Chapter 11
Forewarning System for Rainfall-Induced Landslide—A Laboratory Prototype Model

P. Thambidurai

Abstract Intense rainfall in the mountain region is one of the main slope failure factors. Infiltration and subsequent pore pressure increase causes the failure. The rainfall-induced slope failure mechanism is not yet completely understood, either due to lack of engineering application or non-availability of site-specific data. Lots of attempts have been undertaken to investigate the mechanism of landslide occurrence through the real-time monitoring system. In this chapter, the development of the forewarning system, and its validation via laboratory experiment has been discussed. The flume bed was prepared with a mixture of sand-clay soil with a slope angle of 45° and was subjected to rainfall via the rainfall simulation system. Rainfall and moisture were continuously monitored, and pore pressure was found to drastically increase before slope failure occurred. The moisture and pore pressure were built higher in the toe of the slope and gradually decreased towards the crown of the slope. Once the saturation was achieved, the toe of the slope collapsed, and erosion of the soil took place. Antecedent moisture was noticed as a favorable factor with rainfall intensity towards the slope failure. Repeating the experiment many times with different slope angles and changes in rainfall intensity could give more insight into the mechanism. The study showed that the forewarning system model is effective and could be adapted as a warning system for landslides in mountainous regions.

Keywords Landslide flume test · Soil moisture · Pore pressure · Sensor network · Landslide warning system

11.1 Introduction

Landslide is one of the main natural disasters in the mountainous region. The frequency of landslide events is directly causing serious loss of human lives and property (Singh et al. 2016). The landslide is a complex natural process that could

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not understand the whole geometry and physical characteristics (Thambidurai and Maneeesha 2017). Intense rainfall is the major factor for triggering the landslide along with other parameters, including geology, slope, etc. Rainfall-induced landslide is one of the frequently occurring events which is a wide distributed complex failure phenomenon, and it causes significant slope failures on various scales (Igwe et al. 2015). Over time, the researchers have arrived to conclusion that massive landslide events are correlated with higher cumulative rainfall (Iverson 2000; Dahal et al. 2006) and is considered one of the significant natural hazards (Segoni et al. 2014). Also, the slope failures occur in marginally stable soil (Anderson and Sitar 1995), and generally, the failures are less than 2 m in depth (Chae et al. 2015). The intense rainfall increases the pore pressure, and decreases the effective stress of soil, which reduces the shear strength of the material, resulting in slope failure (Fang et al. 2012). However, the pore pressure varies by influences of topography, hydraulic properties, weathering, and fracture of soil. Also, the effective pore pressure is directly related to infiltration and percolation to develop a perched water table (Terlien 1998). Always the high-intensity rainfall shall develop dissipation of pore pressure causing larger permeability in the soil, and antecedent moisture also has a minor influence on the occurrence of landslides (Abraham et al. 2021). During the infiltration process, a temporary saturation of soil leads to reduced metric suction, which triggers the mass failure. Also, infiltration modifies the soil structure that weakens the cohesive strength of the soil (Reddi 2003). However, the unsaturated zone above the water table may possibly induce slope failure, but if the groundwater table is in greater depth, the wetting front due to rainfall infiltration contributes to the slope failure (Zhou et al. 2009). A large deformation can occur after the failure of the slope in the toe where the soil experience significant strain. Stability of the slope is weakened in a number of ways due to rainfall. The moisture saturation increases the infiltration and then break the bond between soil particles. Destabilising effect acts fluently on the slope by fluid experts towards downhill because of enough gravity force. It weakens the slope because it decreases the capillary pressure and increases the saturation, increasing the soil mass load due to fractional dragging in the downslope direction (Borja and White 2010). Moisture content and rainfall infiltration together increase sliding force (Liu et al. 2013). In general, slope failure occurs due to increase in value of the following factors such as (1) weight of soil mass, (2) water content in soil, (3) groundwater level, (4) lubrication of slope surface and (5) hydrodynamics pressure. The general mechanism of pore pressure leads to the disintegration of soil particles, and failure mass acts as a fluid-like motion, which has been reported in most of the cases of flow slides (Iverson et al. 1997). A common rain-induced landslide is a shallow depth where the groundwater table is absent and debris flows also at the same level of depth scooped due to steep slope between 30° and 45° in the mountain regions. Majority of cases, in granular soil, the debris flow turns into a flow slide due to the mechanical properties of the soil. Fluid mechanics has an inevitable role in landslide research. The shear resistance drastically decreases due to the sudden increase of pore pressure, and when it dominates, greater than hydrostatic pressure results in debris flow (De Wrachien and Brebbia 2010). Detection of landslides is not an easy task, however, in order to find a good solution it may be fairly possible with technological development. In the past decades, many pieces of research brought some improvements and development toward understanding the triggers and the movement of landslides worldwide. Although the alert and alarm system has not yet reached upto the mark to prevent the disaster, laboratory simulation models may provide information to understand the way the landslides initiate and evolve.

