Research Journal of Applied Sciences, Engineering and Technology 13(2): 122-130, 2016
DOI:10.19026/rjaset.13.2923
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: May 7, 2015 Accepted: August 22, 2015 Published: July 15, 2016

Research Article

Model Experiment on Rainfall-induced Slope Failures with Moisture Content Measurements

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Abstract: The aim of the study is to investigate the controlling parameters of flowslide initiation experimentally through laboratory flume. Landslide is still a major frequent hazard in many parts of world despites of number of studies have been done related to slope failure. The most of slope failures are because of rainfall, as rainfall increases the moisture content and the pore pressure that reduce the shear strength of the soil. The slope after failure shows different modes, however every slope failure not produced same damages. The impact of landslide directly related to failure mode, velocity and distance travelled. There are different types of slope failure, however the flowslide is the most dangerous than other type of landslide. The flowslide type of failure occur suddenly without any warning and have fluid like motion that makes it more dangerous. In this study experiments conducted in laboratory through flume in order to investigate the parameters that initiate the flow type of failures. After the preparation of the model slope the sensors installed for the moisture content and the pore pressure. The moisture content measured with advanced sensor Imko Trime Pico-32. From the experiments it was observed that density of soil slope plays an important role in the initiation of flow type of failure. The pore pressure developed after the failure depends upon the thickness and velocity of sliding mass. The pore pressure and moisture content higher at the toe and the pore pressure higher at the base as compared to shallow depth. In the case of antecedent moisture conditions the runoff appeared at the horizontal part of the slope that erode the toe. The flowslide occur from smaller to higher depth of soil slope and significant depth of soil layer involved in flowslide type of failure. From the experiments it was observed that by installing the moisture sensors from toe to mid of the slope at the shallow depth the failure can be predicted.

Keywords: Failure, flowslide, flume, moisture content measurements, pore pressure, rainfall, slope

INTRODUCTION

The natural and engineered steep slopes remain stable in the tropical areas before the rainfall event. The rainfall-induced slope failures are one of the most destructive natural hazards, that occurs in mountains areas of the world after the heavy rainfall. The most of rainfall-induced slope failures are shallow in nature and occurs without warning. The marginal stable slopes mostly failed during the rainfall and consisting of different types of soils, such as residual and colluvial soils. In many parts of the world residual soils are commonly found in the tropical regions. The soils are mostly in unsaturated state because the ground water table usually deep. It is not true that slope failures occurred mainly because of increase in ground water table. As the ground water table deep the pore water pressure is negative with respect to atmospheric conditions. The matric suction or negative pore water pressure provides stability to soil slope. The magnitude of negative pore water pressure above the ground water table plays a significant role in the factor of safety of the soil slope (Fredlund and Rahardjo, 1993).

The slope stability significantly reduced as rain water infiltrate into the soil slope and changes the pore water pressure which in turns controls the water content of the soil (Fredlund and Rahardjo, 1993; Rahardjo *et al*., 2005). The increase in the pore pressure reduce the effective stress of soil that ultimately decrease the shear strength (Brand, 1981). In number of ways earth slope weakens due to rainfall, the bonds created by surface tension between particles of soil broken by increase in degree of saturation due to rainfall. The capillary pressure decreased with increase in degree of saturation, the fluid flow in the slope increases the frictional drag. The soil slope cut and softened by increased in moisture content that increases the sliding forces (Borja and White, 2010; Liu *et al*., 2013).

The rainfall-induced landslides grouped as shallow and deep landslides depending upon the depth and

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mode of failures. The type of landslides influenced by lithology, morphology and the land cover. The sliding surface located greater than 10 m in case of deep-seated landslides, however in case of shallow landslides the sliding surface located within soil mantle or weathered bed rock (Acharya, 2011). The duration and intensity of rainfall directly linked to slope failure (Rahardjo *et al*., 1995), the short duration of higher rainfall intensity trigger the shallow landslides, however longer duration of moderate intensity of the rainfall trigger the deep seated landslides.

