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Discussions

Laboratory experiments on rainfall-induced flowslide from pore pressure and moisture content measurements

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Abstract

During or immediately after rainfall many slope failures have been observed. The slope failure occurred due to rainfall infiltration that rapidly increase the pore pressure and trigger the slope failure. Numerous studies have been conducted to investigate the rainfall-induced slope failure, but the mechanism of slope failure is still not well clarified. To investigate mechanism of rainfall-induced slope failure laboratory experiments have been conducted in flume. The slope was prepared with sandy soil in flume with constant inclination of 45°, because most of rainfall-induced slope failure occurred in sandy soil and on steep slope. The hydrological parameters such as pore pressure and moisture content were measured with piezometers and advanced Imko TDRs respectively. The slope failure occurred due to increase in moisture content and rise in pore pressure. During the flowslide type of slope failure the sudden increase in pore pressure was observed. The higher moisture content and pore pressure was at the toe of the slope. The pore pressure was higher at the toe of the slope and smaller at the upper part of the slope. After the saturation the run-off was observed at the toe of the slope that erodes the toe and forming the gullies from toe to upper part of the slope. In the case antecedent moisture conditions the moisture content and the pore pressure increased quickly and producing the surface runoff at the horizontal part of the slope. The slope having less density suffer from flowslide type of the failure, however in dense slope no major failure was occurred even at higher rainfall intensity. The antecedent moisture accompanied with high rainfall intensity also not favors the initiation of flowslide in case of dense slope. The flowslide type of failure can be avoided by controlling the density of soil slope. Knowing such parameters that controls the large mass movement helpful in developing the early warning system for flowslide type of failure.

1 Introduction

Rainfall-induced slope failures considered as major natural hazard (Segoni et al., 2014) after floods that occur within short period of time without prior warning. The slope failure occurs in various types of soil, such as colluvial and residual types of soil, and occurs on slopes that are marginally stable (Anderson and Sitar, 1995). The most of rainfall-induced slope failures are shallow in nature with depth less than 2 m (Chae et al., 2015). Rainfall-induced slope failures considered as one of the major geo-environmental hazard due to infrastructure development in landslide prone areas.

During the rainfall the pore pressure and seepage forces increased that causes the slope failure (Anderson and Sitar, 1995; Wang and Sassa, 2003). Due to increase in pore pressure the effective stress of soil decreases that reduce the shear strength, and in worst cases the slope failure occur (Fang et al., 2012). Before the rainfall the slope is in stable conditions, however after the rainfall the shear stress is increased, and shear strength of soil reduce due to increase in moisture content, that trigger the slope failure (Chae et al., 2015). Landslides may be small or large, some moves slowly and some moves rapidly that causes lot of problems.

The type of landslide influenced by number of factors such as land cover, morphology, lithology and, frequency and magnitude of rainfall. The short duration of intense rainfall trigger the shallow slope failure such as debris flows, however moderate rainfall intensity of longer duration causes the deep landslides. The variations in the pore pressure during the rainfall highly influenced by hydraulic conductivity, degree of weathering, topography and fracturing of the soil. The increase in the pore pressure may be directly related to rainfall infiltration and percolation, or also result of development of perched or ground water table (Terlien, 1998). During the intense rainfall the development and dissipation of the pore pressure is very rapid in the soil having larger permeability. The higher rainfall intensity causes the slope failure in these cases and antecedent moisture has little influence on landslide occurrence (Johnson and Sitar, 1990).

The main cause of the landslide is the rainfall especially for shallow landslide, as during the rainfall the bulk density of soil slope increased, softens the soil and reducing the stabilizing force of the soil (Fang et al., 2012).

2 Literature review

During the rainfall infiltration the shallow and local slope failures occur due to formation of temporary saturated zone that would leads to reduction of the matric suction. During the rainfall infiltration the shallow soil of landslide mass quickly reaches to saturation and develop the surface runoff, that erode the slope, and seepage field is changed during infiltration of rainfall, as a results moisture content of landslide mass increases. Due to increase in moisture the shear strength is reduced. The shear strength of nearly saturated soil is greater than saturated soil.

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 vanish the frictional or cohesive strength of soil (Reddi, 2003).

Infiltration of the rainfall above the ground water table in unsaturated zone induces the slope failure. From the experience it was revealed that numerous slope failures occur during or shortly after rainfall, as water infiltrates into the slope. Landslide that induces by rainfall is varying in depth and the landslide is the deeper, causing greater damages. These types of failures are characterize by shallow sliding surface usually 1–3 m and developed parallel to original slope surfaces. The ground water tables frequently to be found at greater depth below the surface of ground, and there is no any proof that during the rainfall that water table rise significantly that trigger the shallow failures. Instead, due to infiltration of rainfall wetting front get deeper in to the slope attribute the slope failure (Kim et al., 2004; Zhou et al., 2009). There is large deformation in slope failure in which the soil of the slope undergoes significant huge strain.

Then slope will be in new deformed state after the failure, in that movement of toe and settlement at the crest occurs.

In tropical and subtropical weathered soils the most of rainfall-induced landslide is occurs above the ground water table (Brand et al., 1984; Mokhtar et al., 2012). Earth slope weakens by rainfall in number of ways. The degree of saturation of soil increases by rainfall infiltration, in that way it breaks the bonds that build by surface tension between particles of soil. The fluid exerts the downhill drag force on the slope when infiltrated volume of water is large enough to mobilize the fluid flow within the soil that produces a destabilizing effect on slope. Due to increase in saturation in the soil, when excess fluid can no longer infiltrate to slope, it discharged as surface runoff and erodes the slope. Rainfall weakens the slope because it decreases the capillary pressure as increase in saturation. Besides, it increase the load on the soil due to generation of frictional drag that created by fluid flow (Borja and White, 2010).

Due to infiltration of rainfall the moisture content is increased and the soil of slope cut and softened thereby increasing the sliding forces (Liu et al., 2013). The failure of slope induced by rainfall is mainly caused by (1) the weight of soil mass increased (2) with the increase in water content decrease in suction of unsaturated soil (3) increase in ground water level (4) erosion of slope surface and lubrication of sliding surface (5) hydrostatic or hydrodynamics pressure (Kitamura and Sako, 2010; Fang and Esaki, 2012).