The landslide by the rainfall-induced event has a disastrous impact on the human community because the flow slide has enormous mass moving with very high speed towards downhill which obviously causes huge damages and casualties. Every year, a rainfall-induced landslide occurs more often and has associated declared many lives lost, also damaging local communities in different parts of the world. The risk reduction measure for rainfall-induced landslides is very difficult to predict the event due to the complexity of the phenomena, which cover different domains of sciences like local perception, topography, geology, and hydrological mechanisms. Early warning-based monitoring system is either not successful or highly expensive with location-specific issues. Many researchers have attempted to develop an efficient-inexpensive way of the warning system. However, there is much need for a proper monitoring system for landslide warning to save lives and also helps to get a better understanding of the mechanism of the landslide process, which can be useful for further enhancement of the system model. The cause of landslides can be reduced by developing a suitable real-time monitoring system. An effective warning system is a better tool, which has ablity to perform site-specific analysis for instability of the slope. However, the warning system needs a test and validation to understand geological material and interaction with rainfall to avoid the uncertainty of forecast information. To attain the validation of the warning system, it must be deployed in the field (landslide-prone zone), which can not only take time but may be less effective. In this chapter, an experimental laboratory setup is proposed, which is basically a physical flume model designed to investigate the landslide initiation with various conditions, mechanisms, and controlling factors with sensors embedded in systems for simulating rainfall-induced landslides.

11.2 Design and Development

A flume test setup was developed step by step, as presented in Fig. 11.1. The physical flume model was designed with a dimension of 4.5 m length, 1 m width, and 1.5 m height in a steel frame with the side walls are made up of tempered acrylic glass. The flume bed was divided into 3.5 m for the trigger and 1 m for the propagation of the slide. The trigger bed was kept at a constant slope angle of 45°, and the rainfall simulation setup was fixed 2 m above this bed. The rainfall simulation system had a water sprinkler system connected to 2,000 litre capacity water tank, which was optimised to ensure the uniformity of rainfall and control surface erosion. The bottom of the flume bed was provided with geotextile to control the friction of soil with a steel plate. The individual sensors were placed in the grid system on the designed flume bed. A total of 12 different sensors were deployed on the flume bed to monitor