There are different types of landslides and based on their ways of movement landslides are commonly classified as falls, topples, spreads and flowslides. The flow type of failures are more dangerous than other types of landslide because of their large deformations (Wanatowski *et al*., 2008). The movement in the soil mass after the slope failure resembles to viscous liquid (Rotaru *et al*., 2008). The flowslide is the type of failure that may occur in natural or engineered slopes and mostly granular soil slopes suffers from flowslide type of failure. Most of flowslide are due to rainfall and their effects are much more dramatic and devastating.

The impact of landslides increased with the velocity and the distance travelled. The rapid and intermittent movements are more dangerous than slow and progressive movements. However in both case there is large probability of damages to infrastructure and property (Regmi *et al*., 2014).

During the intense rainfall events slope failure because of increased pore pressure and the seepage force (Anderson and Sitar, 1995; Sitar *et al*., 1992; Wang and Sassa, 2003). The soil at the shallow depth goes through unsaturated to saturated conditions, particularly at the shallow depth. The moisture content and the pore pressure directly linked to progress of landslide, as increase in moisture content and the pore pressure causes the slope failure. The physical and the mechanical properties directly influenced by the moisture content (Fang *et al*., 2012). The shear strength is lower with greater water content and therefore the slope stability is less (Hotta and Ohta, 2000). The status of moisture content of soil mass strongly related to movement of rainfall-induced landslides. The physical index by which soil-water characteristics reflected is volumetric moisture content (Zhang *et al*., 2014). The moisture is increases after infiltration of the rainfall and modifies the structure of soil and thus lessens or vanishes the frictional or cohesive strength of soil (Reddi, 2003).

Various studies have been conducted on investigation of slope instability by numerical analysis associated with infiltration induced by rainfall (Springman *et al*., 2003; Blatz *et al*., 2004; Cai and Ugai, 2004; Sako *et al*., 2006). The considerable amount of research has also been conducted on rainfall induced shallow slope failure under controlled laboratory condition using sloping flumes (Sassa, 1984; Wang and Sassa, 2001; Okura *et al*., 2002; Wang and Sassa, 2003; Wang and Shibata, 2007; Lourenço *et al*., 2006; Reid *et al*., 2008; Iverson *et al*., 2000; Gallage *et al*., 2012). In order to develop the early warning system, it is better to understand the rainfall-induced slope failure.

The objective of this study to investigate the parameters that initiate the flowslide type of failure. Experiments conducted in flume under different soil and hydrological conditions such as thickness, density, rainfall intensity and antecedent moisture conditions.

LITERATURE REVIEW

Number of studies related to landslide have been conducted numerically and experimentally in the field. The numerical simulations are difficult and requires number of parameters related to geological properties of soil and not reliable, however field experiments are time consuming and expansive. The experiments conducted in the laboratory through model flume is the best approach to investigate the rainfall-induced slope failure. The valuable information have been revealed by laboratory experiments (Lourenço *et al*., 2006). In our current studies experiments conducted in laboratory by preparing the soil slopes in model flume under artificial rainfall. The pasts studies related to rainfall-induced landslides as discussed below.

The experiments conducted by Tiwari *et al*. (2013) in plexis model container of 1.2 m×1.2 m ×1.2 m size and the soil slope prepared under loose conditions. The slope inclination was 30° and 40° and failure induced by artificial rainfall. They observed from the their study that with depth of soil slope and amount of rainfall the degree of saturation changes. The changes in degree of saturation vary the apparent cohesion in the soil mass.

Experiments conducted in laboratory under different geological conditions, fines content and rainfall intensities. During the experiments the pore pressure and moisture content measured and from the experiments it was observed sliding failure mood occurred in permeable sand. However in less permeable slity sand the failure initiated by erosion at the shallow depth and then turned into complex mode of flow and slide depending upon the rainfall intensity applied (Chen *et al*., 2012).

Experiment conducted by Moriwaki *et al*. (2004) in large scale flume to clarify the process rainfall-induced landslides using loose sandy soil. The flume was 23 m long and 8 m high and consists of 3 section, an upper part with slope of 30°, a lower section 10° and the horizontal section at the foot of the slope. The failure induced by constant rainfall intensity of 100 mm/hr. From the experiments it was observed that the collapse of loose soil structure during shearing and translational increased the pore water pressure in the upper part of the slope.