Flowslide is the slope failure in that sliding mass characterized by general disintegration and development of fluid like motion with rise in pore water pressure (Wang and Sassa, 2001). The most of the shallow slips turns into flow type of failures as reported from Iverson et al. (1997). Rainfall-induced flowslide can occur in natural and also in man-made fill slopes. The rainfall-induced flowslide have a distartous effect on public and nearby communities, because in shallow flowslide the huge saturated soil mass moving at very high speed and causing damages and casualties. The most of the rainfall-induced landslides are superficial and occurs on the slope where the ground water table is absent due to slope steepness. The debris flow is also type of shallow slope failure that developed from the shallow slides which are located at the steep

slopes (30 to 40°) and typically consists of colluvial deposits. Some forms of landside may turn the debris flow, especially in granular soil in that movement like sliding may turn in to the flow. The mechanism of movement is the main difference between the slide and flow like landslides. The sudden increase of pore pressure greater than hydrostatic may leads to decrease in shear resistance and increase the acceleration of movement, in that condition also generates the debris flow (De Wrachien and Brebbia, 2010). The debris flow is intermediate between sediments rich floods and landslides.

Due to probability of events, size and behavior of soil bodies, the landslide risk analysis is not an easy task. But in order to find the good solutions and to tackle the problem strong efforts have been made from the last decades. Some researchers engaged themselves in the improvement of numerical modeling for triggering and movement of landslides, others are concerned with the development of alert and alarm systems for landslide disasters prevention; finally others are engaged in setting the physical models for simulation of landslides initiation and evolutions.

In short time many places affected by heavy rainfall that more often triggers slope failure and declare many casualties and affect the local communities. The effective measure is difficult to find even though the risk of rainfall-induced slope failure widely recognized. The one reason is that more attention is given to bigger events, and in detail small and shallow slope failures have not been studied. Definitely bigger failure can cause more damages to infrastructures and public, and efforts are being made to overcome that problem. The other reason is may be that the shallow slope failure is affected by geology, hydrology and local perception that are relatively difficult to study in detail. The small slope failures occur suddenly and kill the peoples without cautions.

During heavy rainfall the early warning that based on monitoring of the slope is comparatively is an inexpensive way to save the life of the peoples. This practice is however not an easy, because onset slope failure is affected by many factors such as hydrology, geology, topography and perception intensity. There are two approaches are used for early warning system. Proper monitoring not only used for early warning, but also help to better understand the process of landslide.

3 Related past work

For investigating the mechanism of flowslide, mainly the physical modeling is very useful tool. Even though physical modeling affected by uncertainty due to scale effects, but it is still very helpful regarding the information on mechanism and triggering factors of landslides. For the granular saturated soil the flow like movement is too destructive and occurs in earth fills as well as in natural slopes, when initiated, can attain the velocity of tens of meters (Olivares and Picareelli, 2006).

Experiments were conducted by Chen at al. (2012) in laboratory to clarify the failure mechanism of granular soil slopes under high rainfall intensity. They observed that failure initiated by piping occurred at the toe of the slope, after that it extend upwards and induces the shallow retrogressive slides. They observed that the slope having more fines failed earlier and failure surface was faster and longer, and convex slopes failed later than concave slopes.

In order to investigate the effect of slope inclination on the stability of slopes experiments were conducted by Gallage et al. (2012) on instrumented model embankments. They observed that slopes becomes more vulnerable to failure as slope inclination is increases, the development of positive pore pressure initiate the slope failure, while decrease in soil suction is the dominant factor initiate the slope failure in the case of steep slopes.

The parametric study was conducted by Rahardjo et al. (2007) and found that soil properties and rainfall intensity controls the instability of the slope due to rainfall, while the initial water table and slope geometry played the secondary role. From the parametric study it was also observed that soil permeability influence the significance of antecedent rainfall.

Under artificial heavy rainfall two shallow landslides were induced in large scale slope model and changes in shear deformation and sub-surface flow was monitored by Okada (2014). The sub-surface flow and shear deformation conditions were not homogenous even though sand layers were uniformly packed. The directions of sub-

surface flow and shear deformation were more in general agreement with direction of the slope base, indicating that possible influence on landslide initiation.

Experiments were conducted by Wang and Sassa (2003) in small flume and series of test were conducted to trigger the landslides and found that maximum pore pressure built-up at the optimal density index and the failure mode is also depends upon grain size.

The experiments were conducted in laboratory by Tohari et al. (2007) to elucidate the initiation of rainfall-induced slope failure and observed that slope failure is initiated due to increase of moisture content and slope failed when full saturation occurred at the toe of the slope even though other parts of the slopes remain unsaturated. The paper indicated that critical time of the slope failure can be predicted by measurements of change in moisture content.

The experiments were conducted by Tsutsumi and Fujita (2012) in order to investigate the mechanism of multiphase landslides. That can define as the collapse of blocks of soil mass after one another. Experiments were conducted in flume and modeling approaches were used in order to determine the occurrence of multiphase landslides, and they observed that multiphase landslide may occur on soil layer having internal friction and low cohesion.

During or immediately after the rainfall the many slope failure observed. The experiments were conducted by Orense et al. (2004) in model flume. The failure was induced by artificial rainfall and percolation from side upslope. They observed from the experiments that failure occurred when soil reaches to saturation near the toe of the slope even though other parts of slope unsaturated. They also stated that by monitoring the moisture content and surface displacement at the toe slope, the slope failure can be predicted.

In order to investigate the rainfall-induced slope failure, the most common methods i.e., site investigation, numerical analysis. Site investigation is costly and suitable only for case studies, while numerical methods collect many parameters that related to geological materials (Chen et al., 2012).

The current experimental study uses laboratory model flume to investigate the mechanism and factors that influence the rainfall-induced flowslide by measurements of pore pressure and moisture content by most innovative and advanced types of sensors.