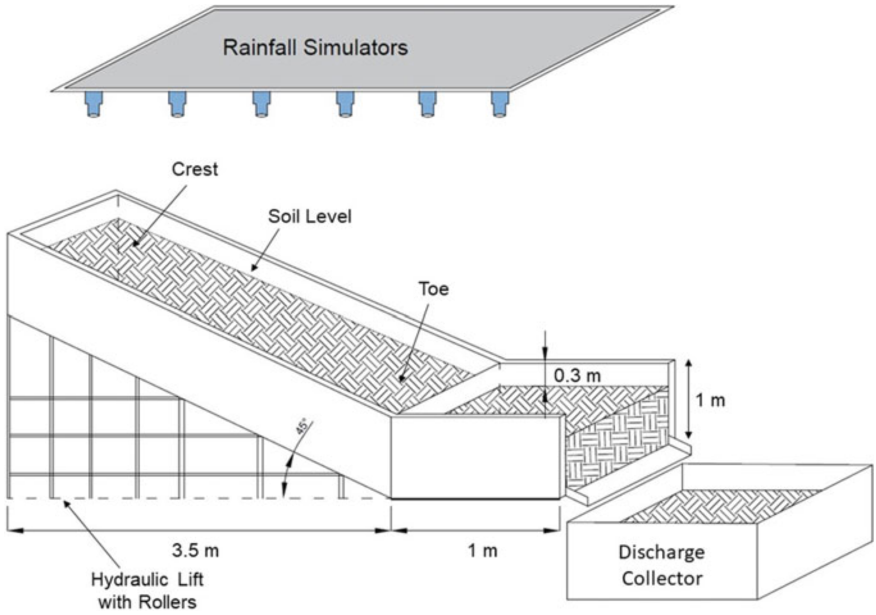

Fig. 11.1 Arrangement of experimental flume system

characteristics and triggering factors of landslide. These sensors included porewater pressure, displacement meter, inclination meter, rainfall tip system, accelerometer, and osmometer. Rain gauges were placed on the top and bottom of the flume bed. Five piezometers were deployed along the slope direction with a depth of 1 m, which covered the porewater pressure changes in the entire process with pre and post-failure behaviour. The entire system was designed to understand the data interpretation and landslide processes in scaled-down conditions. The main purpose of this study was to validate the prototype warning system and its potential detection of landslide events in extreme rainfall conditions.

11.3 Experiments

The validation experiment system was enclosed by flume bed along with a prototype model, which included Sensor Network System (SNS), Data Collection System (DCS), Communication System, Data storage, and Visualisation System. The data collected with data logger and communication system was designed such way to collect data from sensors and then transfer it by Zigbee wireless technology and GSM with serial port server system, which was developed as an alternate data transmit system on the self-organising and self-mesh network for best data collection and transmitted to avoid the data loss or any uncertainties in the system. The data storage server had the capacity to keep huge pockets of data sets and interpretations with different categories of data sets. The final step in the warning system was visualisation, which showed the sensor position with real-time data streaming in x–y graphical representation, spatial distribution of piezometers, and status of each sensor. The first and foremost step in the flume experiment was choosing a soil mass that interacted with water, generated pore pressure, and subsequently triggered the movement of landslide mass. The sandy-clay was scooped from near the instability slope of the hill. Effect of grain size had an essential role in the displacement and movement of landslide mass. Geotechnical parameters of soil were calculated before filling it into the flume bed, such as density, void ratio, conductivity, clay content, etc., and the proper soil layers were uniformly packed and maintained on the entire flume bed. A serious of experiments were conducted with various ranges of rainfall intensity, antecedent moisture, density and thickness of the soil mass. Each experiment took its own time based on the occurrence of failure with respect to occurrence and failure behaviors. The first top portion of the flume was kept for slope simulation with 3.5 m, followed by the horizontal portion which utilised for self-stabilisation of material and post-failure deposition of the soil mass.

Many sensors were connected to the data acquisition unit for successive data communication from the local control system with an indigenous data logger. The prototype system had sufficient channels to connect more sensor clusters in different field conditions. This technology had more concern for selecting required sensors and their accommodation in real-world conditions without modification of the prototype system. The entire sensor network was connected with a central control system, and then both architectures were powered. Rainfall-induced flume test was conducted with the integrated prototype sensor system, and a total period of time around 6 hours was taken to end the experiment. The experiment included two extreme rainfall intensities to understand and observe the significant failure in the soil mass because the amount of rainfall should trigger the slope failure. The incident rainfall can infiltrate and subsequently saturate the soil mass. The researcher must know to set the necessary amount of rainfall to trigger the slope failure during the test (Wang and Sassa 2003). Based on the earlier experiment, it was assumed that extreme rainfall would trigger slope failure in the present flume experiment. The arrangement was prepared in such a way that controlled water from rainfall simulator only interacts with soil mass. The rainfall rate was regulated at approximately 40 mm/hour. Pore pressure, displacement, soil pressure, borehole pressure, and osmotic pressure were logged and collected in the constant rainfall condition up to the occurrence of slope failure. Data was logged at 5 min intervals for the entire experiment.