The experiments conducted in laboratory on model sandy slopes to investigate the factors that initiate the rainfall-induced slope failure. The failure induced in the model slope by water percolation from the side of the upslope or by artificial rainfall on the top of the slope. During the experiments the pore pressure, moisture content and ground deformations were measured. From the experiments it was observed that failure occurred when the soil reaches to nearly saturated conditions at the toe of the slope, even though upper parts of slope in partially saturated conditions (Orense *et al*., 2004).

Experiments conducted in soil tank with sandy soil called as shirasu in order to investigate the failure mechanism of unsaturated soil slope due to increase in degree of saturation. The numerical simulations using 2D unsaturated-saturated analysis and then slope stability analysis performed in order to prove the validity of numerical simulations at the model scale. From the experiments it was observed that before the failure the pore pressure suddenly increased after keeping the constant value (Sako *et al*., 2006).

Model experiments conducted in 5 m long, 30 cm wide and 50 cm deep rectangular flume using medium-grained silica sand. From the observations it was observed that successive sliding failure occurred once the failure initiate at the toe of the slope, after that unstable zone progressed towards the upslope. From the study it was also seen that strong relationship between rainfall intensity, sliding initiation time and the position of its slip surface head (Regmi *et al*., 2014).

The experiments performed in model flume in order to investigate how varying soil depth affect the location and timing of shallow slope failures. From the experiments it was observed that retrogressive slope failure more frequent in shallow depths and depth of initial slip surface decrease with increase in soil depth (Acharya *et al*., 2009).

EXPERIMENTAL METHODOLOGY

The experiments conducted in laboratory flume, the flume was 1 m in width, 2 m in length and 2.1 m in height as shown in Fig. 1. The flume made from plexis glass and installed in steel frame. The glass used in frame in order to observe the process of failure during the experiments. The soil placed in the flume and slope prepared, in order to achieve higher density each layer of soil compacted with steel hammer.

The grain size distribution curve of soil shown in Fig. 2. The soil placed in flume parallel to slope base and slope inclination as fixed with 45° and that slope angle considered as steep. The failure on the steep slope as more rapid and flume consist of two parts, slope and horizontal section. The front end of flume fixed with steel plate in order to hold the soil mass.

The horizontal section provided for self-stabilization purpose and reduces the pre-mature soil erosion. After the preparation of the model slope, the holes drilled and sensors installed at different position. The failure induced by artificial rainfall, artificial rainfall applied by installing the small sprinklers at top of the slope.