4 Experimental methodology

The experiments were conducted in laboratory flume 2.2 m long, 1 m wide and 2.2 m in height as shown in Fig. 1. The sides of flume was made from plexis glass, so that failure can be observed except from front end that was made from steel to retain the soil mass. The flume has constant inclination of 45° and rainfall system was installed 1 m above the flume to induce the failure in soil slope. The slope was made steep, because the rainfall-induced slope failure is rapid and devastating whenever the slope is inclined at steep angles. Experiments were conducted by changing the density, thickness, rainfall intensity and antecedent moisture conditions. The duration of the each experiment was different depending upon the timing and occurrence of failure events and post failure behavior. The inclination and shape of the slope was fixed in the all the experiments. The flume have two sections i.e., slope section and horizontal, the horizontal was provided to avoid pre-mature erosion, self-stabilization and for deposition of soil mass after failure. For measurements of moisture content Imko TDRs were used, that is relatively new, due to higher cost higher accuracy is there. The pore pressure was measured with electrical piezometer model Sisgeo P235S, the range of measurements is from 0 to 100 kPa. The dimensions of the flume were made small due to availability of the funds and handling. The soil sample was sandy soil most of shallow and flow type of failure occur in sand. The grain size distribution of soil is shown in Fig. 2. Based on the results of gradation curve the co-efficient of uniformity C_u and co-efficient of curvature C_v was calculated and it was 3.3 and 0.83 respectively. Density was calculated $1.6 \times 10^3\,\mathrm{kg\,m^{-3}}$, and the void ratio of 0.58. The hydraulic conductivity was $3 \times 10^{-4}\,\mathrm{m\,s^{-1}}$. The pore pressure was measured with piezometers, and data acquisition system was consisting of personal computer and Unilog datalogger of Seba

Hydrometry. Seba software was installed in personal computer. Data were logged at the interval of 2 min. The moisture content was measured with Imko TDR, the TDR consist of 2 rods with 10 cm of the depth, and these TDRs were connected to another Globelog datalogger for data acquisition and same this was logged after 2 min. Each layer of the slope was compacted with fabricated hand hammer with dimensions of 2 feet × 2 feet with handle on the top, till that achieved required height.

5 Results

In this current experimental study the numbers of experiments were conducted in flume in order to better understand the mechanism of rainfall induced slope failure. The soil was placed in flume and slope was prepared and the after preparation the moisture and pore pressure sensors were placed at different location and in each figure the sensors position was depicted. In the case of dense slope the soil was placed in flume in layers and each layer of soil was compacted with fabricated hammer sufficiently till achieve the required height, however in the case of loose slope the soil was placed in one layer and then compacted. The soil was placed parallel to slope base, and initially the soil was placed at horizontal part of the slope and then progressed to upper part of the slope. The failure was induced in the slope by rainfall through small sprinkler installed above the flume. After the starting the rainfall the moisture content was increased and the shallow moisture sensors shows fast response soon after starting of the rainfall, and after the wetting front progressed to base of the slope, initially at the toe of the slope. After the first increase the shallow moisture sensors shows same value, and it increased after the development of water level from the base of the slope. When the wetting front reaches at base of the slope it shows the sudden increments and reaches to saturation, and in the one step fully saturated, however the moisture sensors at shallow depth reaches to saturation in 2 steps. According to Gevaert et al. (2014) the moisture increase in step wise fashion rather than gradual.

The most of measurements of the moisture were made near to the toe of the slope at different depths, because the moisture is higher at the vicinity of the toe, and toe of the slope is critical to rainfall due to higher seepage. The groundwater seepage exerts the seepage force and generates the slope instability at the toe of the slope. The stability of slope affected by the force component of seepage, as seepage is vector quantity and having magnitude and direction (Tohari et al., 2007).

The rainfall intensity controls the degree of saturation, and at the toe of the slope the moisture reaches the saturation early as all the surface and sub-surface water flow towards the toe of the slope due to gravity. Higher the rainfall intensity higher will be erosion, and in all experiments that conducted under dense conditions no major slope failure occurred except the erosion type of failure. So higher degree of saturation and pore pressure cannot trigger the flowslide or major slope failure in the case when slope is under compacted conditions. The soil at upper part of the slop not fully saturated as shown in Figs. 3 and 4.

The extent of rainfall necessary to trigger the slope failure determines from the existing moisture content of the slope. Relatively new and small scale of rainstorm water can trigger the slope failure if the slope mass have significant amount of moisture content prior to rainfall. The most frequent cause of landslide is the combined effect of intense rainfall and wet antecedent moisture conditions. The surface layer saturation not only triggered the landslide, but the surface and sub-surface saturation with combined effect is critical (Ray et al., 2010; Ray and Jacobs, 2007). The antecedent moisture conditions were achieved as end of previous experiment considered as initial conditions for another experiment. The next experiment was conducted after 24 h of previous experiment so that moisture content can be well distributed in the slope, as shown in Fig. 5.

In the case of antecedent moisture conditions the moisture reaches to saturation early as prior to rainfall all the voids were almost filled with water, so when rainfall started and wetting front reaches the soil, the soil gets saturated early. After the saturation at the toe of the slope the runoff was observed that erodes the toe of the

slope. After the saturation gullies were formed starting from the toe and progressed to upper parts of the slope. The gullies were become wide and deep, as after the formation of gullies, become unstable with continuous rainfall due to effect of breaching and damming. Even the soils have significant moisture content prior to rainfall in dense conditions no major slope failure was observed in our experiments. The rainfall after the striking the wall of flume accumulated from the sides of the slope that also erode sides of slope especially at higher rainfall intensity. The rainfall intensity and duration is significantly influence the removal of soil mass from upper part of the slope. After the soil mass detached from soil slope and accumulated at the toe of the slope due to gravity and surface runoff. The soil mass that accumulated at the toe of the slope are pushed by the other soil that newly detached from the upper part of the slope and move to horizontal part of the slope. Rainfall intensity of different duration also effect on the instability of soil mass, initially higher rainfall intensity and then lower rainfall intensity removes more soil from the slope as compared to initially lower rainfall intensity and then higher rainfall intensity of same duration.

The pore pressure is the result of percolation and infiltration of the rainfall, or development of ground or perched water table. The moisture sensors start increase soon after the starting of the rainfall, however the piezometers increased after the saturation and development of ground water level. For our experimental flume the base of the flume served as impervious boundary and after the wetting front reaches at the base of the flume the water level increased. In this model experiments the pore pressure increased gradually in the case of higher density, and the sudden increase in pore pressure was missing. This was may be due to slow shearing rate, low initially soil porosity and high bulk density. However the higher the rainfall intensity the quicker the pore pressure increasedy.

The rainfall infiltration causes variation in ground water level and sometimes plays an important role in stability of soil slope. The depth of slope was 50 cm in all above experiments and soil slope was under compacted conditions. Even with the development of significant pore pressure the large failure was not observed as shown in Fig. 6.

By increasing the rainfall intensity the velocity of rainfall infiltration increases. However with the increase in unit weight of soil, rainfall infiltration velocity tends to decreases (Chae et al., 2015).