11.4 Results and Discussion

The present laboratory experimental study shall be used to better understand the mechanism of rainfall-induced slope failure. Before starting the simulation, moisture and compactness of the soil parameters were measured for reference records. All the sensor connection was thoroughly checked, and the power backup and water source house were investigated. Soil compaction and their density values were checked and noted at each point of sensor location. The sensor position and numbering system for each point were cross-verified with the compactional program. Data loggers and other transmission gadgets were ensured once again. The experiment was started with a flume slope to simulate the rainfall-induced landslide on a fine morning at 8'o clock. Once the rainfall simulation started and the moisture content steadily increased, the first response from the top of the moisture sensor was soon after rainfall started. The wetting front was progressed towards the base of the slope, and after a short span of time, the moisture sensor at the toe of the slope. After sufficient infiltration, the wetting front reached a peak and was followed by a sudden increase of observed, which increased drastically the saturation of water reached in soil. The moisture was increased stepwise, not in a gradual manner (Fig. 11.2) because of many factors (Gevaert et al. 2014) in soil grain size, slope angle etc. However, high moisture vicinity was observed and measured at the toe of the slope due lateral movement of water. Further, seepage was developed, and that force triggered the instability of the slope. The stability affected due to seepage vector quantity consists of magnitude and direction. The surface and subsurface water flow had more affinity towards the toe of the slope due to gravity after saturation of the pore space of the grains. The soil in the upper part of the slope was not fully getting the saturated condition, because the majority of front wetting occurred along the downslope, not in the opposite direction. The runoff started after the saturation at the toe area, and it resulted in formed gullies followed by erosion. As a consequence of intense rainfall, the formed gullies were extended from toe to towards the upper side of the slope and also the gullies became wider and deeper, giving symptoms of breaking and blocking of the runoff water.

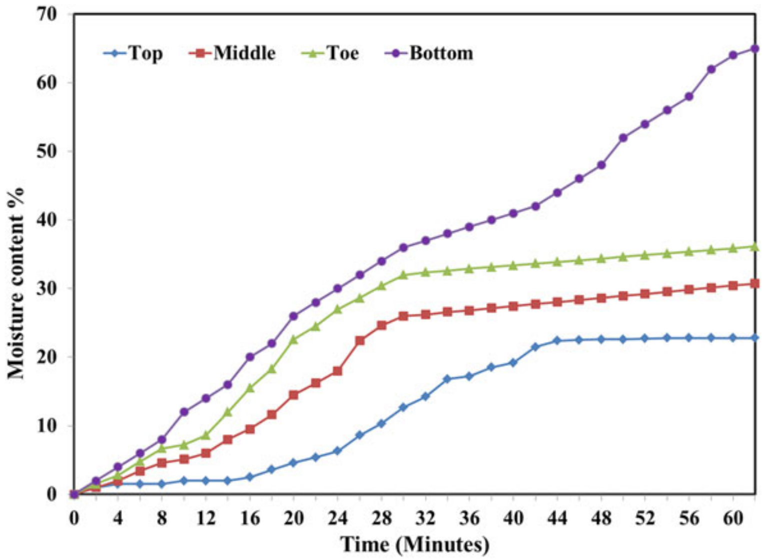

Fig. 11.2 Moisture content variation with time

The study observed that the rainfall intensity was capable of pushing or removing soil from the upper portion of the slope.