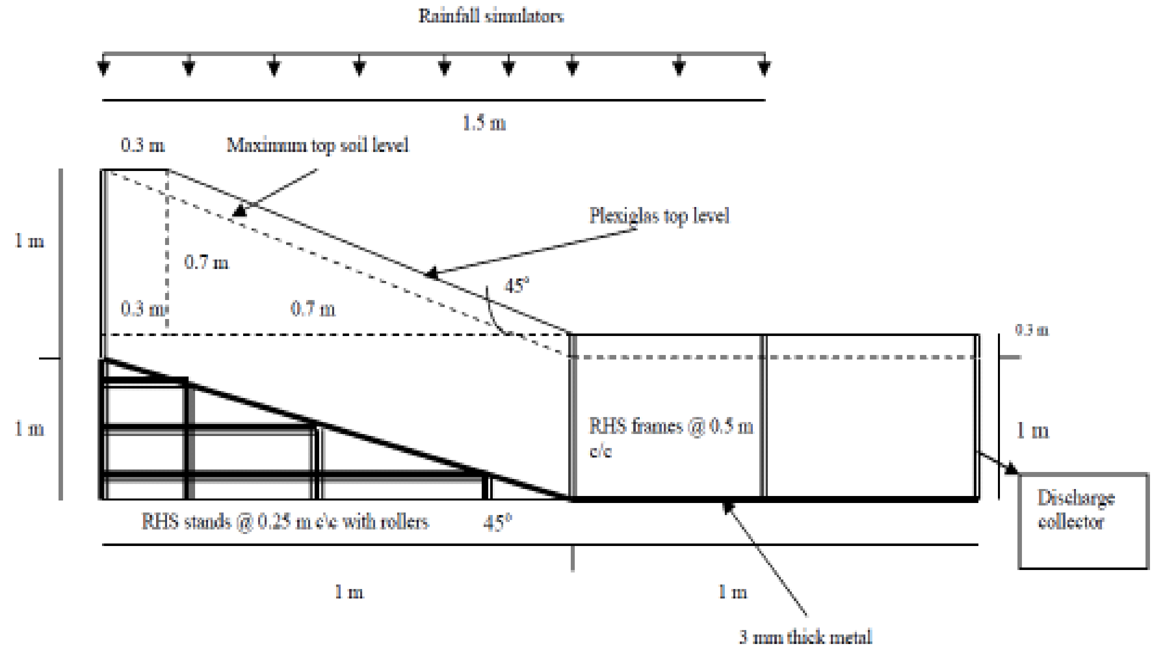

Fig. 1: Side view of model flume

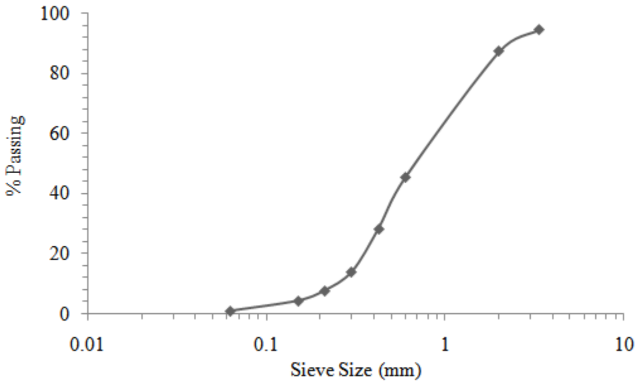

Fig. 2: Particle size distribution curve of soil

Fig. 3: Imko TDR

Fig. 4: Electrical piezometer

The artificial rainfall controlled by flowmeter and valves. During the current study the pore pressure and moisture content measured by piezometers and Imko TDR respectively. The TDR by Imko (Fig. 3) considered as solid backbone for measurement of moisture content for landslide study. As this type of TDR requires less calibration efforts and can be used in difficult soils such as organic and high electrical conductive soils, as problem of energy dissipation during measurements of moisture content.

The TDR by (Imko, Germany) used for measurements of the moisture content and pore pressure measured by piezometer Sisgeo, P235S and that is capable of measuring the pore pressure between 0 to 100 kPa (Fig. 4). The piezometers connected to data acquisition system. The data acquisition system was consisting of personal computer and Unilog datalogger of Seba Hydrometry. Seba software installed in personal computer, data logged at the interval of 2 minutes. The moisture content measured with Imko TDR, the TDR consist of 2 rods with 10 cm of the depth and these TDRs connected to another Globelog datalogger for data acquisition and this also logged after every 2 minutes. As for the experiment huge amount of soil used so after each experiment the soil was removed and after that soil air dried and mixed properly again used for new experiment. The antecedent moisture conditions created as end of previous experiment considered as initial conditions of new experiment.

RESULTS AND DISCUSSION

In order to investigate the failure behavior of landslides the flume is the best approach compare to field studies and numerical approach. The experiments conducted in flume under controlled conditions and within short span of time reliable results obtained with maximum accuracy. The variables in the flume tests include soil density, rainfall intensity, initial moisture conditions and thickness of soil slope. In order to look the effect of soil density, in one case each layer of soil compacted in order to achieve the higher density. However in case of less density the whole soil placed parallel to slope base and slightly compacted. The initial moisture condition achieved as end of previous experiment considered as initial conditions of new experiment. Number of experiments performed in laboratory under different soil and hydrological conditions. The parameters that changed during the experiments include soil density, rainfall intensity, antecedent moisture conditions and thickness of soil slope. The slope inclination made fixed to 45°. Initially the slope prepared under dense condition and then slight loose conditions. After the slope preparation, the sensors installed at different position. The experiment conducted after one day of preparation of the slope, and then rainfall started on the slope.