There are three stages in development of the pore pressure i.e., steady state, unsteady state and steady state. After the rainfall the pore pressure remained constant, when water level rose the pore pressure increased quickly, and after that pore pressure increased gradually. In above experiments the piezometers were installed at the base of the slope. However when the piezometers were placed at the shallow depth it was observed that pore pressure is smaller at the shallow depth as compared to base of the slope.

The pore pressure is higher at the toe of the slope as compared to upper part of the slope. The cracks appeared at the toe of the slope after the saturation indicating the initiation of slope failure; however after the initiation the movement in the slope was not observed due to soil density. In the case of antecedent moisture conditions significant amount of water already accumulated at the base of the slope. So when rainfall infiltrated the slope water level developed quickly and pore pressure increased.

In order to predict the landslide it is very much necessary to know the mechanism leading to failure, and to evaluate whether the slope will fail or not, and the mechanism that control the movement of failure mass. Despite number of studies have been conducted, but still there is uncertainty on explanation of the process of failure and post-failure (Spickermann et al., 2010).

According to Gonghui (2006) there are two types of after failure behavior of landslide in the case of fluidized landslides, the one is flowslide and other is rapid landslide. For the initiation of rainfall-induced fluidized landslides the generation and dissipation of pore pressure considered as dominant key factors. Due to higher density no sudden failure was observed during the current experiments.

The experiments were also conducted on soil slope having less density in flume and different types of soil failure were observed i.e., flowslide, rapid slide and retrogressive slope failure. The experiments were conducted on soil slope under loose conditions

(poorly compacted). The variations in pore pressure and moisture content in the slope under different depths and densities with different rainfall intensities as given below.

The experiment was conducted on soil slope with the thickness of 30 cm with rainfall intensity of 8 $\mathrm{L\,min^{-1}}$. After the starting of the rainfall the erosion was observed, when rainfall was continue the cracks were appeared on the toe first and then progressed on the top of the slope, the width of cracks increased when rainfall continues. The shear surfaces formed over entire soil mass during the failure stage. The progress of failure events is shown in Fig. 9. As in the field the movements of the flowslide are difficult to monitor because of sudden and rapid occurrence, however by current flume experiments we successfully monitored the movement of the flowslide in addition to monitoring the pore pressure and moisture content with innovative type of sensors.

Measurements of pore pressure and moisture content are shown in Figs. 10 and 11 respectively, due to flowslide the pore pressure suddenly increased. According to Okura et al. (2002), Wang and Sassa (2003), and Moriwaki et al. (2004) the sudden increase in pore pressure is generally related to rapid shearing of soil during intense rainfall. The P1, P2 and the P3 are the piezometers that are placed at the base of the slope. M1, M2, M3 and the M4 represents the moisture sensors, due to large failure the moisture sensors displaced from their position and the uncommon variation in moisture content “M4” was because of such displacement as shown in Fig. 11.

Before the slope failure occurs, cracks appeared at the crest of the slope initially and after that crest of the slope settled and the continuous rainfall trigger the flowslide or small slide and then stopped. Detecting this type of settlement is helpful in building the early warning system of the slope failure. In this case when large flowslides occur the whole slope mass flow towards the downslope within very short duration (1 to 2 s).

The slope failure can be initiated from any part of the slope due to increase in moisture results increase in weight of the slope. The mode of the slope failure influenced the pore pressure value as also observed by Deangeli (2009) who performed the experiments in flume to investigate the pore pressure during debris flow initiation. The slope failure behavior can be influenced by mode of initiation, density and rainfall intensity.

When the slope initiated above the toe of the slope, initially cracks were observed over that area after that sliding mass formed, that moved rapidly downwards due to effects of gravity and continuous rainfall infiltration and failed mass accumulated at horizontal part of slope, and again new sliding mass displace the accumulated soil mass at the horizontal part of the slope, this will continues till that rainfall infiltration and remaining soil mass above the toe of the slope.

The flowslide is the type of slope failure that occurs suddenly and very rapid, and may occurs in both natural as well as man-made slope and most of flowslide is due to rainfall. The geometry of model slope was changed when there is sudden movement of failure downwards that increased the rate of seepage from top towards toe and increases the compressive stresses at the toe, resulting in increase in pore pressure. After the flowslide the space is formed at the upstream of the slope that favor input of the runoff that increase the water level at bottom level of slope, that further increase the seepage force and pore pressure that trigger the further flowslide. As long as the gradient of the slope is steep the motion of sliding continues, and at the boundary between sliding earth mass and at the ground liquefaction continues (Takahashi, 2007).

The moisture sensors that inserted for moisture measurement that also displaced from their positions due to flowslide together with failure mass. The slope failure may be initiated at middle or upper part of the hillslope, not necessary at the toe of the slope. In one of the experiment the cracks appeared at the mid of the slope, and after that 10 to 15 cm thickness of soil layer slide from mid of the slope (Wieczorek, 1987; Tohari et al., 2007).

The Figs. 12 and 13 show the variations in the pore pressure and the moisture content, the pore pressure increased rapidly after keeping the constant value, and the P2 was located at the toe of the slope. The P2 increased after the 24 min of the rainfall, while the P1 increased after 28 min of the rainfall. The sudden increase in pore pressure was related with the flowslides. The depth of the slope was 50 cm and rainfall intensity was 4 $\mathrm{L\,min^{-1}}$. In the case of loose soil slope the pore pressure and moisture response are fast as compared to dense slope. The pore pressure increased during

the flowslide because loose soil slope having the larger capacity of holding the water. The Fig. 14 shows the slope after failure.

6 Discussions

Numbers of experiments were conducted apart from discussed above in the flume by measurement of pore pressure, moisture content. Numbers of studies have already been carried out to obtain the characteristics of the pore pressure changes and the deformation characteristics of soil from instrumented slope. During rainfall the changes in pore pressure associated with soil deformation were recorded in instrumented slope. However the collecting the reliable data from instrumented slope is practically difficult, because the deformation in the slope is too small to be accurately measured (Melinda et al., 2004). For the current experiments the pore pressure was measured during the pre-failure and the post-failure during that large deformation and movement in the slope occurred.

As large amount of the soil was used in experiments, so after the each experiment the soil was removed from model flume. After that soil was air dried and mixed properly and then used for new experiment. Form the experimental results it was observed that sandy model slope failed easily during continuous rainfall infiltration. The failure source was only rainfall infiltration for current experiments on model slope. This was due to majority of slope failures are because of rainfall.