The experiment was reached at the peak, and the first slope failure occurred, and it was captured by pressure gauge (pressure) data in the soil mass at 11.10 am (Fig. 11.3). Another failure occurred after 20 minutes, which was observed significantly through the inclinometer data set (Fig. 11.4). The depth of the failure observed in Fig. 11.5. The soil mass movement was noticed half an hour prior to the first failure by sudden changes in the piezometer value of pore pressure and osmometer readings (Fig. 11.6).

The rainfall data showed that the intensity and duration of rainfall had significant influences on the movement of soil from the upper side of the slope to the toe. The mechanism of soil movement dynamics observed that the removed soil, which accumulated at the toe due to gravity, pushed further down because of newly detached soil from the upper portion of the slope. The intensity of the rainfall and its duration had a noticeable effect on the mass movement, however, the effects were initially higher than continuing the same mass removal even after rainfall intensity reduced. It could be losing cohesiveness of soil mass, and it may be a larger amount of fine grain (Mitchell and Soga 2005). The accumulated pore water built pressure within the grains pore spaces, and further percolation and infiltration had developed the groundwater table. The moisture sensors and rainfall data showed that moisture content increased soon after rainfall started, but the piezometer (pore pressure) data value increased after subsurface water saturation. For this mechanism, the porosity

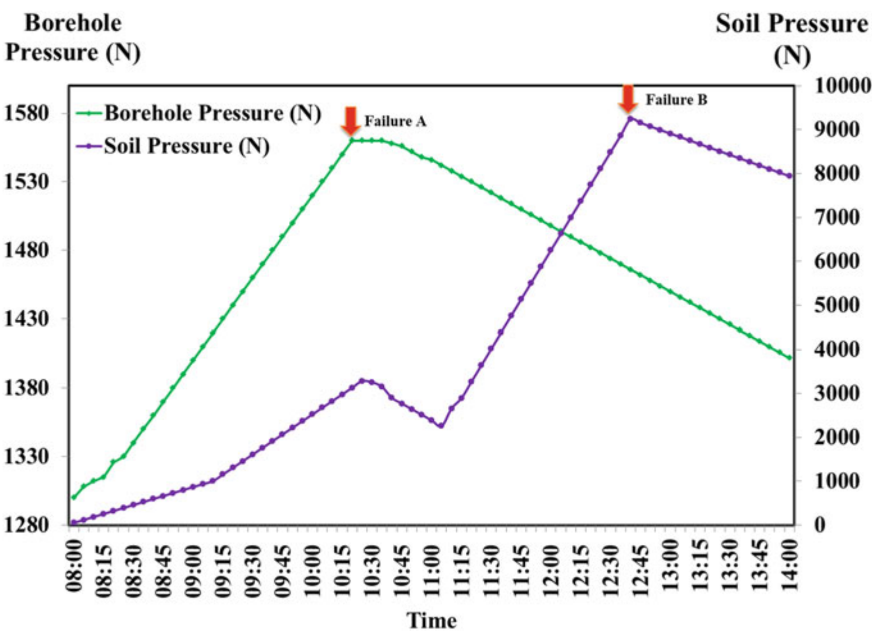

Fig. 11.3 Pressure gauge data with slope failure curves

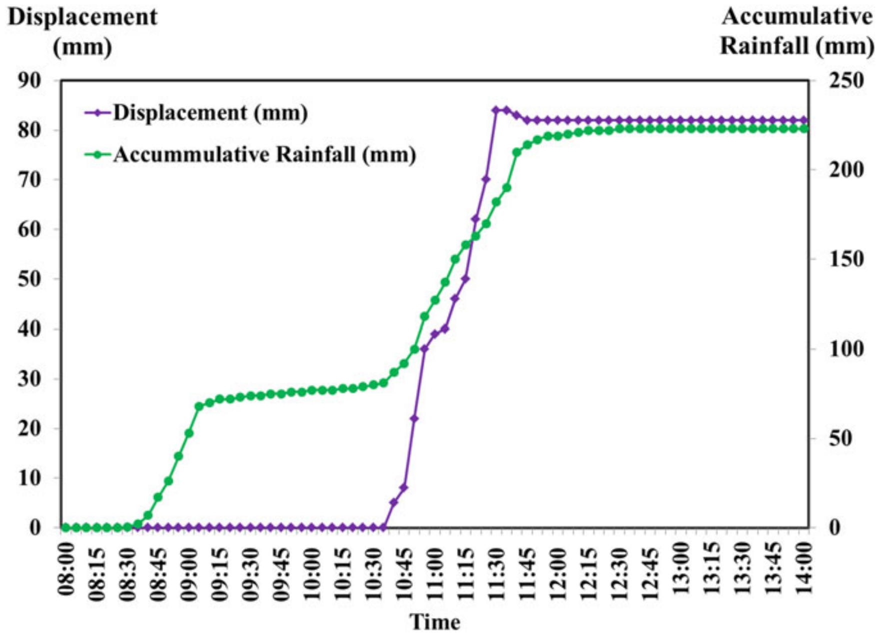

Fig. 11.4 Data plot of rain gauge and the displacement meter

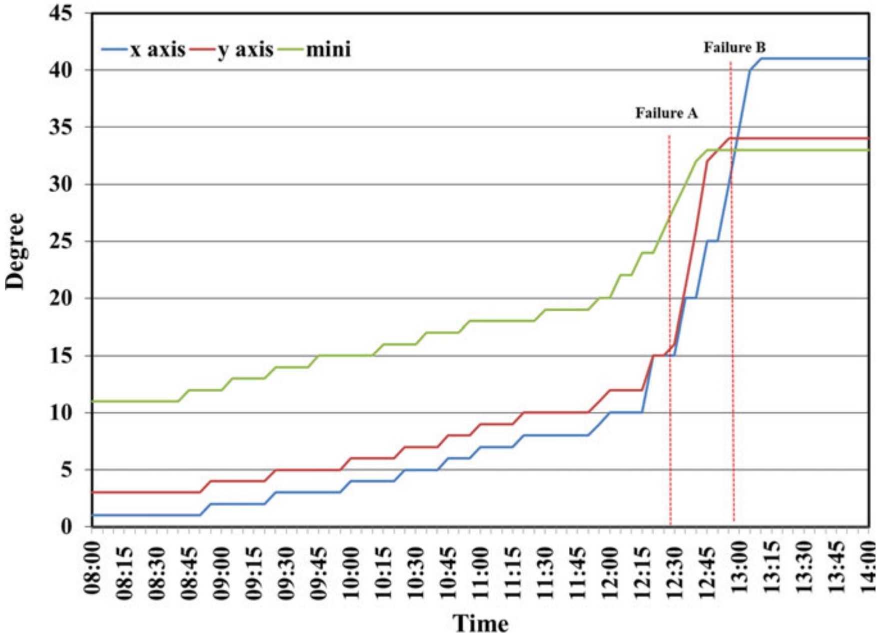

Fig. 11.5 Inclinometer data plot

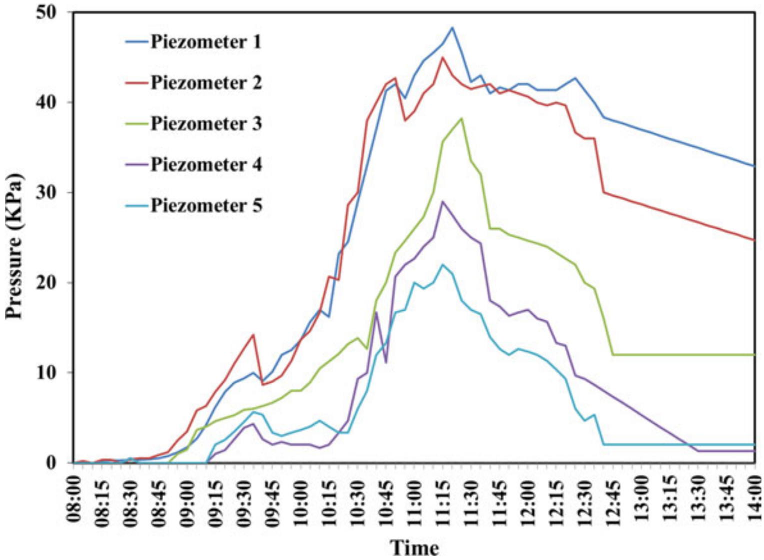

Fig. 11.6 Data plot of piezometers and osmometer