Figure 5 shows the variations in moisture content, with horizontal and vertical axis representing time (minutes) and moisture content (%) respectively. The depth of the slope was 50 cm and the moisture content was measured by installing the moisture sensors at the custom locations. In addition, the “M” represents the measurements of moisture content and the location of sensors is depicted in each figure. After the first increase in moisture content, it remained constant as wetting front progressed downwards, that made the soil partially saturated, and the second increase in moisture content was because of the development of ground water level that made the soil completely saturated. The M1 was installed at the depth of 5 cm and it began to increase after 10 minutes, whereas the M3 was installed at the depth of 15 cm, which increased after 25 min. The rainfall intensity was 2 liters/minute, and all the moisture sensors reached saturation, as all the moisture sensors were placed near the toe of the slope. The M1 reached saturation first, while M2 and M3 reached saturation after 70 min of rainfall. After the saturation, the moisture content remained constant.

Apart from that, Fig. 6 shows the variation of moisture content under rainfall intensity of 10 liters/minute. The M1 increased after 5 min of rainfall, while M4 increased after 13 minutes of rainfall. The major failure was not observed even with higher rainfall intensity, although higher rainfall intensity caused higher erosion, and after sometime, gullies were formed and with continuous rainfall, the width and the depth of the gullies increased.

The furthers experiments were conducted in order to determine the influence of the antecedent moisture conditions on moisture content variations. The experiment conducted with rainfall intensity of 3 liters/minute, as shown in Fig. 7.

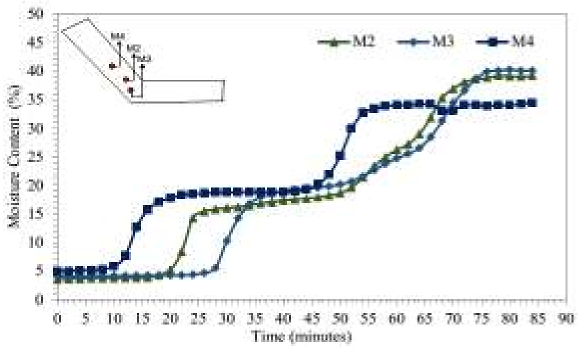

Fig. 5: Moisture content variations for rainfall intensity of 2 liters/minute

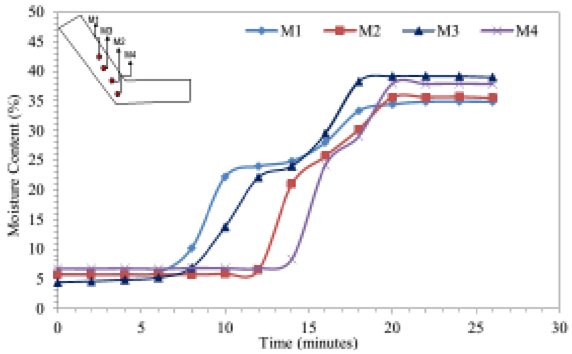

Fig. 6: Moisture content variations for rainfall intensity of 10 liters/minute

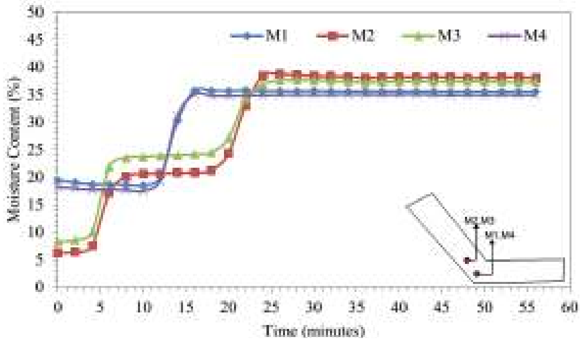

Fig. 7: Moisture content variations for rainfall intensity of 3 liters/minute (antecedent moisture conditions)

Experiments were also conducted on soil slope under loose conditions (poorly compacted). The variations in pore pressure and moisture content in the slope with different depths and densities under different rainfall intensities are discussed below. The experiment was conducted on soil slope with a thickness of 30 cm with rainfall intensity of 8 liters/minute. After the start of rainfall, erosion was observed when rainfall continued, as cracks appeared on the toe first and then progressed on the top of the slope, the width of cracks increased with further rainfall. Besides, shear cracks were formed over the