The instability of slope observed in different failure phenomena (slope failure, or erosion like phenomenon), which turns into different flow-like mass movements (Cascini et al., 2011). The mode of the failure significantly influenced by initial density, pore pressure distribution, hydraulic conductivity and rainfall intensity (Sharma and Konietzky, 2011). For the current experiments that were conducted in laboratory flume the slope failures were consist of different combination of failure events, in some events initially small sliding was occurred and after that retrogressive blocks detached from the slope, however in some cases initially retrogressive block detached from the slop and then small sliding was occurred. Moreover in some cases only small sliding movement was observed and then movement ceased quickly.

From the experiments it was observed that the density of the soil slope plays an important role in the initiation of flowslide, with high density of soil slope even the higher rainfall intensity did not trigger the flowslide, however higher rainfall intensity in dense conditions initiate the debris flow after the formation of erosion gullies. Even in same experiment under same conditions except difference in density, one portion of slope slide due to smaller density, however other portion of the slope remained stable due to higher density.

For the initiation of the flowslide the development of pore pressure is not important as compared to increase in the moisture content, as in may experiments the flowslides were occurred without increase in the pore pressure. According to Eckersley (1990) who conducted the laboratory model test and observed that pore pressure increase is the result rather than cause of flowslide. The sudden increase in pore pressure suggesting that static liquefaction occurring (Damiano et al., 2008). The experiments that were conducted on loose soil slope demonstrated that higher moisture content at toe and mid of the slope responsible for initiation of the flowslide. The higher pore pressure and long run out distances observed in the case of loose soil (Acharya, 2011). The higher density at the toe of the slope also prevent long run out distances.

The phenomenon of flowslide varied greatly depending upon the initial soil density. During the flowslide the excess pore pressure was observed, this was due to rapid shearing of soil slope. The continuous rainfall infiltration and effect of gravity convert the small failure into flow type of failure. Due to plenty of moisture the failed soil mass shows the high mobility during movement.

The moisture increased in two steps to reach the saturation, and the most of the slope failure occurred during the transition of increase from end of first step to starting of the second step. However the piezometers measurement helpful in post-failure behavior as after the failure the sudden increase in pore pressure which can be reference for failure type, as higher or sudden increase shows the flowslide or rapid slide, and

steady increase in pore pressure as progressive type of the failure. The pore pressure is smaller at the shallow depths as compared to base of the slope. The pore pressure increased first at the toe of the slope and then at upper parts of slope.

7 Conclusions

The current study was an effort to better understand the mechanism of rainfall-induce slope failure by laboratory experiments in model flume. For investigation of rainfall-induced slope failure various approaches are used such as numerical simulation, field studies and laboratory experiments. Form these the laboratory experiments considered as best approach, because field studies are expansive and time consuming, while the numerical simulations requires lot of data and also a problem of reliability.

The number of experiments were conducted on model slope with measurements of pore pressure and moisture content. In this study more importantly attempts have been made to determine the controlling parameters of flowslide, the major parameters that changed during the experiments includes density and the rainfall intensity. From the detailed experiments it was observed that density of soil slope is the more important factor that control the initiation of flowslide type of the failure. However the rainfall intensity have significant influence on movement of flowslide, generation of pore pressure and increase in moisture content. In same experiment due to difference of density one part of slope slide due to lower density and other part did not slide due to higher density. Higher the intensity of rainfall higher will be erosion rate, and due accumulation of high sub-surface flow at the toe, the runoff was developed that softens and erode the toe of the slope. Then instability progressed to upper part of the slope due to continuous rainfall infiltration. Before the flowslide occurrence the settlement occurred at the crest of the slope, the reason may be due to small movement at the toe of the slope. The flowslide occurred very soon after observing the settlement at the toe of the slope.

The development of pore pressure is significantly affected by rainfall intensity and antecedent moisture conditions. The water level increased early due to higher rainfall intensity that increase the pore pressure, and due to antecedent moisture conditions the pore pressure develops quickly as compared to dry slope. The pore pressure is also significantly affected by mode of failure i.e., steady failure results steady rise in pore pressure, due to rapid slide and flowslide type of failure the abrupt increase in pore pressure due to rapid shearing and compression. The pore pressure and moisture content is higher at the toe of slope and smaller at the upper parts of the slope. By installing the moisture sensors at toe on the shallow depth the slope failure can be predicted. As the moisture sensors at the shallow depths measure the moisture content in two steps and moisture increased gradually soon after the starting of the rainfall. The measurement of the pore pressure is not reliable for early warning systems as flowslide can be occur before development of pore pressure, and pore pressure not increased before the slope failure. However measurements of moisture content may be useful for early warning of slope failure.

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References

Acharya, G.: Analysing the Interactions between Waterinduced Soil Erosion and Shallow Landslides, PhD thesis, Civil and Natural Resources Engineering, University of Canterbury, Canterbury, 2011

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

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

Brand, E. W., Premchitt, J., and Phillipson, H. B.: Relationship between rainfall and landslides, in Hong Kong, in: International Symposium on Landslides, Toronto, Canada, 377–384, 1984.

Cascini, L., Cuomo, S., and Della Sala, M.: Spatial and temporal occurrence of rainfall-induced shallow landslides of flow type: a case of Sarno-Quindici, Italy, Geomorphology, 126, 148–158, 2011.

Chae, B.-G., Lee, J.-H., Park, H.-J., and Choi, J.: 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, doi:10.5194/nhessd-3-791-2015, 2015.

Chen, R.-H., Kuo, K.-J., and Chien, W.-N.: Failure mechanism of granular soil slopes under high intensity rainfalls, J. GeoEng., 7, 21–31, 2012.

Damiano, E., Greco, R., Guida, A., and Olivares, L.: Early Warning of Fast Landslides Triggering Based on Instrumented Slope Data Analysis, presented at the International Congress on Environmental Modelling and Software, Barcelona, 2008.

Deangeli, C.: Pore water pressure contribution to debris flow mobility, Am. J. Environ. Sci., 5, 487–493, 2009.

De Wrachien, D. and Brebbia, C. A.: Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows III, WIT Press, Southampton, UK, 2010.

Eckersley, D.: Instrumented laboratory flowslides, Geotechnique, 40, 489–502, 1990.

Fang, H., Cui, P., Pei, L. Z., and Zhou, X. J.: Model testing on rainfall-induced landslide of loose soil in Wenchuan earthquake region, Nat. Hazards Earth Syst. Sci., 12, 527–533, doi:10.5194/nhess-12-527-2012, 2012.