and density of soil acted an important role in controlling the saturation mechanism and water level increased in the subsurface zone soil. The infiltration index contributed to the variation of subsurface water level, which played an important role in the stability of the slope. Generally, rainfall intensity can increase the velocity of infiltration, though it decreases in a certain unit weight of soil (Chae et al. 2015).

The pore pressure value remained constant in the initial stage of the experiment, and it quickly increased, and then after, the values of pore pressure gradually increased until the failure occurred. The pore pressure was very high at the toe points compared to the upper side of the slope. Crack started to occur at the toe area with an indication of water saturation in the soil. Although, if antecedent moisture was present in the base of the slope, then the pore pressure suddenly increased. The pore pressure-building mechanism has to be understood at the specific landslide site, which is necessary to evaluate the feature failure of the slope. However, uncertainty is high, still unable to understand the complete mechanism of landslide failure behaviors. The piezometer values were increased due to high-intensity rainfall. Then after the failure occurred, the values suddenly decreased (Fig. 11.6). The geometry of the slope completely changed after the sudden failure of the soil mass towards the downslope direction. The increased seepage was clearly observed from the top of the slope to the toe direction. Subsequently, the water level increased in the toe, and seepage with pore pressure triggered the further failure. At this juncture, the rainfall intensity continues then sliding motion also continues as a liquefaction process. The sensors placed at the toe area have lost data streaming due to a slide occurring in the toe due to sensors displaced from deployed points. Also, minor cracks occurred simultaneously at the crest of the slope but started at the toe. The cracks at the crest indicate that failure may occur on the upper side of the slope in the field. A set of experiments conducted before composing the present article, however, made proper the workable model, and