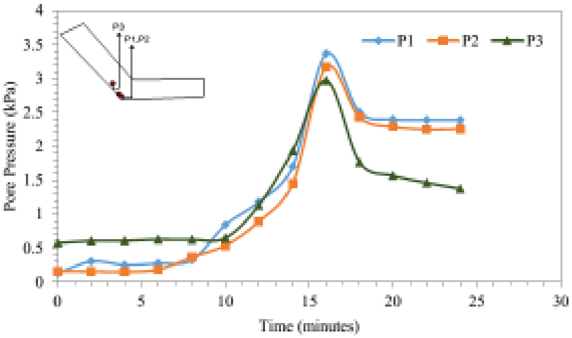

Fig. 8: Pore pressure variations for rainfall intensity of 8 liters/minute

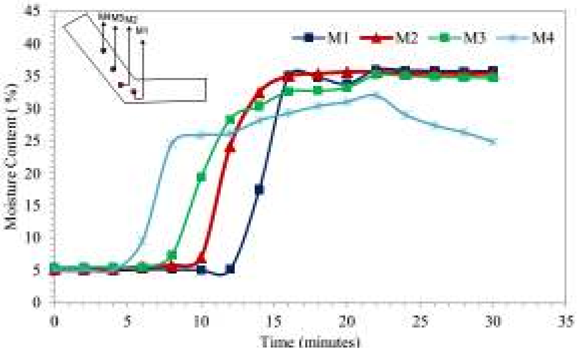

Fig. 9: Moisture content variations for rainfall intensity of 8 liters/minute

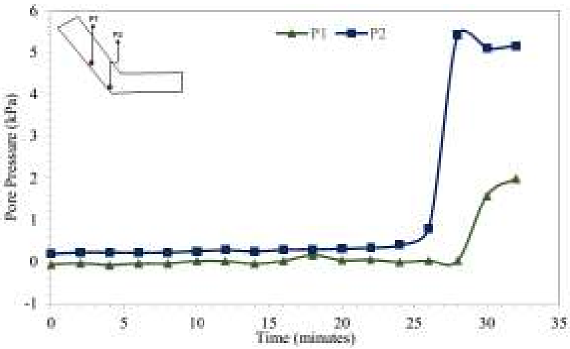

Fig. 10: Pore pressure variations for rainfall intensity of 5 liters/minute

entire surface of the slope during the failure stage. The pore pressure and moisture content shown in Fig. 8 and 9 respectively.

In Fig. 8, the sudden increase in pore pressure was due to landslide, the sudden increase in pore pressure is result of landslide not the cause of landslide. On top of that, M1, M2, M3, and M4 represent the moisture sensors, and due to large failure, the moisture sensors were displaced from their positions, while uncommon variation was discovered in moisture content "M4" because of such displacement, as shown in Fig. 9.

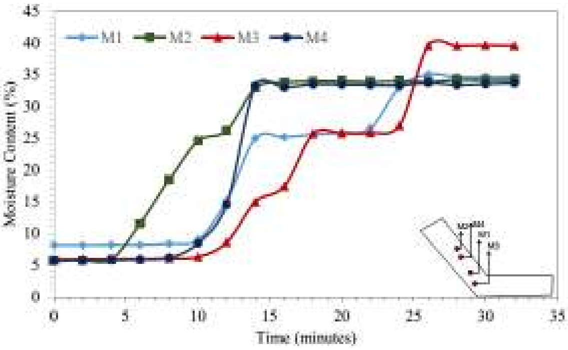

Fig. 11: Moisture content variations for rainfall intensity of 5 liters/minute

Fig. 12: Failure events before flowslide

The experiment was conducted on the model slope with a depth of 50 cm, while the rainfall intensity was 5 liters/minute. The 4 moisture sensors were placed at the depth of 12, 14, 18, and 22 cm and those were placed between mid and toe of the slope. Moreover, only two piezometers were used in the experiment; one was installed 0.4 m from the top of the slope, while the other was installed at the toe.