Fang, W. and Esaki, T.: Rapid assessment of regional superficial landslide under heavy rainfall, J. Cent. South Univ. T., 19, 2663–2673, 2012.

Gallage, C., Jayakody, S., and Uckimura, T.: Effects of slope inclination on the rain-induced instability of embankment slopes, in: Proceedings of the Second International Conference on Geotechnique, Construction Materials and Environment, Kuala Lumpur, Malaysia, 196–201, 2012.

Gevaert, A. I., Teuling, A. J., Uijlenhoet, R., DeLong, S. B., Huxman, T. E., Pangle, L. A., Breshears, D. D., Chorover, J., Pelletier, J. D., Saleska, S. R., Zeng, X., and Troch, P. A.: Hillslope-scale experiment demonstrates the role of convergence during two-step saturation, Hydrol. Earth Syst. Sci., 18, 3681–3692, doi:10.5194/hess-18-3681-2014, 2014.

Iverson, R. M., Reid, M. E., and LaHusen, R. G.: Debris-flow mobilization from landslides, Annu. Rev. Earth Pl. Sc., 25, 85–138, 1997.

Johnson, K. A. and Sitar, N.: Hydrologic conditions leading to debris-flow initiation, Can. Geotech. J., 27, 789–801, 1990.

Kim, J., Jeong, S., Park, S., and Sharma, J.: Influence of rainfall-induced wetting on the stability of slopes in weathered soils, Eng. Geol., 75, 251–262, 2004.

Kitamura, R. and Sako, K.: Contribution of soils and foundations to studies on rainfall-induced slope failure, Soils Found., 50, 955–964, 2010.

Liu, Z.-Z., Yan, Z.-X., Duan, J., and Qiu, Z.-H.: Infiltration regulation and stability analysis of soil slope under sustained and small intensity rainfall, J. Cent. South Univ. T., 20, 2519–2527, 2013.

Melinda, F., Rahardjo, H., Han, K., and Leong, E.: Shear strength of compacted soil under infiltration condition, J. Geotech. Geoenviron., 130, 807–817, 2004.

Mokhtar, K. H., Lateh, H., and Salwa, K.: Towards community-based landslide preparedness in Malaysia, J. Environ. Sci. Toxicol. Food Technol., 1, 1–9, 2012.

Moriwaki, H., Inokuchi, T., Hattanji, T., Sassa, K., Ochiai, H., and Wang, G.: Failure processes in a full-scale landslide experiment using a rainfall simulator, Landslides, 1, 277–288, 2004.

Okada, Y.: Changes in shear strain and subsurface flow prior to rainfall-induced landslide in flume experiments, in: Landslide Science for a Safer Geoenvironment, edited by: Sassa, K., Canuti, P., and Yin, Y., Springer International Publishing, Switzerland, 81–86, 2014.

Okura, Y., Kitahara, H., Ochiai, H., Sammori, T., and Kawanami, A.: Landslide fluidization process by flume experiments, Eng. Geol., 66, 65–78, 2002.

Olivares, L. and Picareelli, L.: Proceedings of the 6th ICPMG '06' International conference on physical modelling in Geotechnics, 2–4 August 2006, Hong Kong, Taylor & Francis/Balkema, Leiden Netherlands, Vol. 1, 99–113, 2006.

Orense, R. P., Shimoma, S., Maeda, K., and Towhata, I.: Instrumented model slope failure due to water seepage, J. Nat. Disaster Sci., 26, 15–26, 2004.

Rahardjo, H., Ong, T., Rezaur, R., and Leong, E.: Factors controlling instability of homogeneous soil slopes under rainfall, J. Geotech. Geoenviron., 133, 1532–1543, 2007.

Ray, R. and Jacobs, J.: Relationships among remotely sensed soil moisture, precipitation and landslide events, Nat. Hazards, 43, 211–222, 2007.

Ray, R., Jacobs, J., and de Alba, P.: Impacts of unsaturated zone soil moisture and groundwater table on slope instability, J. Geotech. Geoenviron., 136, 1448–1458, 2010.

Reddi, L. N.: Seepage in Soils, Principles and Applications, Wiley, USA, 2003.

Segoni, S., Battistini, A., Rossi, G., Rosi, A., Lagomarsino, D., Catani, F., Moretti, S., and Casagli, N.: 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, doi:10.5194/nhessd-2-6599-2014, 2014.

Sharma, R. H. and Konietzky, H.: Instrumented failure of hillslope models with soil-pipes, Geomorphology, 130, 272–279, 2011.

Spickermann, A., Malet, J. P., v. Asch, T. W. J., and Schanz, T.: Analysis of hydrological triggered clayey landslides by small scale experiments, Geophys. Res. Abstr., 12, GU2010-4749, 2010.

Takahashi, T.: Debris Flow, Mechanics, Prediction and Countermeasures, Taylor & Francis, UK, 2007.

Terlien, M. T. J.: The determination of statistical and deterministic hydrological landslide-triggering thresholds, Environ. Geol., 35, 124–130, 1998.

Tohari, A., Nishigaki, M., and Komatsu, M.: Laboratory Rainfall-Induced Slope Failure with Moisture Content Measurement, J. Geotech. Geoenviron. Eng., 133, 575–587, 2007.

Tohari, A., Nishigak, M., and Komatsu, M.: Laboratory rainfall-induced slope failure with moisture content measurement, J. Geotech. Geoenviron., 133, 575–587, 2007.

Tsutsumi, D. and Fujita, M.: An Experiment and Model Simulation on Multi-phased Landslide, presented at the The 3rd International Workshop on Multimodal Sediment Disasters Japan, Takayama City, 2012.

Wang, G.: An experimental study on the mechanism of fluidized landslide – with particular reference to the effect of grain size and fine-particle content on the fluidization behavior of sands, PhD thesis, Kyoto University, Kyoto, 2000.

Wang, G. and Sassa, K.: Factors affecting rainfall-induced flowslides in laboratory flume tests, Geotechnique, 51, 587–599, 2001.

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

Wieczorek, G. F.: Effect of rainfall intensity and duration on debris flows in the central Santa Cruz Mountains, California, Geological Society of America, USA, 1987.

Zhang, G., Li, D., Zhao, B., and Qian, Y.: Analysis of change rule of moisture content for soil-slope under rainfall infiltration, in: Soil Behavior and Geomechanics, American Society of Civil Engineers, Shanghai, China, 214–223, 2014.