receiving reliable data is difficult in small level flume model. However, the designed sensor network and all supporting enclosures performed well and good in the entire laboratory experiment and evaluation of the systems. Despite the success of the research, there are many limitations and barriers in bringing more accuracy and improvement in the designed system.

11.5 Conclusion

The laboratory model experiment was conducted to understand the mechanism of rainfall-induced landslide and evaluation through the flume model of the designed forewarning system. The laboratory experiment is the best practice for understanding landslide phenomena and avoiding the expensive and time-consuming evaluation of the designed system. The study attempts to monitor the moisture and pore pressure changes with respect to intense rainfall on the slope. The antecedent moisture has a great role in building the pore pressure in the soil. The generation of moisture and pore pressure have significant influences on the initiation of slope failure. These parameters are the important controlling factors for soil mass failure. However, rainfall intensity alone influences the slide of the mass in the sense of soil erosion, high infiltration, and high subsurface flow toward the toe of the slope. Also, runoff (surface flow) induced erosion mainly in the toe area, which triggered the instability of the toe of the downslope area. Although the instability continues in the upper direction due to continued rainfall and infiltration. Before the failure occurred in the toe, minor cracks were observed in the crest area due to a slight jerk of soil mass in the toe. The increase in subsurface water level and seepage increased pore pressure significantly in the toe area. Moisture and pore pressure were lower values in the crest area and significantly higher in the toe. Sudden failure of slope due to the sudden jump of pore pressure in the soil mass. Landslide events could be predicted by utilizing moisture and pore pressure sensors in the appropriate points in the toe region with a proper field survey.

