R. B. Rezaur. "Response of a residual soil slope to rainfall." *Canadian Geotechnical Journal* 42, no. 2 (2005): 340-351. https://DOI:10.1139/T04-101
[14] Take, W. A., M. D. Bolton, P. C. P. Wong, and F. J. Yeung. "Evaluation of landslide triggering mechanisms in model fill slopes." *Landslides* 1 (2004): 173-184. https://doi.org/10.1007/s10346-004-0025-1
[15] Tohari, Adrin, Makoto Nishigaki, and Mitsuru Komatsu. "Laboratory Experiments On Initiation Of Rainfallinduced Slope Failure With Moisture Content Measurements." In *ISRM International Symposium*, pp. ISRM-IS. ISRM, 2000. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:5(575)
[16] Tokoro, N., K. Tanikawa, H. Saito, Y. Kohgo, and T. Hori. "On 1G slope failure model tests due to rainfalls: difference of failure patterns due to difference of densities of a subsurface sand layer." In *2nd International Conference on Transportation Geotechnics (ICTG) International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE)*. 2012. https://DOI:10.1201/b12754-116
[17] Wang, G., and K. Sassa. "Factors affecting rainfall-induced flowslides in laboratory flume tests." *Geotechnique* 51, no. 7 (2001): 587-599.. https://doi.org/10.1680/geot.2001.51.7.587
[18] White, D. J., W. A. Take, and M. D. Bolton. "Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry." *Geotechnique* 53, no. 7 (2003): 619-631. https://doi.org/10.1680/geot.2003.53.7.619
[19] Suzuki, Hisashi, and Minoru Matsuo. "Procedure of slope failure prediction during rainfall based on the back analysis of actual case records." *Soils and foundations* 28, no. 3 (1988): 51-63. https://doi.org/10.3208/sandf1972.28.3_51.
[20] Neuman, Shlomo P. "Saturated-unsaturated seepage by finite elements." *Journal of the hydraulics division* 99, no. 12 (1973): 2233-2250. https://doi.org/10.1061/JYCEAJ.0003829