Zhou, Z., Wang, H.-G., Fu, H.-L., and Liu, B.-C.: Influences of rainfall infiltration on stability of accumulation slope by in-situ monitoring test, J. Cent. South Univ. T., 16, 297–302, 2009.

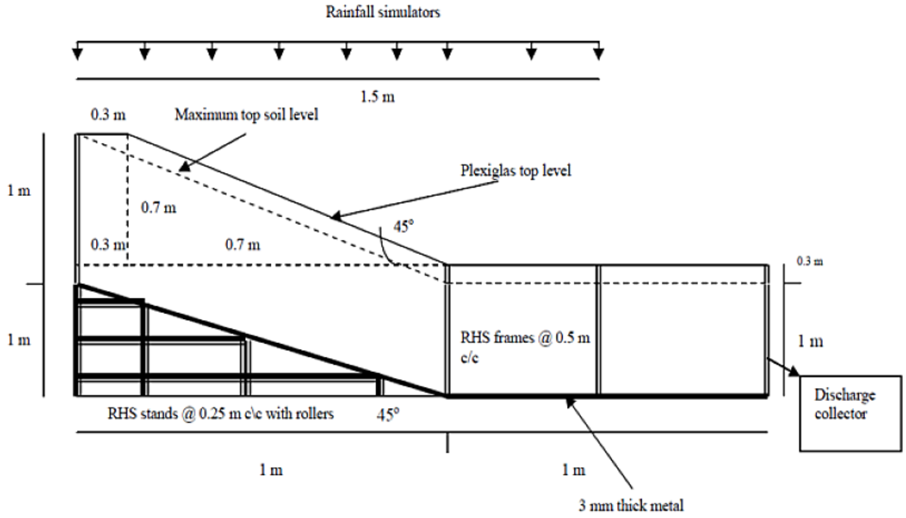

Figure 1. Side view of laboratory flume.

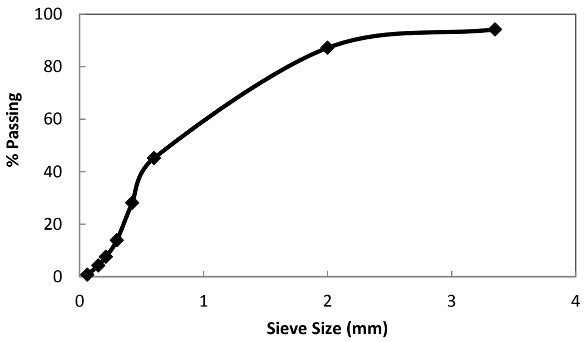

Figure 2. Particle size distribution curve.

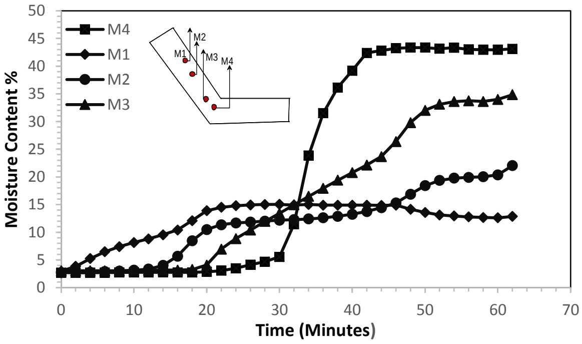

Figure 3. Moisture content variation with time (minutes), rainfall intensity = 3 L min^{-1}.

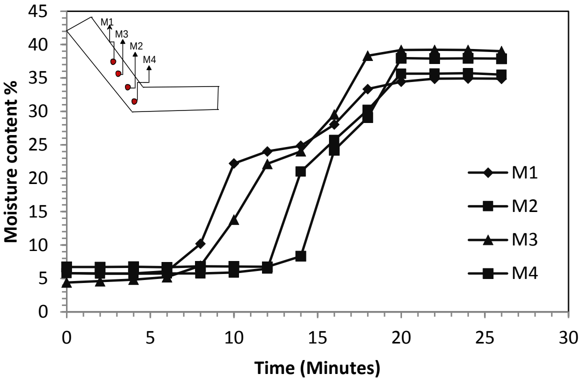

Figure 4. Moisture content variation with time (minutes), rainfall intensity 10 L min^{-1}.

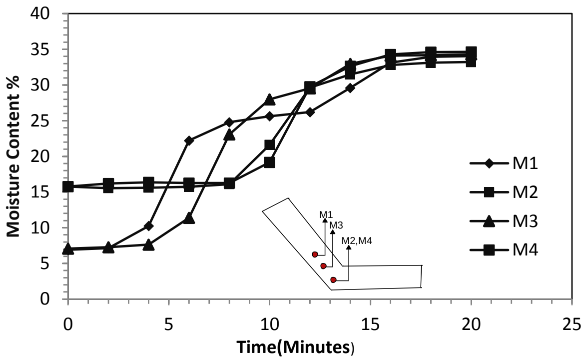

Figure 5. Moisture content variation with time (minutes), rainfall intensity 8 L min^{-1} (antecedent moisture conditions).

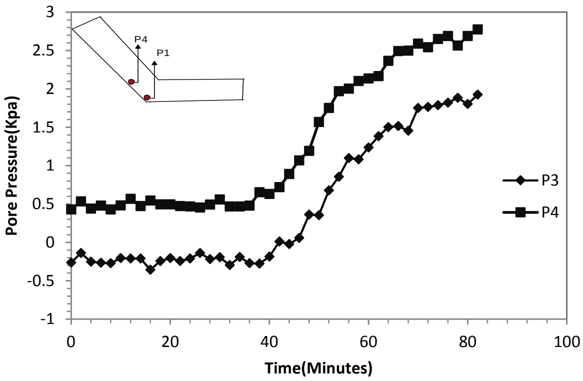

Figure 6. Pore pressure with time (minutes) variation rainfall intensity of 3 L min^{-1}.

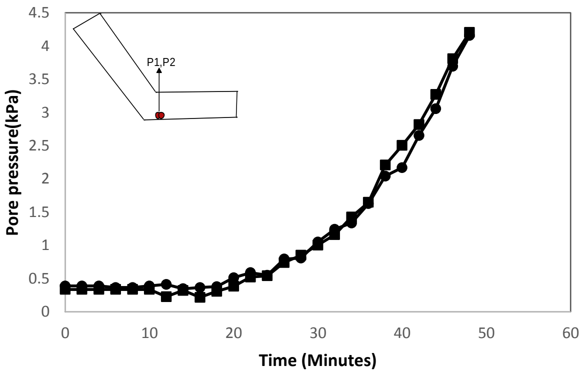

Figure 7. Pore pressure with time (minutes) variation rainfall intensity of 8 L min^{-1}.