Figure 10 and 11 shows the pore pressure and moisture content for that experiment respectively. The summary of experiments shown in Table 1. The moisture content increased in two steps, the first step shows the arrival of wetting front and second shows the development of ground water level. After the first step the moisture content remained constant till the development of ground water level from base to upper parts of the slope. The moisture is smaller at the upper part of the slope and higher at the toe of the slope. As the water that infiltrate at the upper part of the slope, water flows towards the toe because of gravity.

In Table 1, D and L shows the dense and loose conditions respectively. From the number of experiments it was also found that the pore pressure is higher at the base of the slope as compared to shallow depth. Even in case of dense slope higher rainfall intensity accompanied with antecedent moisture not trigger the flowslide or sliding type of failure. In the case of antecedent moisture conditions, the moisture

Table 1: Summary of experiments

Test	Depth of slope	Rainfall intensity	Initial moisture content	Failure type
D1	50cm	3 liters/minute	No	No failure
D2	50cm	10 liters/minute	No	No failure
D3	50cm	3 liters/minute	Yes	No failure
D4	50cm	8 liters/minute	Yes	No failure
D4	30cm	8 liters/minute	No	Flowslide failure
L1	50cm	5 liters/minute	No	Flowslide failure
L2	30cm	8 liters/minute	No	Flowslide failure
L3	40cm	6 liters/minute	No	Flowslide failure

and pore pressure increased quickly that produce the runoff. The hydrological response of soil slope significantly influenced by antecedent moisture conditions. The development of the pore pressure is not only the reason to initiate the slope failure, however soil saturation is also important to induce the flowslide or sliding type of failure specially in case soil slope having less density.

The increase in weight of slope with rise in moisture condition is the important condition for slope failure. Initially in some cases small sliding occurred, after that free space created at the upper part of the slope. The continuous rainfall produced the surface runoff at the crest of the slope that increase the water level in the bottom layer that trigger the large flowslide (Fig. 12).

The movement in the soil mass continue till the slope at the critical gradient. In the case of loose soil slope the rainfall saturated the soil that make the slope more susceptible to flow liquefaction. The minor initiation of soil cracks in the loose soil slope during the rainfall produce higher movement of the sub-surface water and therefore after the failure large runoff appeared at the horizontal part of the slope. The water extracted from pores of soil due to compression during mass movement. The smaller pore water pressure can induce the flow type of failure in the case of loose soil slope. The top layer having less density slide first in the case difference of density in slope layers. Even after the development of water level at the toe of the slope highly unstable zone not formed in the case of dense slope. In the case of dense slope the reduced shear strength still sufficient to retain the soil mass on the slope.

In addition, the development of pore pressure had been necessary, however, not only for the condition of slope failure. The increase in the weight of the slope with the rise in moisture condition had been revealed as important conditions for slope failure. Besides, pore water pressure had been related to rainfall intensity, whereby the higher the rainfall intensity, the higher the pore pressure within the same duration of rainfall, as compared to low rainfall intensity. The pore pressure increased slowly in the case of lower rainfall intensity, and with higher rainfall intensity, the pore pressure increased quickly.

CONCLUSION

The experiments conducted in the flume under artifical rainfall with measurements of the pore pressure and moisture content. The experiments conducted under different soil and hydrological conditions such as density, soil thickness, rainfall intensity and antecedent moisture conditions. Based on the results of experiments obtained, the following conclusions are drawn:

- From the experiments it was observed that density of soil plays an important role in the initiation of flowslide. In the case of dense slope even higher rainfall intensity with antecedent mositure condition not trigger the major slope failure. However in the case of less dense slope the smaller rainfall intensity trigger the flowslide type of failure.
- The pore pressure suddenly increased after the flowslide type of failure and development of higher pore pressure related to thickness and velocity of sliding mass. In the case small failure the pore pressure not increased suddenly.
- The pore pressure smaller at the upper part of the slope as compared to toe and pore pressure is higher at the base as compared to shallow depths.
- In the case of antecedent mositure conditions the runoff preoduced quickly that erode the toe of slope and forming erosion gullies.
- The pore pressure and mositure content increased quickly in case of antecedent mositure conditions.
- The flow type of failure can occur from smaller to higher depth of soil slope and during the flowslide significant depth of soil layer involed in the flowslide type of failure.
- The early warning can be established by installing the moisture sensors from toe to mid of the slope at the shallow depths.

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