References

Abraham MT, Satyam N, Rosi A, Pradhan B, Segoni S (2021) Usage of antecedent soil moisture for improving the performance of rainfall thresholds for landslide early warning, Catena. Elsevier 200:105147

Anderson S, Sitar N (1995) Analysis of rainfall-induced debris flows. J Geotech Eng ASCE 121:544–552

Borja R, White J (2010) Continuum deformation and stability analyses of a steep hillside slope under rainfall infiltration. Acta Geotech Slov 5:1–14

Chae B-G, Lee J-H, Park H-J, Choi J (2015) A method for predicting the factor of safety of an infinite slope based on the depth ratio of the wetting front. Nat Hazards Earth Syst Sci Discuss 3:791–836

Dahal RK, Hasegawa S, Yamanaka M, Nishino K (2006). Rainfall triggered flow-like landslides: understanding from southern hills of Kathmandu, Nepal and northern Shikoku, Japan. In Proceedings of 10th Int. Congr. on IAEG2006. Geol Soc London, vol 819, pp. 1–14

De Wrachien D, Brebbia CA (2010) Monitoring, simulation, prevention and remediation of dense and debris flows III. WIT Press, Southampton, UK

Fang H, Cui P, Pei LZ, Zhou XJ (2012) Model testing on rainfall-induced landslide of loose soil in Wenchuan earthquake region. Nat Hazards Earth Syst Sci 12:527–533

Gevaert AI, Teuling AJ, Uijlenhoet R, DeLong SB, Huxman TE, Pangle LA, Breshears DD, Chorover J, Pelletier JD, Saleska SR, Zeng X, Troch PA (2014) Hillslope scale experiment demonstrates the role of convergence during two-step saturation. Hydrol Earth Syst Sci 18:3681–3692

Igwe O, Effiong BA, Iweanya MR, Andrew OI (2015) Landslide Investigation of Ikwette, Obudu Local Government Area of Cross River State, Nigeria. J Appl Geol Geophy 3(3):01–12

Iverson RM (2000) Landslide triggering by rain infiltration. Water Resour Res 36:1897–1910

Iverson RM, Reid ME, LaHusen RG (1997) Debris-flow mobilization from landslides. Annu Rev Earth Planet Sci 25:85–138

Liu ZZ, Yan ZX, Duan J, Qiu ZH (2013) Infiltration regulation and stability analysis of soil slope under sustained and small intensity rainfall. J Cent South Univ 20:2519–2527

Mitchell JR, Soga K (2005) Fundamentals of soil behavior, 3rd edn. Wiley, Hoboken, New Jersey, p 592

Reddi LN (2003) Seepage in soils, principles and applications. Wiley, USA

Segoni S, Battistini A, Rossi G, Rosi A, Lagomarsino D, Catani F, Moretti S, Casagli N (2014) Technical note: an operational landslide early warning system at regional scale based on space–time variable rainfall thresholds. Nat. Hazards Earth Syst Sci Discuss 2:6599–6622

Singh TN, Singh R, Singh B, Sharma LK, Singh R, Ansari MK (2016) Investigations and stability analyses of Malin village landslide of Pune district, Maharashtra. India Nat Hazards 81(3):2019–2030

Terlien MTJ (1998) The determination of statistical and deterministic hydrological landslide triggering thresholds. Environ Geol 35:124–130

Thambidurai P, Ramesh MV (2017) Slope stability investigation of Chandmari in Sikkim, North-eastern India. In: Mikos M, Tiwari B, Yin Y, Sassa K (eds) Advancing culture of living with landslides. WLF 2017. Springer, Cham. https://doi.org/10.1007/978-3-319-53498-5_42

Wang G, Sassa K (2003) Pore-pressure generation and movement of rainfall-induced landslides: effects of grain size and fine-particle content. Eng Geol 69:109–125

Zhou Z, Wang HG, Fu HL, Liu BC (2009) Influences of rainfall infiltration on stability of accumulation slope by in-situ monitoring test. J Cent South Univ 16:297–302