Figure 8. Failure at the toe of the slope and runoff at the toe (dense slope).

Figure 9. Failure events before the flowslide.

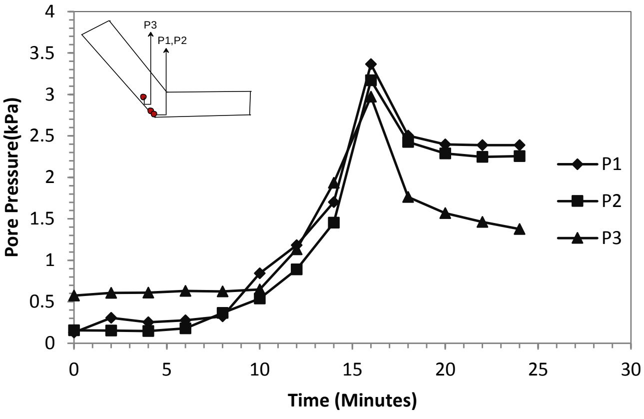

Figure 10. Pore pressure variations, rainfall intensity 8 L min^{-1}.

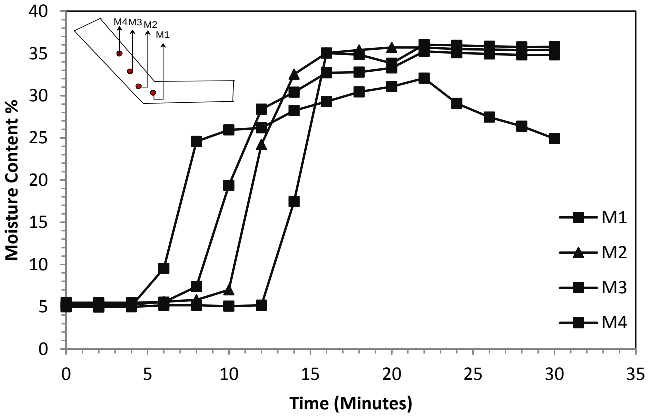

Figure 11. Moisture content variations 8 L min^{-1}.

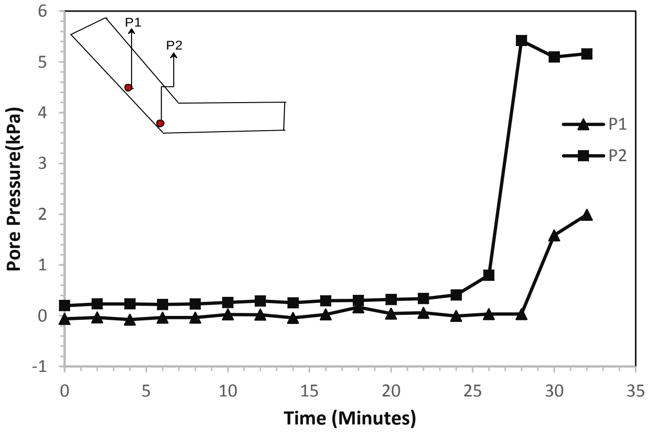

Figure 12. Pore pressure variations, rainfall intensity 4 L min^{-1}.

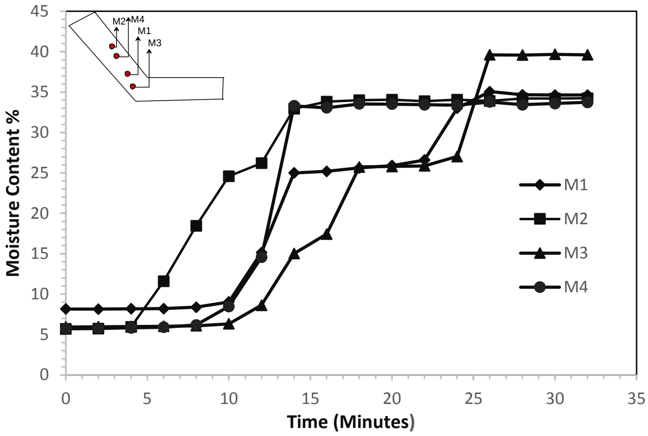

Figure 13. Moisture content variations, rainfall intensity 4 L min^{-1}.

Figure 14. Slope failure (flowslide).

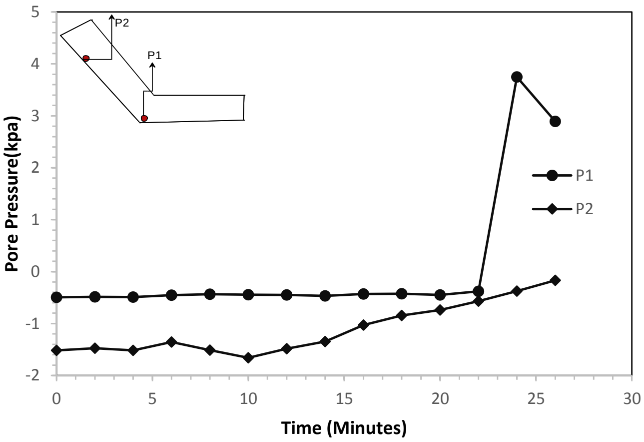

Figure 15. Pore pressure variations, rainfall intensity 5 L min^{-1}.

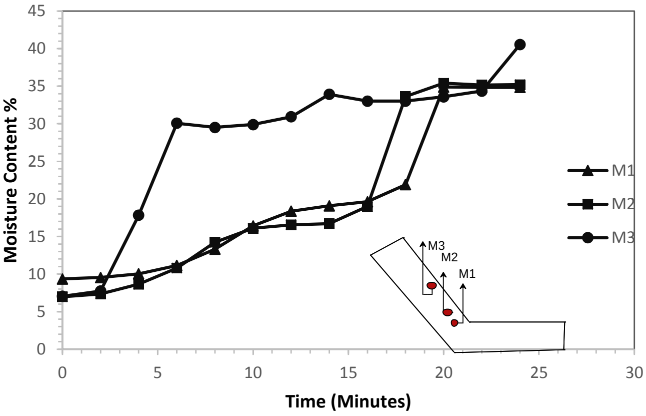

Figure 16. Moisture content variations, rainfall intensity 5 L min^{-1}.

Figure 17. Slope failure (flowslide).